THE PROPOSED CORNELL 10 GeV ELECTRON SYNCHROTRON*

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Electrons are difficult to accelerate to high energy in a synchrotron because of the rapid increase of the radiation loss with energy, i. e.,

$$E_r = 88.5 E^4_{\text{GeV}} / R_{\text{meters}}, \qquad (1)$$

where E_r is the loss per turn in keV. A more relevant quantity than this, however, is the ratio of the total energy lost by radiation during the acceleration cycle to the total energy given to the particles. This is found by integrating (1) over the acceleration cycle with the result:

$$\frac{E_{\text{total rad.}}}{E} = 1.6 \times 10^3 \frac{E^3}{\omega R^2}, \qquad (2)$$

assuming that the magnetic field varies as sin ωt. It is clear from this that the relative amount of energy radiated can be kept in bounds by choosing a sufficiently large orbit radius. As an example, about twice as much energy will be radiated as would be stored by the electrons in a synchrotron of 100 m radius capable of giving a final energy of 8 GeV — the magnet operating at 60 Hz. For 10 GeV in the same machine, the ratio would be about four, and the ratio would be about fifteen if the energy were to reach 15 GeV. Considering resistive losses in the cavities, these radiation losses cannot be considered prohibitive.

We do propose to build a magnet with an orbit radius of 100 m at Cornell University. Although this radius is rather large, we are attempting to simplify the construction so that the effort involved is not greatly different than that of the present 2 GeV electron synchrotron. Now, one happy result of making the radius large is that the power of the magnet is thereby reduced. This is roughly true for a strong focusing magnet in which it is assumed that the magnet opening is kept constant. The crude argument for this proceeds as follows: the magnetic field required for a particular energy varies as $1/R$; the stored energy in the magnet is proportional to the magnetic field squared times the peripheral length; hence the stored energy will vary as $1/R^2$ times R or as $1/R$. For our proposed magnet, the field corresponding to 10 GeV is 3.3 kGs and the magnet-power required might be about 200 kW which would be about the same as that of our 2 GeV synchrotron.

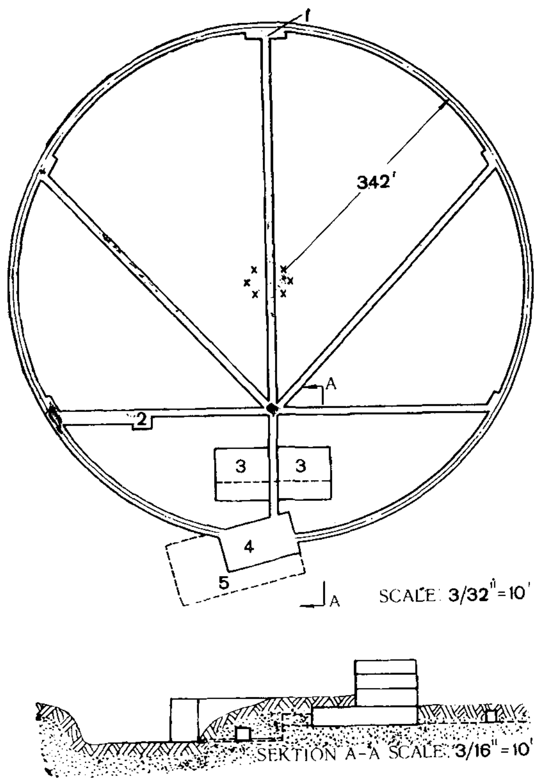

Fig. 1. The plane view of accelerator:
1 — 40′ straight section; 2 — linac; *3* — laboratory building; *4* — experimental room; *5* — concrete slab.

The magnet itself is designed with the idea that it be passive and simple. The experiments and operations are to be located at one side of the magnet ring as shown in Fig. 1, and it is hoped that once the magnet is installed then a minimal amount of attention and servicing

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need be given to it. The ring consists of 192 identical magnets of the kind shown in Fig. 2. Each is 10.7 feet long and is straight. In cross section, the magnet is about 8 × 12″; the gap is 1 inch; and the coil is embedded in epoxy within the H-shaped magnet. There is to be no donut; rather, each magnet is to be enclosed in a vacuum-tight sheath made of 20 mil thick stainless steel that is folded around the magnet and then welded tight. This cover extends out to where it is welded to stainless steel endplates, thereby enclosing the coil ends.

The lattice consists of 48 repetitions of the basic form OFOODO where O stands for a region of no focusing, *F* for a region of focusing, and *D* for a region of defocusing. Two long straight sections, each 40 feet long, of the type suggested by Collins, are inserted in the ring as shown in Fig. 1. Four other straight sections, each of which is 20 feet long, are also inserted as shown, and in these injection and RF acceleration will be made. The 40-foot long sections are to be reserved for research using the circulating electron beam. Two of the basic magnets

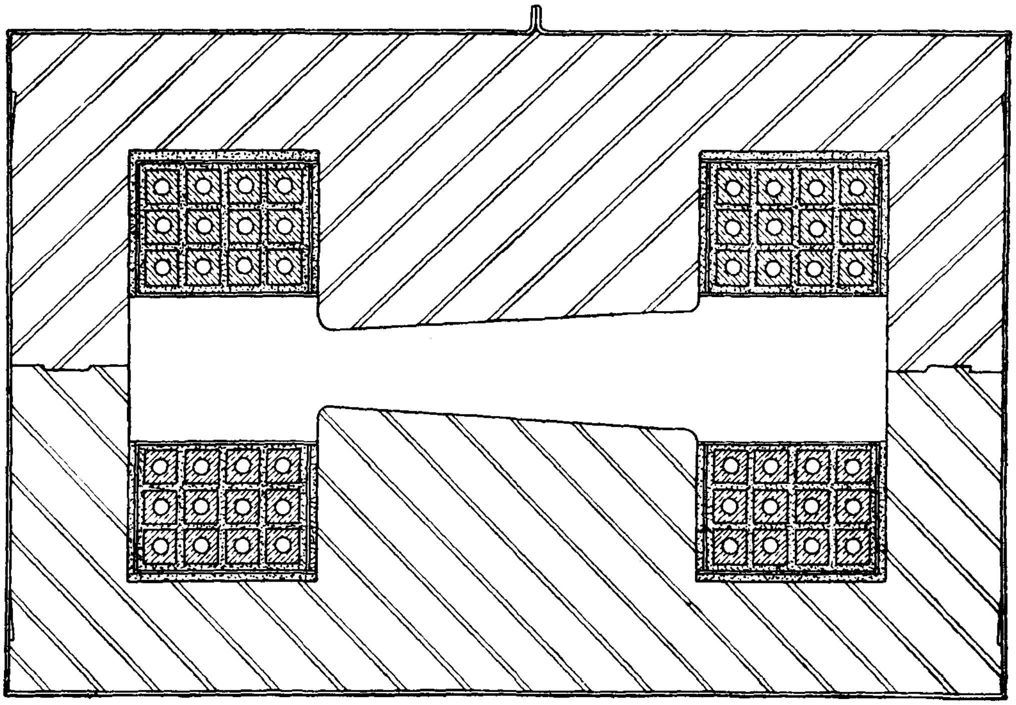

Fig. 2. The magnet cross-section.

The coils are first fabricated and epoxy-impregnated as independent units; then they are placed in the magnet and vacuum-potted again. This ensures that the copper of the coils is enclosed at all points by epoxy, thereby minimizing the possibility of breakdown through vacuum paths. The coil leads all come out through vacuum-tight ceramic seals at one end of the magnet. The units are not large; each one weighs about one ton. A preliminary model of one of these magnet units has been built: it is full scale in the radial and vertical direction but it is three feet long instead of ten feet. A photograph of this model is shown in Fig. 3.

already described are placed directly together to produce a focusing unit, *F*; a defocusing unit, *D*, is made up of two of the same magnets but in a reverse position. Except at the long straight sections, the distance between magnets will be kept minimal: just enough room bein gallowed for a device to measure the beam position and to install vacuum connections, hopefully 20 or 30 cm. Each of the long straight sections will contain two quadrupole lenses — one focusing, the other defocusing. The number of betatron oscillations per turn will be 10.4; the period of radial and vertical oscillations being the same.

The injector is to be a commercially-built 200 MeV *L*-band linac that can be expected to yield about 10^{12} electrons in a one percent momentum interval. The magnetic field at injection corresponding to this injection energy will be 53 Gs. Single turn injection is envisaged, hence the pulse length of the linac should be about 3 μs. The momentum spread of one percent will produce a calculated 3 cm radial spread in the beam. The size and angular divergence of the linac beam, 2×10^{-4} rad, and should produce a further betatron oscillation of about one cm. We should add to this a sagittal excursion of 1.5 cm because the magnet is straight whereas the orbit is curved. Magnet misalignments of the order of 10 mils can be expected to produce beam oscillations of about one cm. Adding all this together linearly would indicate a horizontal beam size of about 6.5 cm — a rather tight fit in the 3 inches of radial aperture that is to be provided. Similar considerations would indicate that the beam height might be about one cm which must be confined within the 1-inch vertical aperture. We hope for a beam of about 10^{11} electrons per pulse.

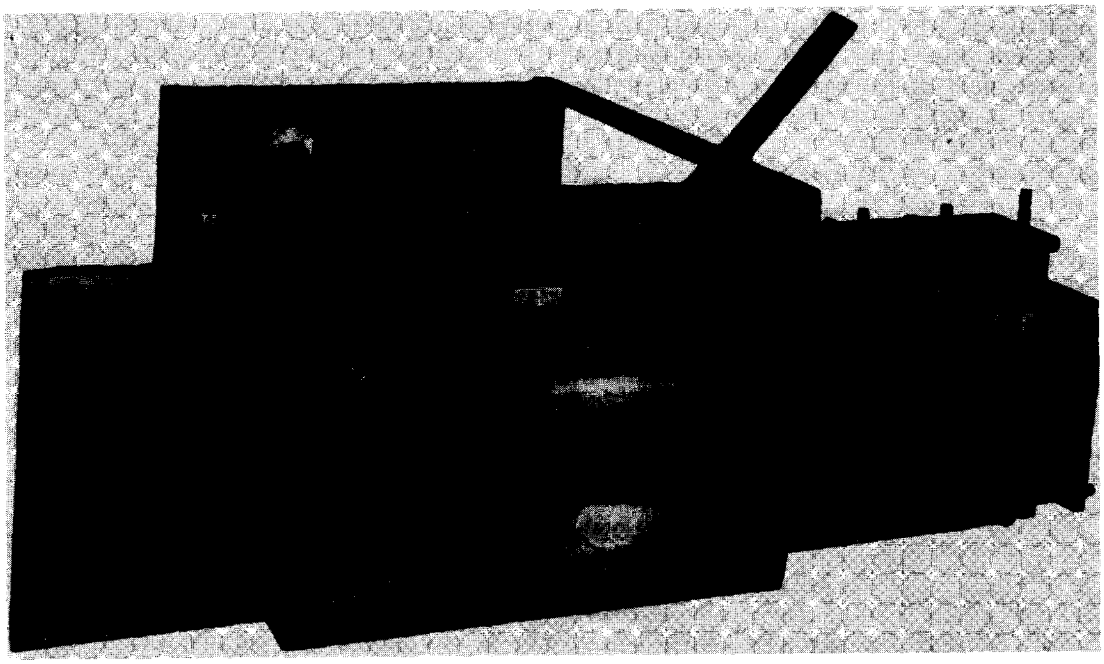

Fig. 3a. Preliminary model of the magnet unit.

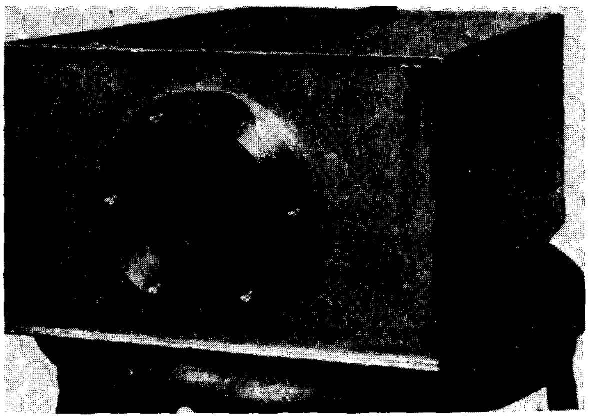

Fig. 3b.

Space is allowed to add additional stages to the linac if experience so indicates. We will also incorporate the possibility of placing a radiator or converter in the linac so that, by a 180°phase change at the position of the converter, a beam of positrons can also be injected into the synchrotron.

The orbit circumference as shown in Fig. 1 is 697 *m* which corresponds to an orbiting period, T, of 2.32 μs for the electrons which corresponds to a basic orbiting frequency of 0.43 MHz. The energy per turn given to the electrons by the RF cavities is partly that required for the acceleration of the electrons and partly that required to compensate for radiation loss. The first part dominates in the early part of the cycle and is given by 4.4 sin θ in MeV/turn where $\theta = \frac{\pi t}{T}$, T being the acceleration time, 8.3 ms. The radiation part is given by $8.8 \sin^8 \frac{\theta}{2}$ and is peaked at the end of the cycle. The maximum energy per turn required during the acceleration reaches a maximum value of about 10 MeV/turn at θ = 165°. Asynchronous phase angle of 65° should be sufficient to keep particle losses due to quantum fluctuations in the radiation rate within bounds, and this implies a maximum total cavity voltage of some 10.5 MV. One solution to this RF requirement is to adopt the system now in use with the present Cambridge 6 GeV synchrotron (CEA). We would install twice as many cavities, i. e. 32 double cavities, which should make possible a peak voltage of 12.8 MV.

Although this system would incorporate twice the number of cavities as the CEA system, the electrons will make fewer turns in our magnet and hence the RF power required would be reduced. For a beam of 10^{11} electrons per pulse, the average power going into the beam would be 18 kW and an average power being dissipated in the cavities can be expected to be about 50 kW. The total power demand would thus be under the 100 kW capability of the present CEA transmitter. The peak instantaneous power demand would be about 300 kW, also well within the 400 kW peak rating of the CEA supply.

As an alternative method, we are investigating the possibility of using a section of linac accelerator operating at the same frequency (L band, 1600 MHz) as the linac injector. It appears that the necessary voltage could be developed in two standard sections each of which is about 10 feet long and which could be placed in one of the 20-foot straight sections. An attractive feature of using this system is that the injected beam is already bunched; hence, if the two systems are properly synchronized, no beam loss need occur at injection. We expect to test the feasibility of this kind of RF system in our 2 GeV electron synchrotron.

An unusual feature of the large radius is that the period of the synchrotron phase oscillation is comparable to the period of revolution of the electrons. The synchrotron oscillation period, given by $(2\pi E/k\alpha V \cos\Phi_s)^{1/2}$ turns per oscillation where k is the harmonic order of the RF oscillator and α is the momentum compaction pdr/rdp, will be about 6 turns per oscillation for the proposed magnet at the time of injection.

Now, turning to the vacuum system, because of the high injection energy, scattering of the electrons by the gas is no longer a dominant effect in giving rise to beam loss. Instead, the principal loss is due to bremsstrahlung from the residual gas. The momentum acceptance of the accelerator is about 1%; therefore, a bremsstrahlung energy loss of 1% or greater will cause an electron to be lost. We need only compute the total path of the electron in radiation lengths from the time it is injected until it strikes the target in order to calculate the loss. For air the fractional loss is given by $6tP_{\mu}$, where t is the time of acceleration and P is the pressure in microns of Hg. For a pressure of one micron and for an 8 ms acceleration time, the loss would be about 1%. The prototype magnet shown in Fig. 3 was found to pump down to a pressure of one micron immediately. After pumping several hours the vacuum would go as low as 10^{-5} mm Hg. Hence, the vacuum in the magnet does not seem to present a serious problem.

In the neighborhood of the RF cavities, the pressure should not be greater than about 10^{-6} mm Hg to avoid electrical breakdown across the gaps. Since the cavities are to be located at only a few places around the ring, this low pressure need obtain over only a small fraction of the circumference.

DISCUSSION

A. A. Kolomenskiĭ

Prof. Wilson was led to the decision in favor of reducing the magnetic field and increasing the radius (for a given energy). They were illustrated by the example of supply power equality for 2 and 8 GeV accelerators and other examples.

It seems to me that in principle, these considerations may not only be applied to electron accelerators but also proton accelerators, although even in the latter case, it is usually not dictated by the presence of radiation.

R. R. Wilson

It does apply to a proton synchrotron too. If you have sufficient real estate make the accelerator big.

W. K. H. Panofsky

According to Wilson's arguments, by making R become infinitely large, the cost becomes zero.

R. R. Wilson

Yes, and the proof of it is that cosmic rays are free!

R. R. Wideröe

How long time will it take to build the machine?

R. R. Wilson

We would expect to use about 3 years to make the magnet and have it work at very low energy — 1 or 2 GeV — and then we would expect to use many years to solve the RF problem and bring it up to high energy.

S. A. Kheĭfets

Up to the present time, an estimate of the costs of linear and ring electron accelerators usually reduces to the conclusion that there is great economy with linear accelerators for energies in the region of 10 GeV and above. I wish to exploit the fact that Prof. Wilson and Prof. Panofsky agree and to request them to tell me what the situation is at the present time. What accelerator is most economical in the region of energies of the order of 10 GeV?

W. K. H. Panofsky

For comparable intensities the intersection in the cost curves of the electron synchrotron and that of the electron linear accelerator is well above 10 GeV. Linear accelerators now built have about two orders of magnitude higher intensity, however.