PRESENT DAY ELECTRON SYNCHROTRONS FOR ENERGIES ABOVE 3 GeV.

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Summary

The characteristics of five accelerators designed for energies exceeding 3 GeV are discussed. The features of the Cornell 10 GeV machine are described in some detail.

There are now in the world a total of 5 electron synchrotrons under construction or operating which have a design energy exceeding 3GeV. These are, in order of their energy, the British machine Nina at Daresbury, The Cambridge Electron Accelerator, Cambridge, the Russian machine at Eravan, the German Machine DESY at Hamburg, and the Cornell machine at Ithaca. Of these, the accelerators at Erevan and Cornell are not yet complete. Table I gives some comparative information concerning these machines.

On scanning this tabulation, we find a broad similarity of the characterists of most of the machines. With the exception of Nina, the current ratings are about 10^{11}/pulse. Injection fields are about 50 gauss, and the orbit radius is such that the field strength at full energy is less than 8,000 gauss. This reflects the limitation on energy due to the energy lost in synchrotron radiation. This energy loss per turn goes like E^4/R and some relief can thus be obtained by going to larger radius. Though it may seem at first sight that this could cause an over all increase in the cost for the magnet, this is not necessarily so, since the maximum field required, the total mass of iron and copper and the total power all decrease with a larger ring diameter. The principal factor increasing the cost of the machine as a result of the large radius is the increased length of tunnel, the tunnel supply facilities and the inconvenience of working with a machine of large radius. There is also a slow decrease in acceptance aperture for constant physical aperture of the machine.

One thing has become quite clear in the years since the advent of the strong focussing machine. With increased experience we have found that there are a wide variety of working choices possible for the lattice of an accelerator. Without serious loss, one may design a lattice for a wide range of combinations of straight sections and magnet lengths.

The two main problems of electron synchrotrons are the provision of high energy and high intensity. These two problems are not unrelated, since in order to obtain large voltage per turn, a high shunt impedance for the cavity is desired, while for the high beam currents, because of the out-of-phase voltages induced by the beam in the cavity itself, a low impedance is to be desired. To my knowledge there is not yet a general solution to these problems, though there are partial solutions.

The total captured beam is limited by various factors: injected beam current, phase space, injection energy, space charge, RF loading at injection time. It does not now seem to be difficult to provide all the injected current which can be accomodated by the RF system. At injection time, the RF loading is particularly bad. To minimize this difficulty, it has been found useful to reject those electrons from the injected beam which would be lost in the capture process. This can be done by making the Linac injector a harmonic of the RF system, which must be a harmonic of the orbital frequency. The injector may then be modulated and bunched so that only those electrons in an acceptable RF phase are admitted to the ring.

Various schemes may be tried to limit the deleterious effect of beam loading on the RF. One may try by some device to lower the "Q" of the cavity system. Another possibility is to detune the cavity at injection time so that the out-of-phase driving currents balance the effects induced by the circulating beam. Both of these approaches are being studied.

Various auxiliary facilities are being provided for most synchrotrons. Slow extraction of external electron beams has become quite conventional. Several accelerators now are preparing to provide accelerated beams of positrons of moderate intensity. Recently an experimental study has been undertaken at CEA to convert that accelerator into an e^+,e^- colliding beams device using what is called a "by pass" system. This system has been described in paper F2.

The high quality performance of the existing machines and associated facilities attest to the thoughtful design and careful execution by the builders of these machines. A clear understanding of the basic problems and their practical solution has been demonstrated.

I would like now to switch to a discussion of the Cornell 10 GeV synchrotron which is nearing completion in Ithaca. Because this machine has certain unconventional features which make its characteristics quite different from earlier machines, I will describe it in some detail.

The two features which have radical influence on the details of the design are the orbit radius and the vacuum chamber. As discussed above, a large orbit radius reduces the RF problems for high energy. In the Cornell machine, this is exploited by choosing the magnetic radius to be 100 meters making the magnetic field at the orbit only 3,300 gauss at 10 GeV. This reduces the total weight of copper and iron per unit length of the magnet to a very low value (195 lb/ft) and makes the magnet very small in cross sectional area, (8" x11-1/2").

The distinctive characteristic of the vacuum system is that it is incorporated in the magnet design so that no vacuum "donut" is used in the gap, but instead, the whole magnet is enclosed in a vacuum can. The most important effect of this is that none of the gap height is consumed by donut wall. This may save up to 30 percent in usable gap height and makes it easier to obtain a wide region of good field gradient for a given pole width. It also reduces the required ampere turns which further reduces the magnet weight and power loss.

The physical layout of the accelerator is shown in figure 1. The guide field consists of 192 magnets arranged as shown. They are grouped into six circular sectors separated by straight sections. On one diameter there are two 40 ft. straight sections, while the remaining 4 straight sections are 20 feet long. The average ring diameter is about 800 ft., approximately the size of the Brookhaven AGS. One of the 40 foot straight sections is located in the main experimental hall, while the other is in a cavern located on the opposite side of the ring. These long straight sections are designed to permit access to the circulating beam for experimental purposes.

The RF cavities are located in the four twenty foot straight sections.

The forty foot straight sections are of the Collins type with two small quadrupoles mounted in the center of the gap. The twenty foot sections have special guide field magnets adjacent to the straight sections which permits the gap to be left completely unencumbered. This modification of the Collins idea was devised by D. Edwards. A linac injector of 150 MeV is located inside the ring to provide single turn injection onto the orbit.

The guide field magnets are laid out in a tunnel having a cross-sectional diameter of 10 feet. This tunnel was bored by a tunneling machine about 45 feet under the athletic field at Cornell. It breaks out of the earth on one side into one of Ithaca's gorges. The laboratory building, including experimental hall, linac and services, offices and laboratory space is a structure straddling the ring and nesting into the bank of the gorge. There is area for future expansion of the experimental area.

In figure 2 is shown the profile of the magnet. Each magnet is a single lens built up of 0.014 inch steel laminations stacked into a linear assembly of 11 feet length. The magnet is "H" type and is constructed using laminations which are split in the median plane. Prefabricated, vacuum-potted excitation coils are placed in a loose stacked half magnet and then this assembly is vacuum potted. After the two halves are formed in this way, they are keyed and glued together, and a 0.030" stainless steel vacuum jacket is welded over the whole assembly. The coils are formed of water cooled cable consisting of a 5/16" diameter hollow central copper tube surrounded by 10 insulated strands of #8 copper wire.

In order to optimize the aperture for a given stored energy we chose to make the gap height in the vertically focussing and defocussing lenses of different values, namely 1-1/2" and 1" respectively. This gap is small compared to other machines, partly because of the absence of the donut and partly because the aperture provided is less conservative than in other machines.

As one might expect, because the coils and the iron are contained inside the vacuum jacket of the machine, the vacuum is not as good as expected in an all metal system. However, we have been able to obtain a vacuum of the order of 10^{-6} mm of Hg. We expect the operating pressure to be slightly greater than 10^{-5} mm which should be quite satisfactory for the operation of the machine. The magnets are mounted on an I beam, two per beam. These beams are supported by tables every 25 feet. One oil diffusion vacuum pump is provided at each table.

The chosen lattice is such that 10-3/4 betatron oscillations are made per turn. This means that the magnet alignment is especially sensitive to magnetic distortions corresponding to the 10th and 11th azimuthal oribital harmonics. A conventional high precision survey grid consisting of 36 points was provided, but within this grid, the individual magnets were located by a magnet-to-magnet off-set survey using stretched wires and calibrated bars.

To control the positioning of the magnets, the magnets are mounted with a dynamic support system which is remotely controlled and indicated. This permits the movement of magnets by operation from the control room while there is a beam in the machine. The complete control system for the machine makes use of a multiplex system to control and monitor these and other operations of the machine. This control system is described in detail in paper I-6 submitted to this meeting.

The magnet excitation system is resonant at 60 c/s. The condensers which resonate the inductance of the magnets are distributed about the machine. Figure 3 shows the excitation scheme. The D.C. bias supply is distributed in the six straight sections of the machine. In order to permit the D.C. to by pass the condensers, chokes are used in parallel with each condenser and the whole system is excited by a sinusoidal driving voltage coupled to each of the chokes as shown. The serial arrangement of condensers and magnets maintains the maximum voltage to ground at any one point to be less than 500 volts r.m.s. The total power requirement for 10 GeV operation is only 770 KeV including all losses.

The injector of the machine is an S-band linac designed for a full load voltage of 150 MeV. It can inject up to 2×10^{12} electrons per 2-1/2 microsecond pulse with a momentum resolution of plus or minus 1/2 percent. We expect to capture approximately 10^{11} electrons per pulse with a 60 c/s repetition rate. The injection from the inside of the ring is made using an achromatic single turn pulsed inflector. The complete inflection system consists of 3 fixed field bending magnets, two quadupole pairs and a pulsed magnetic inflector.

The orbit frequency, the accelerating frequency and the linac frequency are multiples of each other. The RF frequency, 714.94 MHz is 1/4 that of the linac frequency, and is 1800 times that of the revolution frequency. Thus the linac may be modulated so that it injects into a running RF in the proper phase to minimize the loss of beam, the consequent loading of the RF cavities and radiation deterioration of the magnet. The RF power is supplied by a multiple cavity which looks like a cross between a linac structure and a conventional cavity. The total RF power required is 134 kW average and 500 kW peak.

Low field steering coils are provided at 50 points on the orbit, while low field gradient corrections may be made at 12 points. Certain corrections of the field at high field can be made by suitable displacements of the magnet positions and this may be supplemented by high field gradient corrections at certain points around the machine.

The behaviour of the beam may be analyzed by 50 position and intensity detectors which are located around the machine. The orbit behaviour may be further studied by inducing suitable beam bumps in the orbit to determine their effect on the orbit.

The first beams which will be obtained from the machine will be photon beams. These will exit through the side wall of guide field magnets which have been modified to provide a channel for the emerging beam. It is anticipated that within a short time after the machine begins operation a program will be initated to obtain an external electron beam. Several other items are being considered for further development. It is anticipated that an electrical modification to the magnet excitation circuit will eventually provide a flat top to the acceleration cycle. This is useful in extending the practical duty cycle from about 1/15 to as much as 1/3. Radiation undamping may make this difficult at the top energy of the machine but may be overcome by special damping fields of the sort proposed by K.W. Robinson.The linac arrangement has been designed to permit installation of a positron source at a future date.

Probably one of the most interesting considerations is the possibility of increasing the energy of the synchrotron above the nominal design energy. Because the magnetic field in the ring magnets is so low, it was relatively inexpensive to provide for the possibility of increasing the field well above the design energy. The magnets may readily be excited to 15 GeV excitation without high field distortion. It also appears possible to go well beyond 15 GeV excitation if sufficient power is supplied. Many of the components of the excitation circuit were made suitable for 15 GeV excitation at a relatively minor increase in cost. As a result, the main difficulty in arriving at 15 GeV or even higher is the amount of R F power required. It appears that by accelerating to full energy only in alternate magnet cycles or less frequently , and by "brute forcing" the RF system in terms of numbers of cavities and amount of power supplied, it should be relatively easy to exceed 15 GeV for the peak electron energy. Again, it will be necessary to provide damping magnets to overcome the antidamping of the betatron oscillations that result from the synchrotron radiation. Table 2. gives a summary of the nominal parameters for the machine.

Initial integral tests of the system were made in October, 1966 when a section of the linac sufficient to provide 50 MeV electrons was set up in a temporary shelter to inject electrons through the first 2/3 of the orbit. The system was found to behave in the expected manner.

The magnet ring has now been completed. By the end of this week we expect to make our first try for a coasting beam in the machine. With luck, we may even be able to accelerate it to a few GeV using one of the four RF cavities.

The construction contract for this machine was signed in April, 1965, just under two years ago, with the National Science Foundation. The tunnel, and the accelerator construction has been completed in this interval. The conventional laboratory construction is hastening toward conclusion. We hope that the machine will be operating at full energy by October of this year and that the first experiments will be on the floor at that time.

The contract amount was $11,300,000 including tunnel, building and machine. With all purchases nearly completed we are still well within our budget figure. It may be of interest to discuss the staffing and mode of construction which has prevailed. The basic scientific design decisions have been made by a small number of people. A central core of personnel consisting of Professors DeWire, Edwards, Littauer, McDaniel, Wilson, and Dr. Tigner has provided the backbone of the design team. This has been supplemented by the part time assistance of four others, Professors Berkelman, Stein, Talman, and Woodward, in certain special areas such as injection, surveying, and magnet design. Mr. Robert Matyas has served as project manager and Mr. Robert Bower as superintendent of synchrotron construction.

In addition to this staff we have 3 research associates, 3 engineers, and the average full time effort of 30 workers including clerical staff.

This small design staff permits very flexible, well controlled operations with full authority in the hands of few people. It allowed us to solidify major design features before all associated areas were fully explored, and has enabled us to leap frog over many of the troublesome problems.

It is a pleasure to acknowledge the enthusiastic support of the Cornell University administration and the National Science Foundation.

TABLE I

	NINA	CEA	EREVAN	DESY	CORNELL
Energy, GeV.	4	6	6	7	10
Electrons, per pulse	10^{12}	10^{11}	10^{11}	10^{11}	10^{11}
Injection Field Gs.	64	35 (125)	66	42	50
Inj. energy, MeV.	40	28 (100)	50	40	150
Max. Field, Gs.	6,430	7,600	7,920	8,100	3,300
Orbit Radius, m.	20.7	26.4	25.1	31.7	100
Rep. rate cps	50	60	50	50	60
Gap height F cm.	6.2	5.1	6.0	5.6	2.54
Gap height D cm.	7.6	5.1	6.0	8.8	3.80
Total weight steel tons	362	290	400	570	185
Total weight cu tons	40	39	25	80	25
Date, first acc.	12/66	9/62	-	2/64	6/67 ?

Table 2 Parameters for Cornell 10 GeV electron

Nominal electron energy	10 GeV
Radius of curvature in bending magnet	100m
Nominal repetition rate	60c/s
Nominal intensity	10^{11} electrons per pulse
Number of magnet units	192
Length of magnet units	3.43m
Clear length between magnet units	0.25m
Long straight sections	2 each of 12.2m length 4 each of 6.1m length
Magnetic field at 10 GeV	3.3 kG
Injection field for 200 MeV	66 gauss
Betatron Oscillations per turn $\nu_r = \nu_v$	10.75
Magnet excitation power	800 kW
Linac energy	150-200 MeV
Linac frequency	2855 MH_z
R.F. frequency	714 MH_z
R.F. voltage per turn	10.5 MeV
Average R.F. power demand	136 kW
Approximate cost of buildings, Tunnel and accelerator	$12,000,000

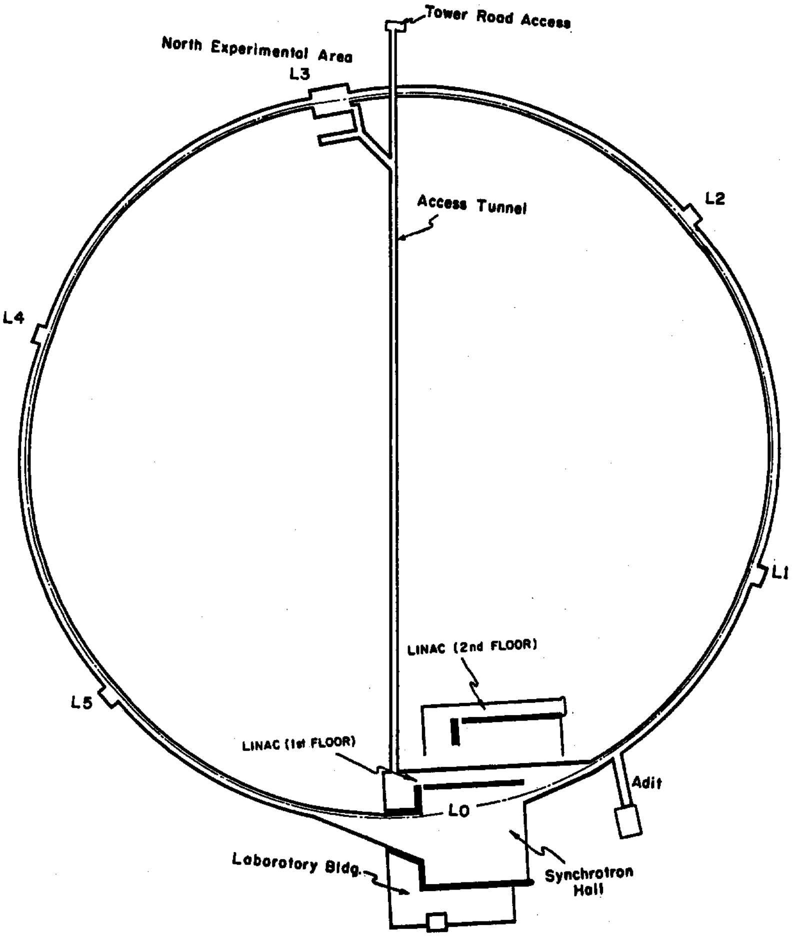

Fig. 1. Laboratory and Accelerator Hall, Cornell 10 GeV synchrotron.

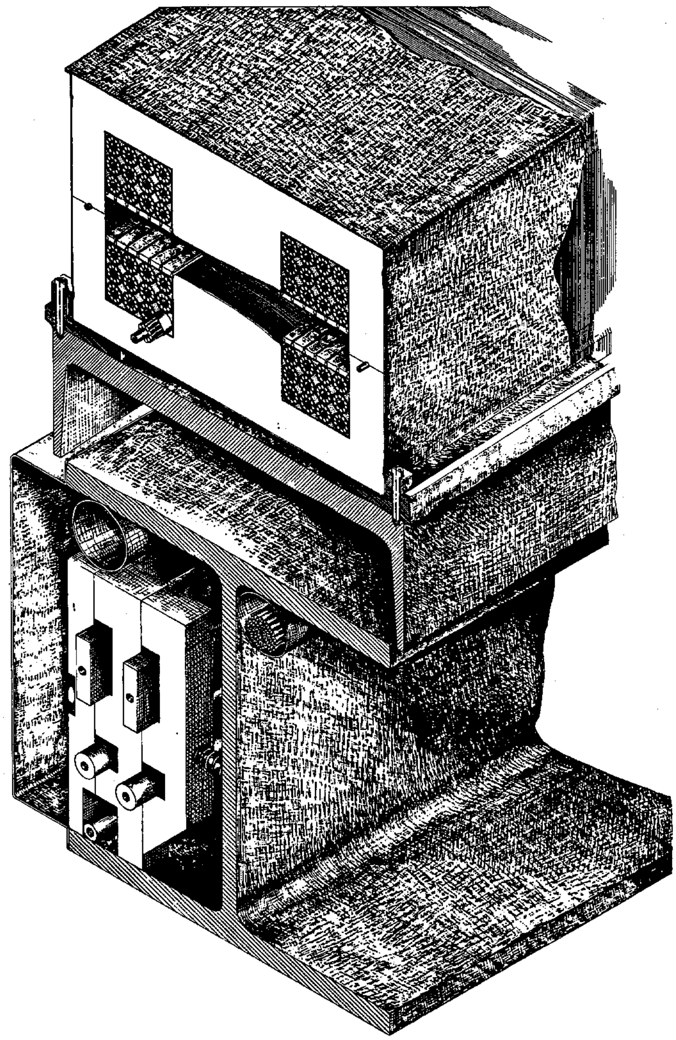

Fig. 2. Section through guide field magnet and supporting beam of Cornell synchrotron.

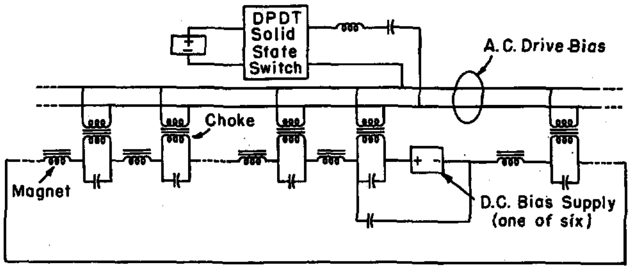

Fig. 3. Excitation circuit for the Cornell synchrotron.

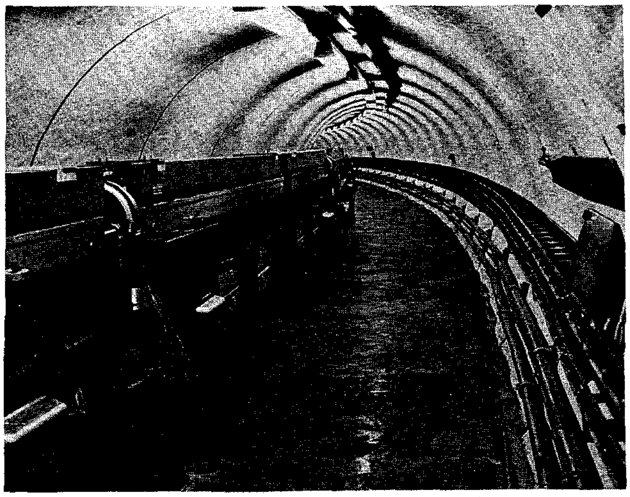

Fig. 4. View of magnet ring and tunnel of the Cornell synchrotron.