THE FUTURE OF ELECTRON SYNCHROTRONS

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Summary

The electron synchrotron has become a highly successful instrument for high-energy physics with the application of alternating gradient focusing. Development toward large orbits and low magnetic fields has brought the problem of radiation loss under control and has stimulated design planning for very high energies. The magnets can be powered at high cycling rates (60 cps) by resonant electrical circuits. The most valuable feature is the long duty cycle available for experiments, of up to 20% of total time. Photons emerge tangentially in sharply collimated beams from targets at the edge of the orbit. Emergent beams of electrons can be ejected with high efficiency, having small energy spread and excellent collimation.

Future developments should bring higher beam intensities as well as higher energies. Positrons can be accelerated in the same orbit, with reversed magnetic fields and a suitable source. The AG magnet system should distribute the damping due to synchrotron radiation between radial, vertical and synchronous modes, as in a storage ring. In principle, particles could be injected in each cycle and stored to develop high-intensity circulating beams. With orbits as large as the giant AG proton synchrotrons of the future, electron energies of 50-Gev or higher could be obtained. A large fraction of the orbit would be filled with rf accelerating cavities spaced between the AG magnet units, powered in phase as in a linac. As for all large-orbit machines the major cost would be for buildings, tunnels and services

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The electron synchrotron has had a new lease on life with the application of alternating gradient focusing. The reduction in aperture made possible by an AG system allows the magnets to have small cross-section and to be excited at a high cycling rate, such as 60 cps, and has reduced the cost of the magnet relative to other components. Use of large orbits and low magnetic fields can hold the radiofrequency power - required to compensate for the radiation loss by electrons in the magnetic field - to within acceptable limits. The most valuable feature of the synchrotron is the long duty-cycle available for experiments, which can be as large as 20% of total time.

The chief competitor of the synchrotron as a source of high-energy radiations is the electron linear accelerator. The linac has certain advantages, of which the most significant is the high beam intensity which can be achieved with sufficient radiofrequency power. This high intensity is primarily useful for producing beams of secondary radiations such as K-mesons. However, the useful duty-cycle of a microwave linac is only one in several thousand. For many types of research experiments, in which the sensitive time of the electronic detection equipment or the counting rate for data accumulation and analysis is the limiting factor, the long duty-cycle of the synchrotron is much to be preferred. In the past it has been assumed that the readily available emergent beam at the end of a linac was also a unique advantage. This is no longer true, now that it has been demonstrated in the Cambridge machine that high quality emergent beams can be obtained.

The synchrotron has other advantages, once the technical problems are solved. The energy spread in the emergent beam can be as small as 0.1 to 0.2%, which is considerably smaller than has been achieved with electron linacs. Despite the large radiofrequency power needed to compensate for radiation loss, the rf power requirements for a synchrotron are smaller than for a linac of the same energy. And the overall cost of an AG synchrotron is still significantly lower than for a linac of the same energy.

Perhaps the fairest evaluation is that the two types of accelerators supplement each other, and that both are needed. Furthermore, with continuing development the capabilities of the two types of machines are approaching each other. The modern synchrotron might be considered to be a set of linac-type accelerating units in a circle, spaced by magnets to provide deflection and focusing, so the rf accelerating fields can be used over and over. Future developments will certainly lead to higher beam intensities in the synchrotron, and much will be gained by utilizing the radiofrequency experience from the linac field. It is also probable that linacs will eventually be equipped with auxiliary magnetic orbits (as in a storage ring) in which the high-current, short-duration pulses can be stored for a time and then ejected continuously to provide a long duty-cycle. Such a development will lean heavily on synchrotron experience.

One statement should now be made clearly. It is not true that radiation loss limits the electron synchrotron to a particular energy and that only a linac can go to higher energies. In the sections to follow I hope to show that synchrotron development is proceeding at a rapid pace and that design concepts are available to extend the energy of synchrotrons indefinitely.

The AG Electron Synchrotron

The AG synchrotron consists of a ring of magnets with alternating gradient fields, to provide strong focusing and small beam aperture, in which the field intensity varies cyclically from low to high values during successive acceleration cycles. Magnet units are spaced with straight sections in which radiofrequency cavities for acceleration can be mounted, as well as beam-injection and beam-ejection systems. The gradient fields produce non-integral betatron frequencies to avoid beam blow-up due to integral resonances, and with many wavelengths per turn to provide momentum compaction and small amplitudes. The cycling rate is high (60 cps) and the magnet system is powered by an efficient resonant electrical circuit using inductors for energy storage.

For high electron energy the orbit radius should be large and the peak magnetic field low, to reduce radiation losses by the orbiting electrons and so the rf power requirements. Radiation loss per turn at high energy is in general large compared with the volts-per-turn required for acceleration, so a fast cycling rate such as 60 cps can be used with no increase in peak rf power. A constant-frequency rf system of high-Q resonant cavities can be used to develop the large volts-per-turn needed at high energy, since electron velocities are essentially constant. This synchrotron frequency should be a high harmonic of the orbital frequency, to reduce the amplitude of synchronous oscillations and to provide a short wave-length so the rf cavities can fit in the limited spaces between magnets. The result is a large number of identical rf cavities spaced around the orbit and excited in phase.

Electrons are pre-accelerated in a linac and inflected into the orbit at a small angle by a pulsed field in one straight section, when the magnetic field in the orbit matches the injection energy. One-turn injection is used, with the inflecting field being pulsed off in a time short relative to the orbital period. The beam remaining in the orbit is captured into synchronous orbits by the radiofrequency field, resulting in large-amplitude synchronous oscillations for particles injected off the synchronous phase. In order to limit these amplitudes the linac beam is modulated at synchronous frequency and this pre-bunched beam is injected at the optimum phase for capture. The linac frequency can be an integral harmonic of the synchrotron frequency and is chopped or modulated to inject one enhanced rf bunch from the linac in each synchronous cycle. Synchronous frequency must be an integral harmonic of the orbital frequency and also an integral harmonic of the number of rf cavities, so the synchronous bunches will be in phase in all the cavities around the orbit.

Electron oscillation amplitudes following injection are damped adiabatically in the rising magnetic field, varying with $T^{-\frac{1}{2}}$, so the high-energy beam is of small cross-section. At high energy the electrons can be deflected outward or inward to strike targets at the edge of the aperture, by pulsed distortions of the magnetic field in selected pairs of magnets (called "beam bumps"). Bremsstrahlung X-rays with energies up to the peak electron energy will emerge tangentially from these targets. The photon beams have small divergence (1×10^{-3} rad) and emerge through ports in the shielding for experimental use. The beam bumps can be programmed to provide a slow deflection of the beam against the targets, resulting in a long duty-cycle over the crest of the magnet excitation cycle, of up to 20% of total time if desired.

An emergent electron beam has been produced at the Cambridge machine, with extraction efficiencies of about 70% of the circulating beam. The beam-ejection device is a current-strip at the edge of the aperture which produces a distorting magnetic field close to the strip. When it is pulsed on, this local magnetic field shifts the radial betatron frequency toward an integral or half-integral resonance for particles which approach the strip. The rapid growth of resonant amplitudes within a few turns allows the particles to jump behind the strip where they are then deflected out of the orbit as an emergent beam. The circulating beam is deflected toward this current-strip septum by a programmed beam-bump, allowing the emergent beam pulse to be stretched to a long duty-cycle if desired. With a short pulse the energy spread of the emergent beam can be as low as 0.1 to 0.2%. The emergent beam is well collimated and can be focused on a target 100 ft from the ejector to a spot size of one square millimeter.

Such a synchrotron is typically housed in a circular underground tunnel to provide basic shielding. Electron and photon beams emerge through apertures in the shielding into an external hall where experimental equipment is mounted. The large number of available straight sections between magnets provide many alternate locations for targets, spaced around the orbit. Beam bumps can be used to divide the beam between targets or to alternate pulses on the several targets so several experiments can share use of the beam simultaneously.

AG Synchrotrons in Operation or Under Construction

The Cambridge Electron Synchrotron, jointly sponsored by M.I.T. and Harvard, started operations in 1962 at energies up to 6 Gev. Construction cost was 11.5 million dollars. As the first of the large AG electron accelerators it has been a prototype for others and has led in a development program to exploit the possibilities of this type of machine. The orbit is 236 ft in diameter and is formed by a ring of 48 AG magnets. They are powered in a fully-biased sine wave by an electrical circuit resonant at 60 cps, and they produce a field at the orbit varying from zero to 7600 gauss. Electrons are injected at 30 Mev when the field is about 40 gauss, from a 2855 Mc linac modulated at the synchronous frequency of 475 Mc (1 pulse in 6). A set of 32 high-Q radiofrequency cavities resonant at this synchronous frequency are spaced around the orbit, powered from a central transmitter through a circular ring of waveguide.

The beam captured at injection has transverse dimensions of 1.5 x 0.5 inches; these are reduced by damping during acceleration to 3.0 x 0.2 mm at maximum energy. Vacuum chambers fitting between magnet poles are formed of laminated non-magnetic steel to minimize eddy currents and are vacuum-sealed with a glass-cloth and epoxy-resin coating. Titanium-discharge vacuum pumps are placed beneath each straight-section manifold between magnets. Targets located at the edge of the aperture in several straight sections are struck by the circulating beam when it is deflected by beam-bumps; the deflections can be programmed to spread the emergent X-ray beam pulses over thousands of turns. Beam intensities up to 2×10^{10} electrons per cycle or 1.2×10^{12} per second have been obtained, limited by beam-loading effects in the high-Q rf cavities.

The Deutsches Elektronen Synchrotron (DESY) at Hamburg has recently been completed and brought into operation. The design is generally similar to the CEA machine, but orbit size is larger and the ultimate energy will be higher - up to 7.0 Gev. It is now in the shake-down period and has not yet been brought into full-scale operation. Intensities are limited by beam-loading effects in the rf system, as in the CEA machine, and it has achieved essentially the same peak intensities.

Several other machines in this energy range are under construction. A machine similar to the CEA and rated for 6.5 Gev is under construction at Yerevan in Soviet Armenia, sponsored by the Armenian Academy of Sciences; it should be completed in 1966. A somewhat lower-energy but higher-intensity AG synchrotron is under construction at the new National Institute Nuclear Accelerator (NINA) Laboratory at Daresbury near Liverpool, rated for 4.0 Gev and also scheduled for completion in 1966.

In the lower energy range is the existing Cornell AG synchrotron which has been re-built and expanded to higher energy several times during the past 10 years, from 0.5 to 1.1 and recently to 2.3 Gev. At the Institute for Nuclear Studies in Tokyo, an AG electron synchrotron of 4 meters radius is operating at 1.3 Gev energy. And at the University of Bonn, construction is underway on an AG synchrotron of 2.3 Gev.

Future Technical Developments

As this first generation of multi-Gev AG synchrotrons is brought into service, a large number of technical improvements can be anticipated which will increase the intensity and the capabilities of this type of machine. The direction of this development program is already evident from work now in process at the Cambridge laboratory.

Intensity: The present limitation on intensity comes from the off-phase voltages induced in the highly resonant rf accelerating cavities by the bunched circulating beam, which shift the phase of the rf fields in the cavities and destroy the synchronous beam for intensities above present levels. The reason for using high-Q cavities is to provide the high volts-per-turn needed at the peak of the cycle to compensate for radiation loss; the intensity limitation occurs at or just following injection, before the demand for high voltage develops and when the applied voltage is only that needed for synchronous capture and acceleration. A modification of the rf system is needed which will reduce the Q at the start of the cycle yet retain the desired high efficiency at the peak of the cycle. This requires a "tuneable-Q" rf cavity system. One possibility involves programmed excitation of some ferrite loading units in the waveguides or cavities. With a reduced Q at injection the induced voltages would be small relative to the applied voltage, and higher beam intensities could be injected and captured; then the ferrite units could be biased to reduce their attenuation and the cavities would provide high voltages at the peak of the cycle.

Cycling Rate: In principle, the cycling rate can be increased above 60 cps with a relatively small increase in power requirements. With proper magnet design the hysteresis and eddy-current losses will rise at a considerably lower rate than the number of beam pulses per second. Beam intensity per cycle should not decrease significantly, so the average intensity will increase. The peak radiofrequency power for compensation of radiation losses will not increase unless the cycling rate becomes so high that the maximum volts-per-turn for acceleration (which occurs at half-energy) exceeds the radiation-loss requirements at maximum energy. The average rf power will increase, however, due to the changing rf voltage duty-cycle. It should be possible to increase the cycling frequency by 2 or 3 times without exceeding technical limits, and so increase the time-average intensity.

Positron Acceleration: Positrons can be accelerated in a synchrotron to provide an auxiliary experimental capability, if a suitable positron source is provided at the source end of the linac. If they are to be brought out as an emergent beam alternatively with electrons, the magnetic fields must be reversed, and also the beam injection and beam ejection systems. The magnets can be operated with reversed polarity if a suitable switching system is provided. The positron source will require development; studies at the CEA suggest that intensities up to 1% of present electron beam intensities can be achieved. Development of fast-switching techniques would allow alternate use of positrons and electrons in the same synchrotron.

Several electron linear accelerators are now being converted for acceleration of positrons, at relatively low energies, so the scientific need is clear. It seems probable that one or more of the larger synchrotrons will eventually be converted to accelerate positrons to multi-Gev energies.

Filling an External Storage Ring: With a high-intensity positron source available, and with a suitable switching system, the synchrotron can be used to fill an external dc electron-positron storage ring, at any chosen energy up to the synchrotron maximum. The two beams can be accelerated alternately in opposite directions, with the same magnet polarity; they can be ejected by separate emergent beam systems, and transported through beam runs to an adjacent storage ring. Recent CEA calculations suggest that, with the positron intensity indicated above, an external storage ring could be filled with 0.5 to 1.0 amp circulating beams in a few minutes. This compares favorably with any other high energy accelerator as a source for filling an electron-positron storage ring.

Beam Storage: It is technically feasible to build up and store a high-intensity, circulating beam in a synchrotron. The magnets would be cycled continuously from injection field to maximum field, with the beam being accelerated and decelerated in each cycle. Continuous cycling of the beam becomes possible due to the damping of oscillation amplitudes by the emission of synchrotron radiation at high energies; particles returning to injection energy will occupy reduced phase-space and a smaller aperture. In principle a new bunch of particles could be injected on each cycle, building up a high-intensity beam.

To accomplish this result, a sequence of technical developments will be required. The magnet system must distribute the radiation damping between the radial, vertical and synchronous modes, as is accomplished in a typical storage-ring magnet. It would seem useful, therefore, to design the magnet systems of future synchrotrons to provide such damping - the modifications to a typical AG system are minor.

Also, it will be necessary to provide an injection system which can inject a new pulse on each cycle without disturbing the circulating beam in the orbit. Such an injection system is technically feasible and design concepts are available, but it differs from the one-turn injection system in use at present.

The usefulness of a long duty-cycle for experimental purposes is obvious, particularly if coupled with high beam intensity. The detection instruments could be time-gated to define the energy of the beam during the cycle, and half of total time would be available with beam energies between half and full value.

Beam-Beam Interactions: It is also technically feasible to produce counter-rotating beams of electrons and positrons in a synchrotron, as in a storage ring, if sources of both particles with fast-switching arrangements are available, and if the technical requirements for injection and storage of circulating beams have been provided. Two multi-cycle injector systems will be required to fill the ring in both directions. The two beams must be separated around most of the orbit to minimize beam-beam interference effects, and arranged to intersect at chosen straight sections where experiments could be performed. Such beam separation can be accomplished by a vertical electric field, with the polarities arranged to provide suitable beam intersections, and programmed in time to maintain the desired separation throughout the acceleration cycle.

Scattering by the residual gas in the chamber will limit the lifetime of a circulating beam and so the equilibrium beam intensity. The vacuum which can be obtained in a laminated and resin-sealed chamber such as is now used to allow 60-cycle operation is much poorer than that possible in a solid-wall, bakeable chamber of the type used for dc storage rings. Some improvement of the average pressure will be required to extend the lifetime of the circulating beams and to allow equilibrium beam currents to be stored with continuous filling which would be adequate for experimental purposes.

Design planning and calculations at the CEA suggest that it would not be possible to obtain intensities greater than 0.1 ampere in each beam, with the technical limitations of the existing CEA machine. The interaction rate at this intensity is several orders of magnitude below that needed to perform significant beam-beam experiments. Planning for future synchrotrons might well include features which would provide an opportunity of developing a higher-intensity capability for counter-rotating beams.

Large-Orbit Synchrotrons

Higher energy synchrotrons for the future must use very large orbits and very low magnetic fields, to keep rf power requirements within practical limits. Radiation loss per turn varies with the fourth power of particle energy and inversely with orbit radius, so orbit radius must increase much faster than with energy. On the other hand, AG magnets become small in cross-section, light in weight, and power requirements are small for low-field excitation. The radiofrequency system becomes one of the most costly components. The optimum orbit size can be roughly estimated by minimizing the total of the costs for the rf power and radiofrequency system and of those which vary with orbit radius such as tunnels, magnets, vacuum systems, etc.

A design study for a "Large-Orbit Electron Synchrotron" was prepared by the CEA staff in 1961 (CEA-88), and was also included as a chapter in the Report of the Brookhaven summer study group in 1961 on the "Designs for 400-to 1000-Gev Proton Synchrotrons." In this study the orbit size was chosen to be the same as that for a 400-Gev proton machine (24,400-ft tunnel circumference), and the practical maximum electron energy was found to be 50 Gev. The basic characteristics of large-orbit AG electron synchrotrons were analyzed and typical design parameters were presented for such a 50-Gev accelerator. Cost estimates of the machine components alone (not including tunnels, housing and facilities) totalled 40 million dollars.

It was shown in the CEA study that the optimum arrangement to minimize radiofrequency power is to allocate 1/3 of the orbit to rf accelerating units and 2/3 to the AG magnets. When additional space is assigned to long straight sections and spaces for magnet terminations, vacuum ports, etc., the same ratio applies to the rf and magnet portions of the orbit. This requirement dominates the physical structure of the machine, and differs significantly from the optimum arrangement for an AG proton synchrotron.

The magnets are formed of many identical AG units (of two types) spaced by field-free straight sections in which the rf units are located. In the design study a magnet sequence of the "FODO" type was chosen, with a large number of AG periods (120). With this arrangement magnet units (F and D) of 45-ft length were spaced by rf units (O) of 22½-ft length. Magnets would be formed of two straight (not curved) half-units of 22½-ft length each. So there would be 320 rf units and 640 magnet half-units, of equal lengths. These units forming the curved orbit would be grouped into 4 sectors, spaced by long straight sections for injection, ejection and other uses. The maximum magnetic field would be 2,500 gauss.

The rf unit proposed was a diaphragm-loaded waveguide similar to those developed for linacs, operating at a frequency of 1000 Mc. Each 20-ft unit would have a diameter of 10 inches and a diaphragm aperture of 4 inches which is considered adequate to enclose the beam. Each unit would be powered from a separate rf transmitter, with modest power requirements of 40 kw each. Total power would be 13,000kw, and the system would develop a total voltage per turn sufficient to compensate for a radiation loss of 800 Mev/turn at 50 Gev.

This plan of using identical module units for the AG magnets and the rf waveguides has the great advantage of engineering economy, both for development and construction and for maintenance. If a small number of rf units were to fail in service, operations could still continue, with the other units providing the volts-per-turn through an automatic shift in synchronous phase. Similar units (possibly identical) could be used for the injection linac. The linac would operate at the same frequency and would provide pre-bunched pulses for injection at the synchronous phase. Injection energy was taken, in the design study, to be 1.0 Gev, for which the magnetic field in the orbit would be 50 gauss. The linac would be formed of 34 additional waveguide modules, in a total length of 760 ft, powered by pulsed transmitters of high peak pulse power and the same average power as required in the synchrotron.

The orbital period would be 25 microsec. Assuming that it could be filled in one turn with 100 milliamps average pulse current from the linac, the beam intensity would be 2.5×10^{12} electrons/cycle or 1.5×10^{14} per sec. This represents a time average current of 25 microamperes; at 50 Gev the beam power would be 1,250 kilowatts! These numbers represent design maxima, and in practice technical limitations such as beam loading might reduce this intensity severely.

Enough has been said to indicate that neither the technical problems nor the costs are excessive relative to other competitive sources of high-energy electrons. As for all large-orbit machines the major cost would be for buildings, tunnels and services.

Conclusion

In summary, it seems clear that the AG electron synchrotron is just entering its major phase of development and of usefulness to science. As long as the origin of nuclear forces remains a mystery, and as long as the present demands by scientists for accelerators of higher and higher energy persist, continued development of this type of machine will be justified. This pressure is already evident. A design study for a 10-Gev electron synchrotron at Cornell University has been submitted to the National Science Foundation as a proposal for construction. At time of writing there are strong indications that the proposal will be accepted and that this machine will be authorized. A design study is also in process at Saclay for a 15-Gev electron synchrotron which might become the future major high-energy facility in France. It is not clear how soon the demand will arise for a machine as ambitious as the 50-Gev large-orbit machine described above, or of a more sophisticated facility for storage of counter-rotating electron-positron beams. However, the state of the art is adequate to develop either of these machines whenever the demand arises.