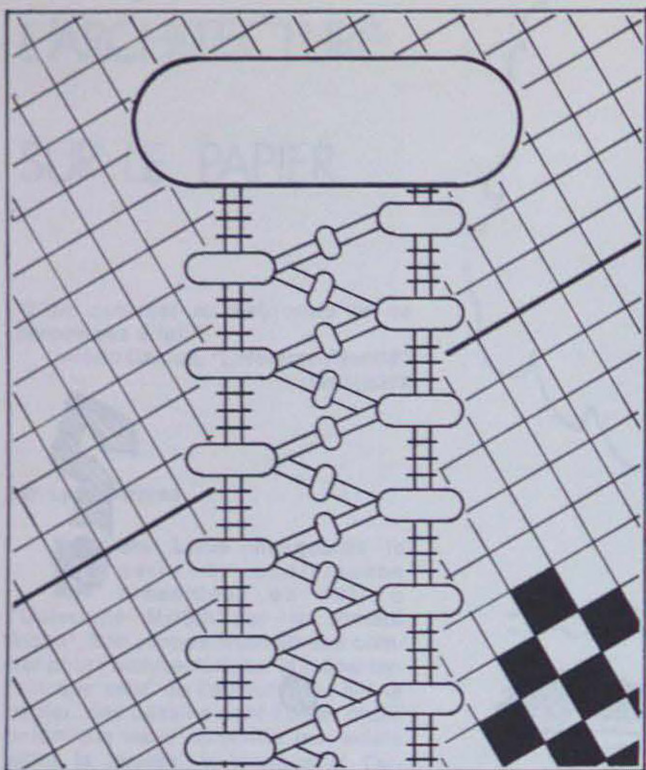

FIG. 1

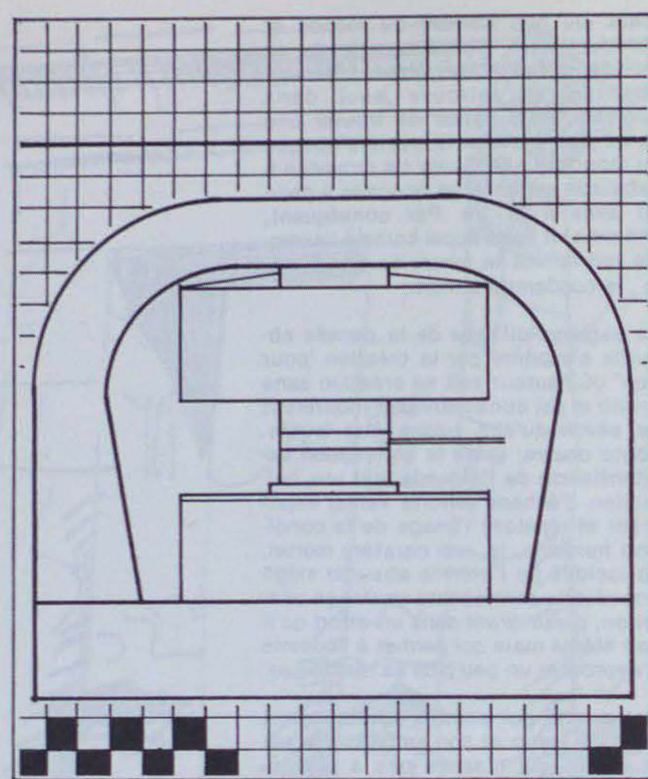

FIG. 2

# CYCLOTRONS

**by Derek L. Livesey**

Physicists do not often occupy themselves with planning cities or designing objects of architectural quality. The great exception was Sir Christopher Wren, who was contributing significantly to the science of mechanics when the City of London was being rebuilt after the Great Fire of 1666. Rarely does a great architect seize his opportunity with such alacrity as Wren, who presented his new city plan to the King within ten days of the fire's eruption, before the city had ceased to smoulder. In the event, of course, his idealistic city plan was never carried out but his genius found full expression in the rebuilding of the City churches and St. Paul's Cathedral.

Physics does not necesarily impose a unique design upon large structures, as is shown by the diversity of designs for massive bridges. One important exception is the construction of high-energy particle accelerators which have reached kilometre dimensions and costs in the billion dollar range. The two accelerators of highest energy (located in Illinois and near Geneva) are not very interesting to look at, though they represent high-precision engineering on the largest possible scale. Each consists of a ring-shaped tunnel of immense radius, containing an apparently endless series of magnets, enclosing an evacuated tube through which the accelerated particles fly. At present, the highest energy achieved with protons (hydrogen nuclei) is 400,000 MeV, equivalent to accelerating each particle through a potential difference of 400,000,000,000 volts.

By comparison, some of the earliest electrostatic accelerators, working at potentials of less than a million volts, were works of art. Just some fifty years ago Cockcroft and Walton in Cambridge, England used a simple array of capacitors and diodes to multiply a few thousand volts (alternating input) up to a final (rectified) potential of 600,000 volts. This voltage could be applied to accelerate protons down an evacuated tube to ground potential where the proton beam struck a lithium target, producing nuclear reactions in abundance. The Cockcroft-Walton set is still used for the first stage of beam production in high-energy accelerators and its generating stack (Fig. 1) has a characteristic profile in which bulbous metal shields form the intermediate electrodes and the diagonal tubes house the rectifying diodes. In such a stack the electrical circuit actually dictates the essential design and high-voltage practice determines the outline.

Almost simultaneously with the work of Cockcroft and Walton, Lawrence and Livingston (Fig. 2) were able to synchronize the acceleration pulses with the particle orbits and achieve repeated accelerations. The protons started off at very low energy at the centre of the chamber and would eventually leave by an exit port at energies around five million electron volts (5 MeV).

At first sight, it would appear that the cyclotron principle must work up to very high energies, limited only by the size and strength of the available

Layout: Graham D. Livesey

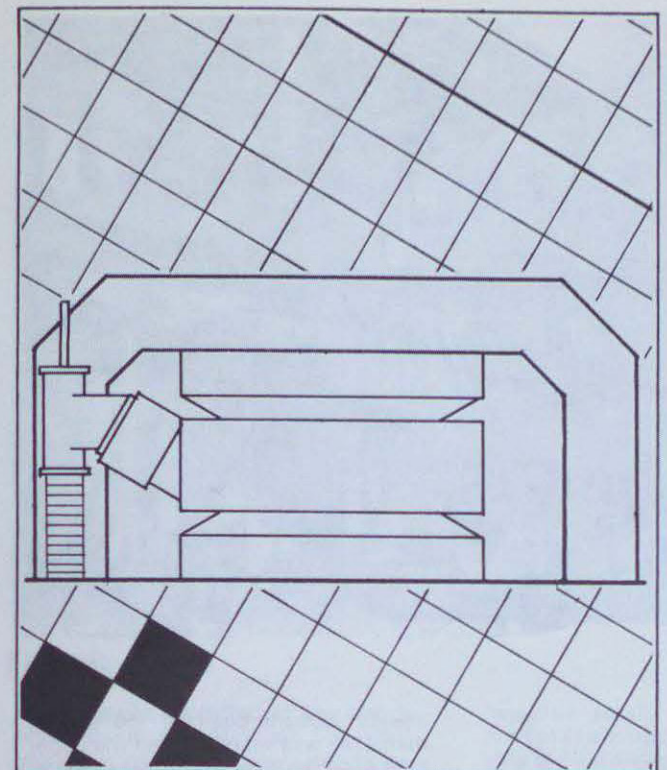

FIG. 3

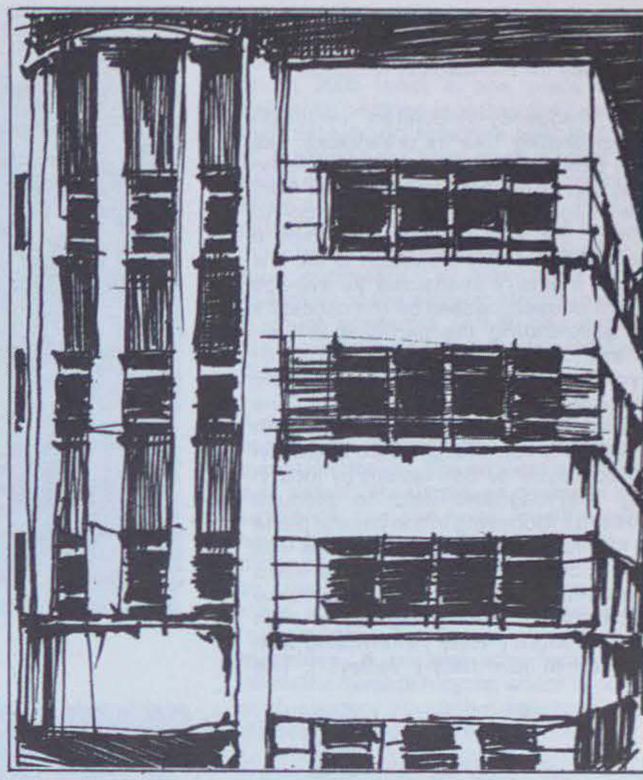

FIG. 4

magnets. Unfortunately, the first generation of cyclotrons (built in the 1930's) suffered from poor beam quality and their low reliability compared to that of the electrostatic machines. The author has vivid memories of running the cyclotron at Liverpool in the 1940's and the perpetual struggles to keep the beam on target (or anywhere near it). Already by 1940 it seemed that there might be no second generation of cyclotrons at all, because it could be shown from Einstein's Theory of Relativity that the increasing mass of a particle at speeds approaching the speed of light causes a de-tuning of the cyclotron acceleration process and that the effective maximum proton energy was about 20 MeV.

However, in 1945, MacMillan and Veksler independently proved that the acceleration in the relativistic (high-energy) region is quite feasible if the particles are handled in bunches. By starting off a bunch of protons at low energy (with the appropriate accelerating frequency) and then changing the frequency of electrical oscilla tion as the particle speed increases, it is possible to keep the particle energy continually increasing until the final extraction energy is reached. Again the size of the magnet is a limitation but Lawrence had already built the enormous 184 inch (pole diameter) magnet at Berkeley and this magnet was used in the first high-energy cyclotron. The machine is housed in a simple dome-covered building on the hill overlooking the campus of the University of California. Unfortunately, one cannot normally see the essential outline of the machine (Fig 3) because it is hidden behind tons of concrete shielding blocks. After several re-vampings, the beam energy was raised to 720 MeV and this is still the record high energy for a cyclotron. The 184 inch machine has made immense contributions to the discovery of new particles and their properties.

The frequency-modulated cyclotron caught on in the late 1940's and, among many machines of this type, one must single out the 100 MeV machine in the Foster Radiation Laboratory on the McGill University campus (Fig. 4). Although not a world-beater in energy, the McGill cyclotron has been remarkably sound in perfor-

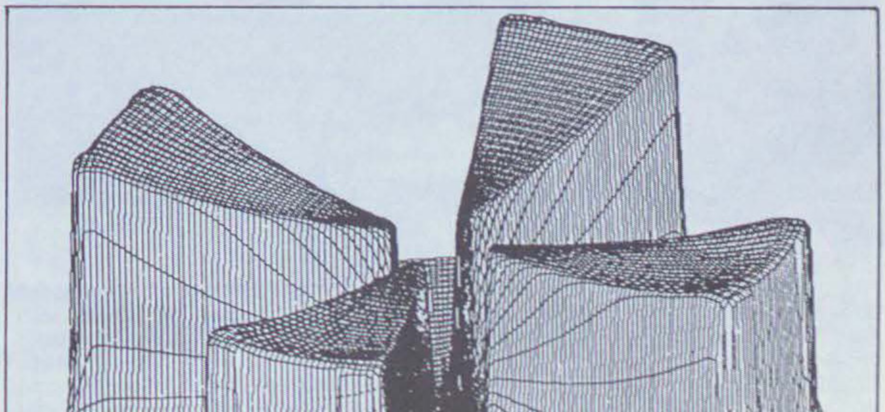

FIG. 5

mance and it is still in use for the production of new nuclear species and of isotopes for bio-medical research.

The frequency-modulated cyclotron unfortunately has its drawbacks, like any design. A minor problem is the extraction of the high-energy beam from the magnetic field region in order to direct the particles to an external target. The major drawback is the low beam intensity (measured as average beam current) caused by the necessity of accelerating the particles in bunches. The latest generation of cyclotrons is based on a principle discovered by Thomas in 1938. The relativistic region can be reached with essentially continuous beam operation (fixed-frequency oscillation) by modfying the magnetic field to produce powerful focussing in the central plane of the vacuum chamber. This idea was first tried out by bolting sector-shaped plates to the pole faces of a Lawrence cyclotron, producing regions of high field strength ("Hills") alternating with regions of low field ("Valleys"). The new field pattern is illustrated by a three-dimensional perspective of the field variation in the South African cyclotron now being built near Capetown (Fig. 5).

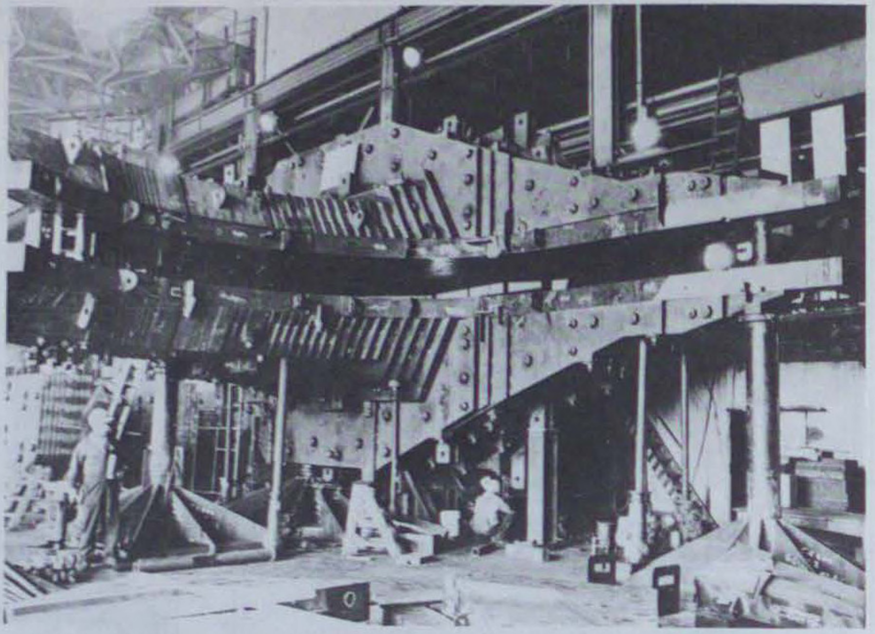

FIG. 6

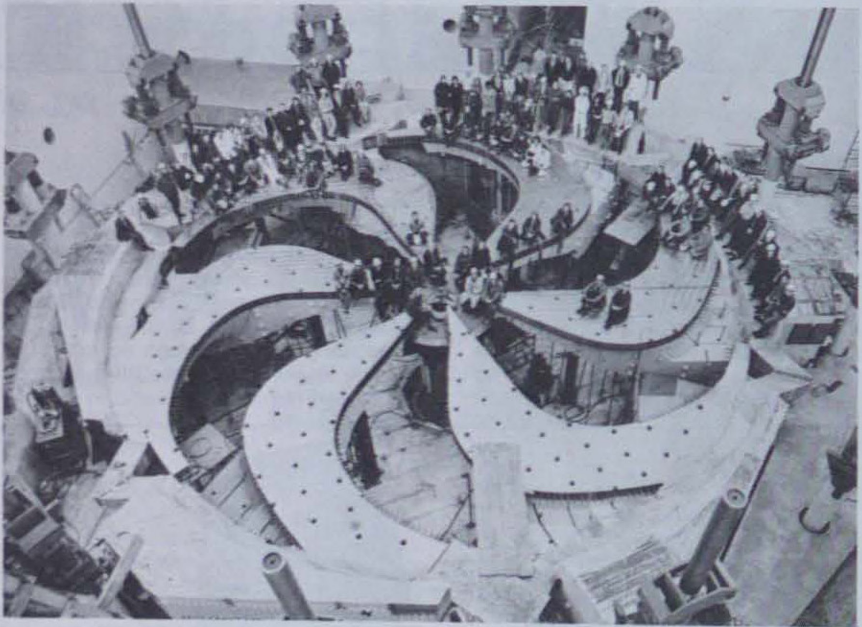

FIG. 7

At this stage a baroque element enters the architecture of cyclotrons because, as higher and higher energies are attained in the Thomas type of cyclotron, the magnetic field becomes more and more bizarre, with spiral-shaped sectors producing the "hill" fields. The most asymmetric design realized to date is that of TRIUMF, a 500 MeV machine located in Vancouver and in operation since 1974. Each of the six major sectors of the magnet consists of a pair of poles, with horizontal spiral-sector plates backed by extraordinary steel-plate assemblies above and below the pole plates proper. In (Fig. 6) we see the test assembly of one pair of poles in the shop at the Davie Shipbuilding Co. in Lauzon, Quebec. The complete 4000 ton magnet was shipped in pieces by rail to Vancouver and then began the complex task of assembling the entire structure in the accelerator vault. When all the lower pole faces were in place a picture was taken of the construction and design staff draped over the steel work (Fig. 7). Then the immense vacuum chamber (56 feet in diameter) was installed and the upper pole assembly was fixed to a large support structure which spans the entire magnet. Another major task was the installation of the water-cooled aluminum coils (each carrying a current of 27,000 amperes) which provide the excitation for the magnet structure.

Some idea of the machine scale and its features may be obtained from the view shown in (Fig. 8). Around the circumference of the cyclotron are twelve jacks which, working in unison, lift the entire upper support structure, the upper pole pieces and the top half of the vacuum tank when inspection of the inside is required. This feature of the design was a practical necessity in the early stages of adjustment to the inner electrodes and the vacuum system, but the extremely high radioactive background set up in the tank by full-beam operation makes inspections very hazardous and remote-control devices are needed to make adjustments during regular operation.

Another remarkable feature of TRIUMF is that the accelerated particles are not protons (H + ions), as is usual in high-energy machines, but negative hydrogen ions (H-) in which a proton is bound to two electrons. The advantage of H- operation is that at any suitable point in the vacuum tank the beam can be intercepted (either wholly or partially) by a thin carbon foil fixed to a moveable probe. The ions lose their electrons on impact with the foil and are instantly converted into H + paticles, which are ejected from the acceleration region by the magnetic field. In this way essentially 100% of the

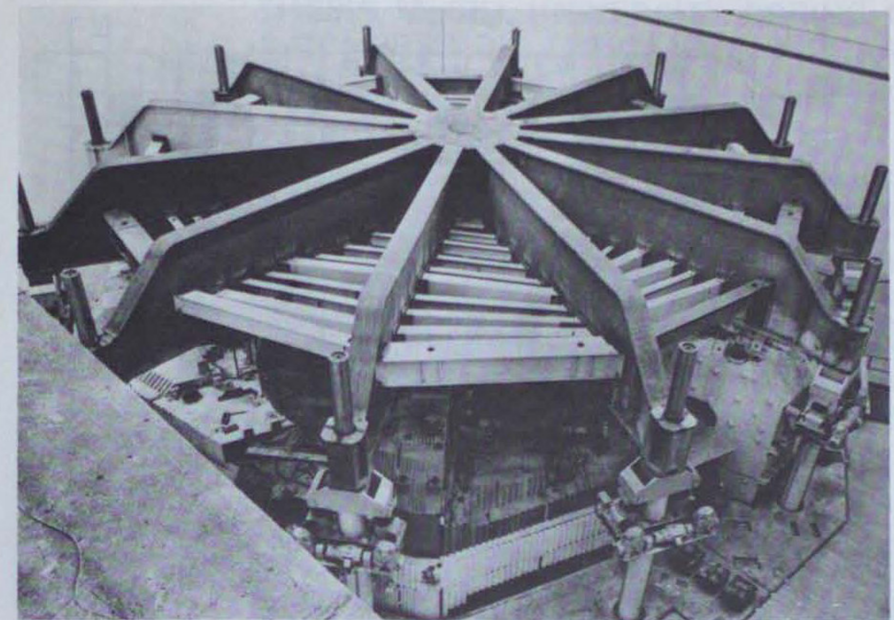

*FIG. 8*

beam may be extracted at any energy from about 100 MeV to 500 MeV. Moreover, part of the beam can be extracted at one energy while the rest of the particles continue to higher energies. In actual operation TRIUMF provides up to three working beams at one time, thereby keeping many experimenters simultaneously happy. The penalty paid for this extra feature of the TRIUMF cyclotron is the requirement that the highest magnetic field strength is comparatively low and the magnet diameter becomes extremely large.

At the time of writing, two major cyclotrons (one in Vancouver and one near Zurich) are working in the 500 MeV region, with special attention paid to the properties of artificially produced particles such as pions and muons. In addition, a machine at the University of Indiana, designed originally for 200 MeV protons and other light particles, has been converted to accelerate heavy ions (nuclei of elements much heavier than hydrogen). In passing one should mention that the South African cyclotron, which is rather similar to the Indiana machine, will be dovoted largely to medical applications. Small cyclotrons (in the region of 50 MeV proton energy) are available commercially and one is now being installed on the TRIUMF site purely for the purpose of radio-isotope production.

The extension of cyclotron design to new fields is still under way. Some blueprints of a super-TRIUMF have been sketched out, with the intention of injecting the TRIUMF beam into a so-called Kaon factory (code-name CANUCK) which is a very strange magnet indeed. At the other extreme a beautiful small cyclotron has been built at Chalk River to accelerate heavy ions to high energies and this machine has the special feature of a very high magnetic field generated by superconducting coils (immersed in liquid helium). A similar accelerator is working at Michigan State University and the Chalk River facility is expected to become operational in 1983.

Is there any kind of aesthetic influence on the design of a complex machine such as a cyclotron? Nowadays accelerators are designed by committees and the results often resemble the ungainly camel rather than the elegant cheetah. To mention a specific example, the problem of raising the upper half of the TRIUMF cyclotron (weighing about 2000 tons) in one piece was solved by welding together the twelve-member support structure seen in (Fig. 9). It would have been more elegant to use a pre-stressed concrete dome (like Wren's airy dome for St. Paul's cathedral) but height limitations in the cyclotron vault rendered a flat structure necessary. In the event the assembly of the support structure was a major headache and it had unfortunate effects on the magnetic field in the central region.

A related question is the degree of complexity required for a successful cyclotron design. The original machine was beautifully simple, as designed by Lawrence, but the beam quality was never satisfactory and there were great difficulties in operation. As time went by, the cyclotron became more and more sophisticated and it eventually joined the ranks of precision machines. A parallel argument concerns the humble bicycle, which is conceptually very simple but now requires elaborate factory techniques for satisfactory fabrication. Sad to say, elegant simplicity of design does not always make for mechanical efficiency. The modern tendency in accelerators is to use a powerful computer to monitor the machine performance and to apply numerous small corrections during operation. Not the most elegant strategy but extremely efficient.

*Dr. Derek Livesey is Professor of Physics at the University of New Brunswick.*

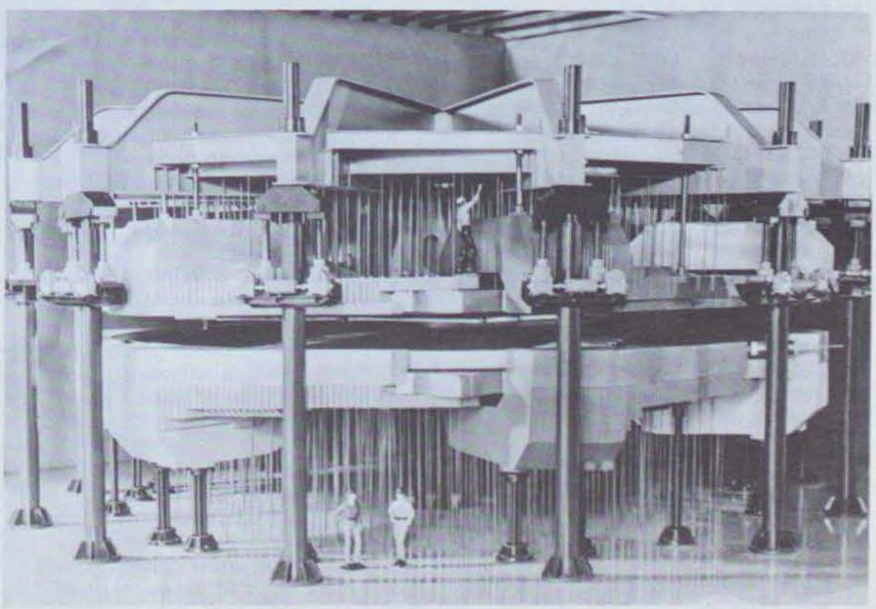

*FIG. 9*