SUPERCONDUCTING CYCLOTRONS AND COMPACT SYNCHROTRON LIGHT SOURCES

Superconducting magnets are the enabling technical component of the highest-energy particle accelerators ("atom-smashers") constructed and planned. These accelerators require both brute force and precision in the magnetic fields, which guide the particle beam on a roughly circular orbit,

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sometimes many kilometers in diameter, in order to return it to a radio-frequency accelerating structure for repeated energy boosts. The tera-electron volt (TeV) energy regime would not have been reached without a technology able to produce magnetic fields in the 5 T to 10 T range, accurate to about 1 part in 10,000, and economical enough to build in kilometer lengths. In this regime, superconducting magnets are the clear technology of choice.

The ability of superconducting magnets to produce strong, accurately shaped magnetic fields over large volumes also motivates their use in lower-energy accelerators, namely cyclotrons and electron synchrotrons, where normal magnets are also an option. Cyclotrons, because of their continuous beams, are usually the technology of choice for nuclear research in the hundred mega-electron volts per nucleon range. Such cyclotrons involve large magnets, in the 1000 ton range for magnets of room temperature design. Cyclotrons are also widely used in the commercial production of radionucleides and are used to a small degree for cancer therapy. The weight-reducing, cost-saving advantage of superconducting magnets (to the 100 ton range) has made them the design of choice in most recent nuclear physics projects. Superconducting magnets have also been used in a few situations for isotope production and for cancer therapy but have thus far not been widely adopted for either of these applications.

The short wavelength optical radiation emitted by electron synchrotrons has in the past two decades become a centrally important element in many research fields and in potentially important industrial applications. The need for sources compatible with on-line use in production facilities has led to the development of compact synchrotron light sources, whose compactness is enabled by the strong magnetic fields available from superconducting magnets.

SUPERCONDUCTING CYCLOTRONS

The cyclotron was the earliest of the circular particle accelerators, earning a Nobel prize for E. O. Lawrence in 1936. First the cyclotron and then the synchro-cyclotron provided the beams for "energy-frontier" physics studies in the 1930s and 1940s. In the late 1950s, the intrinsic cost advantage of the ring geometry of the synchrotron (versus the pancake geometry of the cyclotron) shifted energy-frontier studies to the newly evolving synchrotron. However, because of a series of significant technical innovations (sector and spiral-ridge focusing and superconducting magnets), the cyclotron has retained several important regions of superiority and has not faded from the scene in the fashion of a number of other pioneering accelerator systems (e.g., the synchro-cyclotron and the betatron).

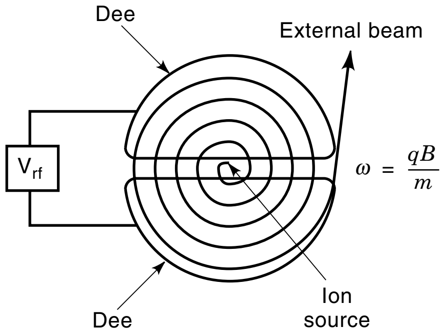

Figure 1. Conceptual drawing of the original cyclotron. The (constant) magnetic field is into the page. (Whereas the beam spirals outward in a cyclotron, in the synchrotron discussed later the beam stays at a constant radius and the energy increases as the magnetic field increases.)

Figure 1 shows the key features of the classic cyclotron, the essence of which is quite eloquently summed up by a child's description: "they (the ions) start at the center and go round and round and come out at the edge." The "round and round" is the result of the transverse force exerted on the ions by the magnetic field, and the spiral path is the result of acceleration provided by a radiofrequency voltage applied to the "dees." The "cyclotron equation" $\omega = qB/m = 2\pi f$ gives the orbital frequency f of a particle in a magnetic field B, where q and m are the charge and mass of the accelerated ion. The cyclotron equation reveals a gift of nature: taking q, B, and m as constant, the orbital frequency f does not depend on the speed of the ion because the radius of the orbit increases just in proportion to the speed, so that the time per rotation is constant. Limits to the cyclotron process resulting from frequency errors from the relativistic increase in ion mass as the speed approaches the speed of light as well as deviations from the constant frequency ("isochronous") magnetic field shape in order to provide stabilizing ("focusing") forces to keep ions on the design trajectory were realized at an early time, and modifications were introduced. First the radio frequency (RF) was modulated to give the frequency modulated or synchrocyclotron. Later strong and weak azimuthal regions in the magnetic field (hills and valleys or sectors) were introduced to provide both focusing to hold the ions near the design path and isochronism so that the ions remain in step with the accelerating voltage and can be accelerated to high energies limited only by the bending power of the magnetic field. The energy limit of the cyclotron thus evolved into a cost limit, and a very natural further evolution of the cyclotron developed. As superconductors lowered the cost of magnetic bending power, the superconducting cyclotron pushed the cost limit to higher energies.

The start-in-the-center-and-go-to-the-outside character of the cyclotron leads, in fact, to an exceptionally large benefit from the use of high magnetic fields. The field must be provided over the complete pole of area πR^2, where R is the maximum radius. The magnetic flux Φ which determines the cross-sectional area of the return path steel, is field × area (i.e., $\Phi = B\pi R^2$. Expressing the flux in terms of the bending power BR then gives

$$\Phi = B\pi R^2 = \pi(BR)^2/B$$

(i.e., for fixed bending power, total magnetic flux varies as $1/B$). The length of the magnetic return path also varies as $1/B$, giving $1/B^2$ scaling for the total volume of steel. Superconducting cyclotrons are then lighter by a very large factor (×10 to ×20) than room temperature cyclotrons with the same maximum bending power.

Table 1 lists the present superconducting cyclotrons of the world, including several now (1998) under construction. Accelerators of this type have assumed a centrally important role in medium-energy nuclear physics—the 5 T · m bending power of the K1200 cyclotron at the National Superconduct-

Table 1. Superconducting Cyclotrons

Name	Location	Purpose	Magnet Bending Power ($T \cdot m$)	First Beam	Sector #	Type
K500	NSCL, Michigan State University, East Lansing MI	Nuclear research	3.2	8/82	3	Compact
TASSC	Chalk River, Ontario Canada	Nuclear research	3.3	9/85	4	Compact
K500	Texas A&M, College Station TX	Nuclear research	3.2	6/88	3	Compact
K1200	NSCL, Michigan State University, East Lansing MI	Nuclear research	4.9	6/88	3	Compact
K100	Harper Hospital, Detroit MI	Cancer therapy	1.4	4/89	3	Compact
OSCAR	Oxford Instruments, Oxford, UK	Isotope production	0.6	6/90	3	Compact
AGOR	Groningen, Netherlands	Nuclear research	3.5	4/94	3	Compact
K800	Carania, Italy	Nuclear research	4.2	5/95	3	Compact
Triton	Munich, Germany	Prototype SOC	1.3	—	12	Separated sector
SRC	Riken, Japan	Nuclear research	6.4	—	6	Separated sector

ing Cyclotron Laboratory at Michigan State University, for example, makes it currently (1998) the world's highest-energy cyclotron, whereas its 300 ton weight is minor compared to the 4000 tons of the largest room temperature cyclotron. [Many beams from the K1200 reach energies in excess of 10 GeV/ion making it also the highest-energy continuous wave (CW) accelerator of any type.] The large superconducting cyclotrons at Catania, Chalk River, Groningen, and Texas A&M form, together with the K1200, a central core of overall world research capability in medium-energy nuclear physics.

The 1.5 $T \cdot m$ cancer therapy cyclotron at Detroit's Harper Hospital and the twelve 0.5 $T \cdot m$ PET (positron emission tomography) cyclotrons manufactured by Oxford Instruments for leading medical centers in many countries have also demonstrated the feasibility and effectiveness of the superconducting cyclotron in situations where sophisticated technical support is much less available than in a major physics research center.

The coils used in most superconducting cyclotrons are cylindrically symmetric so that the very high "hoop stress" caused by the high field density and high current density are largely uniform with azimuth except for variations caused by the sector structure of the iron. Earlier superconducting cyclotrons used "cryogenically stable" helium-bath-cooled coils (i.e., coils with liquid helium in direct contact with each strand of conductor and with sufficient copper in the conductor so that if a section of conductor ceases to superconduct, the resistive power loss in the copper is nevertheless low enough for the conductor to recool as a result of the presence of the liquid helium rather than go into a runaway thermal excursion). Two of the more recent superconducting cyclotrons, at Harper Hospital and at Groningen, in contrast, use an "intrinsically-stable," epoxy-potted winding where cooling is supplied only at the external surfaces of the coil. In this type of coil, it is very important to have a tightly packed, fully impregnated winding because sudden wire motion at the scale of 20 μm to 40 μm will release heat sufficient to drive the conductor normal.

The last two cyclotrons in the Table 1 list (Munich and Riken) are under construction; both attempt to carry superconducting technology an additional step by introducing noncircular coils, which preferentially strengthen the hills in the magnet compared to the valleys. Such a coil configuration is necessary if the cyclotron is to operate at particle velocities $v/c > 0.6$, where axial focusing becomes a critical limiting parameter and open, low field regions are necessary between the hills ("separated sectors" to obtain sufficient axial focusing. The cyclotron at Riken is to produce beams up to 400 MeV/nucleon ($v/c = 0.7$); therefore, the technology of superconducting sector magnets is a central element of the project.

The superconducting cyclotron project at Munich also involves the feature of noncircular coils, but the dominating novel characteristic of this cyclotron is its superconducting RF system (in addition to superconducting sector magnets). Superconducting RF is not only very attractive conceptually because the RF system is normally the dominant power dissipation element in a cyclotron but also very difficult because superconducting RF currents will quench in the presence of dc magnetic fields at the level of about 10^{-4} T. It is very difficult to achieve an almost field-free region in close proximity to magnets of the field strength needed in cyclotrons. The Munich project thus uses an unusual cyclotron structure known as a separated orbit cyclotron, which has been discussed in the literature for many years but previously never built. In such a cyclotron, sufficient RF voltage is provided to achieve some stipulated separation between the last and next-to-last orbits so that extraction of the beam is facilitated. In the Munich example, superconducting cavities provide sufficient energy gain per turn to give a 4 cm separation between final turns, and the cavity system has performed impressively. The magnet in such a cyclotron is, however, quite complicated, with a series of N separate magnets on every turn, where N is the sector number. This gives 240 magnets for the case of the 12 sector, 20 turn Munich prototype. The problem of appropriately adjusting the current in all these magnets without inducing quenches caused by misaligned beam, has lead to a prolonged, presently incomplete period of debugging of the Munich system.

APPLICATIONS AND CHARACTERISTICS OF SYNCHROTRON RADIATION

A relativistic charged particle beam deflected by a magnetic field emits electromagnetic radiation known as *synchrotron* *radiation.* The radiation from a light electron is more intense than from a heavier proton. Therefore practical synchrotron light sources are electron (or positron) storage rings. These machines are the brightest continuous sources of vacuum ultraviolet and X-ray radiation available.

The total power P radiated by an electron beam of energy E and current I when deflected in a magnetic field B is, in practical units,

$$P[\mathrm{kW}] = 26.6E^3[\mathrm{GeV}]B[\mathrm{T}]I[\mathrm{A}]$$

A most useful attribute of synchrotron radiation is its high degree of natural collimation. The power is emitted within a cone of width $1/\gamma$ around the direction of the electron beam, where γ is the energy of the electron divided by its rest mass 0.511 MeV. Hence for a typical source with energy 1 GeV, the synchrotron radiation is confined to a fan in the plane of the electron orbit, diverging with an opening angle of less than 1 mr. Practical devices that store ~1 GeV electron beams of ~100 mA and deflect them in magnetic fields of ~1 T therefore produce tens of kilowatts of collimated radiation, emanating from a line source that can be less than a millimeter in diameter. Large facilities for the production and use of synchrotron radiation have been constructed at research centers in most of the industrialized countries of the world. Compact machines allow use of this radiation to be extended to industrial applications.

Different applications of synchrotron radiation require flux from different parts of the electromagnetic spectrum. The spectrum emitted by a synchrotron source is characterized by the *critical energy* ϵ_c. Half of the power radiated from the source is within a broad spectrum below the critical energy, and half is within an exponentially falling spectrum above ϵ_c. The critical energy is related to the electron energy and deflecting field by

$$\epsilon_c[\mathrm{keV}] = 0.665E^2[\mathrm{GeV}]B[\mathrm{T}]$$

Thus, through proper selection of the electron beam energy and deflecting field strength, the output of a synchrotron source can be centered in the spectral range of interest.

The bend radius ρ of an electron in a magnetic field is given by

$$\rho[\mathrm{m}] = E[\mathrm{GeV}]/(0.3B[\mathrm{T}])$$

Combining these expressions leads to an expression for the bend radius in terms of the critical energy and magnetic field

$$\rho[\mathrm{m}] = 4.09\epsilon_c^{1/2}[\mathrm{keV}]/B^{3/2}[\mathrm{T}]$$

This formula makes explicit the utility of choosing a magnet technology that can produce a high value of B in order to produce a compact synchrotron light source with output of kilovolt X rays. Good-quality normal conducting electromagnets constructed from copper windings and iron pole pieces are limited to about 1.5 T by the saturation properties of the iron. Superconducting magnets using niobium–titanium alloy superconductors operated at liquid helium temperature can produce accurate fields several times larger, and reduce the radius of the synchrotron source by an order of magnitude.

Among the industrial and medical applications of synchrotron radiation for which dedicated machines have been proposed are coronary angiography, protein crystallography, and X-ray lithography. Coronary angiography with synchrotron radiation uses an abrupt change in the absorption of X rays by iodine at 33.17 keV. By injecting an iodine-rich contrast agent, exposing the subject to two beams that straddle this energy, and subtracting the images generated, vascular structure can be clearly visualized. The diffraction of X rays has long been used to determine crystal structure. The superior brightness of synchrotron sources compared to alternative X-ray sources have made crystallographers major users of large synchrotron research centers. Despite continuing interest, as of this writing no dedicated compact synchrotron has been constructed for either angiography or crystallography. However, several have been made to enable the development of X-ray lithography.

X-ray lithography is a candidate to become the successor to optical lithography for the patterning of semiconductors in the highest-density integrated circuits. For 30 years, advances in optical lithography's ability to print fine features has led to geometrically increasing circuit densities and chip performance, a phenomenon characterized by Moore's Law, which observes that the number of transistors that can be put on a chip has been doubling about every 18 months. However, as the size of circuit features is reduced to values comparable to the wavelength of the ultraviolet radiation used to print the pattern (i.e., to 248 nm and below), diffraction effects limit the resolution, and the challenge of maintaining this trend becomes more difficult. X rays with energy near 1 kV, wavelength near 1 nm, diffract much less, and have been used to fabricate transistors with dimensions of 100 nm and below. Lithography of complex, high-density circuits using X rays has progressed to the pilot line stage, using compact synchrotron X-ray sources developed for this purpose. A related technology using higher-energy X rays to fabricate micromachine parts also has much promise.

TECHNICAL DESCRIPTION OF A COMPACT SYNCHROTRON

Compact synchrotrons have the same major subsystems and are designed according to the same principles as larger synchrotrons, although innovation has occurred in the design of the superconducting magnets for compact light sources. Figure 2 shows a photograph of the Helios 1 compact synchrotron manufactured by Oxford Instruments. Other machines include Aurora by Sumitomo Heavy Industies, COSY by COSY Microtech, MELCO by Mitsubishi, and SuperALIS by NTT. The major subsystems on all these machines are

- an RF accelerating structure,
- the magnet system,
- an injector and pulsed injection magnets on the ring,
- a vacuum system,
- beam diagnostics and controls, and
- ancillary power supplies and utilities.

The accelerating structure is a resonant radiofrequency cavity producing a longitudinal electric field imparting energy to the beam particles with each revolution. The energy gain serves both to raise the average beam energy during the acceleration cycle and to compensate for energy losses to synchrotron radiation. Synchrotron operation is based on the principle of

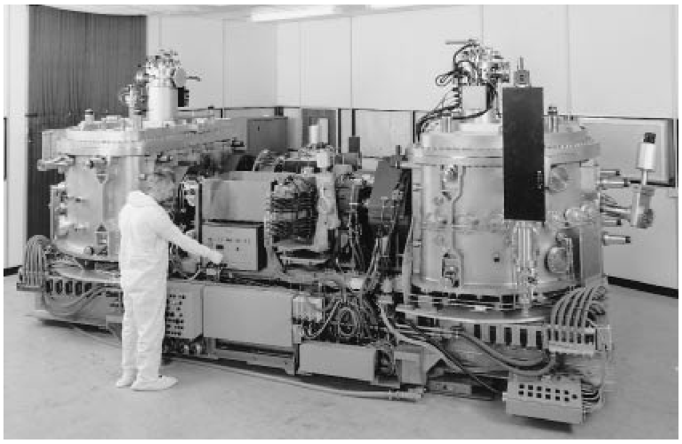

Figure 2. The first Helios compact synchrotron, built by Oxford Instruments. The two superconducting magnets can be seen at either end of the structure. X-ray beams emerge from the ports on the sides of the magnets.

phase stability. Particles with small deviations from the central beam energy follow slightly different orbits and arrive at the cavity at slightly different times. They automatically receive more or less energy according to their phase. The result is effectively a restoring force causing the beam to coalesce into bunches, with individual particles executing longitudinal *synchrotron oscillations* about the center of the bunch. Phase stability puts a constraint on the circumference of the orbit, which must be an integer multiple of the radiofrequency wavelength. The choice of radiofrequency is largely dictated by convenient RF sources. Klystron-based sources at 500 MHz have been used, as have solid-state sources at 50 MHz.

The most common compact light source layout has been a racetrack using a pair of superconducting magnets each producing a vertical magnetic field to deflect the beam by 180°. This configuration allows other machine functions (e.g., the RF structure, optical elements, pulsed magnets for injection, and vacuum components) to be distributed in the two straight sections. It still takes advantage of the small bend radius that can be achieved with a superconducting magnet to produce a device that can be factory assembled and delivered to a user as a complete unit. The magnetic field is increased during the acceleration cycle because the beam maintains a constant orbit in a synchrotron, unlike the outward spiraling orbit of the beam in a cyclotron. In the case of the Helios system, the superconducting magnets produce a field of 4.5 T at full energy, which allows a 700 MeV beam to be bent into a semicircle of radius 51 cm. The entire device, exclusive of the injector and ancillary systems, weighs about 20 tons and comfortably fits on the back of a truck.

In order to allow a beam particle with small deviations from the ideal orbit to survive for perhaps 10^{12} revolutions without being lost, some form of focusing is required. All compact synchrotrons built save one have been *strong focusing, alternating gradient* machines. (The Aurora 1 compact light source built by Sumitomo Heavy Industries was a weak focusing machine.) Focusing in one of the transverse planes can be accomplished by a magnetic field gradient. However, if a magnetic field gradient focuses in the horizontal plane, it inevitably defocuses in the vertical plane, and vice versa. The alternating gradient concept uses the principle that pairs of lenses acting together, one focusing and one defocusing, have a net focusing effect. The gradients necessary for producing stable orbits in a compact synchrotron can be produced by independent quadrupole lenses, as in a separated function machine, or by gradients built into the deflecting field, as in a combined function machine. The Helios source shown uses both. Precise placement of the superconducting wires is necessary to achieve the field quality required.

Most compact light sources have been designed with low-energy injectors. The purpose of the injector is to deliver to the ring an electron beam that is already relativistic and that is high enough in energy to limit the dynamic range required of the synchrotron's magnet system. Because the injection process is inefficient and produces radiation from particles that are not captured by the synchrotron, the energy of injection also determines the thickness of shielding required. Both linear accelerators and racetrack microtrons are in use as injectors for compact light sources. Rings designed for operation at 700 MeV to 1 GeV have successfully used injection energies from 50 MeV to 200 MeV. Pulsed magnets within the ring are required to deflect the incoming beam from the injector onto a stable orbit.

Ultra-high vacuum technology is required in a compact synchrotron because the lifetime of the beam can otherwise be limited by losses from collisions between the electrons and residual gas atoms, especially those liberated by collisions between synchrotron radiation and the vacuum chamber walls. The presence of a cryogenic system for the superconducting magnets makes cryopumping a natural choice. The Helios source has achieved beam lifetimes in excess of 50 h with 200 mA of circulating electrons. Because the injection and acceleration cycle require only about 10 min, a high utilization factor is possible.

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SUPERCONDUCTING DEVICE RELIABILITY.

See SUPERCONDUCTING MAGNETS, QUENCH PROTECTION.