the Bay of Islands ophiolite does, and some resemble island arcs.

An explanation of the Troodos paradox may be that spreading and the creation of new ocean crust did occur but near a subduction zone, where cool, dense ocean crust dives into the mantle, undergoes partial melting, and generates the volcanoes of island arcs. Crust generated at a mid-ocean ridge might become part of an ophiolite through the collision of a ridge with a continent, the edge of the continent lifting part of the thin crust. An increasingly popular view, however, is that many if not most ophiolites originate as ocean crust that forms in a small, marginal basin on the opposite side of the island arc from the subduction zone, or deep-sea trench. The magma generated by the partial melting of wet ocean crust, sediment, and mantle could contaminate the magma source of the spreading center, giving it chemical characteristics of island-arc rock. If the marginal basin closes, the colliding island arc and continent could shove a scrap of ocean crust onto dry land, according to this model.

The catch to this idea is that some typical ophiolites, like Troodos, have subduction-related chemistries but show no sign of an island arc nearby. Casey and John Dewey of the University of Durham suggested one possible explanation. A subduction zone could form suddenly near a spreading center, which for a time continues to form new crust while drawing on subduction-generated magmas. A likely place to make the quick shift, they said, would be at a transform fault, which connects the offset ends of two sections of mid-ocean ridge and allows abutting crustal plates to slide past each other. When the relative motion of the plates changes, their convergence at the now abandoned transform fault could force one of the plates downward, forming a subduction zone and initiating the formation of a young island arc. The new subduction-related magma generation could also feed the adjacent spreading center for a while.

When a continent approaches the young subduction zone, according to this theory, the continent could scrape off the ocean crust that once bounded the active transform fault but later was trapped between the subduction zone and the incipient island arc. The resulting ophiolite would be bounded by transform-related rocks on its inboard side, as both Bay of Islands and Troodos are, and display mid-ocean ridge type chemistry, as at the Bay of Islands, or subduction-related chemistry, as at Troodos. Even ophiolites overlain by island-arc volcanic ash and lava could thus be representative of mid-ocean crust, Casey warned.

One way to deal with the obvious complexities of most ophiolites would be to find one that has not suffered the battering and alteration apparently required to put ocean crust onto continents. R. Varne, B. J. Griffin, and J. A. Jenner of the University of Tasmania think that they have a promising candidate. It forms part of Macquarie Island, the last, lonely outpost south of New Zealand. All of the appropriate crustal layers are there, and the island itself seems to have been simply squeezed toward the surface like toothpaste from a tube. Remoteness, foul weather, and rugged terrain make field studies difficult, but researchers hope that Macquarie will provide an even clearer view of at least one section of mid-ocean crust.

—RICHARD A. KERR

Additional Reading

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New Magnets Enhance Synchrotron Radiation

Most of the wigglers and undulators in future synchrotron radiation centers will be made of samarium-cobalt permanent magnets

Herman Winick of the Stanford Synchrotron Radiation Laboratory facetiously calls it a "death ray" because of its intensity. It is a 2-meter-long array of magnetic dipoles that will be the most powerful source of synchrotron radiation yet produced, when it is installed at Stanford later this summer. Now being tested at the Lawrence Berkeley Laboratory, where it was built under the direction of Klaus Halbach, this dipole array or wiggler is the latest in a series of designs based on the use of samarium-cobalt ($SmCo_5$) permanent magnets. Most of the wigglers and undulators (array of dipoles similar to a wiggler) planned for present and future U.S. synchrotron radiation centers follow Halbach's designs and use the samarium-cobalt compound.

Wigglers and undulators, which are lumped under the term insertion devices, are on the verge of revolutionizing synchrotron radiation research, so the success of samarium-cobalt permanent magnets is far from a technological curiosity. Synchrotron radiation sources up to now have been primarily those portions of electron storage rings where dipole bending magnets keep the circulating electron beam in its curved trajectory. Insertion devices fit in the straight sections between bending magnets. A dipole array forces the electron beam into a sinusoidal wiggle that is superimposed on its circular orbit, thereby shaking out more synchrotron light.

A wiggler generates the same continuous spectrum of light from the infrared to x-rays as a bending magnet does, but the radiation is more intense with the wiggler and extends to even shorter wavelengths. An undulator is designed to maximize the cooperative superposition of light waves emitted by the electrons at each peak of their sinusoidal trajectory. In this way, the smooth wiggler spectrum is broken up into one or more intense bands with a much reduced light output at other wavelengths.

Future synchrotron radiation facilities will rely almost exclusively on the use of insertion devices to generate synchrotron light. The $62-million Advanced Light Source, centerpiece of the proposed National Center for Advanced Materials at Berkeley (*Science*, 18 February, p. 827), is the first of this new generation of synchrotron radiation sources. A committee of the European Science Foundation has likewise turned in a preliminary plan for a $142-million synchrotron radiation facility that is only somewhat less devoted to insertion devices, which will service about three-quarters of 90 to 100 experiments.

Existing synchrotron radiation centers are also emphasizing insertion devices as much as possible. For example, expanded experimental areas are being dedicated to beam lines carrying light from insertion devices to researchers' equipment. The National Synchrotron Light Source at Brookhaven National Laboratory, which is still being broken in, has received administration approval (though not yet congressional approval) for a $19.7-million "Phase II," which will include up to eight insertion devices. Similarly, Stanford, which has two fully subscribed wiggler beam lines, will have the new Berkeley wiggler soon and two more insertion devices are included in a $13.8-million upgrade called the Stanford Enhanced Photon Flux Facility that is also in the fiscal 1984 budget.

From the designer's point of view, the insertion device revolution is the relegation of electron storage rings to race tracks, finely tuned to be sure, merely for the purpose of speeding electrons through an obstacle course of insertion devices. From the researcher's point of view, the revolution is the vastly increased brightness of the synchrotron radiation. A high brightness corresponds to a high flux of photons having almost the same wavelength that are emitted from a small source into a narrow cone (small solid angle). The brightness of the light from a wiggler increases roughly as the number of dipoles in the array, whereas the brightness of that from an undulator rises approximately as the square of the number of dipoles. A commonly cited figure for the maximum brightness of an undulator is 10,000 times that of a bending magnet of the same magnetic field. Since wigglers emit radiation continuously over the entire spectrum rather than into a few bands, the total power radiated by a wiggler is greater than that of an undulator. The Berkeley wiggler will radiate a total of 20 kilowatts, as compared to about 10 watts from the most powerful conventional x-ray tubes.

A recent National Academy of Sciences report (*Science*, 17 December 1982, p. 1211) has called attention to the virtues of high source brightness. In short, with high brightness, researchers can detect species present in minute concentrations, can carry out high-resolution spectroscopic studies, or can take time-resolved "snapshots" of rapidly evolving physical systems.

So, what do samarium-cobalt permanent magnets have to do with all this? The material was developed in the mid-1960's by Karl Strnat of the University of Dayton and several co-workers at the nearby Air Force Materials Laboratory at Wright-Patterson Air Force Base. When samarium-cobalt is in the ferromagnetic state (that is, when the temperature is below the Curie temperature), its magnetization vector lies parallel to the axis of its hexagonal unit cell that is normal to the basal plane. Commercial material is polycrystalline with fine grains about 5 micrometers in diameter and with a preferred orientation so that the normal axes of the grains are approximately parallel. Samarium-cobalt comes in powder form. Exposing the powder to a magnetic field physically aligns the grains. However, after the power is sintered at high temperature, the magnetizations of the grains average to zero because they are randomly parallel and antiparallel. Thus, there is a second alignment procedure of the sintered material in an applied field.

The flipping of the magnetization vector in a grain requires much more energy in samarium-cobalt than in other permanent magnet materials, and it is this property that gives rise to two of this compound's magnetic virtues. One is a high remanent field (field remaining when the magnetizing field is removed). The other is a high coercivity (strength of the external magnetic field needed to demagnetize the material). Samarium-cobalt is unusual in having a coercivity higher than other permanent magnet materials, together with a remanent field comparable to the coercivity.

Future synchrotron radiation facilities will rely almost exclusively on insertion devices.

A third feature of samarium-cobalt is that the net magnetic field due to the permanent magnet and any applied external field is very nearly a simple sum of the magnet's field and the applied field. In most other materials, the net field is a nonlinear function of the applied field. This linear superposition property makes designing magnetic systems a considerably less demanding chore than usual.

An up-to-the-minute example is the Stanford Linear Collider, which will be built at the Stanford Linear Accelerator Center if congress approves the Administration's fiscal 1984 budget. Most of the particles in the two beams pass by one another without colliding, but Stanford physicists hope to maximize the collision rate by focusing the beams down to a cross section of a few square micrometers by the use of quadrupole magnets. One of the options under consideration is to place samarium-cobalt quadrupoles close to the collision point, which lies inside a giant electronic detector that analyzes the numerous elementary particles produced in the linear collider's 100-billion electron volt (GeV) events. This degree of focusing is about 1000 times finer than that achieved in today's electron-positron colliding-beam storage rings and is obviously a delicate affair. Since the particle detector generates a magnetic field of its own, it is important that physicists know precisely how the detector and focusing quadrupole fields interact. The linear superposition property of samarium-cobalt means that they do not interact.

As it happens the first use of samarium-cobalt in accelerators was as a focusing lens for proton linear accelerators. Halbach, having learned about the material at a magnetics conference and meetings with Strnat, designed a focusing quadrupole whose cross section consisted of 16 trapezoidal segments forming a ring, with the particle beam running through the center. The magnetization direction in each segment was perpendicular to the beam in such a way that it changed by 67.5 degrees from segment to segment, thus making the characteristic quadrupole configuration with two north poles facing one another and two south poles doing the same.

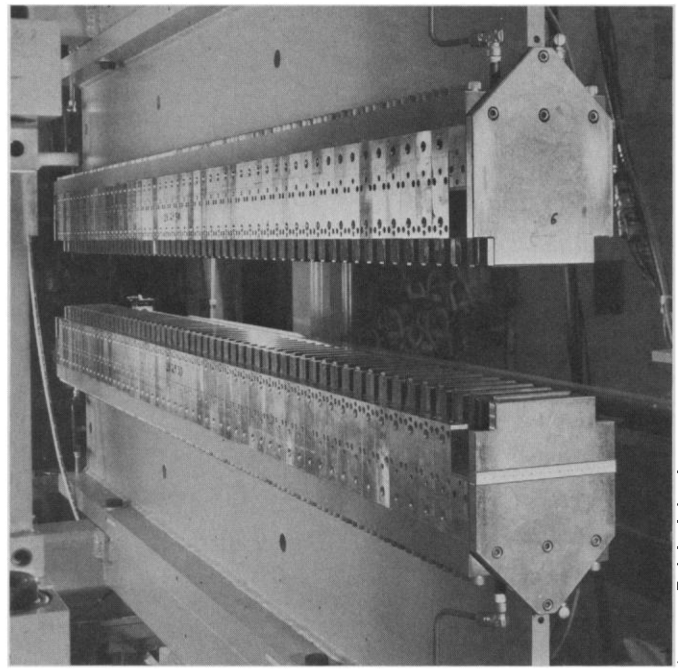
Halbach developed this design in the late 1970's for the Los Alamos National Laboratory, where physicists are working on a classified proton linear accelerator with a high beam current. One of the physicists, Ronald Holsinger, subsequently left Los Alamos for the New England Nuclear Company, which wanted to build a proton linac for radioisotope production. Holsinger, who was in charge of magnets for New England Nuclear, used Halbach's design to build over 100 quadrupoles for this machine. Two years ago, Holsinger formed his own company, Field Effects, Inc., Carlisle, Massachusetts, and by now has manufactured several samarium-cobalt magnet systems.

Samarium-cobalt's entry into synchrotron radiation came in 1978 when Stanford was building a six-dipole, 1.8 tesla wiggler based on conventional electromagnets. There was considerable interest in undulators because two groups in the Soviet Union had begun experimenting with such devices and a French group at the Laboratory for the Utilization of Electromagnetic Radiation (LURE) at Orsay was building a superconducting undulator. Halbach approached Winick with an idea for a permanent magnet undulator. After considerable hesitation a joint Berkeley–Stanford agreement was worked out in 1979.

In the space of a year, an undulator was designed and built at Berkeley and tested at Stanford. The device has 60 dipoles in a linear array. The strength of the field depends exponentially on the gap between the pole faces and varies from 0.23 tesla at a 3-centimeter spacing to 0.05 tesla at 6 centimeters. These values illustrate a principal difference between wigglers, which tend to have a small number of dipoles with high magnetic fields, and undulators. It takes two dipoles to bend the electrons through one period of a sine wave. The two-dipole unit consists of eight samarium-cobalt blocks, four above the electron beam and four below. The orientation of the magnetizations in the upper row would be, for example, north-east-south-west, while in the lower row they would be north-west-south-east. The entire 60-dipole assembly is almost 2 meters long.

Following the successful demonstration of the undulator at Stanford, this basic design has become widespread. The French group at LURE found its superconducting undulator serviceable but cumbersome and scrapped it after 6 months of use. They now have a samarium-cobalt undulator, which was built with Halbach's help. One of the main uses of this device is in a free-electron laser experiment being carried out in collaboration with John Madey, David Deacon, and others from Stanford University. A free-electron laser, proposed by Madey over a decade ago and demonstrated by his group in 1976, converts part of the energy of an electron beam into a coherent optical beam. Madey's original experiment used an electron linear accelerator and had a rather low conversion efficiency. The LURE experiment uses an electron storage ring with a circulating beam and is the first step to a high-efficiency laser. A similar free-electron laser experiment is getting under way at Brookhaven, and there are several free electron laser projects based on linear accelerators, all of which use samarium-cobalt undulators.

The Berkeley wiggler is not a pure samarium-cobalt structure but rather a hybrid that incorporates steel pole pieces. Another Halbach innovation, the hybrid uses samarium-cobalt to be in effect the coils that produce a magnetic field in the steel pole pieces. In this way it is possible to obtain magnetic fields in excess of the samarium-cobalt remanent field of about 0.9 tesla. The use of steel also permits finer tuning of each dipole by adjustments in the dimensions of the steel pole pieces than is possible with pure samarium-cobalt magnets. Commercial samarium-cobalt comes with small variations in the orientation and strength of the magnetic field that make precise engineering impractical. The disadvantage of using steel is that the property of linear superposition is lost.



Hybrid wiggler

Designed by Klaus Halbach and built in Egon Hoyer's shop at the Lawrence Berkeley Laboratory, this 54-pole wiggler will produce light intense enough to melt through thin metal structures in less than a second.

An interesting feature of the hybrid wiggler is that the gap between the pole piece faces is not limited by the size of the vacuum chamber of the Stanford storage ring. The magnet has its own section of vacuum chamber whose vertical dimension is adjustable from 0.4 to 1.8 centimeters. The wide gap is necessary to accommodate the large cross section of the electron beam as it is injected into the storage ring. The narrow gap, after the beam is stored, allows the highest possible light output.

A future development is to place the magnets within the vacuum chamber itself. This capability is most important for enhancing the output of undulators in relatively low energy storage rings, as argued recently by George Brown of Stanford, Winick, and Peter Eisenberger of the Exxon Research and Engineering Company. The wavelengths of the undulator bands are determined primarily by the energy of the electron beam and the length of the sine-wave trajectory in the undulator. To get short wavelengths (x-rays rather than ultraviolet, for example), one wants a high (few GeV) beam energy and a short period length. To get x-rays from an undulator in a storage ring of lower energy, one needs to reduce the period length proportionately. The way the equations work out, it is also necessary to reduce the gap between the pole piece faces in step with the reduction in the period length. Placing the magnets within the vacuum chamber permits the smallest gap.

The requirement for small dimensions points out what may ultimately be samarium-cobalt's chief selling point. Electromagnets, whether conventional or superconducting, require coils and cooling. As the size of the magnet decreases, the coils and the cooling system cannot scale down proportionately. Permanent magnets, lacking these peripherals, do scale down in all respects.

Small size may also eventually lead to some interesting commercial possibilities for synchrotron radiation. One is x-ray lithography, the x-ray equivalent of the visible-ultraviolet technique now used to imprint patterns during the fabrication of microcircuits. Smaller wavelength x-rays would permit making patterns with characteristic sizes of much less than 1 micrometer, whereas the present optical technique cannot delineate features this small. Yves Petroff, the director of LURE, thinks that a 500-MeV storage ring costing $2 million or less would be attractive to electronics companies.

He proposes to build a test storage ring (240 MeV and 16 meters circumference) in which all the magnets, the dipoles and quadrupoles of the storage ring as well as the insertion devices, are samarium-cobalt. Construction awaits testing of a prototype dipole (to be built at LURE) and a prototype quadrupole (to be built by Halbach's group at Berkeley). The quadrupole is a new Halbach hybrid design with a variable strength field achieved by having two concentric magnet rings that rotate with respect to one another. The magnetic field is adjusted whenever operators change the energy or other properties of the electron beam.—**Arthur L. Robinson**