Superconducting Accelerators: High Energy Is Trailing Low Energy

The research enterprise that has done the most to promote the development of superconducting technology, high energy physics, has been disappointingly slow to adopt its own stepchild. The latest two large accelerators built in the United States and Europe were assembled with conventional magnets, and usage of superconducting magnets for peripheral equipment at the big accelerator laboratories is almost negligible, except for notable successes with large bubble chambers. Many laboratories have test designs for accelerator sector magnets and external beam magnets which are superconducting, and they may be operational within 1 or 2 years. But in the meantime, researchers who usually get less limelight than high energy physicists have already produced several superconducting accelerators that are proving quite attractive for research at medium and low energies.

At the University of Illinois a superconducting linear accelerator has been working well for 2 years, producing a dependable beam for low energy research. The 19 Mev beam will soon be upgraded with equipment built at Stanford University to at least 60 Mev. Stanford researchers also have tested a superconducting accelerator, and within 2 years both groups hope to boost their accelerators into the medium energy range, at least several hundred million electron volts.

The superconducting linear accelerators built at Stanford and Illinois are modular devices that produce electron beams with greater energies if either the number of modules is increased or the beam is recirculated through the superconducting part many times. Whereas magnets constitute most of the hardware in high energy synchrotrons, the principal components in linear accelerators are specially designed cavities. High frequency electromagnetic fields boost the beam along as it passes through one cavity after the other down the length of an accelerating section.

Power for these cavities is piped into the accelerator from high frequency power supplies called klystrons. If the cavities are made of copper, as in conventional machines, enormous amounts of power are lost by the normal metallic resistance to intense currents produced in the cavity walls. The power losses in a conventional linear accelerator would approach 1 megawatt for every foot of its length, if it were operated continuously. For this reason, linear accelerators with normally conducting walls are constrained to operate in a pulsed mode, in which the beam is actually "on" for only about one-thousandth of the time. Pulsed accelerators have the disadvantage that they cannot be easily used to recirculate the beam. Pulsed operation also effectively rules out a large class of experiments that investigators would like to study with electron accelerators, namely, those in which the incoming electron scatters another particle out of the target and is observed in coincidence with it.

When the cavities are made of niobium instead of copper, the power losses are reduced dramatically to less than 1 watt per foot. Power losses due to a-c currents in a superconductor are not zero, as they are for d-c currents, but they decrease exponentially as a material is cooled below the temperature at which it first becomes superconducting, which is 9.2°K for niobium.

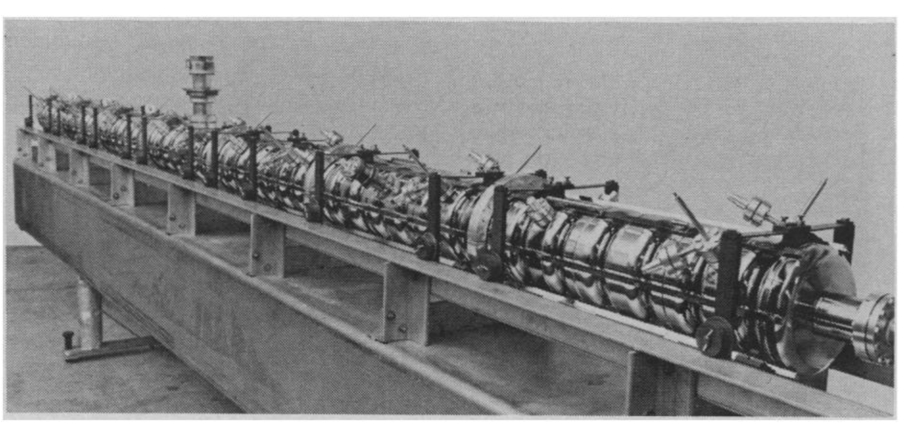

Fig. 1. A 6-meter superconducting accelerator section, fabricated from sheets of niobium by researchers at Stanford University, is shown here without the cryogenic vessel that normally encloses it. When cooled to 1.9°K and powered with 1.3 Ghz microwave radiation, each such section will accelerate electrons by 12 to 20 Mev with very little loss of power.

The properties needed for superconductors in high frequency accelerator cavities are quite different from those essential for superconducting magnets. In magnets, high fields can be attained with superconducting coils specifically because certain alloys allow magnetic fields to pass through their bulk without destroying superconducting properties. In high frequency accelerator cavities, the superconducting surface must have a high degree of homogeneity to avoid excessive power losses, and this is more easily achieved with pure materials, such as niobium, than with alloys. For this reason, niobium is used in linear accelerators, while niobium-titanium alloy is used for superconducting magnet applications at high energy accelerators.

Niobium was not always the preferred material for linear accelerators. In 1961, Perry B. Wilson at Stanford began testing tin and lead superconductors and found lead to be the more attractive candidate, having power losses less than one ten-thousandth of a copper cavity at room temperature. At that time researchers knew that theoretically niobium was a still better material. But tests of actual cavities of niobium in the early 1960's were quite disappointing: some barely became superconducting at all. The simple techniques used for making cavities of lead was not very successful with niobium.

The breakthrough that showed that niobium could be as good as the theory promised came in 1968. When John Turneaure at Stanford and Ira Weissman at Varian Associates, a company adjacent to the Stanford campus, tested cells made of pure, high grade niobium, they found that the losses were further reduced by at least two orders of magnitude, and further work at Stanford and the Siemans Company in Erlangen, West Germany, showed that the critical field, the field that forced niobium to become normally conducting, was quite high. The low losses offered accelerator designers the possibility of a machine that could run continuously with relatively little power consumption, while the high critical field stimulated the hope that a very short accelerator could produce very high energy particles. Further tests with small cavities made of pure niobium convinced the Stanford researchers that they could build an accelerator with an energy gradient of at least 4 Mev per foot (the theoretical limit is 12), with an effective resistance smaller by 10^6 than the high frequency resistance of copper at room temperature. The energy gradient of comparable accelerators is about 0.8 Mev per foot.

Unfortunately, the full-sized prototypes do not work as well as the test cavities did. The prototypes are larger and they do not produce the high energy gradients that had been hoped for, although other qualities of the beam produced are quite good, and the power losses are nearly as low as expected. The lower energy gradients are not completely understood, but what apparently happens, according to John Turneaure, is that small surface defects in the niobium walls cause local heating once a certain field strength is reached, and the heating spreads and causes the cavity losses to rise dramatically. The limit to the field imposed by such thermal runaway effects is typically less than one-tenth the theoretical maximum, and this limit holds the practical energy gradient to about 1 Mev per foot.

The basic subsection developed by the Stanford researchers is a 6-meter-long module (Fig. 1), which is composed of 55 cavities aligned end-to-end with openings for the beam to pass through the middle of each one. For actual operation, the pure niobium section is enclosed in a cryogenic tank and cooled to 1.9°K with liquid helium. To minimize the defects that limit performance, the sections have to be polished to a very high degree of smoothness, chemically cleaned, and carefully annealed. The individual cavities are welded together by an electron beam technique, cleaned, and fired at 1700°C in an ultrahigh vacuum. Even with such precautions, the quality of different sections varies considerably. Stanford researchers have now built five 6-meter sections, and the best produces an energy gradient of 1.3 Mev per foot and has a power loss of 4×10^{-6} the loss of copper.

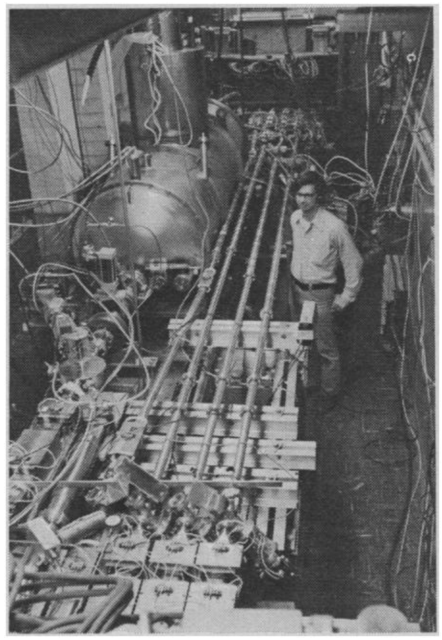

Fig. 2. A 19 Mev superconducting electron accelerator that has been operating for 2 years at the University of Illinois in Champaign. The oblong tank at the left encloses a 1.5-meter supercooled niobium accelerator structure which boosts the energy of an electron beam by 3 Mev each of the six times it passes through. Liquid helium to cool the structure is pumped into the tank through the circular tower on top. The electron beam initially enters from the left foreground, then recirculates five times, once to the left of the tank, then four more times through the beam pipes to the right. Two large magnets at either end of the room double the beam back during each circuit.

In retrospect, it seems clear that the Stanford researchers and their sponsors at the National Science Foundation were unduly optimistic about the promise of superconducting linear accelerators. After the initial tests of niobium proved so outstanding, the High Energy Physics Laboratory proceeded quickly with plans for a 500-foot superconducting accelerator scheduled for completion in 1971. (The name of the laboratory, which is different from Stanford's 2-mile accelerator laboratory, is something of a misnomer because the three electron accelerators it has built now fall in the medium energy range.) A large helium refrigerator was developed and installed, and cryogenic tanks and niobium were purchased for many, if not all, of the 25 sections of the planned accelerator. Tunnels and buildings were completed at a cost of about \$5.5 million, mostly borne by the Office of Naval Research.

The accelerator was to have produced a continuous beam with an energy of 2 Gev, the estimate based on a 4 Mev per foot gradient. But the technical problems of achieving large gradients proved overwhelming, and in 1972 plans for the \$17 million project were shelved.

The setback was not an easy lump for the Stanford physics community, which has a fine record in low temperature research, to take. Nevertheless, the energy gradients and beam qualities already achieved seem quite suitable for a 200 to 700 Mev accelerator. Recently a review board for U.S. medium energy science, chaired by Roger H. Hildebrand at the University of Chicago, found that superconducting electron accelerators offer the principal opportunity for technical advances at medium energies. The Stanford program continues to expend considerable effort trying to improve the sections, and the review board recommended that the program's first priority, for the purposes of medium energy science, should be to complete and gain experience operating a four-section prototype accelerator, recognizing that it might be at the expense of developing higher gradient cavities.

A test accelerator composed of one 6-meter section plus a superconducting injector has been successfully operated at Stanford for 15 weeks during the last year. It produces a high quality beam of electrons at an energy of 25 Mev, with current up to 500 microamperes, although the time-averaged current has more often been 25 microamperes or less. With the addition of another 6-meter module, the test accelerator has produced a 37 Mev beam. The Stanford team plans to add two more sections by the end of the year, and then will gain experience operating a four-section prototype and begin photon-induced nuclear experiments in collaboration with researchers at the Lawrence Livermore Laboratory.

The superconducting sections can be used for other research than nuclear physics, and an effort to produce a novel type of laser is providing some new information, without a wait for more accelerator construction. With the 25 Mev beam from one section, Schwettman and his associates have shown that they can make a "free electron laser" by passing the beam through a series of evenly spaced and alternately directed magnetic fields. Electrons passing through such a configuration radiate coherently, and the device has been used to amplify the 10.6 micrometer radiation from a carbon dioxide laser. With an increase in electron current, the device should have enough gain to operate as a laser by itself. It will be tunable, by adjusting the electron energy, and may soon have a range from the infrared up into the visible wavelength region.

Researchers at the University of Illinois have taken a different tack, emphasizing the recirculation of the electron beam many times through the same superconducting section rather than to build many superconducting sections in a row. In a relatively small set of buildings on the Champaign campus, the Illinois researchers built a 2.5-meter superconducting niobium accelerator, composed of two short sections starting in 1970. When everyone still expected to get high energy gradients, a 3-meter cryostat was made to hold half of a 30 Mev accelerator. But, according to A. O. Hanson at Illinois, when it became clear in 1971 that the most energy they could routinely get from the two sections was 4 Mev (the maximum had been 5 Mev before a vacuum accident contaminated the surfaces of the cavities) they started plans to recirculate the electron beam through the small sections.

That an electron beam can be accelerated many times by one set of electromagnetic fields is, in itself, a demonstration of the special theory of relativity. While heavier particles continually pick up speed as their energies increase from a few million to several billion electron volts, the electron reaches a velocity very near the speed of light by the time it has a few million electron volts of energy. After that, energy boosts do not appreciably change its velocity, which has reached the same value as the wave velocity of the electromagnetic radiation in the cavity—the speed of light. As long as an electron beam returns to the entrance of the linear accelerator on a path which is an integral number of microwave (1.3 Ghz) wavelengths long, the beam will be in the proper phase to be accelerated again. If the accelerator fields are reasonably stable, the beam can be recirculated dozens or even hundreds of times.

First with a system to send the beam back through the accelerator for three orbits, and then with a system for six orbits (Fig. 2), the Illinois group showed that recirculation is indeed feasible and that it does not damage the quality of the beam. Two large magnets at either end of the accelerator section double the beam back in consecutively larger orbits through the tubes shown in the photograph. With three passes, the system produces 5 microamperes of current at an energy of 9.5 Mev, which is suitable for many nuclear physics experiments, such as studies of nuclear excitations and fission induced by photons from the electron beam. With six passes, the machine produces 19 Mev beams (suitable for tagged photon experiments).

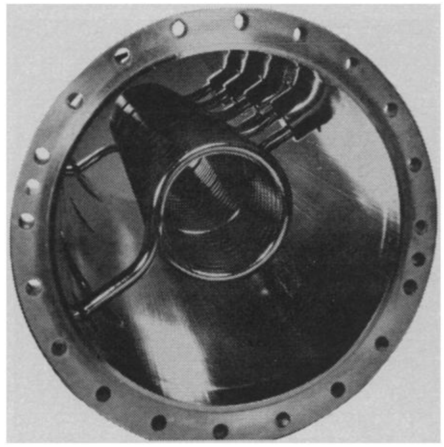

Fig. 3. One section of a superconducting accelerator for heavy ions being developed at Argonne National Laboratory. The 7-cm-diameter coils are made of niobium and cooled by filling the five helical subsections with liquid helium. The 65-cm-long section is a test design for a device intended to accelerate beams of various ions ranging from carbon to copper.

Now that they have demonstrated that recirculation works, the Illinois researchers plan to use it to build a larger accelerator that may eventually reach 200 Mev. The heart of the new system will be a 6-meter section fabricated at Stanford, which has already been tested without a beam at Illinois and seems to be capable of adding 13 Mev to the beam for each traversal. With their present system of magnets, the Illinois team plans to set up a recirculating accelerator designed for six passes through the Stanford section, which should produce beams with an energy of 60 Mev, by next fall, according to Peter Axel. The present magnets are too small for more than six passes, but with a pair of larger magnets, costing about $500,000, the number of passes could be raised to 20, and thus the energy to at least 200 Mev. Since the 6-meter section and the cryogenic equipment to cool it only cost about $150,000 each, the entire project would be a very economical medium energy accelerator.

Stanford researchers also plan to recirculate the beam and already have the necessary magnets. They are requesting a supplement to their fiscal 1976 budget for additional hardware, and hope to build a system that will pass a beam through four sections five times, for a total of 340 Mev in available energy. Eventually they envision the same system with eight sections producing 700 Mev.

Although superconducting accelerators for heavy ions are more difficult to design than superconducting electron accelerators because the ions travel more slowly, the importance of heavy ion research has stimulated the search for a machine that consumes less power than the huge heavy ion accelerators built in the past. The central problem is to slow down the phase velocity of the electromagnetic waves so that it coincides with the velocity of the ions. To do this, Lowell Bollinger and his associates at Argonne National Laboratory have built a structure with helical coils that accomplish the desired retardation. The coils and the surrounding tube (Fig. 3) are made of niobium, and radio-frequency power is supplied to the whole structure.

Recent tests have shown the technical feasibility of the Argonne design, and researchers are proceeding with the design of a 10-meter accelerator, perhaps composed of six structures like the one shown in Fig. 3, to boost the energy of heavy ions from an existing tandem van de Graaff accelerator. A troublesome problem with the helical design is that the coils are springy and are continually susceptible to vibrations that untune the structure. The Argonne design compensates for this with an electronic feedback technique that rapidly switches between high and low frequencies of the radio wave resonator in such a way that the average frequency is stabilized. The same technique, which was developed in the low temperature division of the Caltech physics department, is used at the Nuclear Research Center in Karlsruhe, Germany, for a superconducting proton linear accelerator intended to produce over 1 milliampere of current. A more rigid structure that should not require the feedback technique is being developed in the nuclear division of the Stanford physics department.

The superconducting technology for linear accelerators is quite different from that for synchrotrons. The devices discussed above are smaller and perhaps therefore simpler than high energy accelerators. Nevertheless, the record of the builders of lower energy superconducting accelerators is impressive, and their machines can be expected to improve markedly in the next several years.—William D. Metz