SUMMARY OF FIRST WEEK OF SUMMER STUDY

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The first week of the 1968 Summer Study on Superconducting Devices and Accelerators at the Brookhaven National Laboratory dealt with the rf applications of superconductivity and, in addition, with the superfluid helium technology which is essential to this development. The discussion during the week was lively and productive and the sessions were attended by a broad spectrum of physicists from industrial, government, and university laboratories in this country and abroad.

I. RF PROPERTIES OF SUPERCONDUCTORS AND CAVITY FABRICATION TECHNIQUES

During the first week a great deal of time was given to a careful discussion of recent experiments and planned research on the rf properties of superconductors. This discussion included papers by Hahn from Brookhaven, Turneaure from Stanford, Jüngst from Karlsruhe, Allen and Hogg from SLAC, and Haden from Texas. In addition, because of the particular interest in the recent developments of high Q, high field niobium cavities, Turneaure from Stanford, Meyerhoff from the Linde Division of Union Carbide, and Weissman from Varian Associates described in detail the special techniques involved in the preparation of niobium cavities, and the promising fabrication techniques being developed for construction of practical niobium accelerator structures.

Historically, most of the early experiments by groups interested in superconducting linacs involved measurements on lead cavities. Recently, the greatest emphasis has shifted to niobium, although active experimental work on lead continues. Niobium with a transition temperature of 9.25°K, and lead with a transition temperature of 7.2°K exhibit the very highest transition temperatures and critical magnetic fields among common elemental superconductors. Autler pointed out during the Summer Study, however, that technetium with a transition temperature of 7.7°K should, perhaps, be added to the list of interesting elemental superconductors. The principal disadvantage of technetium is the fact that its nucleus is unstable and beta decays with a half-life of 5×10^5 years. There is good reason for the concentration of effort on the development of pure metals for rf applications. Contrary to the case of high field superconducting magnets, high Q, high field superconducting cavities depend on the absence of flux penetration and it is to be expected that this condition can be satisfied best with pure metals. Despite this fact, a few exploratory experiments are planned at Stanford and at SLAC to investigate the fundamental rf properties of some of the superconducting "alloys" which exhibit marked type II behavior.

Extremely high Q's in superconducting cavities were first obtained at Stanford in 1964 using electroplated lead cavities. From the experiments reported by various groups (Brookhaven, Stanford, Karlsruhe) at the Summer Study, it may be concluded that, for lead-plated TE_{011} mode cavities, Q's in excess of 10^9 are now commonplace and Q's in excess of 10^{10} are frequently achieved. Results reported for TM mode cavities, however, are less encouraging (Stanford, Karlsruhe). Lead surfaces are easily contaminated and in TM mode cavities, where there are large electric fields at the cavity

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walls, dielectric losses are observed to limit the Q's to values that are typically a few times 10^8. In addition, the contamination undoubtedly contributes to enhanced field emission currents when TM mode cavities are operated at high power levels. One interesting approach to this problem is being studied by the group at Karlsruhe. A protective indium layer is plated over the lead. This layer is made sufficiently thin that due to the proximity effect the indium is superconducting even at temperatures above its usual transition temperature. No definitive conclusions have been reached yet in this investigation, but it can be hoped that this method or a similar method will be successful.

Whereas the problem of contamination must yet be solved before lead can be used effectively in accelerator applications, the development of niobium has proceeded well beyond this point. Cavity Q's exceeding 10^{10} and energy gradients exceeding 3 MeV/ft in a standing wave structure, or 5 MeV/ft in a traveling wave structure, have been achieved in TM mode cavities fabricated from commercially available reactor grade niobium (Stanford and Varian) and it is expected that niobium of greater purity will produce even better results. Some confidence was expressed at the Summer Study that energy gradients as high as 6 MeV/ft in a standing wave structure or 10 MeV/ft in a traveling wave structure will eventually be achieved. At 1.3 GHz and 1.85°K, the power dissipation in a traveling wave structure at 10 MeV/ft can be as small as 2.8 W/ft, and thus, with pure niobium, it appears that superconducting accelerators operating continuously at very high energy gradients could be possible.

Fabrication techniques for producing superconducting niobium accelerators must be developed with a view toward obtaining not only high energy gradients and low refrigeration requirements, but also low cost. The cost of a niobium accelerator structure differs most markedly from a conventional copper accelerator structure in that niobium is an order of magnitude more expensive. The expense, for instance, eliminates machining of niobium cavities from solid billets as a practical way for producing an accelerator structure. This technique was used in making the TM_{010} mode niobium cavity which gave the high energy gradient and Q_o reported by Weissman and Turneaure. The cost of producing an accelerator structure can be considerably reduced by providing a more efficient means of forming the niobium. Meyerhoff described a technique of electroplating thick layers of niobium from a molten fluoride salt. The niobium could be electroplated onto relatively complicated cathode geometries and in the process considerable refining of the niobium is achieved. The process for producing the niobium accelerator structure consists of making a copper mandrel, electroplating a layer of niobium about 0.150 in. thick on the copper mandrel, chemically dissolving the copper mandrel leaving a niobium shell, and vacuum outgassing the niobium at high temperature ($\sim$ 2000°K). There are other ways in which an accelerator structure could be formed which differ primarily in the technique of producing the niobium layer. One technique is chemical vapor deposition (CVD) which uses the chlorination-hydrogen reduction reaction of niobium. A second technique is forming reactor grade niobium sheet or tubing around a mandrel by hydroforming, explosive forming, or die forming.

An alternative way to reduce the cost of fabricating a niobium accelerator structure is to plate a thin layer of niobium a few microns thick on a less expensive substrate such as copper. This technique would reduce the cost of the niobium to a negligible fraction of the total cost of the accelerator structure. Q_o's between 100×10^6 and 500×10^6 have been measured at Stanford using thin layers of electroplated (Linde), CVD (Varian), and sputtered niobium. To achieve the highest Q_o's in these cases, it was necessary to polish the niobium layer with alumina abrasive to the order of 1 μ. These mechanically polished cavities appear, however, to have a critical field limited to about 100 G. The development of useful thin layer niobium structures probably awaits the development of more sophisticated techniques for degassing, smoothing, and producing suitable crystal size in the niobium layer.

II. CRYOGENIC SYSTEM USING SUPERFLUID HELIUM

The successful development of large-scale cryogenics using the unique properties of superfluid helium is essential to the operation of a superconducting linac. During the first week of the Summer Study the use of the superfluid properties of helium and the design of a large integrated cryogenic system were discussed by McAshan from Stanford, while developments in superfluid refrigeration were described by Collins from Arthur D. Little, Inc.

As described by McAshan, the special property of helium II that is important in applications is the natural internal circulation of the superfluid component and the normal fluid component which occurs in the presence of thermal differences. For instance, in helium II the superfluid component flows to a heat source and there absorbs a quantity of heat, $Q = ST$, in the process of being converted to normal fluid. To maintain constant density the normal fluid component must flow in the opposite direction. This natural convection is responsible for the unique heat transport properties of helium II which are essential to maintaining local thermal equilibrium in a superconducting linac. Further, if two reservoirs of helium II are connected by a superleak which permits the flow of the superfluid component but inhibits the flow of the normal fluid component, then a small temperature difference results in a large pressure difference across the superleak which in turn can be used to support a column of helium greater than 100 ft in height. The pressure across the superleak, known as the fountain pressure, is an osmotic pressure which arises as the helium tries to equalize the superfluid concentrations in the two reservoirs. This phenomenon can be used to construct a fountain pressure pump for transferring helium II from one reservoir to another for for providing refrigeration to an experiment located far above the main helium reservoir.

Some of the systems problems which are encountered in the design of a large complicated cryogenic system were also discussed. In a system as large and complicated as the superconducting linac planned at Stanford, it is mandatory that the design be sufficiently flexible that in the event of some component failure the relevant cryogenic subunit can be isolated from the central refrigeration system and can be replaced without disrupting the cryogenic operation of the rest of the system. Such problems as reliability, alignment of the accelerator while at low temperature, and even design of specific components were also described and actively discussed.

In addition to a brief description of the 300 W superfluid refrigerator that was constructed by Arthur D. Little, Inc. and is now being installed at Stanford, Collins discussed two questions which are important in the development of future superfluid refrigerators. One of these questions concerns efficiency and the other concerns the feasibility of using a low temperature pump to replace the large and expensive room temperature pumping system now used. Collins suggested a refrigerator design using a low temperature pump which he felt might operate at 25-35% of Carnot efficiency. Such a system would represent a substantial advance in the state of the art.

III. STABILIZATION AND ENERGY RESOLUTION IN A SUPERCONDUCTING LINAC

The superconducting linac, due to its relatively high Q, provides a unique opportunity for the use of feedback to achieve dynamic stability. This fact has encouraged Stanford to strive for energy resolution of 0.01% in the superconducting linac (100 keV at 1 GeV), as compared to the 1% resolution typical of conventional linacs.

Stabilization of the superconducting linac using feedback control was described by Suelzle. In the work at Stanford, the accelerating fields themselves are stabilized so that variations in beam loading do not affect the output energy. The long time constant for changes in the accelerating fields simplifies the feedback problem, and stabilization to one part in 10^4 in amplitude and to 0.1° in phase has been achieved in preliminary tests.

To produce a monoenergetic beam within one part in 10^4 requires, in addition to stability of the accelerating fields, that the electrons be confined to a one-degree phase bunch. This bunching is accomplished in the injector section and the capture section of the accelerator. In the system at Stanford, the electrons are emitted from a regulated triode gun and accelerated to 80 kV. The continuous stream of electrons then passes through a chopper cavity, and an aperture on the far side stops all electrons except those in a 20° phase bunch. These electrons are injected into a specially designed capture section where they are accelerated to about 2 MeV, and where the electron bunch is compressed in phase to one degree. The capture section is a $\beta = 0.95$ structure of 2½ wavelengths, and the design energy gradient is 1 MeV/ft. Chambers from Stanford described calculations of the particle motion in the accelerator sections beyond the capture section, using the actual fields in the biperiodic $\pi/2$ mode structure. These calculations included the effects of radial motion and misalignment of individual accelerator sections.

The excellent stability and energy resolution that can be achieved in a superconducting linac makes possible high resolution experiments at high energy but, in addition, it suggests possible changes in the design of a high energy facility. With good stability and resolution, there is no reason for generating large amounts of radiation along the accelerator or in the beam switchyard. For instance, in the beam switchyard instead of energy defining slits which are designed to handle 10% of the beam power, beam position monitors could be used, supplemented perhaps with slits that are set for several times the inherent width of the beam. Low radiation levels along the accelerator and throughout the beam switchyard could make a significant impact on the cost of a high energy facility.

IV. ACCELERATOR STRUCTURES

Several aspects of structure design for a superconducting linac were discussed during the week by Smith from Stanford, Neal from SLAC and Jüngst from Karlsruhe. Smith discussed in some detail the computer optimization of structures for a superconducting linac with respect to the peak electric and magnetic fields and the shunt impedance, and, in addition, analyzed the effect of individual cell frequency errors on the field profile. Smith also discussed the very important problem of tuning the accelerator sections to the same frequency within one part in 10^9 and described several methods of accomplishing this objective that are being studied at Stanford. Neal from SLAC described the calculated properties of a superconducting traveling-wave resonant ring accelerator and, using these properties, presented sample parameters for a two-mile superconducting linac. Jüngst discussed the proton linac structure design work that is in progress at Karlsruhe and described the electron analogue experiments which are being prepared.

V. RF PARTICLE SEPARATORS

In addition to accelerator applications, superconductivity can be used to advantage in the construction of rf separators. As in the case of the linac, the high Q that can be achieved with superconducting cavities makes it possible to build a separator that operates at a high duty cycle, matching that of the proton synchrotron, and, as a result, there is great interest in this development. A general discussion of the design of rf separators was presented by Brown from Brookhaven, and this discussion was followed by an outline of the superconducting rf separator programs under way at Brookhaven, Karlsruhe, and the Rutherford Laboratory. Halama described the work at Brookhaven where an S-band superconducting separator for 16 GeV/c is being studied. The program at Karlsruhe was described by Jüngst. The Karlsruhe group plans to construct a separator for 10 GeV/c to be used at CERN. At the Rutherford Laboratory plans are being made to construct a separator for about 3 GeV/c, and this was described by Carne.

VI. THE RACETRACK MICROTRON AND THE RECIRCULATING LINAC

One interesting possibility in the construction of accelerators, which is a compromise between the linear and the circular machines, is the racetrack microtron or the recirculating linac. Sutton outlined the very interesting program at Illinois to construct a 600 MeV unity duty cycle racetrack microtron that makes use of a superconducting accelerator section. Sutton described the proposed equipment layout for the microtron and presented detailed calculations of beam optics and phase stability.

This type of accelerator also provides an interesting approach to the construction of a very high energy, say 2000 GeV, machine. As pointed out by Schwettman, however, a practical recirculating linac for very high energy particles is different in several respects from the racetrack microtron mentioned above. First, at very high energy, electrons radiate too much energy to make the scheme useful. But protons, even for a final energy of 2000 GeV, are not subject to this criticism. Second, for a very high energy accelerator, the magnetic deflection system used in the racetrack microtron is impractical. Instead of solid 180° magnets, it would be more reasonable to provide separate beam transport systems and arrange that the average radius of curvature for each beam is nearly the same so that they could all be placed in a single tunnel. For the special case of three passes through the linac, the beam transport system might be particularly simple, since recirculation could in principle be accomplished with a single magnet system for two-thirds of the final energy.

Recently crude cost estimates have been generated for a number of "new technology" accelerators: the superconducting proton synchrotron, the cryogenic proton synchrotron, the superconducting recirculating linac, the superconducting FFAG, and the electron ring accelerator. Relatively little significance should be attached to any of these estimates, since all are based on important assumptions about how the relevant technology will develop over the next few years. What is far more significant and encouraging is that several possibilities exist for the construction of future high energy accelerators and these provide alternatives in the technology that must be successfully developed. This flexibility itself is our greatest asset.

SECOND WEEK - CRYOGENICS

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