New Materials and More Applications for Superconductivity

The list of applications of superconductivity appears to be still increasing. At the third annual Applied Superconductivity Conference (held at Gatlinburg, Tenn., 28–30 Oct.) many of these applications were discussed together with some fundamental studies.

Topics included superconducting quantum electronics (flux movement and oscillations in superconducting rings, and Josephson junctions), radio-frequency devices (microwave cavities, antennas), new materials and superconductor physics as it affects device performance. We heard about the established applications of superconducting magnets to bubble chambers and fusion devices, as well as newer applications to high-speed trains, biophysics and electron microscopes.

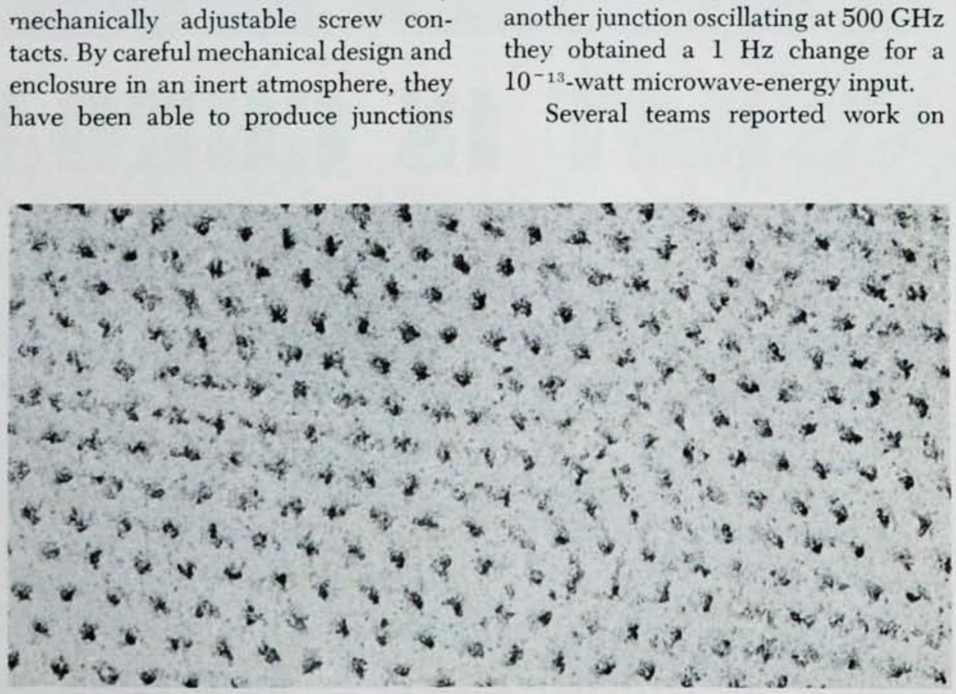
Among the invited papers was an outstanding one by U. Essman of the Max-Planck Institute für Metallforschung in Stuttgart, Germany, in which he described his and H. Träube's methods of studying the arrangement of fluxons in type-II superconductors. (A fluxon is the quantized magnetic unit of flux.) Because the flux lines are separated by distances of the order of microns, extraordinary methods are required to make them visible. Essman evaporates a few monolayers of ferromagnetic material onto the superconductor while it is being held at liquid-helium temperature; if many precautions are taken, the ferromagnetic atoms settle on the rims of the flux lines (10 to 20 atoms per fluxon). After the superconductor is warmed up to room temperature, a carbon layer evaporates and is then stripped off, carrying the ferromagnetic atoms with it. Essman showed a number of beautiful electron-microscope pictures of fluxon lattices. He found the fluxon lattice arrangement to be triangular as predicted by theory (rather than square), and the dislocations of the fluxon lattice were at material inhomogeneities. One interesting result was that, in the presence of a magnetic-field gradient, a fluxon-density gradient is created by means of occasional edge dislocations.

Superconducting quantum electronics. J. E. Mercereau of the Ford Scientific Laboratory gave an invited paper on instruments in which flux moves through superconducting rings that have "weak junctions," which are regions of low critical current. Quantized persistent currents can be stored in these loops, but, at a critical energy, flux vortices move through the weak junction. In the presence of a small ac magnetic field, there is a detectable voltage whose phase with respect to the driving field varies periodically every time a new flux quantum enters the ring. For a large-area ring the applied bias-field change corresponding to one fluxon is very small. Mercereau reported a zero-correcting magnetometer with sensitivities of 10^{-10} gauss and a time constant of 1 sec, and noncorrecting magnetometers that could be used in fields up to about 100 gauss with somewhat lower sensitivities. The superconducting rings themselves are of some interest; they are made of 30-nm-thick superconducting films evaporated on quartz rods between 1 and 5 mm diameter. The weak junctions consist of portions photoetched to a width of 1 micron, an achievement in itself.

James Zimmerman and John Harding of the Ford Laboratory at Newport Beach described superconducting rings in which weak contacts are made by mechanically adjustable screw contacts. By careful mechanical design and enclosure in an inert atmosphere, they have been able to produce junctions that do not change their characteristics even after hundreds of temperature cycles. Zimmerman's rings include a resistive portion, and when current is passed through such a ring the voltage developed across the resistance leads to oscillations in the weak link. The frequency of oscillation can be made to beat with an externally introduced drive frequency, producing resonance effects that can be detected. Another mechanical structure, containing two weak links, was discussed by B. T. Ulrich (formerly of the Ford Scientific Laboratory and now in the Astronomy Department of the University of Texas). The voltage drop across the resistive component of this structure leads to oscillations in the two weak junctions; the frequencies at the two junctions are not the same, and beats produced at the difference frequency are low enough to be detected and were used to study noise processes.

An application of Josephson junctions to instrumentation was reported by R. J. Pedersen and F. L. Vernon of Aerospace Corporation. By setting up relaxation oscillations in Josephson junctions, they could obtain a 1 Hz change in oscillating frequency for an applied field of one microgauss in a junction oscillating at 150 GHz; with another junction oscillating at 500 GHz they obtained a 1 Hz change for a 10^{-13}-watt microwave-energy input.

Several teams reported work on



FLUX-LINE LATTICE on the surface of lead with 6.3 atomic per cent indium, at a magnification of 8300. (U. Essman, H. Trauble, Phys. Letters. 24A, 526, 1967.)

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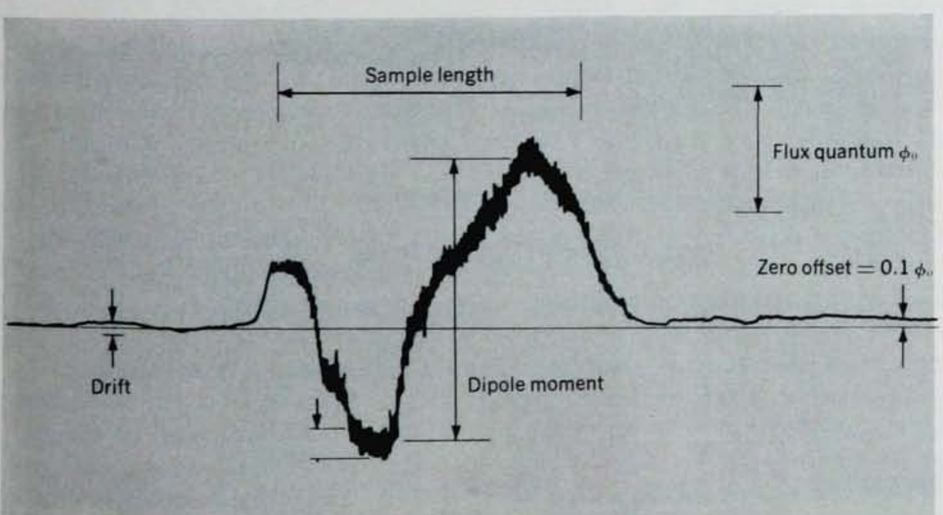
Josephson junctions made of flat superimposed films. The current problem here appears to be making sufficiently thin, but pinhole-free, reproducible oxide layers between the films. Both Walter Schroen and Paul Pritchard of Texas Instruments and Klaus Schwidtal and Robert Finnegan of Fort Monmouth reported satisfactory results with oxide layers grown on lead using a glow discharge. L. O. Mullen and D. B. Sullivan of National Bureau of Standards and J. E. Norman of RCA Labs and University of Wisconsin reported on Josephson junctions made from niobium films. A technologically impressive achievement using niobium films was reported by James Opfer of Stanford; he has made a persistent-current magnetometer with a vibrating superconducting plane to shuttle flux: By multiple-evaporation techniques he was able to produce pinhole-free niobium films that could be etched into meander lines only 10 microns wide with 10 microns separation. Lines such as these may turn out to have applications in cryotron amplifiers and slow-wave structures.

Radiofrequency devices. Interest is growing in the application of superconductivity to microwave cavities, antennas and slow-wave structures. Much of this interest is sparked by the superconducting Linac project at Stanford, which uses a series of very high-Q cavities down the center of which an electron beam is transmitted. The original plan called for lead cavities, but these were found to have inferior quality at high magnetic fields. Niobium cavities with unprecedentedly high Q's made by an electroplating process followed by vacuum anneal, were decribed by R. W. Meyerhoff of Linde. The success of the process depends partly on self-smoothing of the niobium surface during the anneal. In the linac accelerator, 25 superconducting cavities each 6 meters long will have to resonate at the same frequency to within about 1 part in 10^8. T. I. Smith reported on mechanical wall-deformation techniques that will be used for the tuning process.

If the Q requirements are not extreme, the superconducting cavity can be tuned by the photodielectric effect. In this method, described in two papers by William Hartwig and James Hines of the University of Texas at Austin and Jack Stone of Mesa Instruments, Inc., a small piece of semiconductor is placed into the superconducting cavity, and its carrier concentration is controlled by light illumination. If the cavity is resonating at a radiant frequency ω such that $\omega\tau > 1$ (where τ is the semiconductor collision frequency) a large amount of the radiation energy can be stored in the form of electron inertia. As a result the dielectric constant of the cavity, and thus its resonant frequency, vary with carrier concentration. This effect can be used for electronic purposes such as demodulating laser signals, for automatic optical tuning of cavities, and for the investigation of the semiconductor itself. In a superconductor, of course, the time between electron collisions is infinite; inertial



MAGNETIC IMPURITY in copper at 4K. James E. Mercereau of the Ford Scientific Laboratory took these data with the superconducting interferometer, an instrument that can make magnetic measurements routinely to at least 10^{-3} of the flux quantum. In this case flux from the impurity amounts to about ten times the 4K flux noise.

energy can be stored in electrons at all frequencies. This energy storage increases the inductive component of the surface impedance of the superconductor and has been named "kinetic inductance." Peter Mason of Jet Propulsion Lab used the effect to vary the phase velocity of superconducting strip lines, and R. Meservy and P.M. Tedrow of the National Magnet Laboratory studied the kinetic-inductance changes directly.

An application of superconductors to produce high-Q elements at frequencies that are too low for cavities was described by Nicholas Worontzoff of Airborne Instruments Laboratory; he reported on adjustable-frequency superconducting circuits that have Lucalox (a form of alumina) as a support medium. As we mentioned above, it is not easy to change the resonant frequency of a superconducting circuit without introducing a nonsuperconductor into the rf-field region and, therefore, introducing extra losses. In the past, fused quartz has been considered the best material for support with a minimal dielectric loss. Worontzoff reported Q's of 3 to 5 x 10^5 at frequencies of 8–20 MHz.

Instrumentation. Robert Erdman of Keithley Instruments told us about his superconducting galvanometer; his aim was maximal simplicity of fabrication and operation. The instrument has a mechanically vibrating coil system used as a parametric amplifier. The sensitivities reported are 10^{-12} volts with a rise time of about 3 sec for source resistances of up to 3 x 10^{-7} ohms and source inductances of up to 10^{-5} henry. A progress report on superconducting films used as infrared bolometers was given by C. L. Burtin and Kenneth Rose of Rennselaer Polytechnic; they have obtained detectors with responsivities up to 12 700 volts per watt.

Physics of superconductors. The topics in pure superconductivity customarily presented at these conferences are in the main on phenomena that affect device performance. For example W. D. McCaa and N. S. Nahman of the National Bureau of Standards have applied the BCS (Bardeen–Cooper–Schrieffer) theory to the propagation characteristics of superconducting transmission lines; they show that appreciably different dispersion characteristics are predicted by the BCS theory compared with the older two-fluid model. Fortunately the experimental results agree better with the predictions of the later theory. Juri Matisoo of IBM pointed out that the study of Fiske steps in Josephson junctions provides an improved way to measure penetration depth. These steps correspond to resonances that occur when the wavelength of the variation of phase in the junction, as determined by the dc applied magnetic field, is a multiple or submultiple of the junction size.

There is still strong interest in critical temperature and methods of increasing it. Myron Strongin, O. F. Kammerer and J. E. Crow of Brookhaven have found that successive deposition of very thin films of aluminum and germanium, or even aluminum and copper, deposited to a depth of four or five monolayers each increases the critical temperature considerably for the first few layers. They attribute this effect to the decrease in the average phonon frequency $<\omega^2>$ because of the layer structure. Calculations of the decrease of $<\omega^2>$ in the layer structure predict increases in critical temperature that are in rough agreement with experiment. The same equation, as used by B. W. Friday and Joseph Mundy of Rensselaer Polytechnic, explains the dependence of thin-film critical temperatures on strain. Again there is reasonable agreement with experiment.

Crow and Strongin report that cryogenically deposited tin films about 3 nm thick have critical fields of 50 000 gauss at $T/T_c = 0.9$. Extrapolation predicts critical fields of well over 200 000 gauss at absolute zero. Films made in this way will not be stable at room temperature, but R. V. D'Aiello of RCA Labs and S. J. Freedman of Brooklyn Poly report the fabrication of superconducting granular aluminum films that are stable at room temperature. These films were fabricated by vacuum deposition in the presence of controlled amounts of oxygen; data suggest that the conduction processes in these films take place largely by tunneling. The films are reported to have very large penetration depths, which should make them suitable for devices that depend on kinetic inductance.

New materials. Highlights of the materials sessions were the reports on niobium–germanium–aluminum, which has the highest critical temperature yet observed, 20.8 K. Unfortunately B. T. Matthias (University of California and Bell Telephone) was unable to attend to present his history of high-tempera-

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Length: 132,000 ft.
Weight: 104,000 lbs.
Energy: 80,000,000 joules
Vol. of field: 1770 cu. ft. (50,000,000 cm^3)
Bore: 12 ft.

Our Smallest

Conductor: 0.0032″ dia.
Magnetic field: 1.8T
Length: 2300 ft.
Weight: .06 lbs. (28 grams)
Energy: 14.1 joules
Vol. of field: .06 cu. in. (1.0 cm^3)
Bore: ½″ (1.25 cm)

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ture superconductors and speculations on the future. Because the 18 K critical temperature of niobium–tin had remained the highest known since its discovery in 1961, it had begun to grow into an apparent barrier; the first reports last year on niobium–germanium–aluminum were exciting because they broke the spell. Measurements of critical fields by S. Foner (National Magnet Laboratory) confirmed our further hopes with a critical field of 200 kG at 14 K. Extrapolation suggests an ultimate critical field of about 400 kG at 0 K; however, in view of earlier over-optimistic extrapolations for vanadium–gallium and vanadium–silicon, we can presume that some mechanism will appear to reduce this value.

Metallurgical studies at Westinghouse (R. Balugher, N. Pessall and A. Patterson) suggested that crystallographic long-range ordering, obtained by prolonged low-temperature heat treatment to produce an A-15 structure, was responsible for the high critical temperatures. Major problems are the extreme brittleness of the material, low pinning forces and very small critical currents; extensive further metallurgical studies are required before there is hope of developing a practical wire-fabrication process.

Stability. The report of Peter Smith (UKAEA, Rutherford Laboratory) at the 1968 Brookhaven summer study on intrinsically stable conductors suggested that composite conductors, in which the superconducting filaments are less than about 5×10^{-3} cm in diameter and are twisted to transpose the filaments for magnetic decoupling, should prevent coil degradation. The report excited great interest, and it is an indication of the pace of modern technology that these conductors were commercially available in the US only three days later. The only formal report at the conference was A. D. McInturff's decoupling measurements; however, informal exchanges continued to be encouraging. Price may well be the only major problem, and there were many earnest discussions between materials manufacturers and magnet makers regarding applications. Concern with cost was often noticeable at the conference and even a proponent of hollow conductors was heard to grumble on this score; we take this as an indication that superconductivity is already in an advanced state of practical application.

More engineering design data for composite conductor calculations are becoming available. Mark Benz's (General Electric) data on the interrelationship among resistance ratio, magnetoresistance and stress, for copper with various degrees of purity, are a valuable contribution. V. Arp (National Bureau of Standards, Boulder) gave a detailed review on heat transfer to superfluid and supercritical helium. K. R. Efferson (Oak Ridge) presented new experimental data on heat transfer to liquid helium and discussed interesting observations on temperature fluctuations. Unfortunately, design data for heat transfer to liquid helium in the case of forced circulation are still sadly lacking.

A. El Bindari (Avco Everett Research Laboratory) reported on further refinements of his theory of electrical and thermal stability of bare and of compound superconductors. William F. Gauster, our host from Oak Ridge, gave a thorough analysis of the steady-state performance of compound conductors in the current-sharing state. This analysis yields a better understanding of the flux-flow performance of the superconductor and shows that the widely used simple-stability criterion based on maximal nucleate boiling is not by any means generally applicable.

Howard Hart (General Electric) expounded his critical-state model by describing the dynamic stability of a coil wound with composite superconductor–normal-metal tape and flux jumps in niobium–tin solenoids. The topic appears to be so important that further explanation would be very useful to many of us.

Stability tests that appear to have great practical relevance have been developed at the National Magnet Laboratory. Y. Iwasa told us of the Laboratory's computer simulations and measurements of temperature transients that occur in various wire composites when application of a magnetic-field pulse forces a flux jump. The results and predictions appeared to be in good agreement with the currents obtained in practical coils.

Reports on ac-loss measurements appeared to agree with Stefan Wipf's unified theory of ac losses as presented last year at Austin.

Superconducting magnets. In the area of magnets, Purcell (Argonne) and A. G. Prodell (Brookhaven) reported progress in the great bubble-chamber race. At Argonne the 4-meter

magnet has been completed and precooled to about 170 K; the vacuum is excellent, the temperature gradients and thermal stresses commendably slight, and the refrigerator is nearing completion. At Brookhaven the 2-meter magnet was cooled down in May and June. The magnet was partially energized but heat leaks prevented complete filling of the cryostat. The cryogenic system is being modified and the magnet installed in the bubble chamber. We congratulate both groups on their fine magnets.

Of the magnets being developed for fusion research, the Princeton Floating Multipole has presently advanced furthest and now includes a complete control system. Robert Mills reported that since last year he has refined the stabilizing system to obtain complete control of a single ring and that two rings have been operated. The dewars have been operated isochorically and the design steadily improved so that they now bear a striking resemblance to the "artist's conception." The general neatness of Mills's complex experiment is very apparent, at least in his slides of the laboratory! The next stage is to double the size to full scale. At Oak Ridge the Injection Microwave Plasma magnets are advancing to the quadrupoles; the high-current-density requirements bother everybody, but David Coffey is competent enough for us to believe he will succeed.

Clyde Taylor (Lawrence Radiation Laboratory) proposed levitating a superconducting magnet ring between two sheets of superconductor; he showed how the stabilizing forces could be calculated by an image technique. The proposal stimulated vigorous discussion. Taylor argued that, provided the sheets prevented flux penetrating completely, the system should work. It now remains for him to demonstrate it practically.

Magnet applications. Two interesting proposals were made for magnetic suspension systems. With a superconducting magnet moving over a metallic guide, lift can be obtained at quite modest speeds (80 km/hr) and drag is comparatively small particularly at high speeds. For fast trains (500 km/hr), the advantages would be increased tolerance of track-height irregularities and decreased power requirements compared with a ground-effect vehicle (hovercraft). The miracle of the Vuegraph enabled Howard Coffey (Stan-

ford) to present his back-of-an-envelope calculations almost on the back of the envelope itself; however, his oral presentation was admirably lucid. C. A. Guderjahn discussed a proposal for rocket sledges accelerated to 15 000 km/hr. Magnetic suspension in a low-pressure tube appeared to be the only way to tackle this problem.

Robert E. Worsham of Oak Ridge National Laboratory described his work on superconducting lenses for electron microscopes. These lenses have the advantage of better mechanical and electrical stability, and their resolution is close to 0.1 nm. Round lenses with iron pole pieces are used at present.

Bruce Montgomery (National Magnet Laboratory) described the most novel magnet application – "intravascular navigation," or magnetic directional control of an iron catheter tip for brain surgery. He began by showing x-ray photographs of just where he hopes to go. This medical application requires high fields and field gradients in any direction in order to obtain forces of 50 g on the catheter tip; access is of course essential. Conventional electromagnets could not meet these requirements; so we congratulate Montgomery on a novel application of social significance.

The general impression was that the conference was very well organized, and the level of the presented papers was even better than in the two previous years. A poll of the participants indicated that future conferences of this kind are still highly desirable. Plans for the next conference are already under way.

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Sponsors of the Conference were: the American Physical Society, the Magnetics Group of the Institute of Electrical and Electronics Engineers and Oak Ridge National Laboratory in coöperation with the US Atomic Energy Commission. William Gauster was chairman of the conference.

The proceedings will appear in a special issue of the Journal of Applied Physics.

The first part of this report was prepared from material collected by Newhouse; the part starting with "New Materials" on page 105 was based on material collected by Atheton.

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