NRL Report 7023

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Proceedings of Fourth Symposium

1969 Spring Superconducting Symposia

Sponsored by

The Office of Naval Research

and

The Naval Research Laboratory

June 6, 1969

NAVAL RESEARCH LABORATORY
Washington, D.C.

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PREVIOUS REPORTS IN THIS SERIES

"Proceedings of First Symposium, 1969 Spring Superconducting Symposia," NRL Report 6962, March 28, 1969

"Proceedings of Second Symposium, 1969 Spring Superconducting Symposia," NRL Report 6972, April 25, 1969

"Proceedings of Third Symposium, 1969 Spring Superconducting Symposia," NRL Report 6986, May 16, 1969

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PREFACE

The Office of Naval Research and the Naval Research Laboratory recognized a number of advantages on cosponsoring and conducting a series of four one-day symposia on superconducting materials and devices. These meetings, held at the Naval Research Laboratory during the spring of 1969, has as their primary motives...

a. To bring together scientists, engineers, and science administrators from some 18 government, university, and industrial laboratories in the Washington-Baltimore area which are engaged in or sponsoring research programs involving superconductivity.

b. To provide an opportunity for these persons to meet each other, to hear formally prepared papers by their colleagues, and to engage in informal and frank discussions of their research programs.

c. To collect and disseminate comments and opinions of experts regarding the current status and the future of research on superconducting materials and devices.

The morning session of each symposium was devoted to four invited forty-minute papers. Each afternoon the four invited speakers formed a panel to discuss questions posed by the audience.

Recordings, transcripts, and then lightly edited manuscripts of the papers were prepared for publication in the Proceedings, this being the fourth of four to appear. In order to provide an atmosphere of free uninhibited discussions in the afternoon, no recordings were made.

Topics for presentation, speakers, and general planning of this series of symposia were the responsibility of the Organizing Committee. The sixteen papers given represented authors from three government laboratories, eight universities, and four industrial laboratories. Although this series was initially established for the Washington-Baltimore community, early publicity and announcements generated sufficient distant interests so that a number of attendees appeared from outside this geographic area.

It is a pleasure to acknowledge the efforts of the following individuals who significantly contributed to the success of these four symposia:

Mr. John J. Lister, Mr. David N. Ginsburgh, and Mr. John M. Hoggatt; Public Affairs Branch, NRL; arrangements and smooth operations of the symposia at NRL.

Mrs. Mary L. Taylor; Security Branch, NRL; internal security.

Mr. Warren H. Ramey and staff; Graphic Arts Branch, NRL; design and printing of announcements, programs, and proceedings.

Mr. Kenneth A. Klausing; Graphic Arts Branch, NRL; photography of persons and blackboard presentations.

Dr. Edward H. Takken and Mr. John E. Cox; Magnetism Branch, NRL; for their help in editing the transcriptions.

Mrs. E. R. Shapiro; Magnetism Branch, NRL; for her services as receptionist.

The programs for the four days follow.

SYMPOSIUM I, March 28, 1969, "SUPERCONDUCTIVITY AMONG METALLIC ELEMENTS AND ALLOYS"

Chairman and panel moderator — Dr. R. A. Hein

1. Dr. B. T. Matthias, "The Where and How to Obtain High Transition Temperatures."
2. Dr. W. L. McMillan, "Superconductivity and the Electron-Phonon Interaction."
3. Dr. T. H. Geballe, "Intermetallic Compounds — An Unlimited Source."
4. Dr. J. W. Garland, "Mechanisms for Superconductivity."

SYMPOSIUM II, April 25, 1969, "SUPERCONDUCTIVITY AMONG DEGENERATE SEMICONDUCTORS AND SEMIMETALS"

Chairman and panel moderator — Dr. R. A. Hein

1. Dr. J. F. Schooley, "Superconductivity in Degenerate Semiconductors."
2. Dr. C. S. Koonce, "Low Carrier Density Superconductors."
3. Dr. J. K. Hulm, "Superconductivity in Low Carrier Density Rock Salt Compounds."
4. Dr. P. E. Seiden, "Superconductivity in 'Free Electron Like' Superconductors."

SYMPOSIUM III, May 16, 1969, "EFFECTS WHICH ENHANCE THE SUPERCONDUCTING TRANSITION TEMPERATURE"

Chairman — Dr. R. A. Hein; Panel Moderator — Dr. R. Glover

1. Prof. J. D. Leslie, "Electron Tunneling Investigations in Amorphous and Disordered Superconductors."
2. Dr. A. Paskin, "Enhancement of T_c in Thin Films."
3. Dr. F. R. Gamble, "Molecular Enhancement Effects."
4. Prof. J. R. Schrieffer, "Theories of Enhancement Effects."

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SYMPOSIUM IV, June 6, 1969, "SUPERCONDUCTING DEVICES"

Chairman – E. A. Edelsack; Panel Moderator – Dr. W. Gregory

1. Prof. B. S. Deaver, Jr., "Superconducting Devices – Bagatelle or Bonanza."
2. Prof. S. Shapiro, "Infrared Detectors."
3. Dr. W. Goree, "Superconducting Magnetometers."
4. Dr. Z. J. Stekly, "Superconducting Magnets."

Organizing Committee

R. A. Hein – NRL
E. A. Edelsack – ONR

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SUPERCONDUCTING DEVICES— BAGATELLE OR BONANZA?

B. S. Deaver, Jr.
University of Virginia
Charlottesville, Virginia

I would like to modify the title, as it appears on the program there, to add a question mark behind it. I think Ed's inflection added it for me. And then I will immediately go on to say something you already know; that is, I can't possibly answer the question! I think that you may be annoyed with me for using the tactic which is so common on campus these days, of assuming that you have to choose between two extremes. There may be a middle ground somewhere. I hope it is one of the extremes, and you will probably gather from my choice of topic that I see it as a technical or scientific bonanza, at least, if not an economic one. I think, to those companies that have tried to make some money out of superconductivity, perhaps, bagatelle is a euphemism. Bonanza may be more nearly right if you look to the future.

What I thought I would do is to collect a lot of properties of superconductors on the blackboard over here, and then discuss applications of them, so this will be a tour de force. What can you do with superconductors? I sat in Bill Goree's office a week or two ago in Menlo Park and flipped through the literature survey which he and Ed Edelsack had been carrying out, in which they have surveyed the literature on superconducting devices since 1959. It is astonishing how many papers and patents there are. I thought that the most amusing thing was just the very variety of things that have been done.

What I will do is list those properties of superconductors that have been applied in a device or technique of some kind. I am going to collect on the blackboard some symbols to remind us of the various properties (Table 1). The electrical resistance R is zero below some critical temperature T_c and below some critical magnetic field $H_c(T)$. Furthermore, the magnetic field B is zero inside a superconductor. We know that this occurs because supercurrents flow on the surface of the superconductor decaying exponentially with penetration depth λ. Superconductors have interesting thermodynamic properties too. There is an anomaly in the specific heat. The entropy is lower in the superconducting state. There is a latent heat if we go through the transition in the presence of a magnetic field. The thermal conductivity of lead, for example, is 10^5 times less in the superconducting state at ~0.1K than it is in the normal state. Those who think about refrigerators immediately see possibilities in these properties.

Now all of these things were describable in a classical picture. However, from the theory that he and his brother originated to describe the electrodynamics of superconductors, Fritz London was led to the concept that superconductivity is what he called a macroscopic quantum effect. This concept is central to the modern description of superconductivity given by the Landau-Ginzburg theory. I will symbolize this fact by noting that there is a macroscopic wave function in which there are many particles in the same state. Feynman has pointed out that anytime you have a lot of particles, say photons, all in exactly the same state, you can see quantum effects on a macroscopic scale. An example is interference of coherent beams of light. In a sense, superconductors are like

that. It's another case in which we are able to see the properties of a single quantum state because we have many particles all in exactly the same state. Therefore $|\psi|^2$ is proportional to the charge density. The current is related to the gradient of the wave function.

Table 1
Properties and Symbols Pertinent to Superconductors

$R = 0, \quad T_c, \quad H_c(T)$

$\bar{B} = 0, \quad \lambda$

Heat capacity, entropy, latent heat

Thermal conductivity

$$\psi = \psi e^{i\theta}, \quad \rho \sim |\psi|^2, \quad \bar{j} \sim \nabla\theta + \frac{2e}{\hbar c}\bar{A}$$

$$\Phi = \oint \left(\frac{4\pi\lambda^2}{c}\bar{j} + \bar{A}\right) \cdot ds = n\frac{hc}{2e}$$

Quantized flux

London moment

Energy gap

Tunneling characteristics

$\xi, \quad K = \frac{\lambda}{\xi}$, Type I & II, $H_{c_1}, \quad H_{c_2}$

Vortex array

Flux flow, pinning of flux lines

Josephson effects $\quad j = j_0 \sin\left(\delta + \frac{2e}{\hbar}\int \bar{A} \cdot ds\right)$

$$h\nu = 2eV$$

Fluctuations

From this kind of wave function a number of interesting things emerge. If we require that the function be single valved on traversal of a closed path in the superconductor, then it follows that the quantity which London called the "fluxoid" must be quantized. One of the consequences of this property is that for a superconducting ring that is thick with respect to the penetration depth, the magnetic flux contained inside the ring must be quantized. This implies further that it is possible to achieve a region inside a superconducting cylinder in which the magnetic field is zero — the ultimate in low-field shields. Another consequence is that a rotating superconductor becomes magnetized by an amount proportional to the rotation velocity. This property I will symbolize by the name London moment. It can be used to sense the rotation.

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The pairing of electrons in the superconducting state has been assumed explicitly in the expressions I have written for the current and fluxoid quantum. Many of the other detailed properties described by the BCS theory become apparent in applications of electron tunneling, as first demonstrated by Giaever. The energy gap is clearly evident in the I-V curves of superconducting tunnel junctions as illustrated in Fig. 1 for tunneling between two different superconductors.

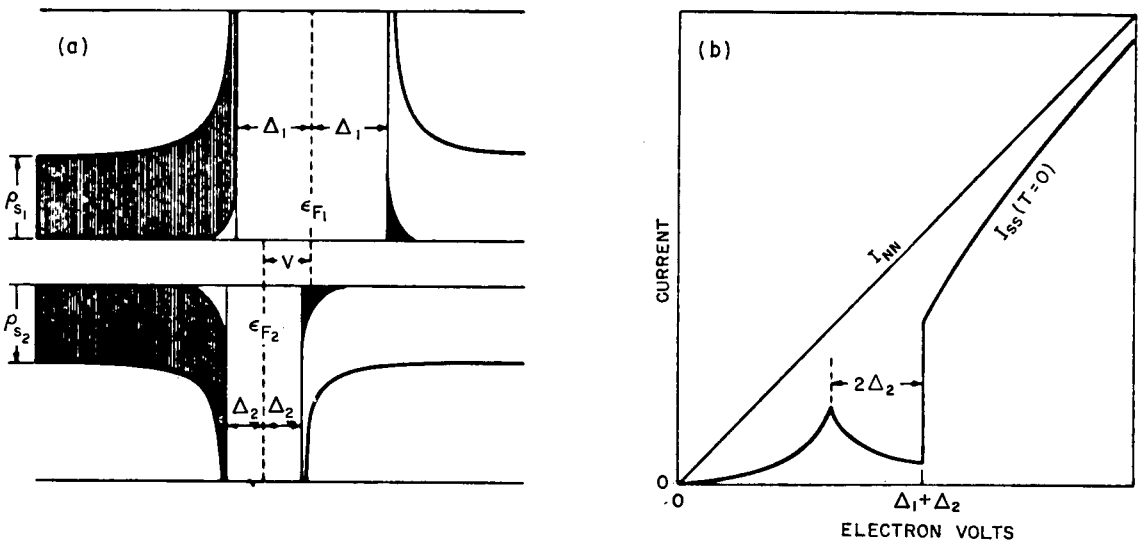

Fig. 1 - Tunnel characteristic for junction between two different superconductors

Continuing simply to list properties, I want to say that there is a characteristic distance ξ over which the density of pairs or the order parameter can vary. We have already said that the characteristic distance for variation of the magnetic field in a superconductor is the penetration depth λ. If the ratio $K = \lambda/\xi$ is small ($< 1/\sqrt{2}$), the superconductor reacts in a magnetic field as mentioned earlier and as shown in the top part of Fig. 2 by expelling all the field up to the critical field H_c. However, if $K > 1/\sqrt{2}$, a reversible magnetization of the type shown in the lower part of Fig. 2 results. This behavior was explained by Abrikosov as the entry of the magnetic field above a field H_{c1} into the sample as an array of flux lines which we know are supported by vortex currents as shown in Fig. 3. These vortices produce an essentially normal core of dimensions ξ, and a magnetic field falling off with characteristic dimension λ. In an ideal type II material, there is a triangular lattice of these flux lines each containing a single flux quantum. Not until an applied field H_{c_2} is reached is the specimen completely filled with flux; the regions in which the order parameter is zero then overlap and the material is almost completely in the normal state.

If a current is passed through a piece of type II material in the mixed state (or a thin film in a perpendicular magnetic field) the interaction of the current with the flux lines can cause them to move and give rise to a voltage across the superconductor and a corresponding dissipation. In some superconductors, flux flow is impeded by pinning of the flux lines on inhomogeneities in the material. This property makes superconductors practical for producing high magnetic fields.

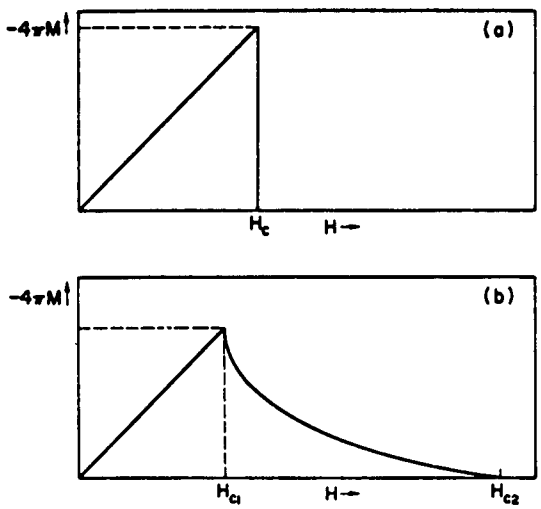

Fig. 2 - Magnetization curves for Type I (a) and Type II (b) superconductors

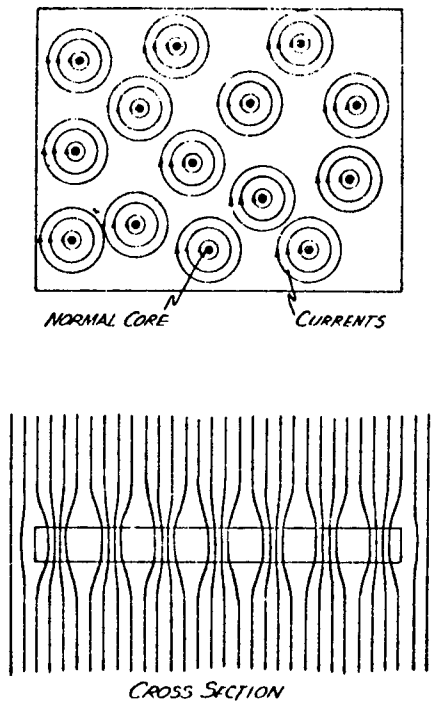

Fig. 3 - Current and field distribution for superconducting film in a uniform magnetic field

As you know, Josephson was the first to point out that if you take two superconductors and put them a little bit apart, separated by perhaps 10-20 Angstroms of insulation, there can be coherent particle tunneling — pair tunneling between the two. If we put a current through such a pair of superconductors there is a finite current before any voltage appears across the junction (Fig. 4). This dc Josephson current depends on the difference in phase (Table 1) between the two macroscopic wave functions on the two sides of the insulator. However, if one now runs too much current through the junction, it will reach a critical current, and voltage will appear across it; the complete I-V curve is shown in Fig. 4. (As Bill Goree will probably describe later, it makes a very great difference how you measure this.) When there is a voltage across the junction there is an oscillating current in the junction at a frequency given by the Josephson relation $h\nu = 2eV$.

Now the next thing I want to mention is that if one takes a junction of two superconductors and applies a magnetic field we know that the phase difference between the two superconductors is affected. That is, the phase difference depends not only on the current through the junction, but also on the flux inside it.

If one does the phase integral it looks just like the integral for a diffraction calculation from a single slit in optics, and Fig. 5 displays some of Mercereau's data that shows exactly that effect. What is plotted here is the maximum Josephson current, that is, the height of the maximum dc spike without any voltage, as a function of the magnetic field perpendicular to the junction. Furthermore, if one puts two such junctions in an otherwise completely superconducting ring and applies a magnetic field through the area of the ring, the phase difference, and therefore the critical current, will depend on the flux through the ring. Figure 6 shows the maximum dc current as a function of the applied

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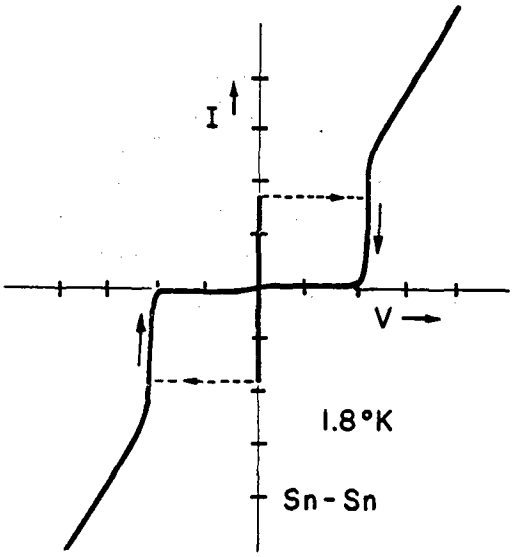

Fig. 4 - Current-voltage characteristic for a Josephson junction

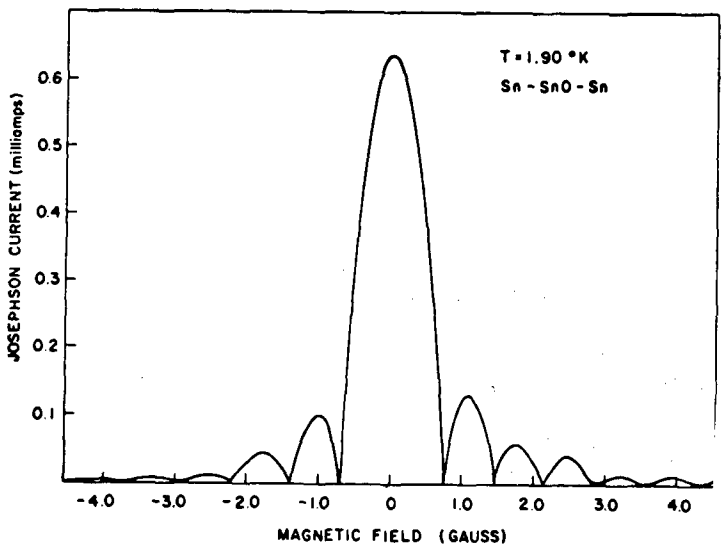

Fig. 5 - Maximum Josephson current as a function of field applied through junction

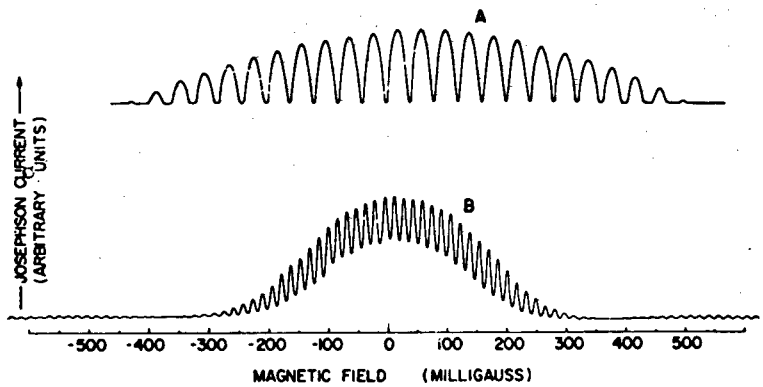

Fig. 6 - Maximum Josephson current through a pair of junctions in a ring as a function of magnetic field perpendicular to the ring

field. It shows clearly the periodic dependence on the field in anology with a double-slit interference experiment.

Similar behavior can be achieved with weak links, for example, a narrow bridge in a thin film or a point contact. These show a critical current and give rise to oscillating currents at frequencies given by $h\nu = 2eV$ where V is the bias voltage. The thin-film bridge can be pictured as having flux flow initiated at the critical current and flux lines flowing through the bridge at ν per second. Then the voltage across the bridge is $V = \nu h/2e$. Just as in the junction and point contact, this corresponds to the phase changing between the two weakly linked superconductors in steps of 2π at a rate of ν time per second.

The ac currents in a biased junction or weak link make possible a number of interesting experiments. If an additional ac current is caused to flow in the junction with an external source, the nonlinear response of the junction can be thought of as mixing the two currents. Currents at the same frequency will result in a dc voltage across the junction, so that the I-V curve can be used to detect the presence of the externally imposed current (or vice versa). Figure 7 illustrates the constant-voltage steps that result at $nh\nu$ when a biased point contact is irradiated with microwaves. This is Sid Shapiro's data. This type effect has been used by Langenberg, Parker, and Taylor to check the Josephson frequency relation to a very high accuracy and, assuming the relation, to evaluate the fine-structure constant to a few parts per million accuracy.

Finally, let me say that there can be fluctuations in superconductors that are of crucial importance for devices and that these are currently the source of much active research.

All I have done so far is to list some of the properties of superconductors that have been used in devices. In the literature survey that I mentioned at the outset, there are listed some 500 or more patents that have been issued and more than 1000 papers discussing applications of superconductivity. Recently there have been conferences on applied superconductivity at Brookhaven, Austin, and Gatlinburg. There was a conference on the physics of superconducting devices at Charlottesville and one on fluctuations at Asilomar, both sponsored by ONR. I'll try to summarize all this activity again with a topical listing of devices and applications with a few specific examples.

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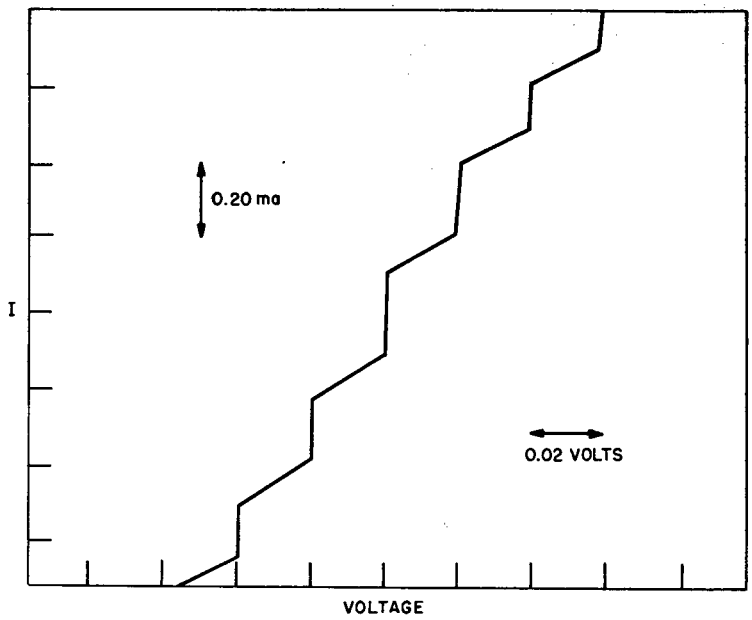

Fig. 7 - Current-voltage (I-V) characteristic of a Josephson tunnel-junction in an applied microwave field

Superconductors have been used to sense or detect a wide variety of physical quantities. I'll start the list with a topic which I will call "sensors" (Table 2). I will at first simply list the quantities and then return to say a few words about some of them: temperature, magnetic field, magnetic flux (I will specifically put magnetic flux here as distinct from field — I will say more about that in a minute), current, voltage, position, acceleration, angular position, angular velocity, electromagnetic radiation, charged particles, and phonons. Two of these items you will hear about later in some detail from Bill Goree and Sid Shapiro, namely, the measurement of magnetic field and the detection of electromagnetic radiation. I won't be able to spend much time on any of these topics, but I would like to make a few remarks about each of them.

Obviously, there are several ways to measure temperature using superconductors. One is simply to measure the resistance as a function of temperature very near the transition. Another is to use the flux flow resistance of a thin film. This type of device can detect temperature variations in the microdegree range and has a frequency response extending to tens of kilohertz. Extremely sensitive measurements of temperature have been made using the change in penetration depth of a superconducting core to alter the inductance of a coil.

An ingenious device suggested by Kamper, and subsequently tested by Kamper and Silver, uses the line width of the Josephson radiation as a measure of temperature. One uses a current flow through a normal resistor to voltage bias a Josephson junction. The frequency spread of the Josephson oscillations is determined by the voltage fluctuations across the resistor, which is a characteristic of the temperature T of the resistor. By measuring the line width, temperatures in the millidegree range can be determined.

Table 2
Physical Quantities Sensed or Detected by Means of Superconductors

Physical Quantity	Property Used or Device	Remarks
Temperature	$R(T)$ $\lambda(T)$	High-frequency response $\Delta T \sim 10^{-6}$K
	Josephson linewidth	millidegree range
Magnetic field	Meissner effect, Φ Junctions and weak links	$\Delta B \sim 10^{-11}$ gauss
Magnetic flux	Φ	$\Delta\varphi \sim 10^{-11}$ gauss cm^2
Current Voltage	Modulated inductance, Φ Junctions and weak links	$\Delta i \sim 10^{-9}$ A at very low impedance $\Delta V \sim 10^{-15}$ V
Position	Changes in inductance	10^{-13} cm
Acceleration	Magnetic support and read out	10^{-12} g
Angular position	Gyroscope, London moment	Probably seconds of arc
Angular velocity	London moment	
Electromagnetic radiation	$R(T)$, point contact	10^{-13} watts rf through infrared
Charged particles	Resistive transition of thin film	Spatially localized detection
Phonons	Tunnel junction	Counts single phonon

Superconductor Applications	Remarks
Signal processors	Amplifiers, detectors, mixers, harmonic generators, superinductors, delay lines, digital devices
Magnets	150 kilogauss, large volume
Magnetic shields	Near-perfect electromagnetic shielding $B = 0$
High Q cavities	Unloaded Q $\sim 10^{11}$
Electron linear accelerator	cw, $\Delta E/E \sim 10^{-4}$
Voltage standard	~ 1 ppm
Refrigerators, Heat switch	
Power applications	Transmission lines, transformers, motors, generators, energy storage
Mechanical support	Trains, structure

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As I said, Bill Goree will be describing, in detail, ways of measuring the magnetic field using superconductors; however, let me at least mention several ways. A very simple technique varies the temperature of a superconducting rod periodically, and a measurement of the voltage induced in a coil wound about the rod as flux is expelled periodically by the Meissner effect gives a measure of the field. A similar device with faster response makes use of a hollow superconducting cylinder and depends on fluxoid quantization to cause the field change rather than the Meissner effect of the bulk. Probably the most sensitive detector of magnetic fields of any kind at present makes use of the periodic dependence of the critical current of a superconducting ring containing one or more weak links or Josephson junctions. One embodiment of this device is the SQUID, originated by Mercereau and others, which is two Josephson junctions in a superconducting ring. The critical current of the device is a periodic function of the field within the ring, as illustrated in Fig. 6, and is an extremely sensitive measure of field. Zimmerman and Silver make use of a superconducting ring with a single point contact providing the weak link. This ring is placed in the coil of a tank circuit operated at perhaps 30 megahertz, and the level of oscillation of the circuit is measured. Again this level is a periodic function of the field or flux through the superconducting ring. Another version used by Mercereau and Nisenoff makes use of a thin cylindrical film with a narrow bridge formed by cutting away the cylinder or by etching, and most recently by placing a small bit of normal metal beneath the narrow region. The cylinder is coupled through a resonant circuit to measure the periodic dependence of the critical current on field. These devices are capable of detecting magnetic field changes of about 10^{-11} gauss.

Actually all of these devices are detectors of magnetic flux since the critical current depends on the total flux enclosed in the ring. One amusing feature of the measurement of magnetic flux with a superconductor is that for small enough flux a measurement of it can be made without having access to the volume occupied by the flux. That is to say, when a superconducting ring is placed around an area and closed, a current is induced in the ring to keep the ring in its nearest quantized flux state. Thus with less than one-half flux unit within the ring, the current is a direct measure of the total flux within the ring. This measurement depends, as do a number of the other measurements of magnetic flux using superconductors, on measuring the persistent current flow in a closed superconducting ring. This brings me to the next topic, current sensors.

Clearly, any of the magnetometers mentioned above can be converted to a current sensor simply by making use of a small coil within the field sensitive region of the magnetometer to sense the field of the current. A very clever application of this idea has been made by John Clarke in his SLUG, which is diagrammed in Fig. 8. It consists of a bit of lead-tin solder placed around a niobium wire and allowed to make contact with the wire at two places through the usual oxide layer. When a current is passed through the solder to the niobium it passes through the two weak links. The critical current of this device shows a periodic behavior as a function of the current passed through the niobium wire, which as can be seen on the diagram produces a flux which links the small area between the two junctions (the cross-hatched area in the figure). It can be used to measure current, with relatively little sensitivity to the external field, and can detect current changes of 10^{-8} amp. If the niobium wire is part of a completely superconducting loop, the device can be used as a magnetometer by measuring the persistent current induced in the superconducting ring by flux changes through the ring. Furthermore, the device can be used as a voltmeter. For example, in series with a 10^{-8} ohm resistor it may typically have a 1-sec time constant and be capable of measuring 10^{-14} volt. Similar (or even higher) sensitivities can be achieved using a superconducting coil and series resistor to couple to one of the magnetometers mentioned above.

Presently, the only commercially available superconducting instrument is a voltmeter marketed by Keithley which is capable of measurements in the picovolt range. This device makes use of two pairs of superconducting coils, one pair vibrating with

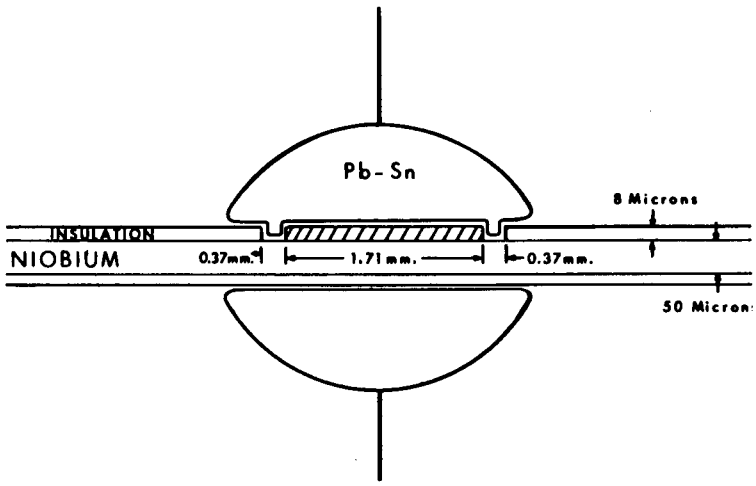

Fig. 8 - Diagram of a Clarke SLUG

respect to the second and consequently modulating the mutual inductance between the pairs. It is operated as a parametric amplifier using the technique described by Satterthwaite and Ries several years ago at the Charlottesville conference.

Most of the devices used for sensing position depend on the change in inductance of a coil or meander strip when a superconducting plane or core is brought nearby. Sensitivities greater than 10^{-13} cm are possible.

An extremely sensitive linear accelerometer is possible using a superconducting ball supported in the magnetic field of a superconducting ring carrying a persistent current. The use of two rings allows the support force and the gradient to be adjusted independently. The position of the ball can again be sensed by measuring the change in magnetic flux through a superconducting ring encircling the ball when the ball moves. Thus, anyone of the previously discussed magnetometers makes a suitable detector. A device of this type is presently being used by John Goodkind as a gravimeter. It should be possible to achieve sensitivities in excess of 10^{-12} g.

A variety of superconducting gyroscopes have been conceived. Some make use of the magnetic support, like that used with the accelerometer, and sense the angular position of the rotating superconducting ball by optical means. Another depends on electrostatic support, but uses two superconducting phenomena for position sensing. That is, since the superconducting ball will become magnetized along its spin axis, a magnetic measurement using one of the sensitive magnetometers can be used to sense the angular position of the ball by measuring the flux change through an encircling loop as the direction of the magnetization changes within the loop. Such a device is being used by W. M. Fairbank with an expected sensitivity of a fraction of a second of arc. Clearly the London moment can also be used as a detector of angular velocity since the magnetization of the superconductor is proportional to the angular velocity.

Since time is moving rapidly on, let me move quickly to some of the other items. You will hear in some detail about the detection of electromagnetic radiation using superconductors from Sid Shapiro. Let me just mention that in earlier instruments the resistance of a superconductor held near its transition temperature was used for very sensitive bolometers. More recently, superconducting point contacts have been shown by Sid to be sensitive to the electromagnetic radiation from low-frequency rf through the infrared wavelengths. He has demonstrated sensitivities as high as 10^{-13} watt.

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Superconducting films have been used to detect alpha particles and other heavily ionizing particles by means of the resistive pulse produced in a thin film carrying a rather large current. Such devices have been suggested as very useful for angular distribution measurements because of the small size of the detector. It has been suggested also that nuclear radiation can be detected using a tunnel junction biased below the gap by detecting the excess charge produced on the passage of the radiation through the junction.

The last item on the list refers to Dayem's use of a biased superconducting tunnel junction for the detection of phonons. He biases the junction below the gap so that there is very little current through it. If the phonon with energy sufficient to break a pair is incident on the junction it can produce quasi-particles, and thus anomalous current in the junction. This is then a phonon counter.

As a second general topic I will list "signal processors." Under this rather prosaic sounding term I will include a multitude of ingenious devices, some of which show considerable promise for future significance in miniaturized electronics and integrated circuits. I will be a little more specific and write amplifiers, detectors, mixers, harmonic generators, superinductors, delay lines, and digital devices.

A number of amplifiers using cryotrons have been devised. As I mentioned earlier, there are numerous ways of using superconductors to modulate an inductance, and this immediately makes possible parametric amplifiers for use over a wide frequency range and with an exceptionally good noise figure. Detection, mixing, and harmonic generation have been demonstrated and used at radio and microwave frequencies, usually with point contact or weak link devices.

One interesting and rather new idea is the superinductor suggested by Little. He pointed out that for a small superconductor with a limited number of superconducting electrons, a significant fraction of the total energy can reside in the kinetic energy of the pairs when a current is flowing. For an ordinary conductor almost all the energy of a current resides in the magnetic field. For a small superconductor the energy residing in the kinetic energy of the carriers can result in an enormously increased inductance. This fact is illustrated in Fig. 9, which shows the measured inductance of a superconducting sample about 50 Angstroms thick, 20 microns wide, and a few centimeters long. Similar ideas are involved in producing long delays with superconducting lines.

A host of digital devices has been conceived and tested using a variety of properties of superconductors. The cryotron and persistatron make possible the storage of digital information. Quantized flux trapped in small superconducting rings has been used for digital storage. The periodic response of magnetometers using superconducting, weakly linked rings has been used to provide digital output for magnetometers and other instruments. An amusing scaler is possible using the magnetization of two concentric hollow superconducting cylinders. Figure 10 shows a magnetization curve of such a pair of cylinders with the larger one having an area approximately 5% larger than the smaller. By clipping and counting these peaks this phenomena has been used for scaling. With proper loading a Josephson junction can be used to provide very high speed switching from the no-voltage to finite-voltage condition in a stable and repeatable way. The vortex array produced by flux trapped in a superconducting film has been investigated as a digital memory unit.

Magnets certainly constitute one of the most important, and in dollars probably one of the largest, applications of superconductivity. Since John Steckley is going to talk in detail about magnets, I will say very little here except that very large volume magnets are now being built, and high-field magnets up to 150 kilogauss are now available.

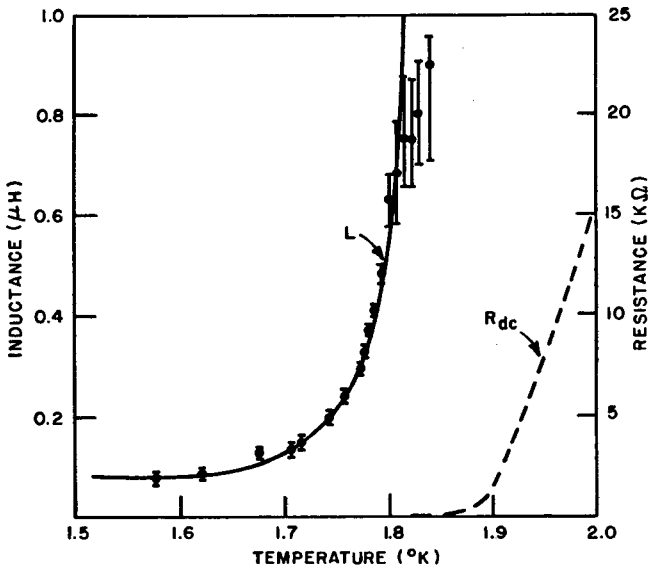

Fig. 9 - Inductance of small superconducting strip as a function of temperature

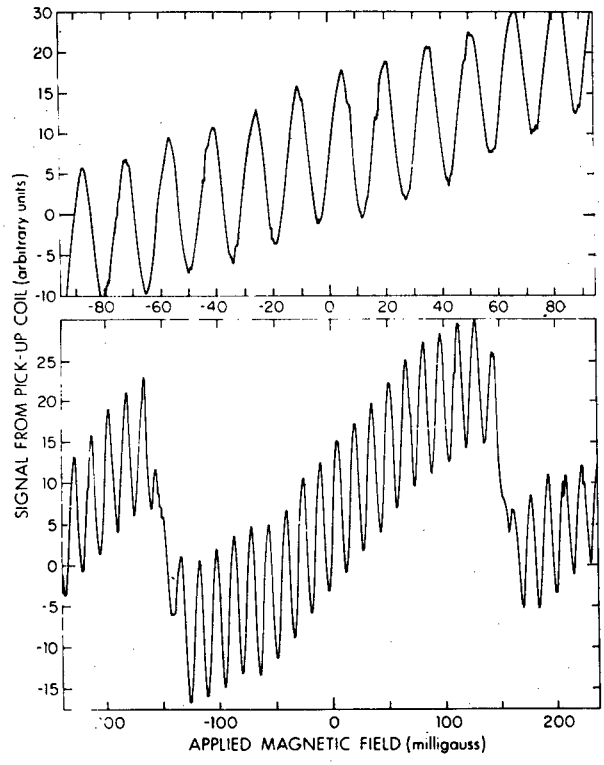

Fig. 10 - Equilibrium magnetization curves for a pair of concentric superconducting cylinders

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In addition to providing a method for achieving very high magnetic fields, superconductors are making possible perhaps the achievement of the ultimate in low magnetic fields, namely zero magnetic field. The quantized flux property implies that when a superconducting cylinder is cooled in a sufficiently small field, currents will be induced to expel the last bit of flux from its interior, resulting in really zero field inside. Experiments are in progress at Stanford to try to achieve a zero-field region. To achieve the initial small field they are cooling a lead "sock" through its transition temperature while in the folded state and then unfolding the sock, thus achieving a volume of reduced magnetic field inside. Then a second folded sock is placed inside the first, cooled, and expanded. So far this technique has produced fields of about 10^{-8} gauss. I believe that Bob Brown at NOL somewhat earlier had experimented with unfolding superconducting shields in a venetian blind geometry to produce reduced fields. Once such a zero-field region is obtained, others of us can simply take our superconducting shield, cool it inside of this region, and then bring home a sufficient number of liters of zero field for our own experiments.

Unloaded Q's as high as 10^{11} are now possible with superconducting cavities. These have been achieved at Stanford and involve extremely careful surface preparation of the cavities. Niobium cavities baked out at a pressure of 10^{-9} at about 2000°C are being used for the Stanford superconducting linear accelerator. By extrapolating measurements on present cavities, the linear accelerator which is now nearing completion at Stanford may ultimately be capable of producing about 6 MeV per foot as a result of improved breakdown qualities of these highly cleaned cavities. The accelerator will be capable of continuous operation and have a beam energy spread of about 10^{-4}, characteristics which were inconceivable with normal linear accelerators.

I mentioned earlier the experiments of Parker, Taylor, and Langenberg using the induced constant-voltage steps on a Josephson tunnel characteristic to measure the fine-structure constant to high precision. The procedure can be inverted and used to establish a voltage standard accurate to a part per million.

The next two items which I will list are actually related, namely refrigerators and heat switches. I will take only long enough to say that the latent heat of a superconductor in the presence of a magnetic field has been used to accomplish cooling. The large change in thermal conductivity of lead between the normal and superconducting state has been used in a cyclic adiabatic demagnetization refrigerator to alternately connect and disconnect the cooled volume from the paramagnetic material.

Another application which seems to have considerable promise, if not actual accomplishment, to date is power generation and transmission. Designs and some tests have been made of transmission lines, transformers, motors, and generators, and some concepts with energy storage using superconducting coils have been considered. The Navy in this country and in England has been conducting experiments with large superconducting motors. For example, a low-speed, high-torque motor of 3,000 hp with a gross weight of perhaps 40 tons (instead of six times that) is envisioned. Experiments with a motor of 50 hp already show considerable promise.

As a last item I will indicate mechanical support. An interesting idea that is being considered at Stanford Research Institute and at Sandia Corporation is the support of high-speed trains using superconducting magnets in the cars riding above a conducting track. The induced eddy currents would provide support and would give lift off at about 30 miles an hour. At 300 miles an hour the train might be suspended six inches off the track. Calculations indicate very favorable lift-to-drag ratios. I believe initial experiments are planned with a high-speed rocket sled.

Recently, a group of architecture students came to me at the University of Virginia and asked about the possibility of supporting parts of a building using superconducting magnets. I don't know where this type of discussion will lead, but it certainly was an amusing idea.

What is the outlook for the future? I am not going to try to predict. However, I am going to comment on some things which will affect future applications of superconductivity. One is the easy availability of liquid helium, cheap liquid helium. Second is the availability of large-scale, low-temperature laboratories like the one at Stanford, which resides above the superconducting accelerator. Since the accelerator will contain some 20,000 liters of liquid, an additional 1,000 liters or so siphoned into an experiment upstairs is not apt to cause a major perturbation, and I think that the availability of large-scale refrigeration revolutionizes our concept of what can be done with superconductors.

In addition to large refrigerators the availability of reliable and relatively inexpensive small cryogenic refrigerators promises to have considerable impact on the application of superconductivity and other low-temperature techniques.

Finally, I think there is a synergistic effect of combining several low-temperature techniques in a common system. In order to make good use of the sensitivities provided by many superconducting sensors it is necessary to house them in an environment extremely well shielded from electromagnetic and other disturbances. The near-perfect shielding of electric, magnetic, and electromagnetic fields by superconductors may be indispensable to exploit these devices. Further, the dimensional and thermal stability possible, the near-perfect isothermal control of large volumes, even in the presence of appreciable heat inputs, and the low noise temperature of the environment are other advantages available in a low-temperature environment. I think the future holds some exciting possibilities for superconducting systems.

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INFRARED DETECTORS

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We are going to talk today about Josephson-effect detectors. The emphasis always will be on what we do and what we observe — and we shall only touch lightly on theory. We will try throughout to give a feeling for what physical concepts and considerations are important in this business. We will spend quite a bit of time talking about high-frequency effects, including the infrared but not exclusively the infrared; I emphasize that to avoid confusion.

The first thing we want to do is show the kind of structures used in Josephson-effect detectors. These are shown in Fig. 1. In contrast to Bascom's elegant slide, this one is very schematic. Under "A" you see the granddaddy of them all, the thin-film oxide tunneling junction. They are still used. In fact, we are using them for some high-frequency work now, but most of what I will talk about has to do with the point-contact form shown under "C", which you can arrive at via route B. The "A" geometry has two conductors crossing one another, but slightly separated, and you can see how that transforms into the very simple form of two crossed wires, as first used by Jim Zimmerman in his very characteristic way. If you get fancy about his kind of a point contact you end up with form "C". I am not going to say anything about the quantum interferometer loop "D" or the SLUG shown in "E", namely the device named Superconducting Low-Inductance Undulating Galvanometer (SLUG), which was named by John Clarke. I am sure Bill Goree will have quite a bit to say about those two forms of junction.

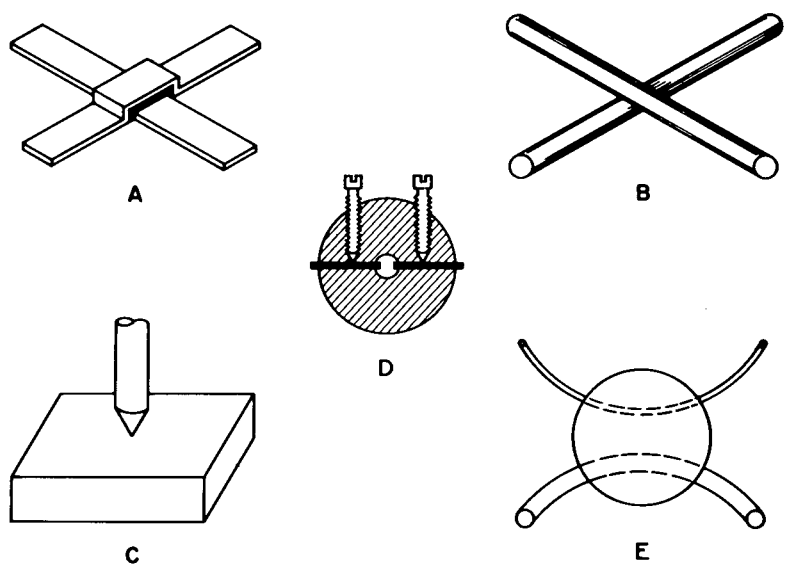

Figure 1

Now, if we take a point contact, let's say one of the form "C", and we look at the voltage-current characteristic of it, what we see is shown in Fig. 2. Here I have just shown an oscilloscope trace. The voltage is plotted vertically, and the current horizontally, so you may have to tip your heads, as I see some people doing. This slide is rotated 90° from the kind of data that Bascom showed in the first talk. What you see very clearly is a flat region at zero voltage. This flat region is significant, and we will see others like it as we go along. Even more significant for high-frequency properties is the fact that when you exceed some critical current (which is small for these point contacts and Josephson devices in general, compared to the current that can be carried in a piece of bulk superconductor) you then develop voltage between the two superconductors across the junction. Thus, you can operate in the voltage or finite resistance part of your device characteristic.

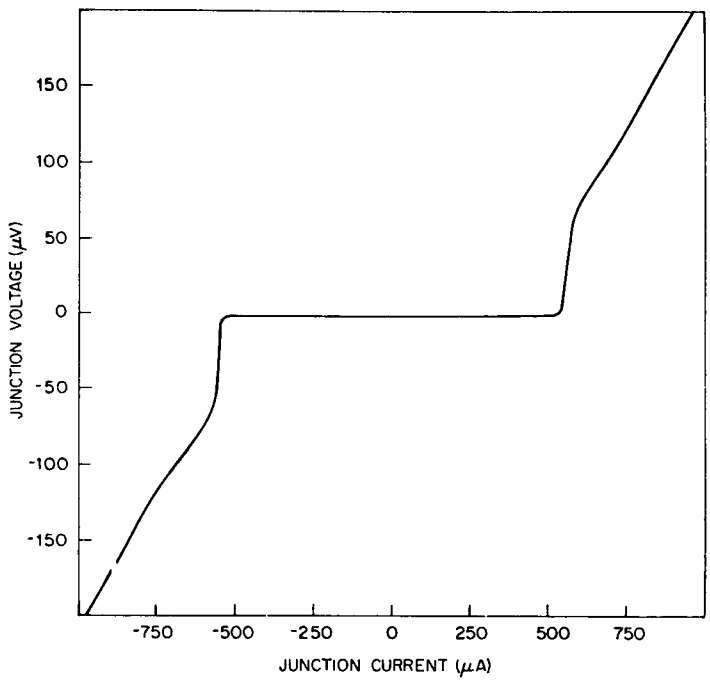

Fig. 2 - Representative voltage-current characteristic for a Nb-Nb point-contact Josephson junction at 4.2°K

Now, what I want to do at this point is to give a prescription for describing this voltage-current characteristic in the most elementary framework. I am not going to explain anything. I am just going to put down a framework that we use to talk about the device characteristic of Fig. 2 and the somewhat more complicated characteristics that we will encounter later. Since this description is due to Josephson, we will refer to the equations used as "Josephson's phenomenological equations." I use that phrase very frequently, though I guess Darrow has criticized the term "phenomenological" as being abominable. Josephson says that what we want to account for is a pair tunneling current, the current associated on the V-I curve with the zero-voltage regime. You can drive current through the contact without developing a voltage across it; you want to focus on the observable current, which I write as J. What will J be equal to? We will write the current in terms of things that we can get hold of — voltage, magnetic field, time-dependent rf, etc., but we do this via a parameter with the current written initially as

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a constitutive relation in terms of this parameter. Instead of Ohm's law, where we have current equal to conductivity times electric field, as the constitutive relation for the normal metal, we will now write a parametrized kind of constitutive relation that accounts for Josephson effects. We do this by writing $J = J_1 \sin \varphi$ where J_1 is a scaling factor. Now, this φ is a small φ and represents the phase difference between the superconducting wave functions across the junction. I've contrasted this φ with the Φ which Bascom used to denote the magnetic flux and associated properties. The parameter φ that we use now in the Josephson discussion is a phase parameter related to the macroscopic wave functions of the superconductors.

We need other equations to enable us to work with and use the parameter φ. In particular, φ will be a function of space and time coordinates. Now, in this framework the space dependence of our phase parameter φ is accounted for by a differential equation involving the space gradient of φ and the magnetic field. I am not even going to write it down, but what we can do is to say that whatever form this equation has, the spatial variation of the current that we observe through a junction is determined by the magnetic field. For the balance of this talk, I am going to ignore spatial variation. We are talking implicitly about constant or zero magnetic field.

What we are interested in here is the time variation of the parameter φ. As you might guess, the time dependence of φ is related to the presence of electric fields or voltages in the problem. We write that down as $d\varphi/dt = (2eV/\hbar)$. Now I am only going to do one thing with this equation and then I am not going to write another equation or refer to it again. I hope we will see how the argument goes.

Let us take this voltage which, of course, now in our problem may be time dependent and in the general problem may be space dependent. All I want to do is look at this when we have a constant voltage, a steady dc voltage. So, if we have that then we say that the phase parameter φ increases linearly with time, the solution of the differential equation being $\varphi = (2eV_0/\hbar)\, t$. The current you then have is $J = J_1 \sin (2eV_0/\hbar)t$. So this is our framework. If we have a fixed voltage the current varies as a simple oscillatory function, the sine of some angular frequency times the time, with the angular frequency $\omega_0 = 2eV/\hbar$ directly related to the voltage. The number $2e/\hbar$ is 483.6 MHz per microvolt. It is a large scaling factor which makes for a lot of the fun.

Now, if you have a current that is varying simply and sinusoidally in something like a point contact, or even in a thin-film device, then depending on how you arrange the environment of the structure you can have that current couple to the outside world via electromagnetic energy. You can have it serve to generate radiation, but what you've got to do is to maintain a constant dc voltage across the device if you want to have essentially pure frequency. As soon as you deviate from a constant voltage the solution of the equation for $d\varphi/dt$ becomes a mess, and correspondingly the current that you get will be a mess in the sense that it will have all sorts of harmonics and subharmonics of your operating main frequency. O.K., so that then is the basic idea which underlies the voltage part of a device characteristic. When we put a voltage on we have oscillatory currents in our junction. Of course we don't see them when we plot the dc or low-frequency V-I characteristic.

How do we make these currents manifest? How do we see them? Well, the real problem is maintaining a constant voltage. You can maintain a constant voltage by the

Zimmerman-Silver technique that Bascom spoke about in connection with the temperature measurement, by putting a physically large, but very low resistance, shunt across the device. Then what you have are very strongly localized currents in a very low impedance kind of environment. Free space is 377 ohms as everyone knows, and it is very hard to match an exceedingly low impedance element to a very high impedance element. So the shunt technique is not a very good way to maintain V constant if you want to talk about high-frequency radiation *outside* the element. That technique is perfectly fine if you are interested only in having these currents present *in* the element.

Well, we want to talk about generating fields outside the element, so we must make an impedance transformer. Fortunately, it is very easy to make impedance transformers in the microwave-millimeter range. An impedance transformer is shown in Fig. 3. This impedance transformer was used by Aly Dayem and Mike Grimes to generate radiation. What is it? As you can see the secret is even given away. It is labelled "cavity," and in the case shown is a coaxial cavity. Why is it an impedance transformer? Because the electromagnetic field configuration has a standing-wave configuration in the cavity region and has a characteristic form. At some places the impedance is low, that is, if you want to look at it from the other point of view, at some places in the cavity the currents are large while the voltages are low. We put the point contact at such a low-impedance region. At other regions of the cavity the currents are low while the voltages are high, and we put the coupling hole to an outside waveguide at such a high-impedance region. Thus the cavity is an impedance transformer from our point of view. If you then want to match the radiation capability of your device to the outside world, you can do it via a cavity. We will come back to that as we go along. I hope that I will make it clear why I have spent so much time on the importance of the junction's cavity environment. This environment is needed for impedance transformation so that one can use the junction and get at it from the outside world.

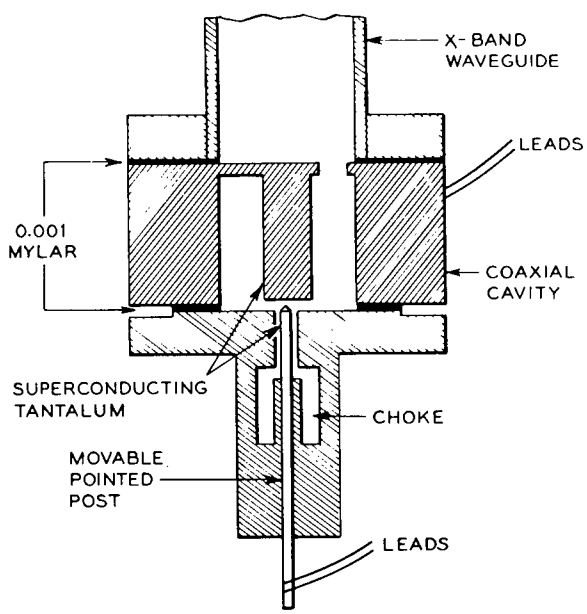

Figure 3

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Now, I don't want to say anymore about signal generation, as such. The main burden of our talk is detection. The experiment worked, I can say that. Dayem and Grimes did get radiation out. The maximum radiation out was 10^{-10} watts. I don't think that is terribly useful. To sit here and turn a knob and say "Ah, I can tune my radiation, and here is the source of the radiation" isn't really terribly useful to us. What is important to us is the fact that there are rf fields at variable frequencies or at specific frequencies in the immediate environment of the device. I will come back to that in a moment, but the point that we want to speak about primarily is detection.

To detect radiation what we need to do is to shine some radiation on the device. In particular, let us shine millimeter radiation on the device from a nice coherent tube-type source. Shine it on the device, and what do we see? Well, we are going to look at the V-I characteristic again on Fig. 4. Again I am plotting voltage vertically and current horizontally. In the middle of the figure we see the zero-voltage region, and we see that there is still a finite current at zero voltage. But with the radiation on we have clearly modified the characteristic from the type that was shown earlier because in the finite voltage part of the characteristic we see that there are additional "low-resistance steps," if you will, regions where the current increases suddenly over a small range of voltage. Now, this modification in the V-I characteristic — the rf induced constant-voltage steps, to give it a name — occurs because of the radiation. We can then use this modification of the V-I curve as a detector of the radiation. The character of the modification is an rf-induced step at a voltage where the corresponding Josephson frequency, $\omega_0 = 2eV/\hbar$, that I wrote down before, is equal to the applied frequency for the first step, or to a harmonic of the applied frequency. The second step corresponds to the second harmonic — so we have a specific kind of detection. The modification of the V-I characteristic occurs at voltages such that the Josephson frequency is harmonically related to the applied frequency. This is true of course for a coherent source, and it is true for all coherent sources over the range in which the Josephson junction operates.

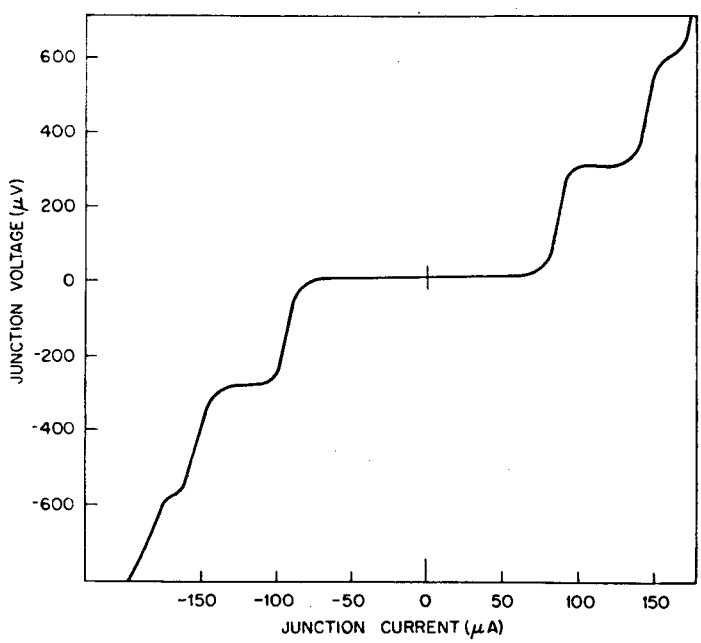

Fig. 4 - V-I characteristic for an In-In point-contact Josephson junction at 1.3°K in the presence of about 10^{-9} W of radiation at 5 cm^{-1} (150 GHz)

How high in frequency can it go? Well let me rephrase the question and ask how long a wavelength the device can handle. We will have some data on that in a moment, so I will simply say that the longest wavelength that I know that has been used successfully is 311 microns. If you take that laser and shine it on your junction, you see a modification in the voltage-current characteristic that is similar to what is shown in Fig. 4. You see steps induced. The 311 microns for a niobium junction happens to be at a frequency which is already greater than the superconducting energy gap, and so the gap does not represent an automatic cut-off to us. We will see shortly what role the gap does in fact play in the frequency response of this kind of detector.

My remarks up to now have been with respect to coherent sources — essentially single-frequency sources — and, as I say, 311 microns is the limit so far of what has been observed using a Josephson junction subject to a monochromatic input. But when we talk about infrared many of the applications and much of the experimentation is done with incoherent sources, mercury arc lamps for instance. So, how does a junction respond to such sources? Well, without going into the details let me say that basically the same kind of effect takes place as for monochromatic sources. The voltage-current characteristic is modified by the radiation, and these modifications can be observed. All the frequencies cohere at essentially one point. They are integrally related to the Josephson frequency zero by the integer $n = 0$. That simply means that all input frequencies affect the zero-voltage current in a similar way. They tend to decrease the zero-voltage current. If we look then at the effect on the zero-voltage current of an incoherent source and do a frequency separation kind of magic called Fourier transform spectroscopy, then we can see the spectrum of response of the junction to all the frequencies contained in the incident radiation.

Now I don't want to go into all the details. Basically the data I am going to show comes about from using an exceedingly simple system. You just shine radiation down on the junction and do some signal processing on it to unfold the frequency spectrum. All I want to show is the result for this frequency spectrum. But the basic idea again is that the junction just sits there and gives you a response to the radiation. It is a passive little animal that doesn't participate in anything except to change itself in some way so as to indicate its response to radiation. It changes its voltage-current characteristic.

Figure 5 shows the spectrum for a junction formed of two pieces of indium in a point-contact configuration. I am not interested in having you take the details of this curve seriously — there are all sorts of instrumental limitations on the details. For instance, if we look at the low-frequency or long-wavelength region it indicates that the response cuts off. Well that clearly is not true for a junction — we have a response at zero frequency, we have a response at 1 GHz, we have a response at 150 GHz. The cut-off indicated in this diagram is the consequence of the mercury arc source. Folded in on this data in addition to the actual spectral response of the junction is the spectrum contained in the source and also the spectrum modifications introduced by the apparatus. So don't take the details of Fig. 5 seriously, only the generalities. First of all there is a response, and the signal-to-noise ratio is good. The response may not be quite as good as indicated here but it is quite good. It is rather simple with standard types of techniques to see this result. The response extends to rather high frequencies corresponding to energies greater than the gap of the indium. We have a response peaking somewhere in the region of the energy gap and going up to a factor of roughly two or so beyond it in frequency.

What if we use a different material with a larger energy gap? Well, that is easy. The results for a niobium junction are shown in Fig. 6. Again we have a response, and one that extends out to a frequency of about a factor of two times that corresponding to

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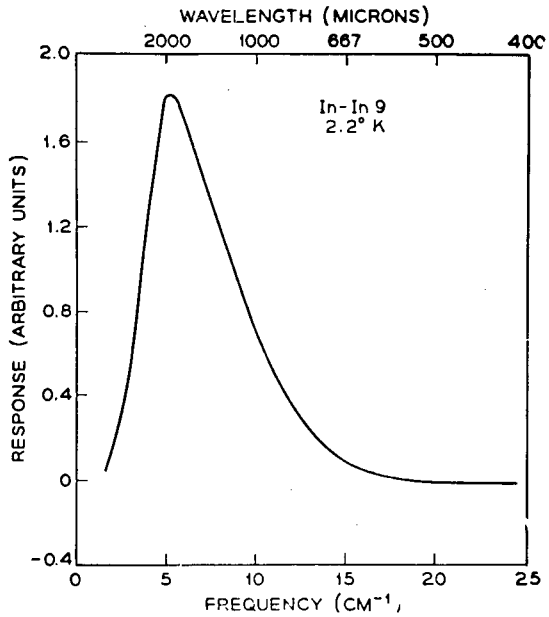

Fig. 5 - Spectral response of an In-In junction at low resolution, which smooths out and eliminates structure associated with geometrical resonances

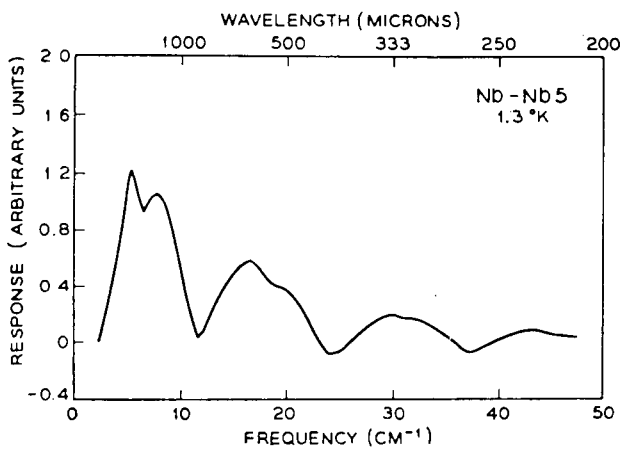

Fig. 6 - Spectral response of a Nb-Nb point-contact Josephson junction

the frequency of the niobium energy gap. Again, on this curve there is detail and structure that one should not take seriously. The curve is indicative of the fact that again we have a rather good signal-to-noise ratio. These detectors are quite sensitive, and I will give a figure at the end of the talk. They detect out to frequencies of about twice the energy gap, in this case clearly 250-300 microns.

Why does a junction operate out so far? There wasn't anything in the simple equations that I wrote down that would give any indication of why this should happen. Figure 7 shows results from theory. The theory we have talked about up to now was all for low frequencies, namely the ac Josephson effect when the applied voltage is small compared to the energy gap. The portion of the curve marked $Re\ j_2$ in Fig. 7 is roughly what detailed theory tells us ought to be the response of the junction to rf signals. We have a finite current at zero frequency. Instead of dropping off from this value as we go to higher frequency, theory says that the amplitude of this current, because of the existence of the energy gap, ought in fact to peak at the energy gap and then fall off rather slowly. Now this is very crudely the kind of behavior that we see in the response curves just shown (Figs. 5 and 6). I am not claiming that those response curves verify this kind of theoretical prediction. Rather, they are indicative of the theoretical prediction. The two go hand in hand. The fact that we do have a response well up beyond the energy gap and the fact that theory predicts a response in this form are consistent. Thus we have some confidence in extrapolating the correlation to some other superconductors.

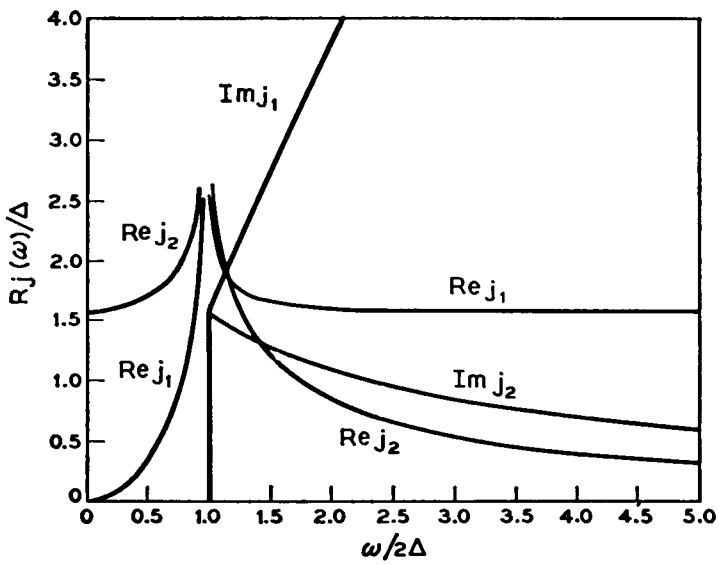

Figure 7

Figure 8 shows a case where that happy story doesn't work. For lead, as you see, we have a very sharp single peak with some noise on it. The sharp peak is at a frequency which is very low compared to the energy gap of lead. What happened? What happened is that up to now for this infrared data we have not taken account of the fact that the junction is mounted in an environment. It isn't sitting all by itself out in free space. It sits in a box. The box has resonant modes, particularly at high frequencies. In other words, the box acts like a cavity at some frequencies, and you really can't do much about the problem. You can shift the resonances around or lower their Q but you can't really kill

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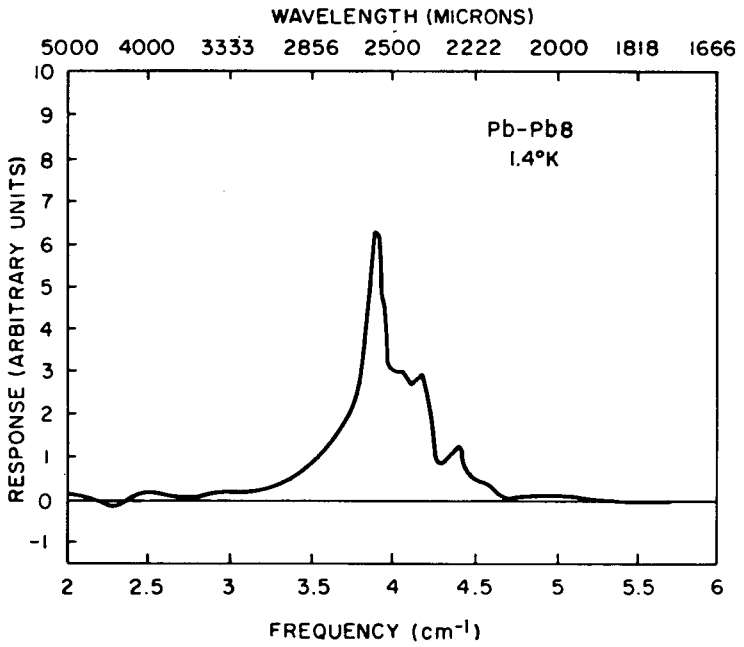


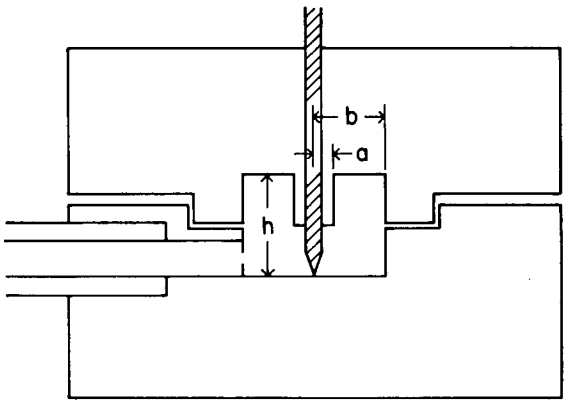
Fig. 8 - Spectral response of a Pb-Pb point-contact Josephson junction

them entirely. There are always some resonant frequencies for any kind of box. We feel that the data in Fig. 8 indicates a coupling to the resonant modes of the box with the junction no longer just sitting there saying, "OK, you are shining some radiation on me so I'll change my voltage-current characteristic for you a little bit." What it's doing is saying, "Aha, you are trying to make me respond to your radiation, but I am so excited that I am generating radiation of my own as I sit in this box. I am oscillating away at frequencies characteristic of the box in which I sit, like the Dayem-Grimes generation experiment, and when you shine your radiation on me all I will do is to act as a mixer and beat the resonant mode frequency with the incoming radiation. I will modify the voltage-current characteristic at dc, which is what you look at, in a way not characteristic of a simple video detector but characteristic of a mixer detector operating at one frequency or, rather, over a very narrow band of frequencies." That is the explanation for the sharply peaked data of Fig. 8.

Paul Richards, with Sterling, one of his students at Berkeley, has done very careful experiments of this type in the infrared region and has confirmed this hypothesis in great detail. Instead of trying to build a box that has very low Q modes or no modes at all, Richards builds a box for which he knows the resonant modes and the Q values. He is able to obtain peaked response curves at known frequencies and to move the resonance from one mode to another by locating the junction at different points in the box. A given point couples to a particular mode with a certain frequency. By locating the junction at a different location one sees it operate at a different frequency for a different mode. Thus, the device has potential for an active as well as a passive infrared detector, and that is the point of that discourse.

Now again, the experiment on the Pb-Pb junction, as well as Richard's experiments, is done with incoherent sources. What we have done is essentially the same kind of controlled mixer-detector experiment but using *coherent* — rather than incoherent — sources in the 4-mm region. Before summarizing the numbers on the talk I want to show some

results and comment on them. Figure 9 shows the form of the cavity. It is similar to the Dayem-Grimes coaxial cavity with the point contact located at a high-current point. The additional fact is that now the cavity structure and the point junction are used to generate radiation. The cavity is excited by current fed into the junction from the dc battery at the voltage corresponding to the resonant frequency of the cavity, so an rf field builds up in the cavity. We introduce some 4-mm radiation, just sprayed from a waveguide. Some of the radiation couples into the junction. We expect there will be a mixing between this incoming 4-mm radiation and the radiation in the cavity due to the junction.



a = .102 cm b = .363 cm

h = .538 cm

Figure 9

That's very nice, but there is something missing. We don't have a coupling hole to get out this difference radiation. Well, we didn't put the coupling hole in on purpose because we don't have the equipment that would see this radiation even if we brought it out. Its intensity is pretty low. As you remember in the Dayem-Grimes experiment the maximum they had was 10^{-10} watts in the first-order effect. Here we are using a mixing product and there is not going to be very much radiation. But we don't need to detect the radiation directly because the junction is responding to the currents that are in it regardless of how poorly it might be coupled to the external world. We need only look at the voltage-current characteristic of the junction.

Figure 10 shows the V-I characteristic. Again, when we have no incident rf we see an indication in the voltage-current characteristic of the coupling of the Josephson radiation to the mode of the cavity. We see a step, sort of a self-rf-induced step, in the voltage-current characteristic at the resonant mode frequencies TEM_{01} or ω_c and TEM_{02}. Now we shine rf on the junction, and we see the rf-induced step at the much higher frequency ω_{RF}. What we see in addition is a step at the difference frequency $\omega_{RF} - \omega_c$. This is a clear indication of the nonlinear mixing of the type that I spoke about. In fact, it goes one step beyond in that, in order to observe the step at $\omega_{RF} - \omega_c$, the junction is biased at a point which does not correspond to the cavity frequency. Yet the cavity is excited. It is excited via the nonlinear mixing of the Josephson frequency at $\omega_{RF} - \omega_c$ and the incoming signal at ω_{RF}. This mixing in turn couples back and excites the resonant cavity at ω_c. So the potentialities for using the active properties of Josephson junctions in detectors for the millimeter and infrared regions are there. The pertinent part of

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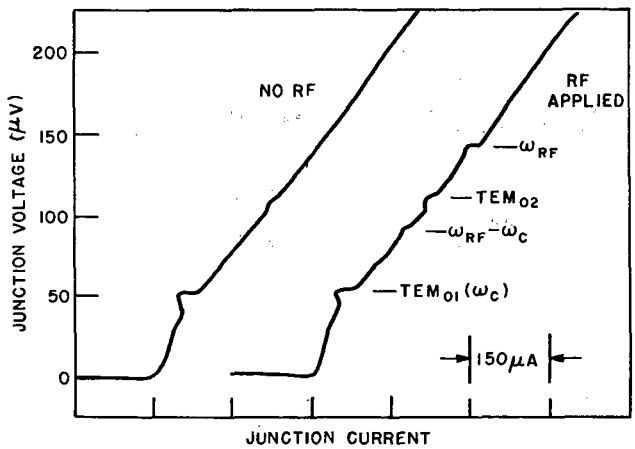

Figure 10

this experiment is to show that those active properties are present. They can be manipulated; they can be used.

Let me quickly summarize. I want to mention some figures that have been achieved for sensitivity, speed, and bandwidth. A sensitivity, in one cycle bandwidth, of 5×10^{-13} watts was obtained for the simple video detector. The speed — at sacrifice of sensitivity — was less than 10 nanoseconds. A bandwidth, as you have seen on the niobium, was up to better than 300 microns. With improvement, the mixer detector sensitivities should increase from a factor of 10 to 100. The speed is limited fundamentally to one over the gap frequency, which is about 10^{-12} second, so I think we haven't run into the inherent limit yet. Somewhere between 10^{-8} and 10^{-12} second the inherent speed of the device should show up. The bandwidth, as you have seen, goes with the energy gap. If materials that are now known could be used to fabricate these detectors, the bandwidth would be extended to 100 microns. New materials might push it beyond that.

SUPERCONDUCTING MAGNETOMETERS

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INTRODUCTION

Bascom Deaver talked about many different applications or devices that use properties of superconductivity, and Sid Shapiro discussed one of these. I am going to discuss another, superconducting magnetometers — one application, but three different techniques using superconductivity.

What I plan to do is to discuss three types of magnetometers: one that uses flux motion; a type I am going to call the Mercereau magnetometer;* and tunneling magnetometers, which use the dc Josephson tunneling properties of superconducting point contacts. What I would like to do is first show how each of these magnetometers works — how you get a signal that is proportional to the magnetic field — and to describe a little of the physics that affects the construction of the magnetometer. I will then show you some comparisons of sensitivities of different magnetometers and briefly discuss noise properties that affect the response of each of these types.

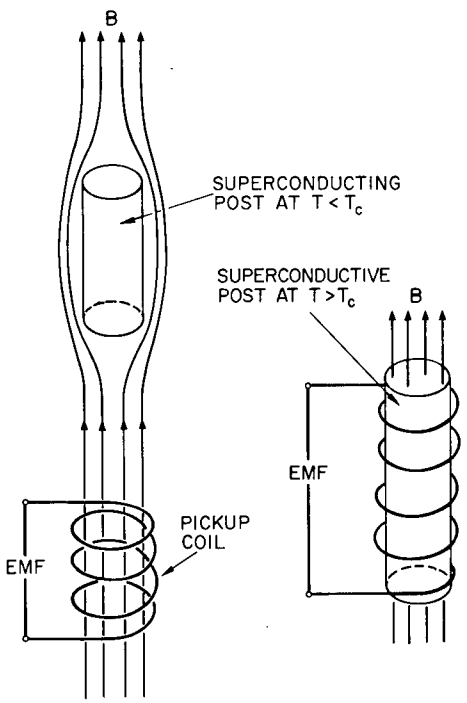

Fig. 1 - Meissner-type magnetometer

FLUX MOTION MAGNETOMETERS

The first magnetometer we will consider is the flux motion magnetometer. This can be viewed very simply if you consider a pickup coil placed in a magnetic field, as shown in Fig. 1. If you move a magnetic sample in and out at the pickup coil — it doesn't even have to be superconducting — you induce a voltage V across the terminals of the coil, proportional to the magnetic flux change that this object produces in the coil and to the number of times, or the frequency, with which you move the sample. This is similar to the Foner vibrating sample magnetometer that many of you are familiar with, and also similar to the Ries-Satterthwaite vibrating coil, where two coils are moved relative to each other. You can use properties of superconductivity to

*This has been described as a flux flow magnetometer, but that is not a precise term either; I'll go into that in more detail later.

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get this same effect of the motion of the sample in and out of the coil by putting a superconducting post inside a pickup coil, and then switching the post between the superconducting and the normal state. When it is normal, the magnetic field permeates the whole post uniformly, as shown on the right side of Fig. 1. When it is superconducting, the Meissner effect expels the magnetic flux from the post and the field lines pushing outward cut the windings of the coil and induce a voltage. Again you get an emf or voltage across the pickup coil, and that is proportional to the amount of flux that is moved each time the modulator is switched. The advantages of this type of magnetometer are, first of all, that it is very simple intuitively — you can see the physics of the flux motion very clearly. It is also absolute. If there is zero field present at the post, there will be zero signal. The response is linear; the larger the field becomes, the larger the output signal. There are several disadvantages. These are mainly associated with noise and sensitivity: it's a fairly noisy and slow process to switch a volume of superconductor between the superconducting and normal state. You have flux moving in and out of the material, and there is a random motion of this flux that induces noise in the pickup coil; this is a background noise on the magnetic signal.

In Fig. 2 I have sketched the way we normally build these Meissner-type modulators. The superconducting layer can be vacuum deposited, electroplated, or cast, depending on the size you want. It is normally 1 cm long and 1 mm or so outside diameter. Then we wrap a pickup coil around the modulator assembly. This magnetometer is sensitive to magnetic fields in the axial direction of the pickup coil. It is basically a vector instrument in that it is insensitive to magnetic fields in the transverse direction, except for noise induced by these fields. Flux linking the modulator in this transverse direction is also excluded when the modulator becomes superconducting. This flux can link the coil by both the helical angle of the windings and by changes in the orientation of the flux, as it is excluded from the cylinder.

We have switched these modulators at frequencies as high as 30 kHz, although you don't get much increase in signal as you go up in frequency because the Meissner effect, or the modulation that you get from switching the superconductor, decreases with increasing frequency. What I mean is that you don't get the same flux exclusion if you switch 30 kHz as you would get if you switched it 1 or 2 Hz, because the flux doesn't have time to move out, since eddy currents retard the motion.

Now you can modify this type of magnetometer into a quantized flux circuit by putting a much thinner layer of superconductor on the outside of the insulating film. I have shown the response of Meissner and quantized flux magnetometers in Fig. 3, where φ_0 is the flux quantum and $\Delta\varphi$ is the external magnetic flux. The difference in the quantized flux is, as Bascom Deaver showed, if you have a superconducting cylinder in a magnetic

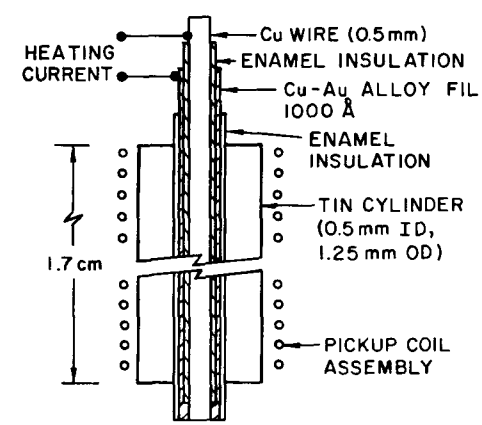

Fig. 2 - Meissner modulator construction

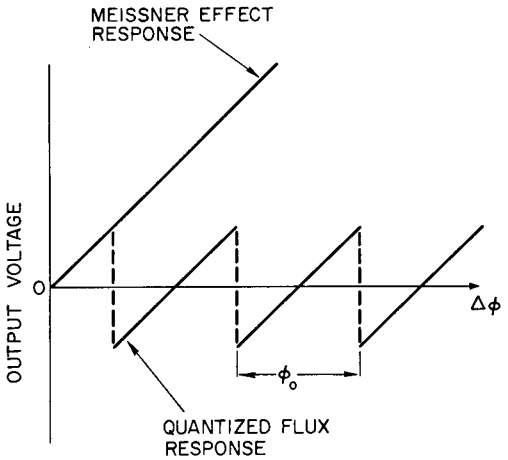

Fig. 3 - Response of Meissner effect and quantized flux magnetometers

field, the total flux linking the cylinder is quantized in units of $h/2e \simeq 2\times10^{-7}$ gauss-cm^2. If you cool down a cylinder in a field that produces some nonintegral value of magnetic flux linking the cylinder, then currents are spontaneously induced in the cylinder to change the flux linking it to the nearest integral flux quantum. What we are really plotting in Fig. 3 is the instantaneous magnetization of a superconducting cylinder as we very slowly sweep the magnetic flux linking the cylinder; i.e., the voltage is proportional to the amount of flux and the direction of the current flow. As you start increasing the flux the circulating current gets larger and larger in one direction until you get to half a flux unit linking the cylinder, then it becomes energetically more favorable to exist in the next higher quantum state, the currents reverse at their maximum value producing a negative voltage pulse, and then they decrease until you get to the integral quantum value and then the currents are zero. You thus get a periodic response to changes in magnetic field where the period is the flux quantum (2×10^{-7} gauss-cm^2).

In general, quantized flux modulators have a finite wall thickness, and the final response is a combination of the Meissner effect of the walls and the periodic quantized flux response. That gives a finite slope to the response. We have obtained field resolution of the order of 10^{-7} gauss with a magnetometer of this type.

Another flux motion magnetometer is a very elegant system that has been developed by Professor Fairbanks' groups at Stanford. This is called a vibrating ground plane magnetometer. It's almost identical to the Ries-Satterthwaite vibrating coil or the Foner vibrating sample magnetometer, except for the construction details. Zero resistance alone is the crucial superconducting property used in this magnetometer. A sketch of this circuit is given in Fig. 4. In operation a superconducting ground plane is vibrated very rapidly near a superconducting pickup coil. Basically the vibrating plane modulates the inductance of the pickup coil in the same way as with the other modulators discussed earlier. In the Fairbank-Opfer circuit the ground plane is evaporated on the surface of a quartz crystal, which is driven electrically at frequencies from 0.1 to 1 mHz. One significant feature of this magnetometer is that none of the superconducting components are switched out of the completely superconducting state. Also, the response is linear with magnetic field. Thus, the noise due to eddy currents, flux flow, temperature change, etc., should be eliminated.

Potential noise sources, of course, are the fluctuations in the amplitude of the quartz crystal; they have also found that when they cool these down they get thermally induced currents that produce background flux in the circuit, and in fact you can trap flux in these ground planes, and that moves relative to the pickup coil. Presumably that will produce

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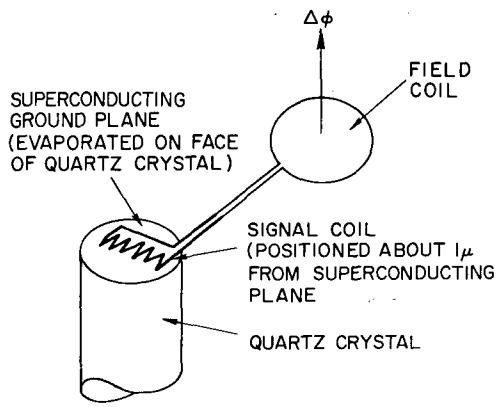
Fig. 4 - Fairbank-Opfer magnetometer



a dc background, but if it is large compared to the field change that you want to measure, it can be a noise source. They project field resolution on the order of 10^{-11} gauss. That limit is set by this flux trapping problem and the noise calculations that they have done.

Now, in summary, all of the magnetometers we have talked about so far are basically flux motion or modulated inductance devices. Figure 5 shows a schematic that would represent any of these three circuits where we have a pickup coil, a magnetic field transfer coil, some kind of modulator, and a readout circuit. We can either read out by coupling mutually or directly to this circuit.

Another superconducting circuit element is also shown on Fig. 5. This is called a magnetic field amplifier. This amplifier can be used to greatly extend the sensitivity of magnetometers of this type and, in fact, the Josephson-type magnetometers as well. You isolate the detector and the pickup circuit in a superconducting magnetic shield so that the environment is constant — that reduces the noise at the detector. Then you apply a field at the pickup coil and measure the resultant field that is induced at the detector. You find if you go through the calculations that the amplification of the magnetic field $\Delta B_2/\Delta B_1$, which is the change in the field at coil L_2 for a given field change at coil L_1, is related to the relative inductance L_1 and L_2, the turns ratio N_1/N_2, and the area ratio A_1/A_2 of the two coils, and you can easily get magnifications like fifty this way. The final amplification depends entirely on the coil geometry. The advantage of amplifying the

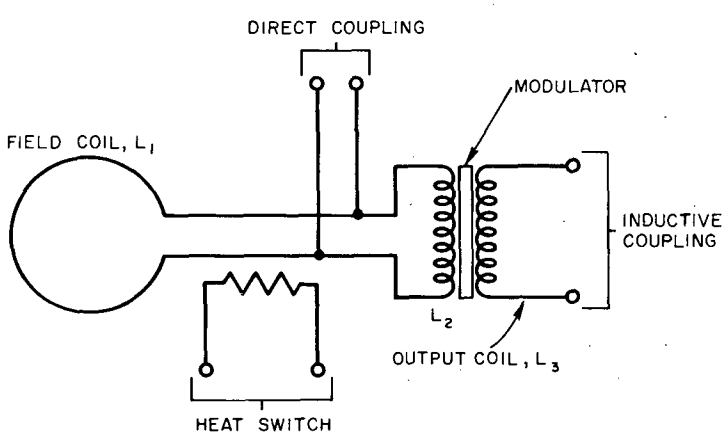


Fig. 5 - General flux motion circuit

field in this fashion is that it is a completely superconducting circuit and is therefore basically noiseless, so you are amplifying a field before you go to the detector. If there is a fixed noise caused by the detector and you can get field amplification before that, you amplify the signal-to-noise ratio.

MERCEREAU MAGNETOMETER

Now the second type of magnetometer that I will discuss is the Mercereau circuit. This is very similar to the Meissner and quantized flux magnetometers except for the physics of the way it operates. Figure 6 shows the general construction of this magnetometer. Instead of the modulator being a completely closed cylinder, it's only closed by a little bridge at the middle. The way this operates, very qualitatively, is that if you apply an axial magnetic field you induce circulating currents in the cylinder. All the current has to flow through the bridge, and at some value you will reach the critical current of the bridge. When you do that the magnetic flux inside the cylinder can change, allowing the current through the bridge to decrease, and the bridge becomes superconducting again. The total flux linking the cylinder is quantized, as with the quantized flux modulator. The detailed process of the way magnetic flux enters the cylinder is rather involved; in fact there is not a complete theory for it. You can view the bridge as a point contact or a Josephson junction, writing the current through it as some $j_1 \sin \varphi$ where φ is the gauge-invariant phase difference across the bridge, and can show that the emf induced across the pickup coil is given by

$$\text{emf} \simeq \varphi_{rf}\omega J_1\left(2\pi \frac{\varphi_{rf}}{\varphi_0}\right) \cos\left(2\pi \frac{\varphi_{dc}}{\varphi_0}\right) \sin \omega t \, .$$

The term φ_{rf} is a radio frequency field such that the amplitude of the rf is sufficient to induce several flux units change at the cylinder. φ_{dc} is the ambient dc field of the modulator. We see that the emf is proportional to this first-order Bessel function J_1, of the rf flux, and to the cosine of the dc flux.

Figure 7 is a sketch of the response that Mercereau and Nisenoff have obtained with this type of magnetometer. We have plotted the amplitude of the rf flux along the vertical axis. The amplitude of these different periods as we increase the rf flux is not quite periodic in the flux quantum; it goes as this first-order Bessel function. The amplitude as you change the dc magnetic flux is periodic in the flux quantum; it goes as the cosine of this dc flux over φ_0. To make a magnetic measurement they will sit at some dc field and get an rf power out, and then change the field a little and measure the change in the detected amplitude. They can resolve a little better than 10^{-10}-gauss field change with this circuit. It is a simple circuit to build using vacuum evaporation and photoetch techniques. Also, one only needs two wires going to the circuit for its operation. You can put the rf signal in and read the response out and put a dc calibration field in on the same leads.

TUNNELING MAGNETOMETERS

Now the next class of magnetometers utilize the tunneling properties of superconductors that have been talked about so far in both papers preceding this one. First, just to remind you of the tunneling junction, there are two superconductors separated by an insulating barrier, as shown in Fig. 8(a). In general, this is a dielectric, like an oxide of the metal of one of the superconductors, and is on the order of 10 Å thick. The barrier can even be a metal, such as copper, and in that case you can go up to 10,000 Å or so in barrier thickness and still get the same basic Josephson tunneling properties. The

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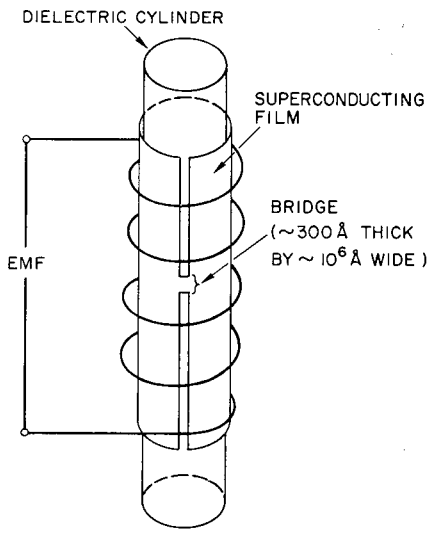

Fig. 6 - Mercereau-Nisenoff magnetometer

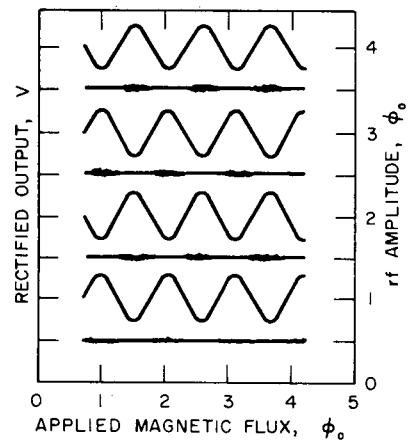

Fig. 7 - Schematic response of the Mercereau-Nisenoff magnetometer

difference is that the voltages for the metal barrier junction are on the order of 10^{-9} volt, whereas they might be millivolts or so with the insulating barrier. This presents a serious problem in measuring the response of the junction. Bascom Deaver noted that the critical current of a single Josephson junction is a function of the magnetic flux linking the junction. It obeys an equation just like the single-slit diffraction pattern, $(\sin x)/x$, where x is the normalized magnetic flux linking the junction. Figure 8(a) also shows a schematic of the way the critical current varies with flux. This is not a particularly sensitive magnetometer because the junction area is very small. Reported field resolution is usually on the order of a milligauss.

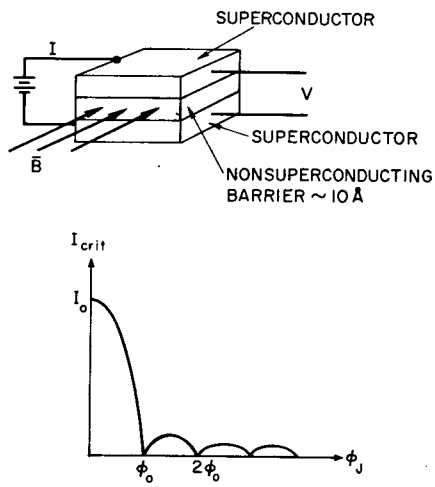

Fig. 8(a) - Single Josephson junction

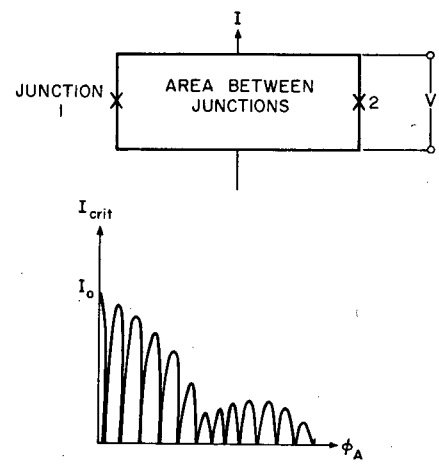

Fig. 8(b) - Double Josephson junction

A far more sensitive magnetometer may be constructed if two junctions are connected in parallel, as shown in Fig. 8(b). In this circuit, superconducting electrons can flow from one side of the device to the other through either of the two paths, and interference can result from phase changes along these paths. This interference produces an additional modulation of the critical current of the parallel combination of junctions, as given by an equation analogous to an interference equation for a two-slit optical interferometer:

$$I_{crit} = I_0 \frac{\sin\left(\frac{\pi\varphi_J}{\varphi_0}\right)}{\pi\frac{\varphi_J}{\varphi_0}} \cos\left(\frac{\pi\varphi_A}{\varphi_0}\right)$$

where φ_A is the magnetic flux linking the circuit that connects the two junctions, and the critical current variation with magnetic flux is given on Fig. 8(b). Additional parallel junctions give a field response analogous to a multiple-slit interferometer.

Since the area of the circuit connecting the Josephson junctions may be orders of magnitude larger than the area of the junctions, the internal flux may modulate the critical current very rapidly compared with the diffraction effect of the individual junctions.

I would like to discuss now a bit about the nature of the current-voltage curve of a single Josephson junction, as schematically shown on Fig. 9. When we exceed the critical current, a voltage is developed. The nature of the current vs voltage curve, after this point, depends on the type of measurement that you are making. If you are using a constant-current source, where as soon as you exceed the critical current you fix the current at that value, then a typical Josephson junction will switch very quickly from the zero-voltage regime over to the quasi-particle tunneling regime in times, as Sid Shapiro mentioned, of less than 10^{-8} sec. So you end up with a rather large voltage across the junction. That is not a particularly suitable response for a magnetometer because, for measuring magnetic fields, what you want to measure is a change in the critical current with magnetic field. You will end up measuring very small changes of a very large voltage if you switch the junction back and forth between the critical region because the field-induced voltage change will occur on top of the large bias voltage. If you operate a typical Josephson junction with a voltage source, you get a response, also shown on Fig. 9, where the current very quickly goes to zero as you increase the voltage. Then the voltage follows the quasi-particle tunneling where this is a nonpair tunneling through the insulating barrier. For a magnetometer what we would like to have is a response that looks more like the ideal response shown on Fig. 9. You reach the critical current and then the voltage increases very smoothly and linearly as you increase the current. If this were the case then you could fix a bias current just above the critical current and read the voltage, then change the magnetic field slightly. That decreases the critical current, and since you still have the same bias current, the voltage increases to a new value. The voltage is zero or very near zero at the maximum critical current, and then it increases up to a maximum value where the critical current is zero. That means the load line is shifted all the way down to the origin, and it's just this response, the voltage vs magnetic field, that is the actual magnetometer response.

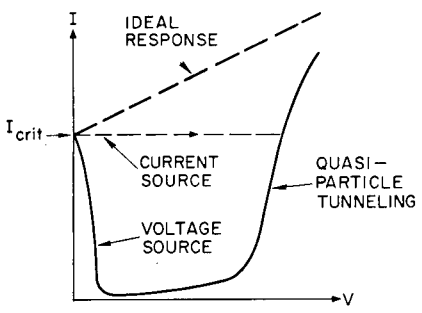

Fig. 9 - Current-voltage curve of thin-film Josephson junction

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What we would like to do then is to understand how to make Josephson junctions that exhibit near-ideal response. I have shown several of the standard Josephson junctions in Fig. 10. Figure 10(a) shows a junction similar to the one Sid Shapiro showed, i.e., an evaporated superconducting film — an oxide layer between, and another film crossing it. Then there are the point contacts (Fig. 10(b)) which can be a superconducting wire etched to a sharp point and pushed against a superconducting surface, or a Clarke SLUG type. In Fig. 10(c) we show a Dayem bridge circuit: the thin-film bridge where you weaken the superconductivity by reducing the area. In this case, as in the point contacts, there is an actual superconducting metallic link between the two bulk superconductors. If the critical current of this link is exceeded, then flux flow or changes in the phase of the order parameter across the junction can occur and a voltage will be developed.

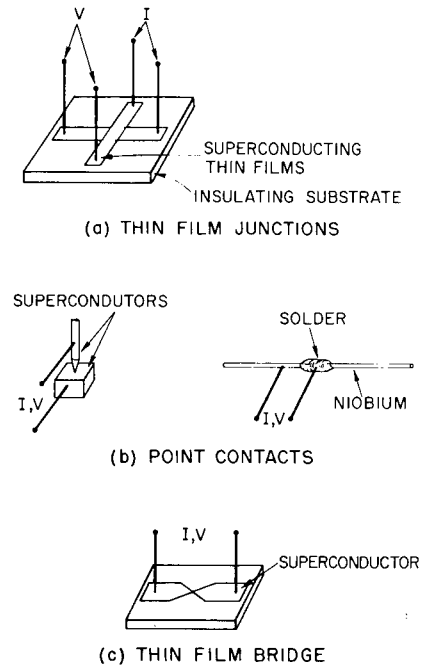

Fig. 10 - Different types of superconducting junctions

There are two recent papers (by D. McCumber and W. Stewart*) that describe the detailed nature of this I-V curve of Josephson-type junctions, and these are important in the sense of instrument development, in that you can get a feel for what you have to do to produce junctions that have the characteristics you want for a particular instrument. They analyze the ac impedance of a Josephson junction and show how this can affect the I-V curve. By ac impedance, I mean that as soon as you exceed the critical current you have a finite voltage across the junction and the supercurrents oscillate at the Josephson frequency $h\nu = 2eV$. These currents then see an impedance associated with detailed properties of the junction and these properties affect what happens when you exceed the critical current. There are other things that can affect this, but it appears that at least you can explain the nature of the I-V curve by considering these ac impedance effects and probably that's the predominant effect. Stewart and McCumber have shown that, if you consider the junction I-V curve, schematically shown on Fig. 11, when you exceed the critical current for a junction with a large capacitance (of the order of 10^{-8} farads) between the two superconductors, such as you would get with a thin evaporated film junction, then you get the hysteretic behavior when you reach the critical current.

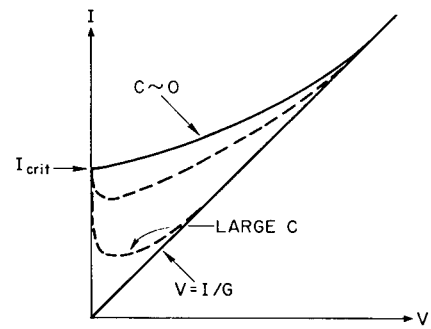

Fig. 11 - Current-voltage curves for a junction driven by a constant current source

As you decrease the capacitance until the capacitance approaches zero you find that the voltage increases smoothly, not linearly, but at least smoothly once you exceed the critical current. Driving the junction with a current source now, we reach the critical current, then slightly increase the current and the voltage increases very smoothly on

*W. C. Stewart, Appl. Phys. Letters, 12:277 (1968); D. E. McCumber, J. Appl. Phys., 39:3113 (1968).

up until you finally reach the resistive behavior of the junction when you have broken all the superconducting pairs of electrons.

The $C = 0$ case is very ideal behavior for a magnetometer. The response is easy to analyze and can be used to make very sensitive magnetometer devices. The significant property here is that the junction capacitance should be very low. If you want a device that will switch quickly from superconducting to normal, which you would want if you were building computer elements, then you would want rather high capacitance and this would indicate that you should use thin films. For magnetometers we would like to have the capacitance very low. That is exactly what you obtain if you use point contacts. You have one very thin point against a surface: there is very little area and you have low capacitance. The $C \simeq 0$ type of I-V curve shown on Fig. 11 is normally obtained with point contact devices. This indicates that you would want to use point contacts or Clarke SLUGs or devices of that type for magnetometers and thin-film junctions for computer elements.

There is one problem with magnetometers of the interferometer type and this is that the flux linking the area between junctions is not equal to the applied flux. What we really do in an experiment is to apply an external magnetic flux to the junction φ_x. What we would like to do is to know how this applied flux is related to the actual flux linking the area between junctions. We could then plot out the true response of the magnetometer to an external field. If you go through the equations of the quantized angular momentum and the induced current produced by the applied flux, then you can see if you have a closed superconducting loop and apply a magnetic field, there won't be any change in the flux inside. You will induce currents to exactly cancel the applied magnetic flux. Since you have point contacts or other "weak" sections in the ring though, you can get a flux change φ_A that is going to be equal to the applied flux minus the induced flux.

Going through the math, which I won't take the time to do now, you can get the following equation for the external flux in terms of the internal flux:

$$\varphi_x = \varphi_A - LI_{\mathrm{crit}} \sin \frac{2e}{\hbar} (\varphi_A - k\varphi_0) .$$

This is a transcendental equation that can be solved for particular values of these circuit parameters: zero-field critical current I_{crit}, and the circuit inductance L, and for particular choices of the magnetic flux. You find that for certain values of these parameters, the internal flux varies smoothly with the external flux, such as shown in Fig. 12(a). By that I mean you can pick any value of external flux and you've got a unique value of the internal flux. But, for other choices of these parameters you can find regions where the internal flux increases smoothly with external flux up to some point, such as point a on Fig. 12(b); then the equation predicts that the external flux has to decrease, but it can't do that since you are applying a smoothly increasing external flux. If you keep increasing the external flux then the internal flux jumps up to point b, etc. What that does in the magnetometer circuit is to decrease the modulation depth. Instead of the critical current modulating all the way to zero as the cosine term would predict, it will modulate down to an intermediate point.

Now what you would like to know in the terms of magnetometer design is then what determines how deep the modulation depth is, because that affects the magnetic field resolution. You can determine the critical circuit parameters by differentiating the equation for external versus internal flux and find out where the slope φ_x/φ_A is infinite. This gives the maximum value of the circuit parameters where the internal flux is a smooth function of the external flux; i.e., $I_{\mathrm{crit}} = \varphi_0/(2\pi L)$ as shown on Fig. 12(c). This is very simple, and in design it means that you want to limit the inductance or the critical current such that this relation holds to get full modulation. This gives inductances

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on the order of 10^{-8} henries as typical values for double-point contact circuits with $I_{crit} \approx 10\ \mu a$.

Another very useful instrument for measuring magnetic fields is the gradiometer. This uses the zero resistance property of superconductivity in a unique way to produce an instrument that automatically cancels uniform field changes. That, I think, is the principal advantage of a superconducting gradiometer. If you wind two coils in parallel planes but in opposite directions, then connect the two with superconducting leads, a uniform field change will induce opposing currents in the two coils which cancel, resulting in zero circulating current in the connecting leads. Thus, uniform field changes are automatically canceled before you get to any detection system. If you apply a field gradient, on the other hand, you will end up with a net circulating current. This current can be measured by putting a SLUG on one of the connecting leads, as shown in Fig. 13, and by measuring the response due to the current through the SLUG. Also you can wind a coil in one of the leads and put that inside a SQUID or Mercereau-type magnetometer and measure the field change produced at the magnetometer. It's fairly straightforward to get on the order of 10^{-9}-gauss resolution at the coils, and then the gradient sensitivity is just a function of how far apart the coils are placed. You have another advantage of the low-temperature environment in that the gradiometer is dimensionally stable. You don't get motion of the coils relative to each other, and the gradient you measure is then the true gradient between the two coils.

Figure 14 shows a magnetometer fixture that we have developed. It is just a typical cryostat insert: a helium dewar and nitrogen dewar. There is a pickup coil with very low inductance leads that go up to a Clarke SLUG that is mounted in a separate superconducting shield. Magnets fit around the pickup coil, and what we are doing with this particular circuit is measuring the decay of persistent current in different solenoids.

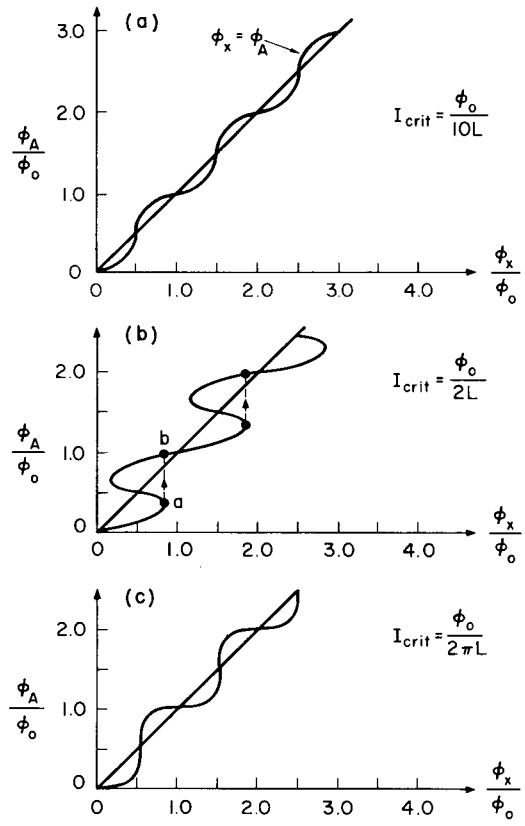

Fig. 12 - Internal versus external magnetic flux for a superconducting interferometer

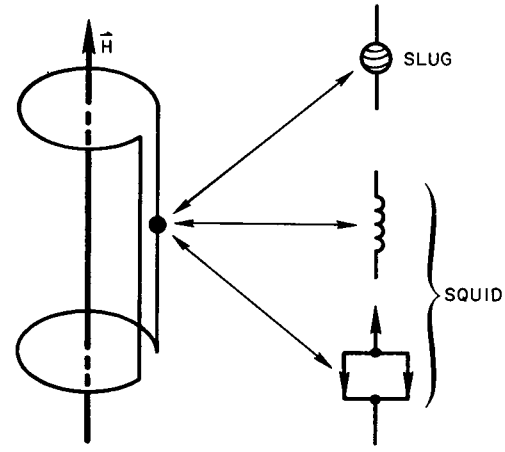

Fig. 13 - Magnetic gradiometer circuit

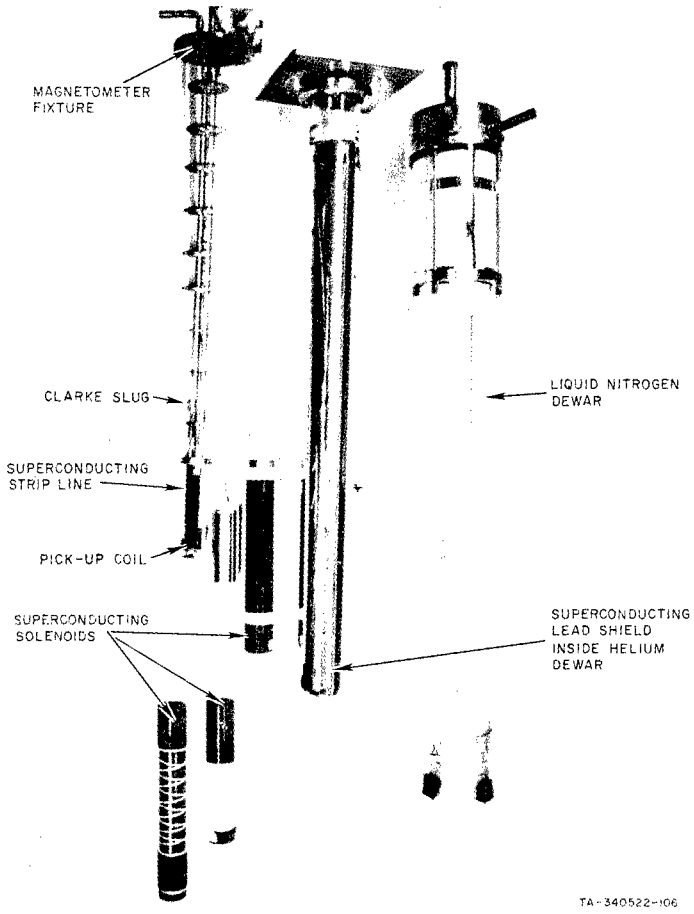

Fig. 14 - Magnetometer assembly

We can detect a field change at the center of the solenoid of about 10^{-7} to 10^{-8} gauss in applied fields as high as 5 kilogauss. We can measure drifts very easily of a part in 10^{10} per sec, and by measuring for longer times we can get a part in 10^{12} or 10^{13}. We have seen decays on the order of one part in 10^{10}/sec in all three of the solenoids tested; one pure niobium, one niobium-titanium, and the third niobium-zirconium.

Table 1 presents a summary of all the different types of magnetometers that we have discussed: the Meissner effect with field resolution on the order of 10^{-6} gauss; quantized flux on the order of 10^{-7} gauss; the flux flow (this is the Mercereau-type split cylinder) of the order of 10^{-10} gauss; and the SQUID or the double-point contact, like 7×10^{-11} gauss. The Clarke SLUG is like 10^{-8}. All of these numbers could be changed using a field amplifier coil, of course. For example, if you want to put a 1-mile-diam loop onto a Clarke SLUG, you could make that several orders of magnitude more sensitive. I have compared these with other room-temperature magnetometers such as the cesium vapor, proton precession, helium, flux gate, and the new rubidium vapor magnetometer. These are on the order of 10^{-6} or 10^{-7} gauss, except for the rubidium vapor magnetometer

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reported at a conference in Paris just a few weeks ago (which was also reported in Phys. Rev. Letters*) where they used it to measure magnetic properties of optically pumped helium. It has a field resolution of about 10^{-9} gauss and they think that the noise level may be closer to 10^{-10} gauss. This is a room-temperature optically pumped rubidium vapor device.

Table 1
Summary of Magnetometer Performance

Magnetometer	Resolution (gauss)	Time Constant (sec)	Vector (V) or Scalar (S)	~ Size (cm)
Meissner	10^{-6}	1	V	length ~1 OD ~0.2
Quantized flux	10^{-7}	1	V	length ~1 OD ~0.01
Flux flow	10^{-10}	1	V	length ~1 OD ~0.1
Double point contact	7×10^{-11}	1	V	loop diam ~1
Clarke SLUG	10^{-8}	1	V	loop diam ~2
Cesium vapor	10^{-7}	1	S	2 cm^3
Proton precession	10^{-6}	1	S	length ~15 OD ~15
Helium	10^{-6}	1	V	length ~15 OD ~15
Flux gate	2×10^{-6}	1	V	3 cm^3
Rubidium vapor	10^{-9}	3	V	diam ~6

I was going to talk a little about noise — the only thing to say about that is that no one has really seen intrinsic noise in superconductivity except for flux motion or flux flow noise. There is no clear indication that any of the devices discussed in this talk are sensitivity-limited by an intrinsic noise process. It seems that the limit so far is external noise.

*C. Cohen-Tannoudji, J. DuPont-Roc, S. Haroche, and F. Laloë, Phys. Rev. Letters 22(No. 15):758 (1969).

SUPERCONDUCTING MAGNETS

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If we take a broad interpretation of the word "magnet" as denoting something which produces a magnetic field (whether steady state or transient) and include devices which have magnets as a component then the title "superconducting magnets" denotes most of the superconducting devices proposed to date with the possible exception of electronic devices.

As such, superconducting magnets include not only such direct current devices as small (a few centimeters diameter) laboratory magnets and large (several meters) magnets for bubble chambers, but also all other applications where superconducting windings generate a magnetic field.

For instance, the use of a magnetic field generated by superconductors for shielding astronauts in outer space against solar flare protons is as much a superconducting magnet as anything else.

In applications such as rotating electrical machinery, superconducting field windings make use of general superconducting magnet technology.

In energy storage applications, superconducting windings are used to store magnetic energy. In this case, the charge time and discharge time determines whether the application is ac or dc.

The term "magnet" is an integral part of most electrical devices that store or convert energy.

Most devices that utilize superconductivity have, in one form or another, a magnet, and the problems are quite similar when you get down to engineering them. I will not talk today about the cryogenic problems, which are of prime importance in many applications, but I shall restrict myself to the coils themselves.

Figure 1 shows the state of the art of superconducting magnets as of August 1968. I thought of bringing it up to date. However, I decided to leave it as is because it brings out several important points. The data are for round coils only and so exclude magnets which provide a field perpendicular to the bore. The figure shows the diameter of the bore versus the magnetic field that has been achieved. The open circles, as of a year ago, were design points only, and the closed circles are fields that had already been achieved.

The high-field end is characterized by a 6-in.-diam magnet made with niobium tin ribbon that has generated 140 kilogauss (point No. 8 on the figure). The maximum field achieved to date using superconductors is now 150 kilogauss in a 1- to 2-in.-diam bore, so the state of the art, as far as intensity of magnetic field is concerned, is now 10 kilogauss higher than a year ago. I know of no effort that will conclude within approximately

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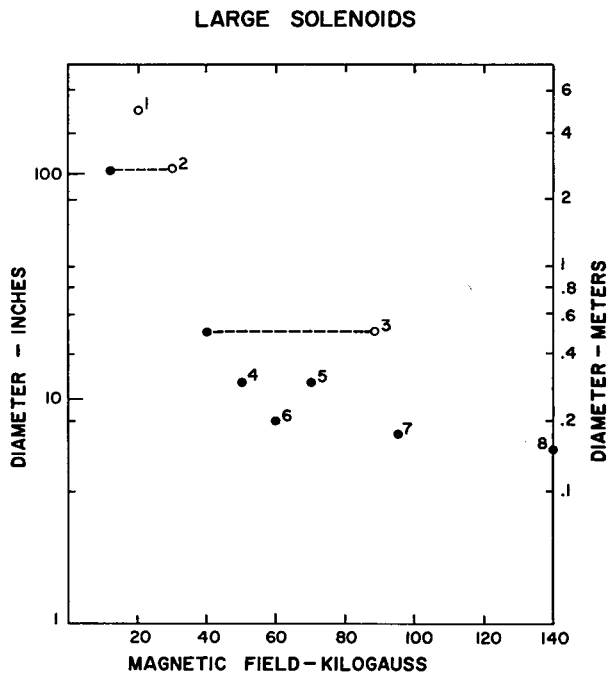

Figure 1

the next year that will significantly increase this magnetic field. The current approach to increasing the field generated with superconductors is to use superconductors in hybrid magnet systems in which the superconductors are used to generate fields of the order of 100 kilogauss or so in a bore large enough to insert a room temperature or cryogenic normal magnet, which then generates the high field.

At the low end of the magnetic field scale, point No. 1 on the figure refers to the 12-ft-diam, 18-kilogauss bubble chamber magnet at the Argonne National Laboratory. A year ago, the magnet system was still under construction. Since then the magnet has been tested to its full design value — 18 kilogauss. The magnet itself has approximately 80 megajoules of magnetic energy stored in it, and while some cryogenic problems were encountered, these were overcome and the system is operational.

The coil represented by point No. 2 is a similar 7-ft-diam coil system, also for bubble chamber use, built at the Brookhaven National Laboratory. This coil system has been tested to over half of its design field of 24 kilogauss. Testing to its full field awaits completion of associated equipment. However, results obtained to date are very promising and do not indicate any obstacles to achieving full design field in the near future.

The coil system represented by point No. 3 has a 20-in. bore and is intended for thermonuclear fusion research at the NASA Lewis Research Center. As of a year ago, a field of approximately 40 kilogauss was achieved in partially assembled sections of the system. In January 1969 the fully assembled system achieved the design value of 88 kilogauss.

The main reason for not updating the state-of-the-art curve is to be able to point out that, in these three instances, the projected performance was fully achieved in two instances and will be achieved in the near future (according to all indications) in the third instance.

Future plans in high-energy physics call for even larger diameter magnets. A proposal for a 25-ft-diam bubble chamber requiring a 40-kilogauss magnet is undergoing serious evaluation. Such a magnet would significantly alter the state-of-the-art curve in Fig. 1.

It is interesting to relate the state-of-the-art curve with cost. Each of the points 1, 2, 3, and 8 are within a factor of two of $1,000,000, so that one cannot help but speculate whether the state of the art from now on is likely to be limited more by the availability of funds than anything else.

The next series of figures show some of the different coils typical of those built in the recent past. They are not intended as an exhaustive review, but rather as a sampling of the different coil geometries and applications. The examples have been picked more for variety than anything else.

Figure 2 is a coil several years old which was built at the Lawrence Radiation Laboratory, Livermore — its shape earns it the name of a "baseball" coil. This particular geometry provides a magnetic well for particle containment in fusion research. The particular coil shown was wound with cabled superconductors and has a bore approximately 1 ft in diameter. Although it is only a model, it has been successfully used for experiments in thermonuclear fusion, and Fig. 3 shows the coil in place in the plasma physics apparatus. A larger, higher field version is currently under construction. This larger coil will have approximately a 1 m internal diameter and will generate fields of the order of 75 kilogauss at the windings. There are several other superconducting coil efforts in the fusion field. Among these are two systems, one at Princeton University

Figure 2

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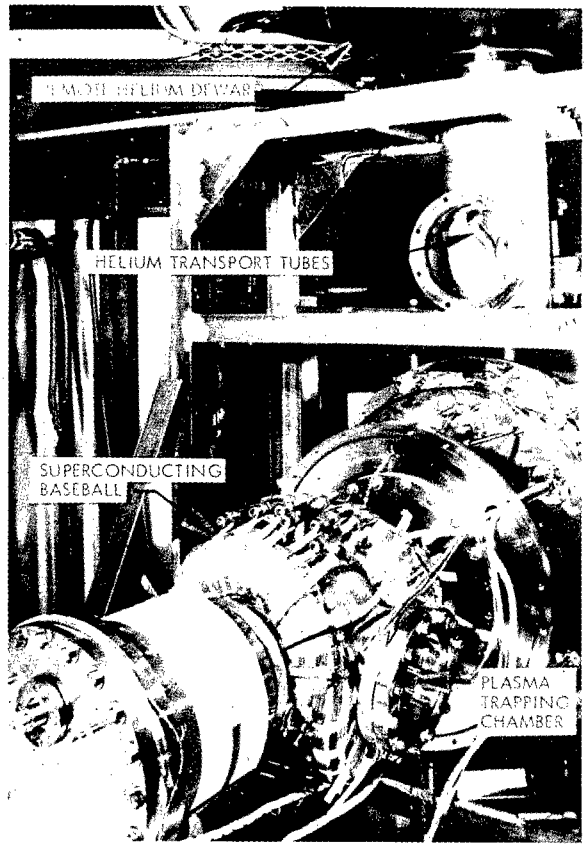

Figure 3

and the other one at Lawrence Radiation Laboratory at Livermore, that plan to use superconducting coils that are levitated by means of magnetic fields. These are not impressive in terms of either field strength or size (they are both approximately 1 m in diameter). However, the superconducting coils are to be operated isolated from any connections to room temperature and completely levitated by external magnetic fields.

Figure 4 shows the machining of the spool for yet another type of superconducting magnet. The grooves being machined in the metal cylinder are for the superconducting windings. This coil was built at the Lawrence Radiation Laboratory at Livermore approximately two years ago. It is part of a balloon-borne high-energy-physics experiment. It produces 10 kilogauss in a direction perpendicular to the 1-m-diam bore. There is an amusing story that goes along with this magnet. Like every large effort, this program ran into minor scheduling problems and the complete instrumentation package was ready several months before the superconducting coil. To prevent delays, the first test flight of the balloon system was made without the superconducting coil. Unfortunately, during the recovery operation, the package dropped into the ocean. The only part of the apparatus that survived was the superconducting coil, which was not yet ready.

A detail of the coil winding is shown in Fig. 5. The conductor is a cable consisting of copper-coated niobium-titanium and plain copper conductors. The cable was wrapped with Mylar tape and wound into the machined grooves. The insulators on the side of the grooves have passages in them to allow helium to flow around the conductors during operation.

Figure 4

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Figure 5

Superconducting magnets require a stabilizing substrate as part of the overall conductor. Copper has been used as this stabilizing substrate. The larger the magnet, the more cooling has to be provided. This requirement strongly influences the detail design of the winding package. In designing a superconducting coil, the placement of the conductors is influenced by the required magnetic field. In addition, the characteristics of a magnet as a structure must be considered in detail (especially so for the large high-field magnets). From the superconductor stability point of view, the coil package is a heat exchanger. Last, but not least, the turns must also be electrically insulated from each other. The combination of these requirements, which are basically incompatible, determine the particular coil configuration. The general trend is, the larger the magnet, and the larger the energy it stores, the more conservative the design. The large magnets are better cooled, generally have more copper stabilizer, and operate at lower current densities than their smaller laboratory counterparts.

Figure 6 shows a superconducting magnet for magnetohydrodynamic power research. The picture shows the end view of the coil system which has conductors running axially along the bore which is 12 in. in diameter. The conductors cross over at the ends and return axially on the opposite side. The windings are placed in between aluminum shells, the ends of which are visible in the figure. (The windings themselves are not visible.) The picture illustrates the importance of structural integrity in magnets of this type. The outer rings make the coil assembly look very much like a solenoid; however, their purpose is to provide structural integrity. For a coil of this type in which the windings run parallel to the bore, the structural requirements are quite severe when compared with circular windings in which the conductor can be used effectively as part of the structure. The magnet had 6000 pounds of stabilized conductor and approximately 10,000 pounds of aluminum structure. The total superconductor weight was less than 200 pounds.

Figure 7 shows a schematic diagram of the 12-ft hydrogen bubble chamber at the Argonne National Laboratory. There are two sets of coils which are separated to provide

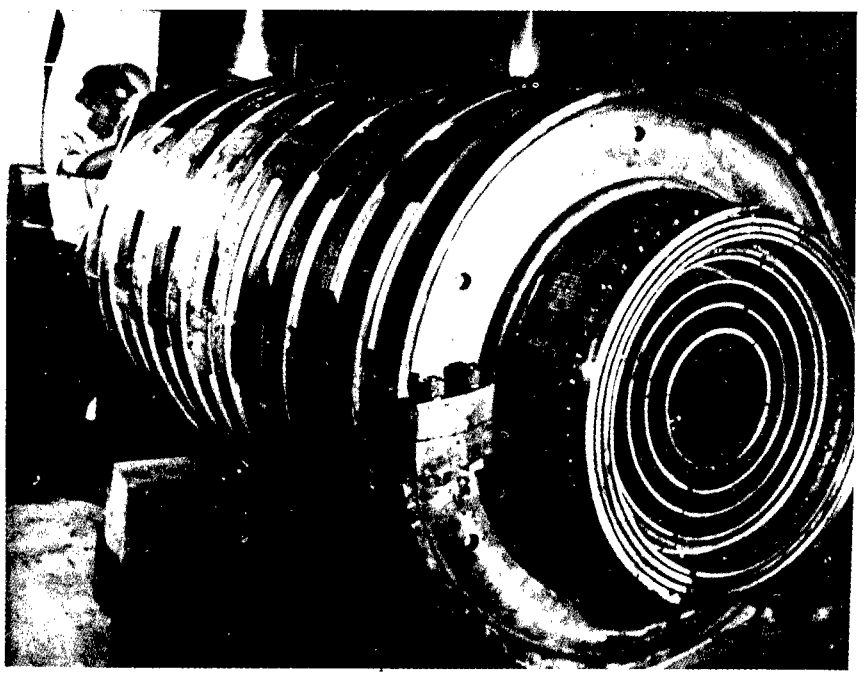

Figure 6

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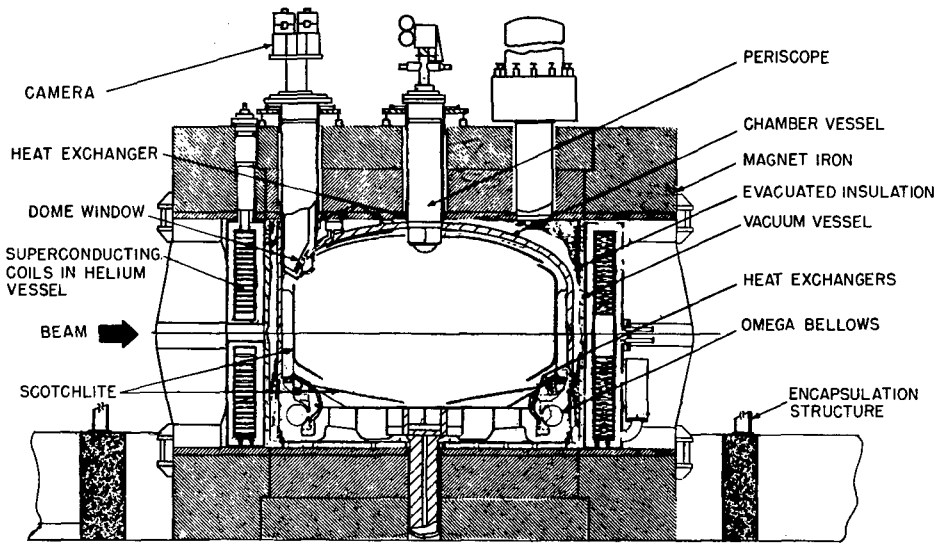

12-FT HYDROGEN BUBBLE CHAMBER

Figure 7

entrance to the beam. The bubble chamber itself is centrally located. The coils are placed between iron pole pieces at the top and bottom. A segmented return path is also used. The iron provides approximately half of the field, so the windings by themselves contribute approximately 9 or 10 kilogauss. This use of iron is typical of high-energy-physics applications (at least the ones that are now being considered). The iron not only shields other experiments or instruments from the magnetic field but also reduces the amount of superconductor required. As superconductors become less expensive, the decrease in amount of superconductor used will be less important than the shielding properties in an iron magnet design.

Figure 8 shows some of the construction details of the magnet. It is made up of many pancake coils 2 in. wide which are stacked up. The whole system consists of two identical coil assemblies, one above the other. Figure 8 shows one of these assemblies. After being fully assembled, both are welded into a helium temperature container, which is suspended from the top part of the bubble chamber.

A detail of the winding is shown in Fig. 9. The pancakes are separated to provide access of helium between the pancakes for cooling. The current density in this coil is quite low compared to what one normally associates with superconductors. The conductor current density is less than 2000 amps per square centimeter. (This includes the cooling passages, etc.)

From a stability point of view, there is enough copper surrounding the superconductor and enough surface area in contact with the liquid helium in this magnet that, should all the superconductor become normal, the temperature of the conductor (with all the current in the copper) is below the temperature at which the superconductor becomes normally conductive (with no current flowing through it). This being the case, the superconductor cannot be normally conducting. Consequently, the only stable operating condition is with all the current in the superconductor (provided that there is helium present).

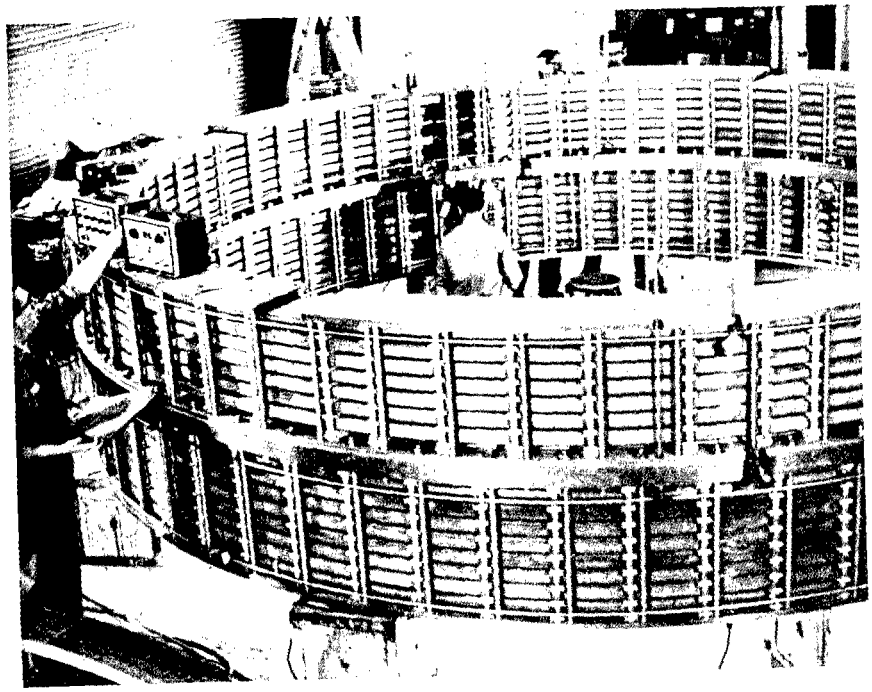

Figure 8

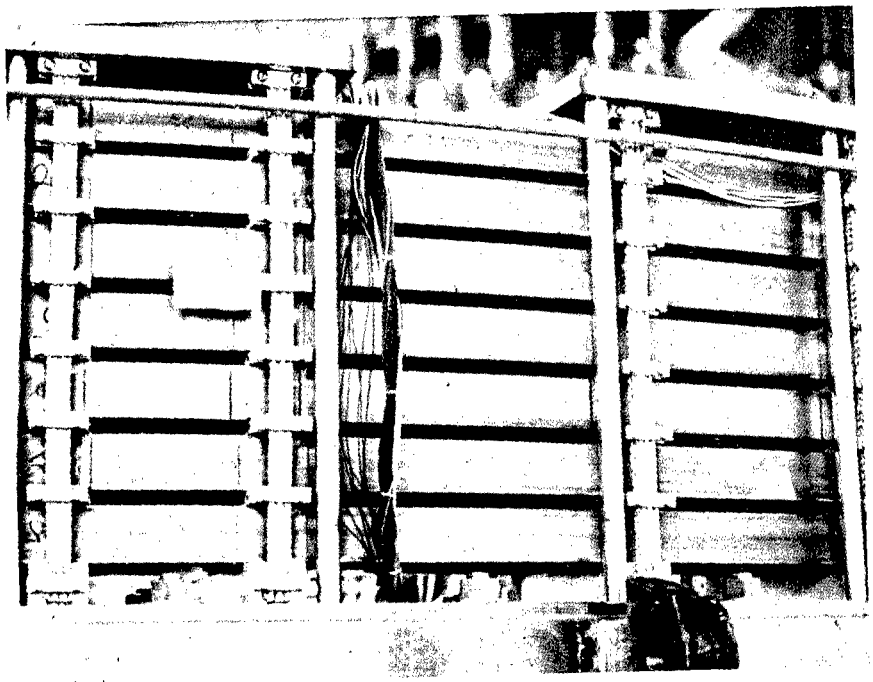

Figure 9

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Another reason for the low current density in this magnet is that at this current density the conductor is self-supporting at the design field and requires no additional structural material.

The design of the Argonne magnet is such that the top pancake can operate completely out of helium without propagating a normal region to the adjacent pancakes. This is achieved by using spacers between the pancakes of high thermal conductivity. These are interconnected with metal straps, to provide heat conduction paths to the lower part of the coil assembly which would usually be immersed in helium. This is, at present, the largest superconducting coil in existence both in terms of size as well as magnetic energy stored (12 ft diameter and 80 megajoules of magnetic energy). The design is conservative when compared with smaller magnets or with what can potentially be achieved in the future as regards to large magnets.

Let us now examine some of the details of the superconductor behavior as well as specific conductor configurations. Figure 10 shows the overall current density of several conductors. The curves labelled R60291, SR2101, SR2100, 22CY030, and 22CY015 are Nb_3Sn conductors. Curves labelled T48B.018", SG100D, and SG286S are composed of Nb-Ti in a copper substrate or matrix. SG700 is NbZr with a large copper substrate. (The figure is not all inclusive as far as the current availability of conductors.)

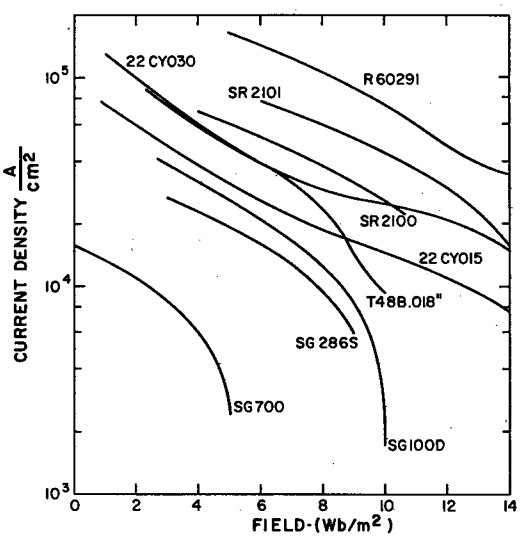

Figure 10

At the upper limit of current density in short samples of conductors, the current density is in excess of several times 10^5 amps per square centimeter. (These are short-sample tests.) This value is higher by about two orders of magnitude than the conductor used for the Argonne bubble chamber magnet. For that magnet, there is a potential decrease in conductor weight of two orders of magnitude.

Most magnets being built today have overall current densities that range between 5000 and 10,000 amps per square centimeter on an overall basis, and between 1×10^4 and 2×10^4 amps per square centimeter in the conductor itself.

The thermal conductivity of a typical superconductor (Nb-Ti) is of the order of 10^{-3} watt per centimeter-°K. This is the same order of magnitude as the thermal conductivity of nylon at helium temperatures. On the other hand, the current density in the superconductor itself exceeds 10^5 amps per square centimeter. In the normal state or in the flux flow regime, the resistivity of the superconductor is of the order of 10^{-5} ohm-cm. The combination of these properties is a material that carries a current density that is extremely high, coupled with a low thermal conductivity and a resistance (when not in the superconducting state) of the order of stainless steel. Transient disturbances that require flux motion or generate local normal regions create a serious problem as far as heat generation is concerned, since there is no way of getting the heat out of the superconductor.

As a consequence of this, superconductors are used in small sizes; the niobium-titanium conductors which are being used today have strands within the conductor that vary typically from 1 mil to 10 mils. This minimizes the problem of any heat generation within the conductor by reducing the thermal resistance of the superconductor itself. The addition of copper further alleviates this problem. In a conductor composed of the superconductor surrounded by copper, heat is generated in a time that depends on the rate of change of magnetic field, i.e., during the diffusion of current into the superconductor during a transient. The magnetic diffusivity in the superconductor is determined by some fraction of the normal state resistivity in the material in the flux flow state, so that magnetic diffusion times in the superconductor are comparable with magnetic diffusion times in steel at room temperature. However, copper at helium temperatures has a resistivity of the order of 10^{-8} ohm-centimeter (much lower than the flux flow resistivity of the superconductor). The copper around the superconductor, therefore, reduces the rate at which magnetic flux diffuses into the superconductor by two to three orders of magnitude, approximately. Since heat generation is then determined by the rate of diffusion of magnetic field through the copper, more time is available to conduct out any heat generated within the superconductor.

The cross section shown in Fig. 11 is of a typical Nb-Ti conductor with the small superconducting strands in a copper matrix. The particular conductor shown has an overall diameter of 100 mils.

Figure 12 illustrates the variety of shapes which are currently available. (All the conductors shown are Nb-Ti in a copper matrix.) The 0.250-in. square conductor is of the same geometry as that being used for the large baseball magnet.

Figure 13 shows a Nb-Ti conductor, 0.050 in. by 0.125 in., with 252 cores which illustrates some of the fabrication process. The conductor was fabricated in several steps. First, conductors with 28 cores were fabricated. These were then bundled together and reprocessed to end up with the 252-core conductor.

As I have pointed out, the stability and performance of a conductor gets better the smaller the strand, and the amount of copper needed decreases as the strand size decreases. The trend is, therefore, to smaller and smaller strand sizes. At the Brookhaven National Laboratory, for instance, a commercial 20-mil-diam wire with approximately 80 cores of superconductor was drawn down to a few mils so that the individual strands were only a fraction of a mil in size.

It has been found that in order to achieve the full benefits of small size of the superconducting strands, it is required that the conductor be twisted. This effectively "uncouples" the strands and allows them to act independent of each other.

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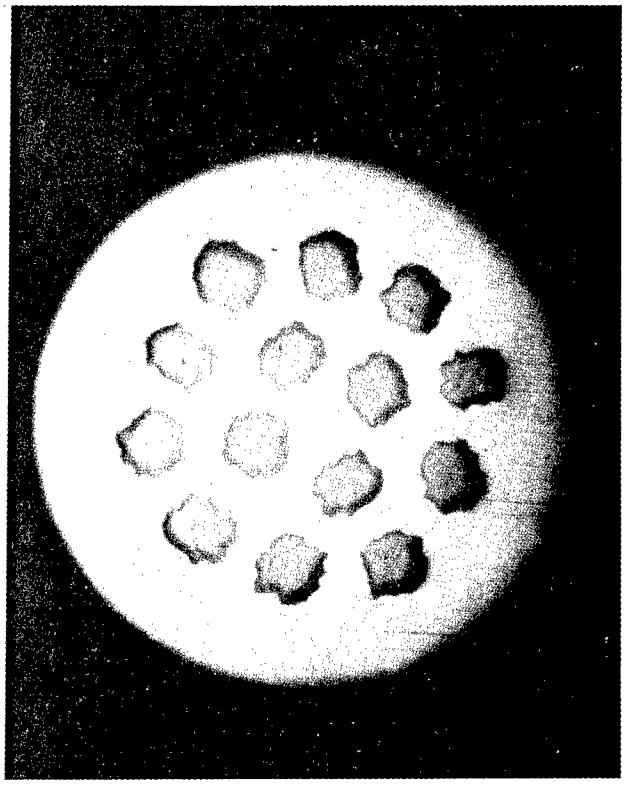

Figure 11

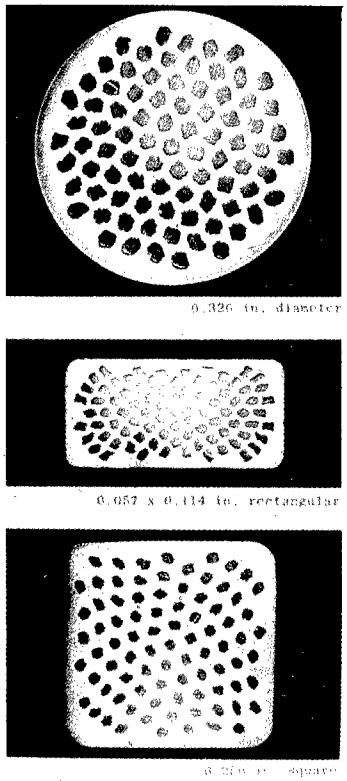

Figure 12

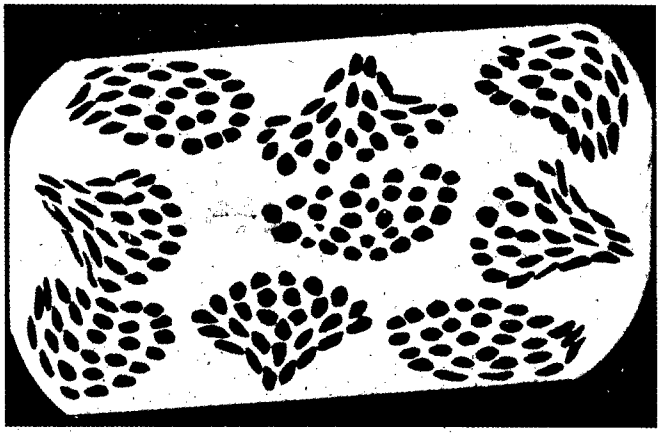

Figure 13

In contrast with the conductors in the last three figures, the one shown in Fig. 14 is the conductor used in the large bubble chamber magnet at Argonne. There are six flattened rather large Nb-Ti strands (only four of which are clearly visible in the picture). The degree of conservatism is evident from the large ratio of copper to superconductor.

Before concluding, I would like to discuss the terminal characteristics of a short conductor. The situation is best understood by referring to Fig. 15.

Figure 14

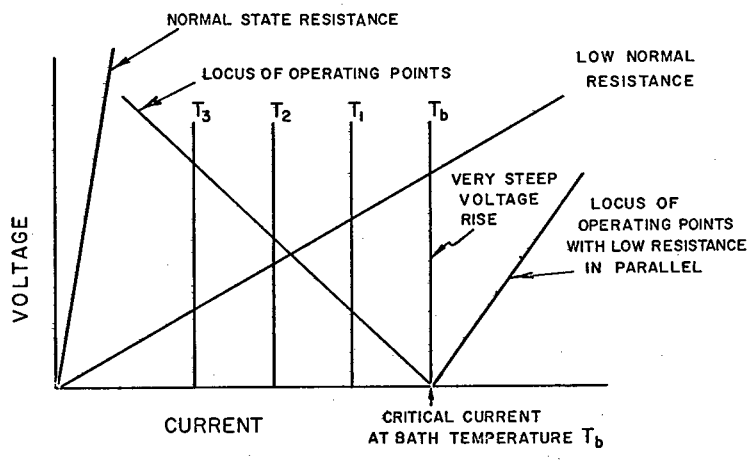

Figure 15

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To begin, let us consider a superconductor without any copper in any externally applied magnetic field. Up to the critical current, the voltage would be zero. However, at the critical current the voltage begins to rise with an attendant heat generation. At the high superconductor current densities, the voltage increases very steeply.

If the temperature were initially higher, then the critical current would be lower, as shown by the curves labelled T_1, T_2, and T_3.

If we start with a sample at temperature T_b, there is no steady voltage or heat generation until the critical current is reached. As voltage appears, heat will be generated, raising the temperature. The locus of equilibrium operating points forms a curve sloping upward to the left for increasing temperatures and heat generation. This curve continues until it intersects the curve of normal state resistance.

If the superconductor is at some fraction of the critical current with zero voltage across it, and is subjected to an external magnetic field disturbance, a heat pulse, or should a redistribution of currents occur within the superconductor, the only other stable operating point is on the fully normal curve. (Operation on the negative resistance curve generated by the locus of equilibrium points is unstable.)

This means that the superconductor has two operating points — fully superconducting or fully normal. Since in the fully superconducting state it may be subjected to various disturbances, it would be very desirable to eliminate the fully normal operating condition. This can indeed be done by adding a low resistance in parallel with the superconductor, as indicated in Fig. 15. If a low enough resistance is added in parallel, then the locus of operating points shifts to a curve sloping upward to the right. Under these conditions, only the superconducting state is stable below the critical current.

The explanation of the phenomena as I have described them above is, of course, very much simplified from what actually occurs.

For illustration, an actual terminal characteristic is shown in Fig. 16. This data was generated at Oak Ridge National Laboratory and shows the terminal characteristics of an 86-mil square conductor. It has 15 strands of niobium-titanium, approximately 10 mils in diameter, in a copper matrix. The voltage vs current is shown at several fields. The field dependency comes from variations of current density in the superconductor, as well as the magnetoresistance of the copper matrix. At low fields (where the current is high) the slope just above the critical current is almost vertical (but still slopes upward to the right). At higher fields, the critical current drops and the voltage rises less steeply above the critical current. The break point, which is labelled "take off," occurs when the limit of nucleate boiling heat transfer to the helium is reached. At this point, a transition into a fully normal state occurs. On lowering the current, the voltage decreases to the recovery point where a joint transition for the normal state to the superconducting state occurs concurrently with the transition from film to nucleate boiling.

The curve shown is a steady-state one. For steady-state stability, we require heat transfer to helium, as well as a fairly large amount of copper. Current research is aimed at means of stabilizing the conductor against the transient disturbances only. This means that even though negative resistance region may exist in the steady-state terminal characteristics, the conductor itself will be stable enough for short periods of time so that a transition from the superconducting state into the fully normal state will not occur for finite disturbances. This requires that the magnetic flux diffuse into the conductor without triggering a permanent transition to the normal state during the transient. If this kind of stability is achieved, one can potentially increase the current density by the removal of the fairly large amounts of copper currently being used in conductors.

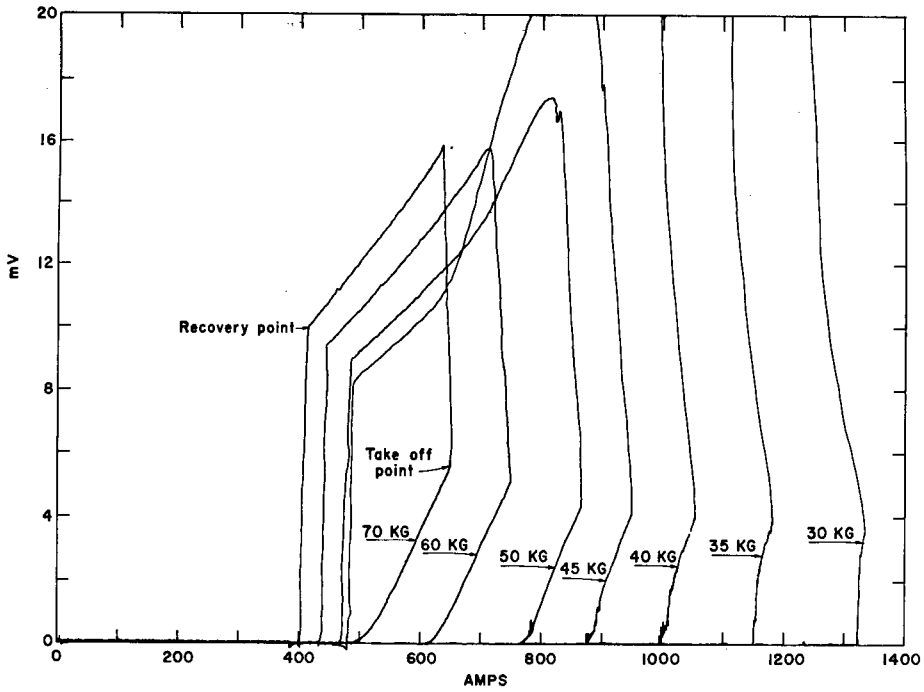

Figure 16

To conclude, the state of the art in magnet construction and in the understanding of conductor behavior has progressed very rapidly during the past decade. All of the fundamental mechanisms of conductor and magnet behavior have been identified. However, there still remains much to be done in terms of increasing the current density without decreasing the reliability of superconducting magnets.

Security Classification

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

PROCEEDINGS OF THE FOURTH SYMPOSIUM, 1969 SPRING SUPERCONDUCTING SYMPOSIA

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Proceedings of the fourth in a series of four symposia.

5. AUTHOR(S) *(First name, middle initial, last name)*

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6. REPORT DATE June 6, 1969	7a. TOTAL NO. OF PAGES 58	7b. NO. OF REFS 3
8a. CONTRACT OR GRANT NO. NRL Problem P05-02B b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7023 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Office of Naval Research), Washington, D.C. 20360

13. ABSTRACT

The Office of Naval Research and the Naval Research Laboratory recognized a number of advantages in cosponsoring and conducting a series of four one-day symposia on superconducting materials and devices. These meetings, held at the Naval Research Laboratory during the spring of 1969, has as their primary motives...

a. To bring together scientists, engineers, and science administrators from some 18 government, university, and industrial laboratories in the Washington-Baltimore area which are engaged in or sponsoring research programs involving superconductivity.

b. To provide an opportunity for these persons to meet each other, to hear formally prepared papers by their colleagues, and to engage in informal and frank discussions of their research programs.

c. To collect and disseminate comments and opinions of experts regarding the current status and the future of research on superconducting materials and devices.

The morning session of each symposium was devoted to four invited forty-minute papers. Each afternoon the four invited speakers formed a panel to discuss questions posed by the audience.

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

☆U.S. GOVERNMENT PRINTING OFFICE: 1970-397-174/67

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Superconductivity						
Transition temperature						
Electron phonon interactions						
Semiconductors (materials)						
Electron density (concentration)						
Metalloids						
Thin films						

Recordings, transcripts, and then lightly edited manuscripts of the papers were prepared for publication in the Proceedings, this being the fourth of four to appear. In order to provide an atmosphere of free uninhibited discussions in the afternoon, no recordings were made.

Topics for presentation, speakers, and general planning of this series of symposia were the responsibility of the Organizing Committee. The sixteen papers given represented authors from three government laboratories, eight universities, and four industrial laboratories. Although this series was initially established for the Washington-Baltimore community, early publicity and announcements generated sufficient distant interests so that a number of attendees appeared from outside this geographic area.