

The Basic Physics of Superconducting Devices

A magnetic-field-free region, a cw linear accelerator, direct current transformers, voltmeters with sensitivities greater than 10^{-15} volt (equivalent to Johnson noise across a 10^{-7} -ohm resistor at 1°K), comparison of voltage standards to one part per million, magnetometers as sensitive as 10^{-10} gauss, acceleration measurements of less than 10^{-9} g, an infrared detector with sensitivity greater than 10^{-13} watt per cycle and rise time less than 10^{-8} sec—all are possible because of the unique properties of superconductors. These and other new devices, techniques and applications were discussed last April at the Symposium on the Physics of Superconducting Devices held at the University of Virginia in Charlottesville and sponsored by the Office of Naval Research.

The purpose of the symposium was to exchange ideas on new applications of superconductivity, with emphasis on the basic physics and inherent limitations. (Computers and high-field magnets were specifically not included in order to limit the size of the meeting.)

There were approximately 170 participants in the two day meeting, where 22 papers were presented in four sessions chaired by Felix Bloch, John Bardeen, John Daunt and Richard Ferrell.

Theoretical framework. In a summary talk at the end of the meeting Michael Tinkham sketched a theoretical framework into which most applications could be fitted. The idea underlying most of the devices is the existence of a long-range order of coherence in superconductors. He described this idea with a macroscopic wave function of the Ginsburg-Landau type:

$$\psi = |\psi| \exp i\phi(r)$$

The current can be expressed, somewhat schematically, as the number of superconducting electrons multiplied by a velocity:

$$\mathbf{j} = |\psi|^2 \mathbf{v}_s$$

With the usual relation between momentum and velocity in the presence of a magnetic field

$$\mathbf{p} = m\mathbf{v} \times \mathbf{A}/c$$

the current becomes

$$\mathbf{j} = |\psi|^2 \left(\nabla\phi - \frac{e}{mc} \frac{\mathbf{A}}{\Phi_0} \right)$$

($\Phi_0 = hc/2e$ is the flux quantum.)

The assumption that the phase of the macroscopic wave function is constant everywhere yields the familiar result $\mathbf{j} \approx -\mathbf{A}$ which describes the Meissner effect and from which the two London equations can be obtained by taking derivatives with respect to time and space coordinates. This relation underlies what Tinkham termed strong superconductivity, as opposed to weak superconductivity which involves a local region where the phase varies spatially, such as for weak links, tunnel diodes, etc.

Specifically in the case of the Josephson junction, in which a thin insulating layer separates two superconductors, conduction occurs only by tunneling. In this case, a current will flow with no voltage drop across the insulator. The tunneling current depends on the difference in phase between the two superconductors and is given by $j = j_1 \sin \delta$ where $\delta = \phi_1 - \phi_2$ and j_1 is the critical current for the junction. For more complicated geometries or arrays of junctions,

the current may be some more complicated periodic function of the phase difference.

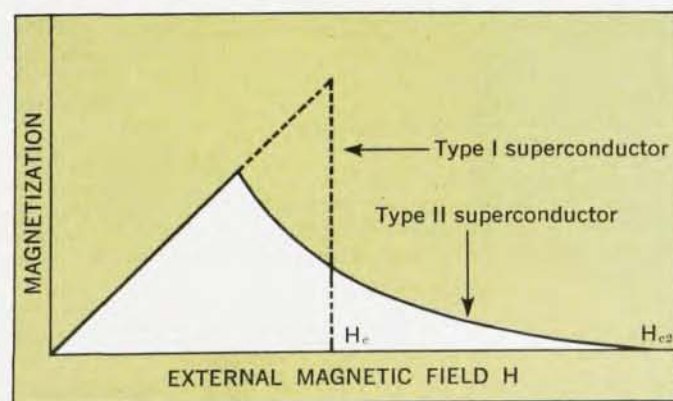
If the current exceeds the critical current for the junction, a finite voltage appears across the insulator. In this case, the phase difference is time dependent, giving rise to a periodic current oscillation in the junction at frequency ν given by $h\nu = 2eV$ where ν is in fact the frequency with which flux quanta cross the junction.

Most of the ideas discussed at the meeting can be described by these equations and classified as strong or weak superconductivity. For example, magnetic shields and high- Q circuits are examples of strong superconductivity, whereas detectors depending on various forms of tunneling fall in the second class.

In addition, the talks fell in two general categories: fundamental experiments for which the properties of superconductors are crucial to their success and techniques and devices made possible by the properties of superconductors.

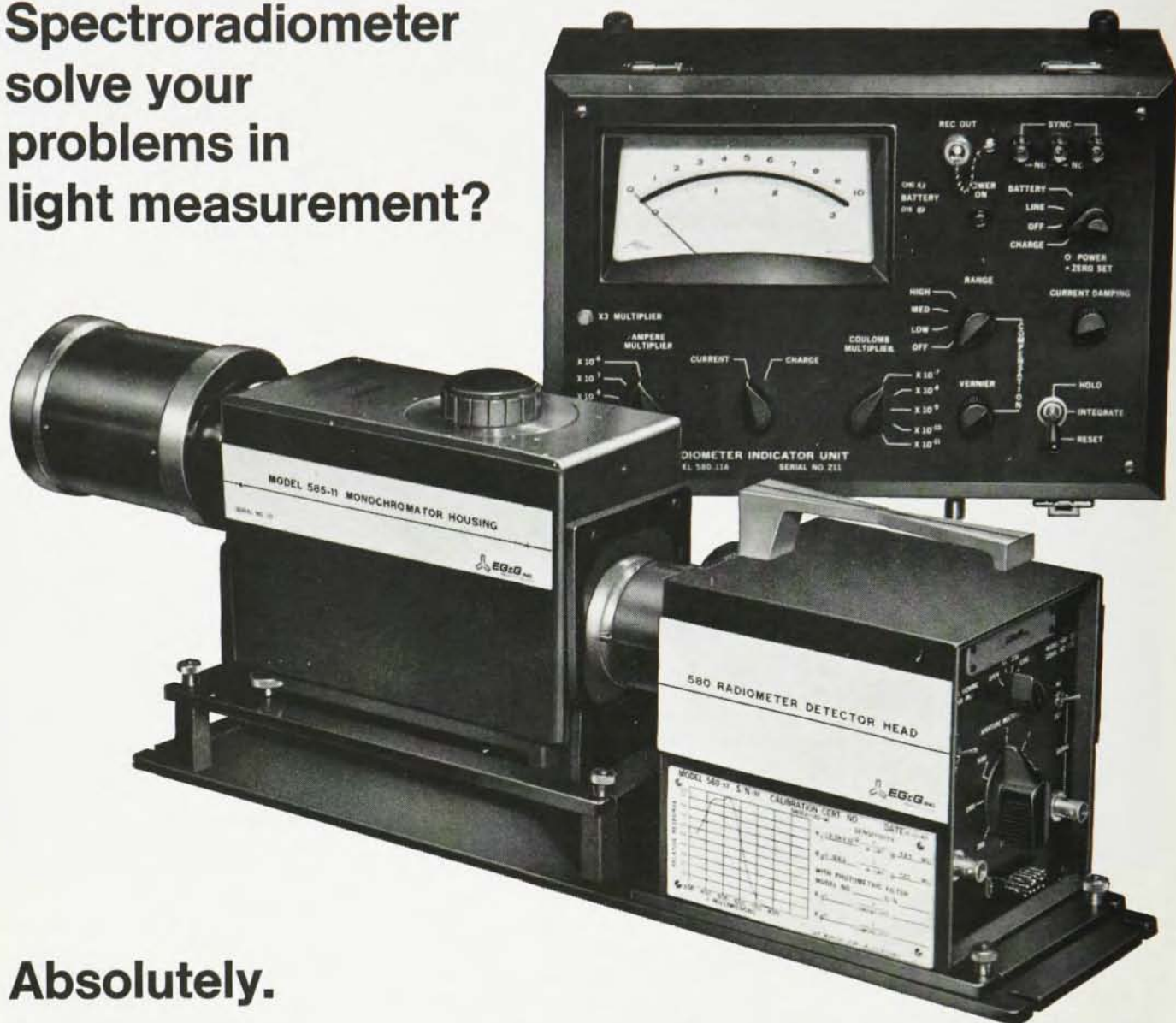
Fundamental experiments. William Fairbank (Stanford) described three fundamental experiments that depend on several properties of superconductors:

1. A test of general relativity with an electrostatically supported superconducting gyro in a satellite. The orientation of the spin axis of the gyro is sensed by



MAGNETIZATION curves for two types of superconductors.

Can the versatile EG&G Spectroradiometer solve your problems in light measurement?



Absolutely.

For scientists, the versatility of the EG&G 580/585 Spectroradiometer has made it the ideal system for many different applications. It can measure continuous and pulsed light sources as fast as 1 nsec, with a spectral range from 200 to 1200 mμ, over six decades of incident light energy and power. The 580/585 can perform absolute spectral measurements, with direct meter or recorder output, of:

- Average power of continuous light sources
- Average power of a train of light pulses
- Integrated energy of pulsed light sources as fast as 1 nsec
- Peak power and pulse shape (with an oscilloscope).

The complete system, with detector head, monochromator grating, and input optics, is calibrated against standards traceable to NBS. The detector head is also calibrated as a basic radiometer and can be used for absolute measurement of narrowband light

sources. The system operates on a 110v line for laboratory applications and on an internal, rechargeable battery for field use. A unique compensation system negates the effects of ambient light and allows most measurements to be made under normal laboratory conditions. In addition, a new wavelength transducer accessory is available to complement the new Y-axis recorder output of the indicator unit. This new accessory provides an X-axis recorder output allowing a complete X-Y plot of amplitude vs. wavelength to be plotted directly on a standard X-Y recorder.

A typical 580/585 Spectroradiometer system is priced at \$5830 with 2-4 week delivery. A detailed data sheet and application note are available. Write: EG&G, Inc., 161 Brookline Avenue, Boston, Massachusetts 02215. Telephone: 617-267-9700. TWX: 617-262-9317.



measuring the London moment with a superconducting magnetometer.

2. An experiment to search for a permanent electric dipole moment of the He^3 nucleus (such a moment would violate time reversal invariance). In this experiment a nuclear He^3 gyro is in a zero-magnetic-field region inside a superconducting shield. The magnetic field must be less than 10^{-12} gauss for the success of the experiment. This appears possible with a superconducting shield from which the last flux unit has been expelled.
3. An experiment to search for quarks with a superconducting circuit that senses the position of a charged superconducting sphere in a uniform electric field.

Linear accelerator. Fairbank also described a major new achievement in charged-particle acceleration, a linear accelerator that depends on the low ac losses made possible by superconducting microwave cavities and capable of unity duty cycle.

A 1.5-meter long section with cavities that have electroplated lead walls has achieved unloaded Q 's of 10^9 at 956 MHz. It has operated at accelerating voltages of 6 MeV/meter and at currents of $10 \mu\text{A}$. A full scale accelerator is being planned.

High- Q circuits. M. S. McAshan (Stanford) described experiments performed in conjunction with the linear-accelerator program in which he measured the surface resistance and reactance of electroplated tin and lead cavities at 2.8 and 11.2 GHz. He achieved residual Q 's of 5×10^9 with lead; experiments with solid and plated niobium cavities yielded slightly lower Q 's. Critical fields approached bulk dc values.

K. Siegel, R. Domchick, and F. Arams (Airborne Instr. Lab.) reported measuring Q 's of 4×10^6 for self-resonant coils of niobium stannide ribbon at 27 MHz, near 2°K .

Magnetic shielding. In a variety of experiments people have used superconducting shields to attenuate external magnetic fields.

A. F. Hildebrandt (U. of Houston) reported achieving fields less than 2×10^{-6} gauss over a spherical volume of 7.5-cm diameter in a cylindrical shield 30 cm long with a 7.5-cm hemispherical bottom and constructed of high purity lead sheet 0.25 mm thick. He found that thermal gradients during switching can produce trapped fields of 10^{-3} gauss even when cooling in much smaller ambient fields.

Because of quantized flux, it should be possible to cool a superconducting cylinder through its transition in a field producing less than half a flux unit through the cylinder and have the cylinder expel all flux within it, producing identically zero field inside. J. M. Pierce (Stanford) described experiments in which superconducting flexible bags were cooled while collapsed, then expanded to produce lower field regions inside. Multi-staged bags sequentially reduced the field. When a last collapsed bag is cooled in a field producing less than half a flux unit through it, it should produce a zero-field region when expanded.

Magnetic-field measurements. J. E. Mercereau (Ford Scientific Lab., Newport Beach) reported alternating flux flow induced through the wall of a hollow superconducting cylinder. With an inductively coupled coil he found the flux to flow in integral multiples of the flux unit and at a rate depending on the field through the cylinder. He has constructed a magnetometer using this effect and can detect flux changes as small as 10^{-3} quanta.

He also described a tunneling device, a double point-contact interfer-

ometer ("Squid") for measurement of thermal magnetic noise in normal and superconducting samples. The sensitivity of this device was about 10^{-3} flux units, corresponding to a field sensitivity of 10^{-9} gauss.

M. R. Beasley and W. W. Webb (Cornell) commented on using a double point-contact interferometer (Squid) to detect field changes of 10^{-7} gauss in the presence of 2000-gauss applied fields.

A unique form of multiple-junction interferometer was described by J. Clarke (Cambridge U.). A solder blob placed on an oxidized niobium wire formed a tunnel junction (this device is referred to as a "slug"). He has operated the device as an extremely low impedance ($\sim 10^{-8}$ henry) current sensor with sensitivity of 10^{-6} amp. As a magnetometer the slug has measured fields as small as 10^{-8} gauss.

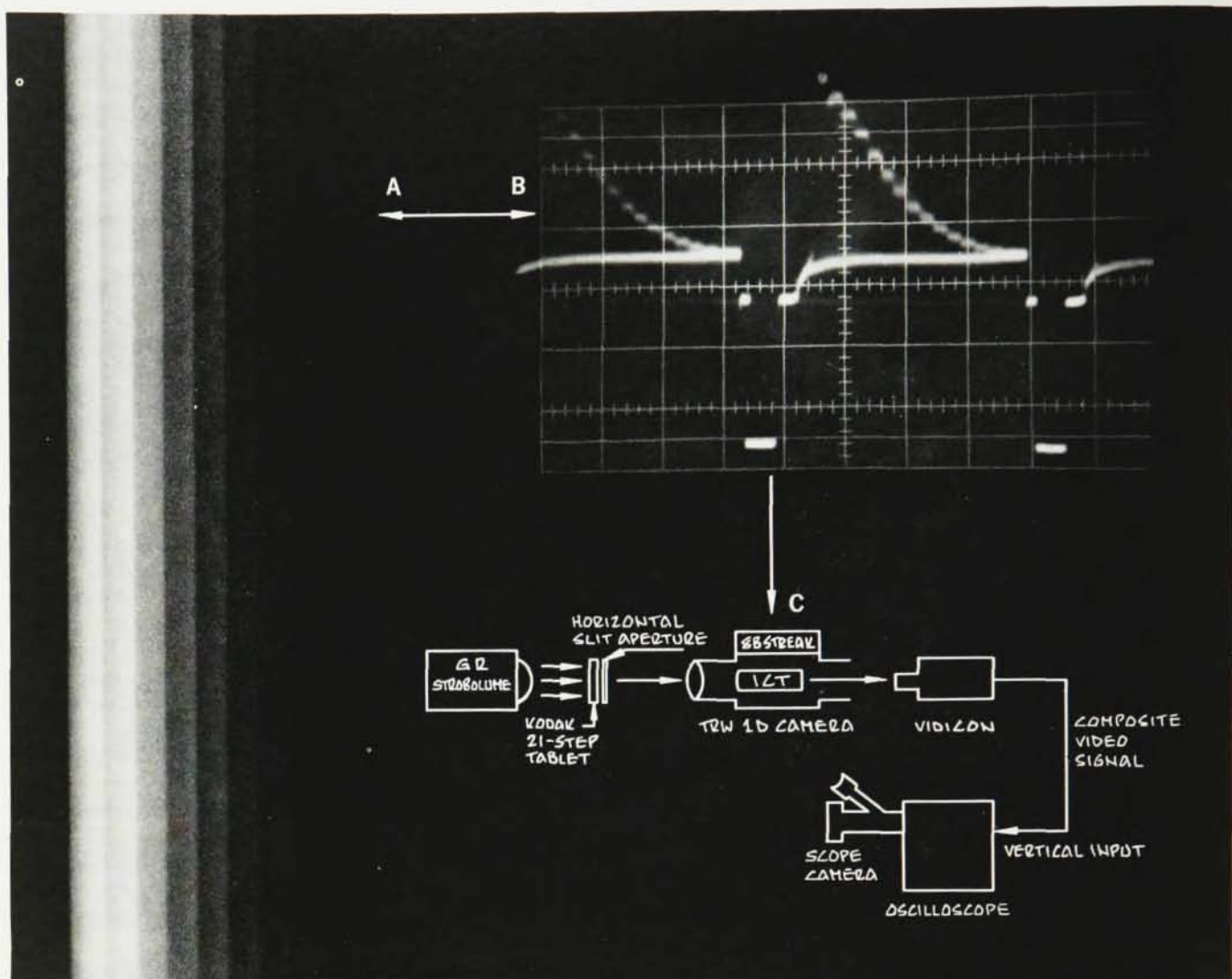
Still another magnetometer with high sensitivity was described by John M. Pierce (Stanford). The inductance of a closed superconducting circuit is varied at high frequency. A persistent current in the circuit is modulated and the resulting ac voltage measured. A thermally-switched, hollow superconducting cylinder is heated at 10^5 Hz inside a niobium coil and has been used to measure flux changes of 0.01 flux units. A superconducting plane vibrated by a quartz crystal at several megahertz is used in a magnetometer which is expected to have a sensitivity of 10^{-10} gauss.

Voltage measurements. J. Clarke reported that his interference device (slug) has measured an emf of 10^{-15} volt with a time constant of one second. He described multiple staging



SUPERCONDUCTING MAGNETOMETER of James E. Mercereau.

Need nanosecond photographic instrumentation for field experiments?



Simply couple vidicons or image orthicons with the TRW Image Converter Camera, as we did to make this picture. A is a streak photograph of a backlighted step tablet, B is the vidicon composite video signal, and C shows the instrumentation setup.

If you need ultrahigh-speed photographic information in a situation where your TRW camera is inaccessible, under water for instance, or if you need photographic information in a millisecond or two from a remote location such

as in explosives research, you will want a copy of T. H. Bulpitt's paper, "Use of Television With the TRW Image Converter Camera for Remote Readout and Enhanced Sensitivity."

For a copy of the paper and information on the TRW Model 1D camera, write or call **TRW Instruments, 139 Illinois Street, El Segundo, California 90245; (213) 535-0854.**

TRW INSTRUMENTS
Dept. PT-967
TRW®

TRW Instruments develops and manufactures state of the art diagnostic instruments for basic and applied research.

of slugs for sensitivities several orders of magnitude higher in principle.

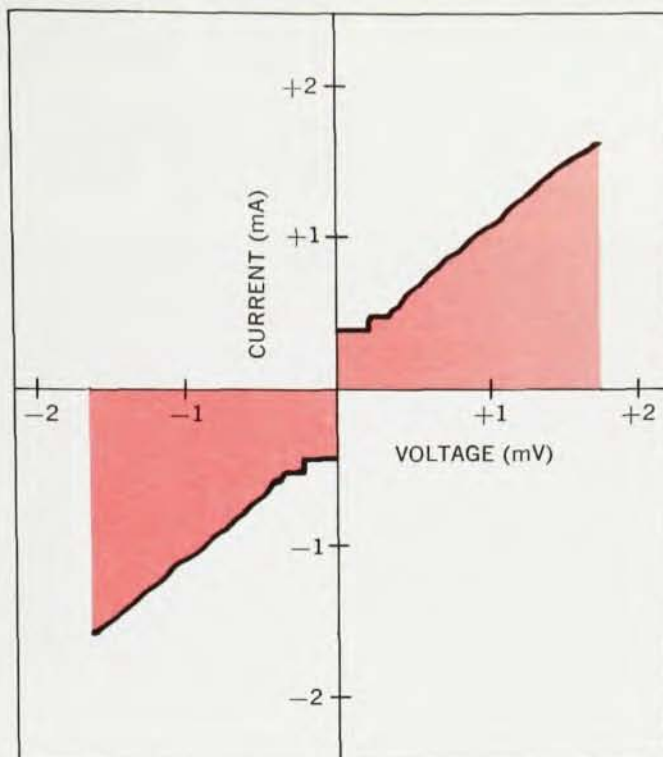
A parametric amplifier, with a superconducting inductance modulated by vibration of one of a set of coils at a frequency of 1000 Hz, was reported by R. P. Ries and C. B. Satterthwaite (U. of Illinois). Sensitivities of 4×10^{-14} volt with a source resistance of 4×10^{-7} ohm and time constant of one second have been obtained.

B. N. Taylor (RCA Labs.) reported on work with W. H. Parker and D. N. Langenberg (U. of Pennsylvania) on an ac-Josephson-effect technique to compare standards of electromotive force. They used the microwave-induced constant-voltage current steps of the ac Josephson effect in tunnel junctions to check the constancy and to compare emf standards at an accuracy of one part per million.

Far infrared detector. The critical current of a point contact or tunnel junction is changed when radiation is incident on the junction. S. Shapiro (Bell Labs.) reported experiments demonstrating that this detection mechanism extends well into the far infrared. The response of Nb-Nb junctions was found to extend to wavelengths shorter than 300 microns, that is, to about twice the superconducting energy gap. At 4 mm the sensitivity was 5×10^{-13} watt in a one-cycle bandwidth with a 10^{-8} -sec rise time.

Oscillator-detector. A. H. Silver (Ford Scientific Lab.) uses a voltage-biased weak link as a tunable oscillator. He inserts a small resistance into a superconducting ring containing a weak link to achieve voltage bias with a current source. When the device is in the presence of a resonant absorber, while the frequency is varied through the resonance, power is transferred and absorption is detected by observing the weak-link impedance at some arbitrary measuring frequency. Silver has used the device to observe the Co^{59} nuclear resonance.

Millidegree noise thermometer. Assuming that the line width of the ac Josephson radiation is caused predominantly by thermal fluctuations in the bias voltage, R. A. Kamper (NBS, Boulder) suggests a circuit similar to that of Silver as a thermometer. Johnson noise on the bias resistor would



I-V CHARACTERISTIC for superconducting tunnel junction of John Clarke. Response shows dc tunneling (region of finite current with no voltage) and step structure of ac Josephson effect from discrete modes in the junction.

produce a broadening of the Josephson line, and, assuming a resistor of a few micro-ohms in the ring containing the point contact and a one-cycle-per-second frequency resolution, he estimates that the temperature resolution of the device should be about one millidegree. It has the advantage of directly reading electron temperature.

Josephson junctions as mixers and switches. G. K. Gaulé reported work, with R. L. Ross and K. Schwidtal (USAECOM, Ft. Monmouth) on analysis of the behavior of Josephson junctions and weak links as microwave mixers. Experiments on biased and unbiased junctions near 10 GHz verified the computed results and the promise of junctions as useful mixers in this range.

J. Matisoo (IBM Research Center) has demonstrated use of a tunneling junction as an active two-state device. It is switched controllably between the zero-voltage Josephson regime and the quasi-particle tunneling state for which $V = 2\Delta$ over a large range of current. He has demonstrated a configuration with a current gain of 10 and transition time less than 10^{-9} sec.

Phonon generation and detection. A very versatile new technique for ultrasonics was described by A. H.

Dayem (Bell Labs.) with Sn-SnO₂-Sn tunnel diodes as both generators and detectors of phonons. The generator junction is biased above the energy gap so that excited quasi-particles decay, emitting phonons. He uses a second tunnel junction biased below 2Δ as a phonon counter that responds to phonons with energy $\geq 2\Delta$.

Measurement of the anisotropic energy gap in niobium. With up to 8 Nb-Nb oxide-In tunnel junctions at various crystallographic orientations on a single niobium crystal, M. L. A. MacVicar and R. M. Rose (MIT) were able to determine an anisotropy of 7-8% in the niobium energy gap at 1.8°K. Some unexplained structure was found in the tunnel characteristics and there was some evidence of a second much smaller gap in niobium.

Superinductors. W. A. Little (Stanford) investigated the low-lying collective electronic modes of long thin superconducting strips and showed they have an effective inductance dominated by the charge carriers' kinetic energy rather than magnetic field energy. The effective inductance is determined by the ratio of the square of the penetration depth to the cross-sectional area of the sample. Measurements on strips 4×10^{-3} mi-

This complete kit for holograms—just \$150



Everything you need for creating them with your ULI laser

With the Model 210 Holography Kit and one of ULI's He-Ne continuous gas lasers, instructors and students can now easily create excellent three-dimensional holograms under conditions common in normal physics labs. No special tables, unwieldy setups, or expensive apparatus needed.

Holograms—incredible, three-dimensional lensless photographs—are fascinating to make and they become a dramatic, graphic method of teaching many principles of physics and optics.

In the kit, ULI provides everything you

need: a complete laboratory manual covering practice and theory; spectrographic plates; beamsplitters; front surface mirrors; lenses; developing and fixing chemicals; trays and rinsing tanks; and all other necessary items. The manual gives step-by-step instructions for creating original holograms rather than merely reconstructing images from already existing transparencies.

Holography is already being used in microscopy, integrated-circuit manufacture, and data processing. And this laser-born technique of the future is available

now for today's classroom. Using this simple but high-quality ULI equipment, a student group can make a good hologram—from start to finish—in under one hour.

Specifically designed for operation with ULI's family of gas lasers, the Model 210 Holography Kit is equally excellent for use with any gas laser that operates in the uniphase TEM₀₀ wavefront mode.

Write today for full information. University Laboratories, Inc. / 1740 University Ave., Berkeley, California 94703 / Telephone: (415) 848-0491.

UNIVERSITY LABORATORIES, INC., 1740 UNIVERSITY AVE.
BERKELEY, CALIFORNIA 94703

Please send information on: ☐ ULI Holography Kit ☐ ULI Continuous Gas Lasers. ☐ Please reserve a Model 210 Holography Kit from your current production. My official purchase order and shipping instructions will follow.

Name _____

Organization _____

Address _____

City _____ State _____ Zip _____

Terms: 2% discount 10 days, net 30 days. ULI products returned for any reason, prepaid and undamaged, within 30 days will receive full credit.

University Laboratories

cron thick, 20 micron wide and 3 cm long showed effective inductance approximately 50 times larger than the magnetic inductance. As devices these are promising not only because of their small size, but because they can be controlled and modulated by all agents affecting penetration depth.

DC transformers. The motion of quantized vortices in a thin film with a current was discussed by Ivar Giaever (General Electric Research). He described a direct current transformer constructed with two thin superconducting films separated by a thin oxide layer. Flux lines linking both films are caused to move by a current flowing in the primary, and with good coupling a secondary voltage just equal to the primary voltage is developed. Because of the pinning forces on the vortices, flux motion cannot occur until a certain threshold current is exceeded. A current imposed through the secondary can be used to control the apparent pinning force of the vortices in the primary. This property has been used to make a controlled rectifier.

Gravity meter. A combination of superconducting properties and devices helped J. M. Goodkind (U. of California, San Diego) construct an extremely sensitive gravity meter. The device is a hollow superconducting sphere suspended in the magnetic field of two persistent-current coils. The vertical position of the ball is monitored by means of a flux detector of the flux-flow type described by Mercereau. The sensitivity of the device is 5×10^{-9} g and he has obtained data on earth tides.

Fluctuations. There were two theoretical papers on fluctuations in superconducting circuits. D. J. Scalapino (U. of Pennsylvania) calculated the power spectrum of the current fluctuation in superconducting tunnel junctions. For thick junctions in which there is no pair-phase coupling he expressed the power spectrum in terms of the observed dc current-voltage characteristic of the junction and showed that it reduces to the Nyquist relation at high frequencies and to a shot-noise spectrum at low frequencies. He also obtained the spectrum for a Josephson junction carrying a dc

supercurrent and for a voltage-biased Josephson junction.

R. E. Burgess (U. of British Columbia) discussed the frequency spectrum of flux fluctuations in a hollow superconducting cylinder near T_c , assuming the fluxoid is the rigorously constant quantity. He also discussed the decay of persistent currents in completely superconducting cylinders and in ones containing a tunnel junction.

The meeting served to emphasize the diversity of problems to which superconductivity can be applied and the large amount of effort and ingenuity that is being expressed in applying these techniques to new physical measurements. The incidence of discussion about fluctuations and noise in superconductors during the meeting indicated a growing concern with these topics, both from a fundamental point of view and as limitations on superconducting devices.

* * *

The proceedings of the symposium will be published in September and will be available through the Office of Naval Research, Physics Branch, Code 421, Main Navy Building, Washington, D. C., Attention: E. A. Edelsack.

BASCOM S. DEEVER JR
University of Virginia

WILLIAM S. GOREE
Stanford Research Institute

Acousticians Hear Many Sounds in New York

Reports covered a wide variety of acoustical topics at last April's seventy-third meeting of the Acoustical Society of America, in New York City: physiological acoustics, biological and general ocean sound scattering, psychoacoustics, speech, hearing, music, noise, physical acoustics, shock, vibration, electroacoustics, architectural acoustics.

Physiological acoustics. An invited paper was presented on the ability of various fish to localize the origins of sounds in their medium. Most of the contributed papers at this session emphasized the interplay of electroacoustic properties with the parameters of the living system. A workshop session on biological scattering followed the invited paper mentioned, reviewing the nature and characteristics of biological

Scintillation Counting?

Here's the Most Convenient Way to Minimize Thermionic Dark Current



Temperatures as low as -30°C can be achieved with EG&G's new completely self-contained Photomultiplier Tube Cooling Chamber. It requires no pumps or dry-ice and yet can effect very cold temperatures for maximum dark current reduction.

Standard temperature controllers are available for stabilizing the temperature of the PMT from $\pm 0.5^{\circ}\text{C}$ down to a proportionally-controlled $\pm 0.01^{\circ}\text{C}$, depending upon your requirements.

The standard EG&G chamber, which is $7\frac{3}{4}''$ square by $12\frac{1}{2}''$ long, is adaptable to any end-on PMT with a tube envelope up to 2" in diameter and up to 6" in length. All chambers have magnetic shielding around the tube, interchangeable tube sockets, dynode resistors, a double window to eliminate fogging, and a thermal limit switch for automatic power cutoff.

All models of the standard chamber are available for delivery within four weeks. For more details write EG&G, Inc., 161 Brookline Ave., Boston, Mass. 02215. Telephone: 617-267-9700. TWX: 617-262-9317.

 **EG&G INC.**