

AD612113

No DDC limit

(1)

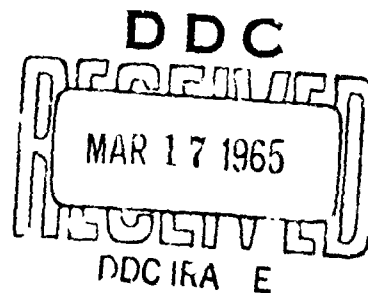
COPY	1	OF	1	Price
HARD COPY				\$. 1. 00
MICROFICHE				\$. 0. 50

13p

PROCEEDINGS
OF THE
1964 ARMY SCIENCE CONFERENCE
UNITED STATES MILITARY ACADEMY, WEST POINT, N. Y.
17-19 JUNE 1964

VOLUME I
(Principal Authors "A" thru "H")

PROCESSING COPY
ARCHIVE COPY



limit



GAULÉ, BRESLIN, ROSS and
LOGAN, 2d Lt, USAR

AD612113

SUPERCONDUCTORS IN ADVANCED ELECTRONICS

GERHART K. GAULÉ, JAMES T. BRESLIN
RAYMOND L. ROSS and ROY S. LOGAN, 2d Lt, USAR
U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY

1. INTRODUCTION

A superconductor is completely free of ohmic losses for a direct current and nearly free of such losses for alternating currents with frequencies up to Mc/sec and higher, depending on the circumstances. Circuits with superconducting inductors and capacitors, and superconducting interference shields for such circuits thus appear as a natural choice where a minimum of loss, noise, and interference from the environment is desired, as for example in the first stage of a communications receiver. Superconducting resonant circuits with very high Q values (10^6 and higher) have indeed been successfully operated in the Mc/sec range (1), (2), but the tuning of such circuits proved to be difficult. It was recognized at USAELRDL (3) that remotely controlled switches would solve the tuning problem provided the switches would introduce no loss into the circuit. The "cryotron," a superconducting computer element (4), has often been called a superconducting "switch," but it is really only a current gate with zero resistance in the "closed" position and a finite resistance--a few hundred ohms at most--in the "open" position. A superconducting switch with a true "open" position (virtually infinite resistance) was, however, deemed necessary for tuning and, in fact, for most purposes. It was predicted (5) that a novel combination of superconducting solenoids with superconducting contacts would constitute a remotely controlled superconducting switch with the desired properties. Experimental work was begun in fall 1963 which soon resulted in the construction of an actuating mechanism capable of giving contact forces up to 1000 g (Section 2). The search for a suitable superconducting contact material and a suitable contact configuration proved much more difficult, but contacts which would reproducibly control supercurrents of 16 A had been developed in spring 1964 (Section 3). This surprisingly high current value permits the use of the new relay switch not only for the low power applications mentioned in the beginning but also for high power applications, especially in

GAULÉ, BRESLIN, ROSS and
LOGAN, 2d Lt, USAR

connection with the now widely used superconducting solenoids for the generation of high magnetic fields. Using the analogy between a hypothetical lossless capacitor and a superconducting inductor or solenoid, basic circuits for the "charging" and "discharging" of a superconducting solenoid were developed (6) and some of them tested (Section 4).

The low operating temperatures of the presently used superconductors often prevent the application of superconducting devices and circuits in spite of their obvious advantages. Recent progress in this area as a result of simplified cooling methods and of improved materials is outlined in Section 5.

2. RELAY MECHANISM WITH SUPERCONDUCTING COILS

The mutual attraction and repulsion of two similar superconducting coils were used to actuate the first experimental relay switch built by the authors, shown in Fig. 1. Other possible magnet configurations have been discussed elsewhere (5). No soft iron return path was used for the magnetic flux, because this would increase the cooling requirements for the relay, and also because the high magnetic fields generated by superconducting coils tend to magnetically saturate the iron, thus making it useless.

Each magnet coil was made by winding approximately 1300 turns of molybdenum-rhenium wire on a nylon bobbin with 1.6 cm outer diameter. Molybdenum-rhenium is a "hard" superconductor, that is, a material remaining superconducting in a strong magnetic field and when carrying a large current.

The relay consists of two simple bakelite parts, one stationary and one movable, each carrying one coil and one contact, (Fig. 1). The magnetic force, magnified by lever action, acts on the two contacts. To measure the contact force, as a function of coil current, a nylon string was attached to the upper contact and connected to a balance on top of the cryostat in which the relay was kept at the temperature of 4.2°K. Some of the results are given in Table II, Section 3. The force increases strongly with the coil current and reaches ≈ 1000 g for the maximum current carrying capacity of the coils (≈ 6.4 A). A conventional copper wire of equal thickness (0.25 mm) in place of the Mo-Re wire would sustain no more than ≈ 0.1 A. It is this difference in operating current for a given winding which makes superconducting coils so superior to conventional ones in producing mechanical forces for the operation of contacts and other purposes.

3. CONTACTS FOR LARGE SUPERCURRENTS

In 1914 Kammerlingh-Onnes, the discover of superconductivity, made the first superconducting "switch" when he pressed two

GAULÉ, BRESLIN, ROSS and
LOGAN, 2d Lt, USAR

pieces of superconducting lead together and found superconductivity across the contact (7). Later workers found that an oxide layer and even an insulating layer of moderate thickness (up to 10^{-7} cm) between the contact surfaces does not prevent superconductivity across the contact (7),(8). This surprising effect was explained theoretically only recently by Josephson (9) ("Josephson-Tunneling").

When the current through a superconducting switch is raised, a critical current value, I_{cr} , is finally reached at which the superconductivity across the contacts vanishes. This becomes evident as a voltage across the contacts. I_{cr} can be determined by observing this voltage with separate voltage leads, as shown in Fig. 1. All the switches reported in the literature had small I_{cr} values, usually much less than 1 A. Various contact pairs used in the initial phase of this work were found superconducting, but with disappointingly small I_{cr} . Results for three typical contact pairs are listed in Table I.

TABLE I

contact 1	contact 2	contact force (g)	I_{cr} (A)
multifinger arrangement of Nb wire (0.4 mm)	Nb - sheet	650	$2 \cdot 10^{-4}$
		750	$2 \cdot 10^{-4}$
Pb-Sn alloy (40/60), ball shaped	Nb - sheet	350	$2 \cdot 10^{-3}$
		400	$11 \cdot 10^{-3}$
		550	$73 \cdot 10^{-3}$
		800	$74 \cdot 10^{-3}$
Pb-Sn alloy (40/60), ball shaped	Pb-Sn alloy (40/60) ball shaped	550	$18 \cdot 10^{-3}$
		850	$18.5 \cdot 10^{-3}$

It was deduced from these data that (a) increasing the contact force beyond ≈ 500 g gives little improvement, and that (b) at least one of the contacts should be of a soft material, such as the lead-tin alloy used in two of the experiments. It is known, however, that even this alloy becomes rather hard when cooled to liquid helium temperature. Pure lead was chosen therefore for the next experiments. Lead retains a plasticity at 4°K comparable to that of copper at room temperature. The plasticity of a contact material appears to secure the formation of an "effective" contact area larger than that obtainable with a hard material (7). The contacts finally used in this work were of lead galvanically coated with a very thin layer of tin. The contacts were kept under helium gas during the cooling down period. These measures were aimed at preventing the formation

GAULÉ, BRESLIN, ROSS and
LOGAN, 2d Lt, USAF

of layers of oxide, ice, or frozen air on the contact surfaces. The results with tin coated lead were excellent and vastly superior to any previous results, as shown in Table II. This table also gives the contact force as a function of coil current.

TABLE II

coil current (A)	contact force (g)	I_{cr} (A)
1.5	350	< 1
2.3	475	2.3
3	600	13
4	800	13.5

These results were quite reproducible. In one run an I_{cr} value of 16 A was attained. Technical refinements of the crude experimental set up, shown in Fig. 1, will undoubtedly improve the performance of the superconducting relay switch further.

4. APPLICATIONS

The successful operation of radio frequency and of microwave circuits made of superconducting components has been reported by other groups (1),(2),(10). The new superconducting relay switch described in the previous section now makes possible the tuning of such circuits by remote control. Several switches could serve, for example, to add capacitors or inductors to a superconducting, high Q resonant circuit. Since the switches have zero resistance in their "closed," and virtually infinite resistance in their "open" position, the switches will not introduce any losses into the circuit (3). An older switching device, the "cryotron," could not be used for this purpose, because it has no true "open" position, as discussed in Section 1.

The first step toward high power applications of the new superconducting switch was taken by the authors when they connected the new switch to the terminals of a high field (42 kOe) superconducting solenoid, and used it to control the solenoid current. The solenoid is of medium size (1.25 cm bore) and has an inductance of ≈ 5 Henry. The highest supercurrent which could be controlled so far was 12 A. One purpose of these experiments is to explore the storage of electrical energy with the solenoid. The storage of electrical energy in low loss capacitors has been used in electronics for many years for the operation of pulsed transmitters, of pulsed light sources, and also in plasma research. A superconducting solenoid can be considered as an inductor which is lossless in low frequency applications. The properties of such an inductor are set in analogy to those of a hypothetical leakage free capacitor in Fig. 2. The quantum of charge for the capacitor is of course e , the electronic

GAULÉ, BRESLIN, ROSS and
LOGAN, 2d Lt, USAR

charge; its equivalent for the inductor is the newly discovered (11) quantum of magnetic flux, $hc/2e$ (h : Planck's constant, c : velocity of light). Since both "charge quanta" are very small, they are not observed except under very special conditions and the charging processes can be treated as continuous in the following. Charging the capacitor is accomplished through the transfer of electric charge between the capacitor plates, resulting in a voltage between the plates. "Charging" the inductor is accomplished by building up a current through the winding, resulting in a magnetic flux threading the hole of the inductor. The charged state of the capacitor is characterized by an open circuit, the analogous state of the inductor by a short circuit (produced by the closing of a superconducting switch). The maximum charge of the capacitor is limited by dielectric breakdown, the maximum magnetic flux of the inductor is limited by the field induced breakdown of the superconductivity of the winding. Technically attainable values for either kind of breakdown are used in Fig. 2 to demonstrate that the energy, w , which may be stored per unit volume of the device is much greater in the case of the solenoid. Formulas for the total amounts of energy, W , storable in either case are also given in Fig. 2. The largest superconducting solenoids which are now commercially available have bores greater than 15 cm and inductances up to 1000 Henry. Carrying a typical current $I \approx 20$ A, such a solenoid stores $W \approx 2 \cdot 10^5$ Joule. The corresponding value for a capacitor of comparable size and weight would be much smaller.

The bottom part of Fig. 2 illustrates the transfer of the stored energy into an outside load R' . For the capacitor, this is accomplished by closing a switch, for the inductor by opening a superconducting switch. Until now, only thermally activated cryotrons were used in connection with superconducting solenoids. The resistance of a "thermal" cryotron can be varied only slowly (within ≈ 20 sec) from zero to the maximum value of a few ohms. Most of the stored energy is thus consumed by the cryotron itself and transfer to an outside load is ineffective. The discharge process presented in the right bottom part of Fig. 2 is possible only with a superconducting switch which goes from "zero" to "infinite" resistance immediately, such as the relay switch built and used by the authors.

Figure 3 shows the two analogous basic charging circuits for alternating current. The timing for the periods of charging is indicated. The superconducting switch across the inductor is open only during the charging period. When it is closed, no voltage is applied to the inductor and its current not influenced by the power source. The charging is completed when the supercurrent through the inductor equals the peak current of the power source.

Figure 4 shows two circuits employing current transformers. One winding of a current transformer is outside of the cryostat. The energy transfer is through the wall of the cryostat by induction. This is superior to the direct transfer of energy through

GAULÉ, BRESLIN, ROSS and
LOGAN, 2d Lt, USAR

heavy current leads which are difficult to cool. Except for the current transformer, the first circuit in Fig. 4 operates like that in Fig. 3. The second circuit in Fig. 4 is analogous to a vibrator circuit with capacitors. It converts the stored direct current into alternating current by using a reversal switch S2, and by immediately storing energy in the superconducting transformer winding W2 combined with the closed superconducting switch S3. The timing of the switches for discharge is indicated. With different timing, the same circuit is used for charging.

Figure 5 indicates the storage of energy in a superconducting combination S and L as before, but a switching transistor T1 outside of the cryostat is connected parallel to S. In the "standby" position, S is opened and the solenoid current is forced to flow through T1. The storage is then of course no longer loss free, but the loss during a short standby period is tolerable. For operation, the switching transistors T1 and T2 are alternately opened and closed with the resonance frequency of the transmitting circuit, thus converting the stored energy into a very powerful radio frequency signal.

The equations at the bottom of Fig. 2 indicate that a "discharging" inductor behaves essentially like a constant current generator. This feature, together with others listed above, makes a superconducting solenoid combined with a superconducting switch particularly attractive for the operation of pulsed light sources. At the onset of the pulse the resistance of such a device is usually high; the solenoid then applies a high "igniting" voltage. Later on, when the resistance of the device drops, the voltage drops accordingly, and the initial current is never exceeded. This is in contrast to the action of a capacitor--essentially a constant voltage generator--which tends to apply too much voltage after "ignition," so that much of the pulse energy must be destroyed in a stabilizing resistor or the like. Superconducting solenoids and relay switches capable of delivering pulses of several hundred volts and many thousands of Joules should be obtainable. Fig. 6 shows a simple circuit for pulsed light sources, based on principles similar to those of Fig. 5.

COOLING PROBLEMS

In the usual laboratory operation of a superconducting circuit the circuit is housed in a cryostat which is cooled by transferring liquid nitrogen and liquid helium into appropriate compartments of the cryostat. The transfer of a cryogenic liquid is a difficult and time consuming manipulation which is necessary because the consumer of the cooling energy, the circuit, is separated from the source of the cooling energy, namely the liquefier for the helium or nitrogen. In this fashion several cryostats can be served from one liquefier, permitting simultaneous work on several experiments. The laboratory method of cooling, however, is neither necessary nor even suitable in the technical application of

GAULÉ, ERESLIN, ROSS and
LOGAN, 2d Lt, USAR

superconducting circuits. Here, the best approach is obviously through a combination of the cryostat with the liquefier (or another source of cooling energy), such that fully automatic operation without any external transfer of cryogenic liquids is accomplished. Refrigerators of this advanced kind, called "closed cycle refrigerators" are now commercially available in various sizes, even rather small ones. A closed cycle refrigerator has several "cooling stations," essentially cooled metal plates. The superconducting circuit is mounted of course at the station with the lowest temperature. Electrical leads, coaxial cables, and waveguides connected to the superconducting circuit are also thermally linked to the stations with intermediate temperatures. In this fashion, the heat flowing into the cryostat is "intercepted" at a relatively high temperature level. The thermodynamical efficiency of a closed cycle refrigerator is therefore excellent even when heavy cables or waveguides or the like are used.

Progress would be still greater, of course, if it were possible to operate the superconducting circuit itself at a higher temperature. Although many superconductors with transition temperatures, T_c , between 15°K and 18°K are known (12), lead ($T_c = 7.2^\circ\text{K}$) and similar metals are predominantly used now in electronic circuits. As discussed in Section 3, lead is also the best contact material known. If a search for materials with satisfactory high frequency and contact properties among the superconductors with $T_c \geq 15^\circ\text{K}$ proves successful, the operating temperature could be raised accordingly. This would in turn permit at least a tenfold reduction in refrigerator input power.

6. CONCLUSION

The low power as well as the high power applications of superconductivity are increasing. Both are expected to benefit from the high current relay switch developed by the authors. In contrast to previous "switching" devices, the new switch has a true "open" position, and is thus loss free in either position. A novel method for the storage of electrical energy is given by connecting the new switch with a high current, high inductance superconducting solenoid. The basic circuits are derived from analogous capacitor circuits. The inductive energy storage is superior to the capacitive one in the operation of pulsed light sources, for example. A sharp distinction should be made between the cooling methods suitable for the laboratory and those for technical applications. For the latter, greater use should be made of the now available closed cycle refrigerators. Higher operating temperatures for superconducting circuits are sought through improved materials. The development of special low loss dielectric materials for these circuits is also suggested.

GAULÉ, BRESLIN, ROSS and
LOGAN, 2d Lt, USAR

7. ACKNOWLEDGMENT

The authors wish to thank Dr. Hans Meissner, Stevens Institute of Technology, Mr. Charles Nixon, Army Ballistic Missile Agency, Huntsville, Alabama and Mr. J. Mellichamp, Mr. M. Woodruff and Mr. L. Dathe of USAELRDL for stimulating discussions. The authors wish to express their appreciation to Mr. Lester Wilcox for fabrication of the first experimental relay switch.

8. BIBLIOGRAPHY

- (1) W. H. Hartwig, "Superconductive Frequency Control Devices." Final report, DA-36-039-AMC-00036(E) August, 1963. W. H. Hartwig, paper presented to the Frequency Control Symposium, Atlantic City, N. J., May, 1963.
- (2) F. L. Arams, Cryogenic "Radio Frequency Tuner." DA-36-039-AMC-03321(E).
- (3) G. K. Gaulé, L. C. Dathe, "Switching System for Superconducting Circuit," invention disclosure, U. S. Army Electronics Patent Activity, Docket #14,238.
- (4) T. W. Bremer, "Superconducting Devices," McGraw-Hill Book Co., New York, 1962.
- (5) G. K. Gaulé, M. W. Woodruff, R. S. Logan, "Remotely Controlled Superconducting Switches and Actuators," invention disclosure, U. S. Army Electronics Patent Activity, Docket #14,713.
- (6) G. K. Gaulé, "Switching Circuits for the Charge and Discharge of Superconducting Solenoids," invention disclosure, U. S. Army Electronics Patent Activity, Docket #14,718.
- (7) R. Holm, Electric Contacts Handbook, Springer Verlag, Berlin, 1958, page 128.
- (8) Isolde Dietrich, Zeitschr. Physik 132, p. 231 (1952); Zeitschr. Physik 133, p. 499 (1952).
- (9) B. D. Josephson, Phys. Letters, 1, 251 (1962).
- (10) R. J. Allen, "Microwave Memory Techniques Project, "Final Report, AF30(602)-2414.
- (11) B. S. Deaver, W. M. Fairbanks, Phys. Rev. Letters, 7, 43 (1961). R. Doll and M. Nabauer, Phys. Rev. Letters, 7, 51 (1961).
- (12) G. K. Gaulé, "Rules for the Occurrence of Superconductivity among the Elements, Alloys and Compounds," USAELRDL Technical Report 2329.

GAULÉ, BRESLIN, ROSS and
LOGAN, 2d Lt, USAR

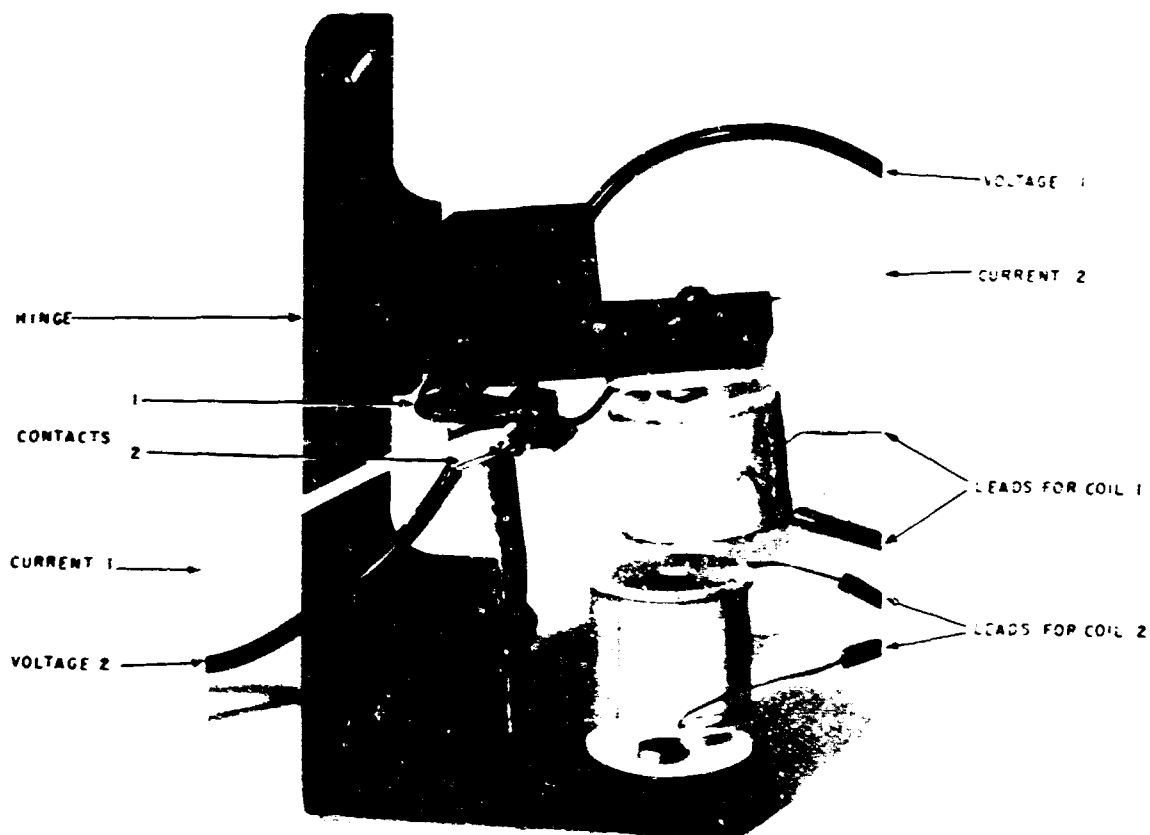


Fig. 1

Experimental superconducting relay switch. Coils have approximately 1.6 cm diameter and 1300 turns of Mo-Re wire, 0.25 mm thick. Critical current of contacts, $I_{cr} \approx 14$ A. Voltage leads on contacts are used to determine I_{cr} .

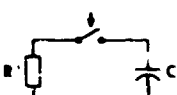
ONE-TO-ONE CORRESPONDING ENTITIES	CORRESPONDENCE BETWEEN LEAKAGE FREE CAPACITOR AND (SUPERCONDUCTING INDUCTOR)	
QUANTIZED CHARGE (FLUX)	$Q_0 = e = -1.6 \times 10^{-19} \text{ A SEC}$	$\phi_0 = hc/2e = 2.1 \times 10^{-15} \text{ V SEC}$
CHARGING PROCESS	$Q = ne = \int i \, dt = UC$ $C \text{ IN FARAD} = \text{A SEC/V}$	$\phi = n \phi_0 = \int U \, dt = IL$ $L \text{ IN HENRY} = \text{V SEC/A}$
LIMITATION OF CHARGE (FLUX)	$U < U_{\text{MAX}}$ DIELECTRIC BREAKDOWN	$I < I_{\text{MAX}}$ BREAKDOWN OF SUPERCONDUCTIVITY
TOTAL ENERGY STORED (IN JOULE = V A SEC)	$W = U^2 C / 2 = UQ / 2$	$W = I^2 L / 2 = I \phi / 2$
ENERGY STORED PER UNIT VOLUME (IN JOULE/cm ³)	$w = \epsilon_0 E^2 / 2$ $w = 0.04 \text{ FOR } E = 10^6 \text{ V/cm}$	$w = \mu_0 H^2 / 2$ $w = 60 \text{ FOR } H = 10^5 \text{ A/cm}$
DISCHARGE THROUGH OHMIC LOAD, R' , SWITCH CLOSSES (OPENS) AT $t=0$, PRIMED QUANTITIES, U' , I' REFER TO LOAD.		
FOR $t < 0$	$I = I' = 0$ $U = U_0 = \text{CONST. } U' = 0$	$U = U' = 0$ $I = I_0 = \text{CONST. } I' = 0$
FOR $t > 0$	$I = I' = -U/R' = Q/UC$ $U = U' = U_0 \text{ EXP } (-t/R'C)$	$-U = U' = -UR' = \phi/L$ $I = I' = I_0 \text{ EXP } (-tR'/L)$

Fig. 2
Analogies between the storage of electrical charge in a hypothetical leakage free capacitor (center) and the storage of magnetic flux in a superconducting inductor (right).

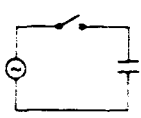
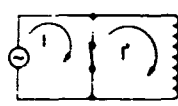
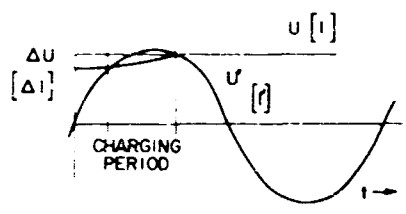
CORRESPONDING ENTITIES	LEAKAGE FREE CAPACITOR	SUPERCONDUCTING INDUCTOR
BASIC AC CHARGING CIRCUIT, WITH CONSTANT VOLTAGE (CONSTANT CURRENT) SOURCE.		
		
CHARGING PERIOD BEGINS, SWITCH CLOSSES (OPENS) WHEN	$U' = U + 2U$	$I' = I + 2I$
DURING CHARGING PERIOD	$I = I' > 0$	$U = U' > 0$
CHARGING PERIOD ENDED, SWITCH OPENED (CLOSED) WHEN	$I = I' = 0$	$U = U' = 0$

Fig. 3
Corresponding a.c. charging circuits, as in Fig. 2.

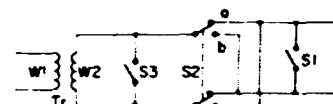
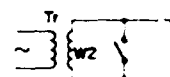
CHARGING CIRCUIT SIMILAR TO ABOVE, BUT WITH AUXILIARY TRANSFORMER TR. WINDING W2 IS SUPERCONDUCTING.

THIS CIRCUIT CAN ALSO BE USED FOR DISCHARGE. WHEN CONNECTED TO RESONANT LOAD CIRCUIT

CIRCUIT WITH REVERSAL SWITCH. EQUIVALENT TO VIBRATOR CIRCUIT WITH CAPACITORS.

W2 IS SUPERCONDUCTING AND STORES CURRENT I' , FLUX Φ' . UPON REVERSAL AND OPENING OF S3, FLUX IN TR CHANGES TO Φ'' , PRODUCING VOLTAGE IN W1.

SWITCHING SEQUENCE FOR DISCHARGE SEQUENCE FOR CHARGING ANALOGOUS SEQUENCE ALTERNATES WITH S2 IN POSITION 'a' AND S2 IN POSITION 'b'.



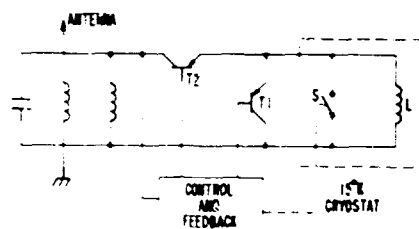
	S1	S2	S3
STANDBY a	1	0	a
DISCHARGE	0	1	a
REVERSAL	1	1	b
STANDBY b	1	0	b
CONTINUED AS ABOVE			b

Fig. 4 Charging circuits for superconducting solenoids using superconducting switches and transformers. Primary transformer winding (W1) couples through wall of cryostat. Heavy current leads into the cryostat are thus unnecessary.

EMERGENCY TRANSMITTER FOR HIGH POWER PULSES.

LOSSLESS STORAGE IS PROVIDED BY SHUNTING THE SUPERCONDUCTING INDUCTOR L WITH SUPERCONDUCTING SWITCH S. IN THE STANDBY POSITION CURRENT IS TRANSFERRED OUT OF THE CRYOSTAT AND GOES THROUGH SWITCHING TRANSISTOR T1 WITH $R \approx 10^{-3}$ OHMS FOR THE EFFECTIVE RESISTANCE OF T1. DECAY IN THE STANDBY POSITION IS DESCRIBED BY A TIME CONSTANT $\tau = L/R \approx 10^4 - 10^6$ SEC.

OSCILLATION THROUGH OPENING AND CLOSING OF T1 AND T2 WITH RESONANCE FREQUENCY IN CONVENTIONAL MANNER.



	S	T1	T2
LOSSLESS STORAGE	1	1	0
STANDBY	0	1	0
START OF OSCILLATION	0	0	1
OSCILLATION WITH RESONANCE FREQUENCY T1, T2 CONTROLLED BY FEEDBACK NETWORK	0	1	0
	1	0	1
	0	1	0
LOSSLESS STORAGE	1	1	0

Fig. 5 Example of potential future application of energy storage in superconducting solenoid. Lossless storage is given with superconducting switch S. Energy is lost only during the standby and operative periods, when solenoid current is controlled by switching transistors T1 and T2.

GAULE, BRESLIN, ROSS and
LOGAN, 2d Lt, USAR

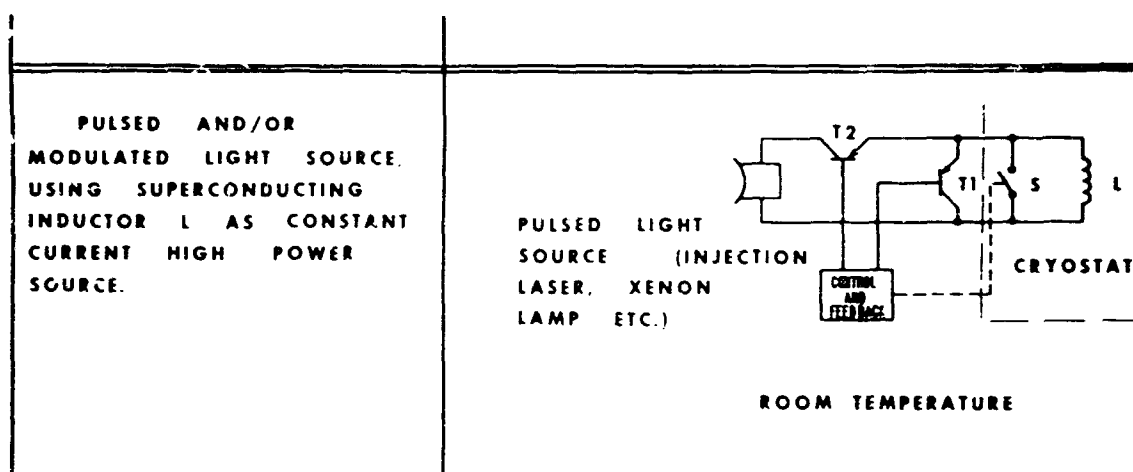


Fig. 6

Operation of pulsed light source from superconducting solenoid, similar to Fig. 4. In contrast to a capacitor bank, a superconducting solenoid is essentially a constant current source which is more suitable for many pulsed light sources.