Superconducting Magnet for a Ku-Band Maser

R. Berwin, E. Wiebe, and P. Dachel
Communications Elements Research Section

A superconducting magnet to provide a uniform magnetic field of up to 8000 G in a 1.14-cm gap for the 15.3-GHz (Ku band) traveling wave maser is described. The magnet operates in a persistent mode in the vacuum environment of a closed-cycle helium refrigerator (4.5 K). The features of a superconducting switch, which has both leads connected to 4.5 K heat stations and thereby does not receive heat generated by the magnet charging leads, is described.

I. Introduction

This paper reports on the development of a superconducting magnet which provides the magnetic field for a Ku-band traveling wave maser. The advantages of using superconducting magnets to assure high phase and gain stability for traveling wave masers are listed, and the configuration of the magnet is described.

II. Discussion

The Ku-band traveling wave maser operates at frequencies between 14.3 and 16.3 GHz.[1] The required operating magnetic field for this maser must be continuously adjustable from 7000 to 8000 G. Present masers in the DSN use permanent magnets to provide 2500 G for S-band and 5000 G for X-band and these magnets weigh 90 kg, or more. In order to increase the magnetic field to 7500 G, while maintaining the spatial uniformity and large gap necessary to enclose the closed-cycle refrigerator shields, the size and weight of the magnet and supporting structure become a limiting design factor. Sensitivity of the permanent magnet to the Earth's magnetic field results in phase variations of the signal through the maser when the antenna is rotated. This sensitivity to external magnetic fields results from the low relative permeability at which the permanent magnet is operating. Additionally, ambient temperature changes produce variations in the permanent magnet field unless temperature compensation is employed. Although good compensation has been obtained, the optimization process is time consuming.

A superconducting magnet has been designed to attain magnetic fields of up to 10,000 G and to provide phase and gain stability of the signal through the maser (of less than ± 5 deg). Due to the high relative permeability of the iron in the superconducting magnet, the iron acts as a shield against external magnetic fields. The superconducting magnet is mounted to the same 4.5 K heat station on the closed-cycle refrigerator (CCR) as is the maser and operates in a persistent mode. The temperature inside the CCR is stable to within 0.001 K and, therefore, temperature compensation of the magnet is unnecessary. Listed below are significant results which have been obtained with the use of superconducting magnets with maser systems:

[1]The Ku band maser is described in "Low Noise Receivers: Microwave Maser Development," by R. Clauss and R. Quinn in this issue.

(1) Allows higher magnetic fields to be attained for higher frequency masers without a significant increase in superconducting magnet weight or refrigerator cooldown time.

(2) Decreases maser/CCR package weight from 180–220 kg (with external magnet) to 63 kg.

(3) Reduces physical size of maser/CCR package.

(4) Eliminates need for temperature compensation process.

(5) Eliminates need for stable power supplies to control magnet trim current.

(6) Reduces sensitivity of superconducting magnet field to external fields by 2 orders of magnitude.

(7) Enables rigid mechanical coupling between maser structure and magnet.

Achievement of items 4, 5, 6, and 7 are expected to reduce the phase variations as compared to present TWMs by approximately 2 orders of magnitude.

III. Description

Figure 1 shows the Cioffi-type (Ref. 1) superconducting magnet used in the Ku-band maser. Figure 1a is a cross-sectional view looking into the magnet gap. The 9 "U" shields are each made of a 50-mm-wide 0.27-mm-thick tape of copper-plated Nb_3Sn material. The Nb_3Sn thickness is 0.03 mm and the copper clad thickness is 0.12 mm on each side. The magnet is wound with 0.127-mm core NbTi wire, which has a 1.5:1 copper-to-superconductor-area ratio and is coated with 0.025-mm Formvar insulation. The pole pieces and return paths are Hiperco 27 (27% cobalt, 73% iron), machined and annealed to specification.

Figure 2 shows the magnet with the side return paths and superconducting shields removed to reveal the maser amplifier situated in the gap. The base plate is at 4.5 K and includes the superconducting junction A, the wire heat sink B, and the shield C for the superconducting switch which contains a light bulb to provide radiant heat to the switch wire passing through the housing. The other wire heat sink D is another 4.5-K heat station which is connected to the base plate with a stainless steel tube.

A. Superconducting Switch Design

Figure 3 shows a schematic of the superconducting switch and magnet coil located in the vacuum of the CCR. The switch consists of a NbTi superconducting wire shunt which passes through a radiation shield containing an incandescent light bulb which provides radiant heat to operate the switch.

When it is desired to change the magnetic field, the light bulb is turned on and the heat radiation drives the switch wire normal. During this time the current in the magnet, which is still superconducting, can be changed by means of an external power supply. As long as there is a changing current dI/dt in the magnet greater than a certain minimum threshold, the light bulb may be turned off and the induced voltage (approximately 2 mV minimum) across the magnet will keep the switch wire normal. When the current in the magnet reaches a stabilized level, the switch wire will become superconducting and the magnet current will operate in a persistent mode, at which time the external power supply can be turned off.

The superconducting switch operates in a vacuum environment with radiant heat to initiate it, and is thermally isolated from ambient loads by two 4.5-K heat stations (Fig. 3). These two heat stations provide electrical isolation between the parallel ends of the magnet leads and switch wire.

In addition, they act as heat sinks for power which is conducted from the switch wire and from the external power leads. The switch wire, where it is heat sunk to the No. 2 4.5-K heat station, (Fig. 2) has about 12-mm bared wire and by varying the length of the bared wire, the wattage to the bulb necessary to create a normal switch wire is varied. There is a compromise, however; the shorter the exposed or bared switch wire, the higher the bulb wattage required to normalize the wire. With 12 mm exposed, the voltage on the bulb is approximately 16 V ($\sim$ 0.6 W power) and the switch operates in less than a second.

B. Other Magnet Considerations

With a persistent-current superconducting magnet it is necessary to have a junction where the winding ends are joined so that the resistance is zero below the critical temperature and at a current necessary to operate the magnet. Many different types of junctions were investigated. The most successful joint was made by stripping the copper cladding off the wire and winding the exposed superconductor into a filament. This filament was then compressed into a matrix of copper with 12 mm of superconducting wire extending through the matrix. The wire that extended through was welded in a helium gas atmosphere. This type of joint has passed a persistent current of 20 A for 3 wk without any noticeable degradation in magnetic field.

IV. Results

Two magnets were developed for the Ku-band maser: one with a 15.2-mm gap and one with a 11.4-mm gap. These two gaps were obtained with different length pole pieces, and the dimensions of the return paths are the same.

Figure 4 shows a measure of successive charging time for the 11.4-mm gap magnet, obtained in 1.5-A steps. For example, for the first step, the current through the shunt was set at 1.5 A while the magnet was in a persistent mode. The bulb was activated, driving the switch normal, and the voltage across the switch was monitored. The time for the magnet to charge is defined as the time from when the superconducting switch went normal until the switch went superconducting (i.e., in a persistent mode). This time is a sensitive measure of the inductance of the magnet and, therefore, of the permeability of the iron. At approximately 8000 ampere-turns the magnetic material (Hiperco 27) begins to saturate. Below 2000 ampere-turns, the permeability has not yet reached its maximum value.

Figure 5 shows the magnetic field versus ampere-turns for the 15.2-mm-gap magnet. At approximately 11,000 ampere-turns, the effective permeability of the magnet is decreasing due to saturation of the Hiperco 27. Correlation of the saturation region between Figs. 4 and 5 can be seen by multiplying the ampere-turns of Fig. 5 by the ratio of the two magnet gaps ($1.14/1.52 = 0.75$). Thus, 11,000 ampere-turns on the 15.2-mm-gap magnet corresponds with 8500 ampere-turns on the 11.4-mm-gap magnet, and it can be seen from Figs. 4 and 5 that the agreement on the saturation regions is good.

V. Conclusions

The use of superconducting magnets in place of external permanent magnets in maser/CCR systems results in: (1) reduced package size, (2) reduced package weight (⅓ of original weight at Ku-band), and (3) improved phase and gain stability. This type of magnet is especially desirable for masers above X-band where the size and weight of permanent magnets become extreme. After field evaluation of the superconducting magnet in the Ku-band maser, the design will be adapted for use in S- and X-band maser/CCR systems.

Reference

1. Cioffi, P. P., "Approach to the Ideal Magnetic Circuit Concept through Superconductivity," *J. Appl. Phys.*, Vol. 33, No. 1, March, 1962.

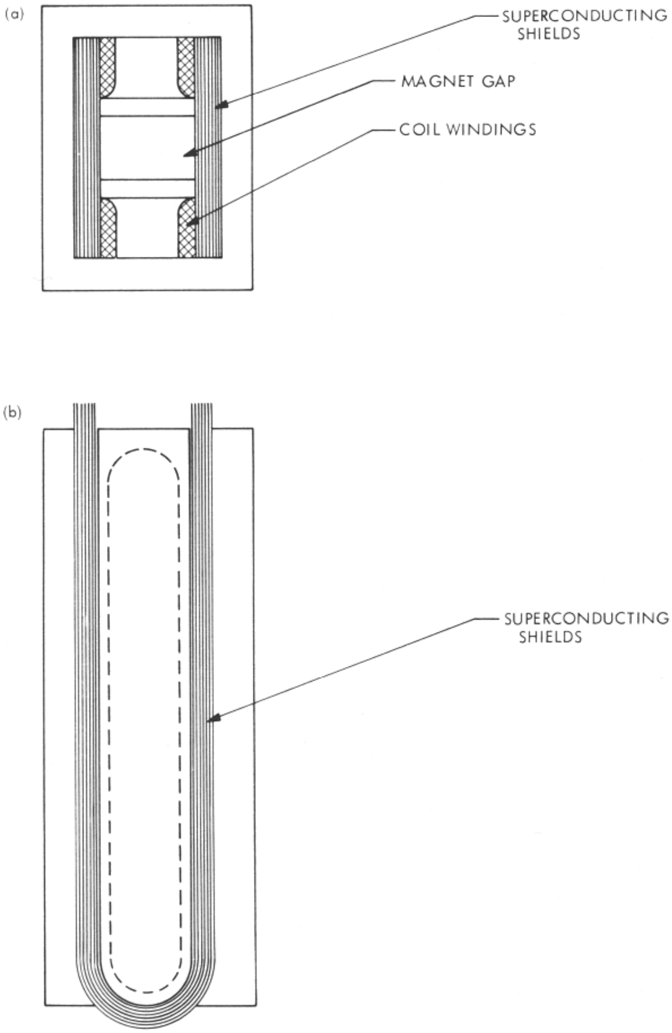

Fig. 1. Cross-sectional and side view of Cioffi-design superconducting magnet

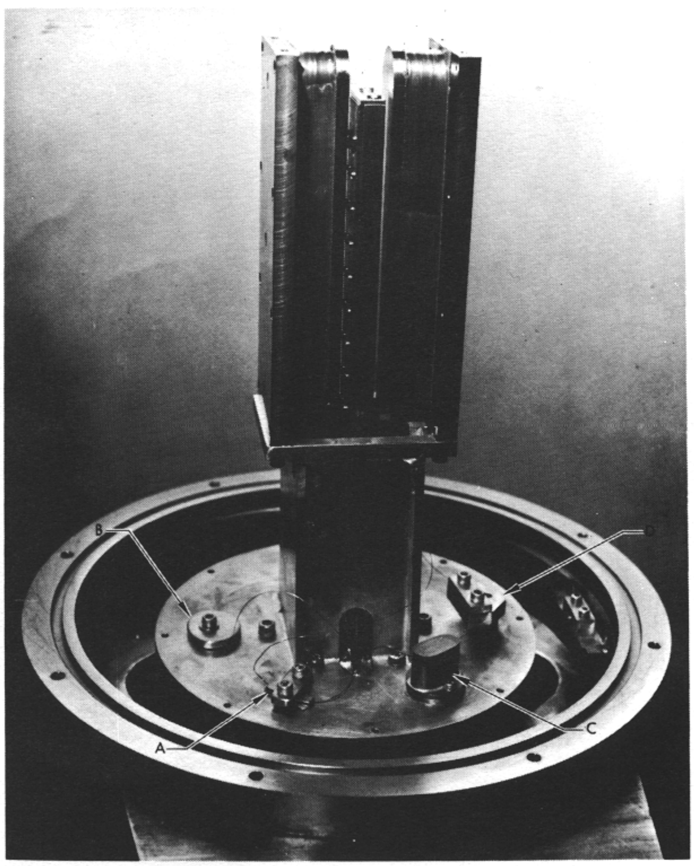

Fig. 2. Superconducting magnet with side return paths and shields removed to show Ku band maser amplifier in gap

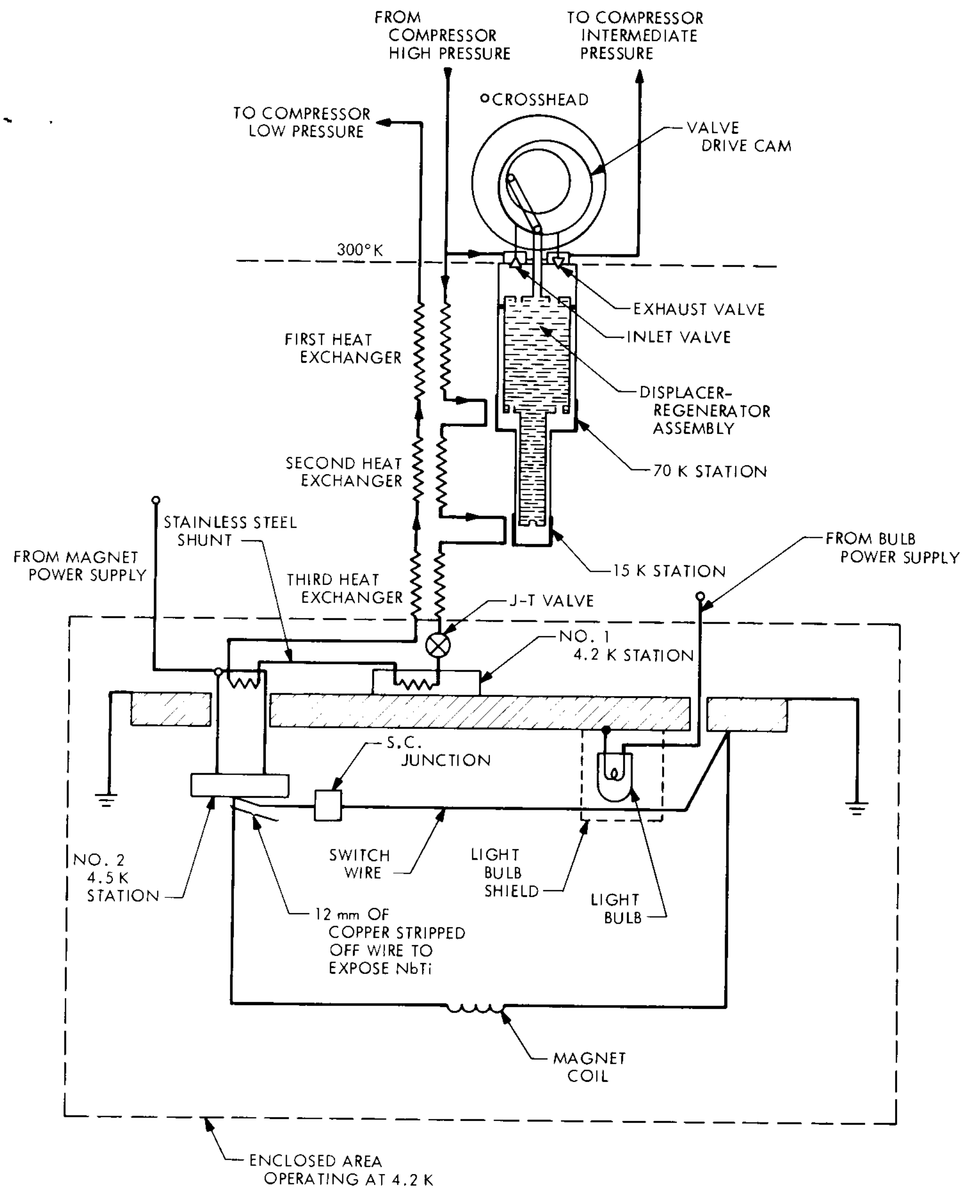

Fig. 3. CCR and schematic of superconducting switch

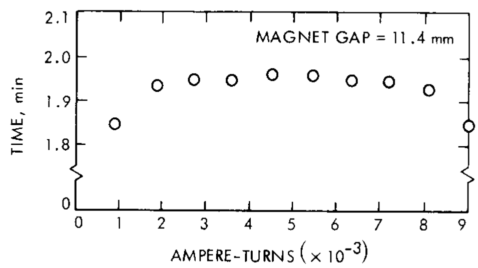

Fig. 4. Charge time of magnet versus ampere-turns in 900 ampere-turn increments

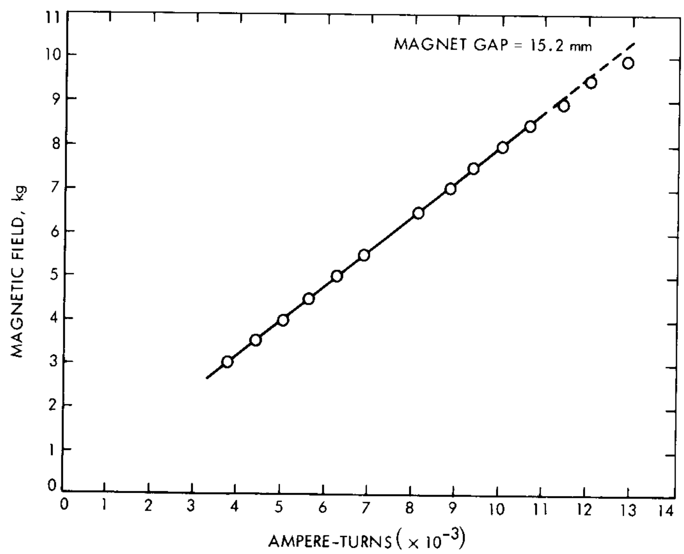

Fig. 5. Magnetic field versus ampere-turns