THE USE OF CRYOGENIC TECHNIQUES TO ACHIEVE HIGH SENSITIVITY IN GRAVITATIONAL WAVE DETECTORS

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Abstract. Cryogenic detectors for gravitational wave astronomy promise greatly improved sensitivity over room temperature detectors. The 3 mK detector which we have under construction should give an improvement of 10^6 over existing detectors. The cryogenic antennae are described and the calculated low temperature performance is detailed. New superconducting instrumentation is described.

1. Introduction

We are embarked on a cooperative program between Stanford University, Louisiana State University and the University of Rome to build large scale gravity wave detectors at each location which can be cooled to the lowest attainable temperature, hopefully the order of 3×10^{-3} K, 3 mK. The calculated sensitivity of these detectors for gravity waves is 0.1 erg cm^{-2} Hz^{-1} (Fairbank *et al.*, 1972; Paik, 1972), which would represent an improvement of 10^6 over existing room temperature detectors. This level of sensitivity would make possible the detection of gravitational wave signals at the level predicted from known astronomical sources, and would offer improved resolution on the events reported by Weber.

In 1959 Joseph Weber (Weber, 1960, 1961) started an experimental program with the purpose of detecting gravitational radiation. His pioneering work during the 1960's led to the development of a mass quadrapole antenna capable of detecting gravitational wave signals with an energy as small as 10^5 ergs cm^{-2} Hz^{-1}. Since 1969 Weber has reported evidence that he is receiving signals of roughly this order of magnitude (Weber, 1970). The large energy associated with these signals have prompted theorists to again look into possible sources of gravitational radiation. We are hearing at this meeting about the results from other room temperature detectors built with similar sensitivities to Weber's.

The most likely theoretical source of high intensity gravitational radiation is gravitational collapse to a neutron star or black hole (Hewish *et al.*, 1968), Supernova, which are thought to be the result of collapse of a star to a neutron star are observed in other galaxies at the rate of one supernova every 30 yr. This is one every few days in the Virgo cluster of 2500 galaxies, but hopelessly rare in a single galaxy. Recently the discovery of X-ray sources (Giaconni *et al.*, 1972) and their binary nature has given us a tool not only to measure the masses of neutron stars but also to identify other collapsed objects, namely black holes (Ruffini, 1972). It has been postulated that many collapses can take place in binary stars without supernovae. The estimate

of collapsed objects which are neutron stars or black holes has been put at approximately 10^9 in our own galaxy on the basis of the experimental evidence. Recently the discovery of bursts of γ rays from outside our solar system (Klebesadal et al., 1973) with energies of 10^{-3} ergs cm^{-2} per burst at the surface of the Earth has raised the question of whether these could be associated with gravitational collapse in our Galaxy. Important theoretical research has paralleled the experimental breakthroughs involving gravitational collapse. The theory predicts in all cases the emission of an energy between 10^{49} and 10^{52} ergs per burst (Ruffini, 1972).

The calculated increase of 10^6 over existing room temperature detectors would enable one to see the details of the bursts of gravitational radiation emitted by collapsing objects in our own Galaxy. This would also make possible the detection of strong signals of the order of a solar mass, 10^{54} ergs, from the nearby 1000 galaxies. It is important to emphasize that there is no better way to inquire about the formation of a collapsed object than to look for the millisecond gravitational waves emitted in the process of formation. This also provides a possible tool to check the relativistic analysis of radiation from particles falling into black holes.

In this paper we wish to show the reasons why a low temperature detector can be built with a theoretical improvement of 10^6 over existing room temperature detectors.

The program to build such detectors at Stanford, Louisiana State University and Rome envisions two and eventually three detectors at each location. This would allow one to monitor continuously all of the observable sources over the sky 24 h a day. Interferometric measurements would give clear indications of the direction of the source for signals sufficiently above noise to determine the phase of oscillation of the individual antennas. The achievement of increased sensitivity might make possible a correlation between gravitational events and astronomical events in the electromagnetic spectrum, providing a basis for a new gravitational wave astronomy.

2. Sensitivity of a Cryogenic Detector

In order to understand the source of the great improvement in the sensitivity of gravitational wave detectors made possible by cooling both the antenna and the receiver to very low temperatures, let us begin with a review of the expressions for the sensitivity of existing Weber type room temperature detectors using piezoelectric crystals as transducers to transform the mechanical energy in the aluminum gravity wave antenna to an electrical signal in the amplifier.

The energy absorbed by the nth vibrational mode of a noiseless gravitational wave antenna of cylindrical shape from an incoming gravitational wave pulse of energy density $F(v_n)$ (erg cm^{-2} Hz^{-1}) emitted by a favorably polarized source whose line of sight is perpendicular to the longitudinal axis of the antenna can be shown to be (Ruffini and Wheeler, 1971)

$$E_s = \left[\frac{8}{\pi} \frac{1}{n^2} \frac{G^2}{c} \frac{v_s^2}{c^2} \right] F(v_n)\, M, \tag{1}$$

where M is the total mass of the antenna, v_s is the speed of sound in the antenna. G is the gravitational constant and c is the velocity of light. n will be set equal to 1 in the following discussion. In this case, for aluminum the above formula becomes

$$E_s = 1.6 \times 10^{-27} \, F(v_n) \, M \text{ ergs cm}^{-2} \text{ Hz}^{-1}. \tag{2}$$

To determine the minimum detectable signal one is interested in the ratio E_s/E_N where E_N is the effective noise energy in the received signal. For Weber type detectors with a piezoelectric pickup it has been shown that (Gibbons and Hawking, 1971; Tyson, 1971; Paik, 1972)

$$\frac{E_s}{E_N} = 1.6 \times 10^{-27} \, F(v_n) \, M \left[\frac{\frac{\pi}{2} \beta Q_A Q_R}{k^1 T_A T_R} \right]^{1/2}, \tag{3}$$

where Q_A is the antenna Q, β is the coupling coefficient of the antenna to the transducer, T_A is the noise temperature of the antenna, T_R is the noise temperature of the receiver, k is Boltzmann's constant and Q_R is the loaded Q of the receiver adjusted for optimum E_s/E_N.

For a piezoelectric crystal of the type used by Weber,

$$\frac{1}{Q_R} = \tan \delta + \omega_n R_s C \tag{4}$$

where $\tan \delta$ is the dissipation factor of the transducer, ω_n is the angular resonant frequency of the antenna, R_s is the series noise resistance of the preamplifier and C is the capacitance of the piezoelectric transducer. Equation (3) suggests all the essential features of the optimization procedure for a Weber type detector. To increase the signal strength, one should increase M consistent with keeping the fundamental resonance in the millisecond region and maximize the term in the brackets.

By cooling to very low temperatures and using a superconducting resonant diaphragm in place of the quartz crystal and a superconducting SQUID (Superconducting Quantum Interference Device) magnetometer with a measured noise temperature less than 10^{-4} K as a parametric amplifier, it is possible to improve not only T_A but also T_R and $\beta Q_A Q_R$. Paik (1972) has analyzed in detail the superconducting diaphragm and SQUID magnetometer being built at Stanford for the 3 mK gravitational wave detector and shown that $\beta Q_A Q_R / T_A T_R$ is theoretically improved over the parameters reported by Weber (1972) for a room temperature antenna by 10^{11}. This coupled with an increase in M from 1.4×10^3 kg to 5×10^3 gives an overall improvement in E_s/E_N of 10^6. This gives for E_s a minimum detectable signal 0.1 erg cm^{-2} Hz^{-1}. An untuned version of the superconducting detector is being built at Louisiana State University. The calculated sensitivity of this detector is equivalent. A third version of the detector is being designed and built at Rome.

An E_s of 0.1 erg cm^{-2} Hz^{-1}, as predicted for the 3 mK gravitational wave detector represents a flux which would be produced by a source at the center of our galaxy which converts $7 \times 10^{-7} \, M_\odot$ or 1.2×10^{48} erg into gravitational radiation in 1 ms

(1 kHz bandwidth). Therefore, as was discussed in Section 1 this detector will enable us to analyze the pulse shape and the polarization of the predicted signals coming from our Galaxy. It should also make possible the determination of the direction of the source and the velocity of propagation of gravity waves through the use of gravitational wave interferometry.

3. Superconducting Transducer

3.1. RESONANT DIAPHRAGM WITH SQUID

The principle of the tuned cryogenic detector is as follows. The energy of the antenna in the observed mode is coupled out to a small resonant mass (niobium diaphragm) tuned to the antenna resonant frequency. The motion of this resonant mass modulates the inductance of a superconducting loop carrying a dc current and this produces an ac magnetic field which is in turn detected with a low-noise superconducting magnetometer. For the details of this system, see the paper by Paik (1972). A schematic diagram of the transducer along with a symbolic representation of the magnetometer is shown in Figure 1. Two flat coils L_1 and L_2 are wound with niobium-titanium wire 0.005 cm in diameter and 0.01 cm away from the two superconducting surfaces
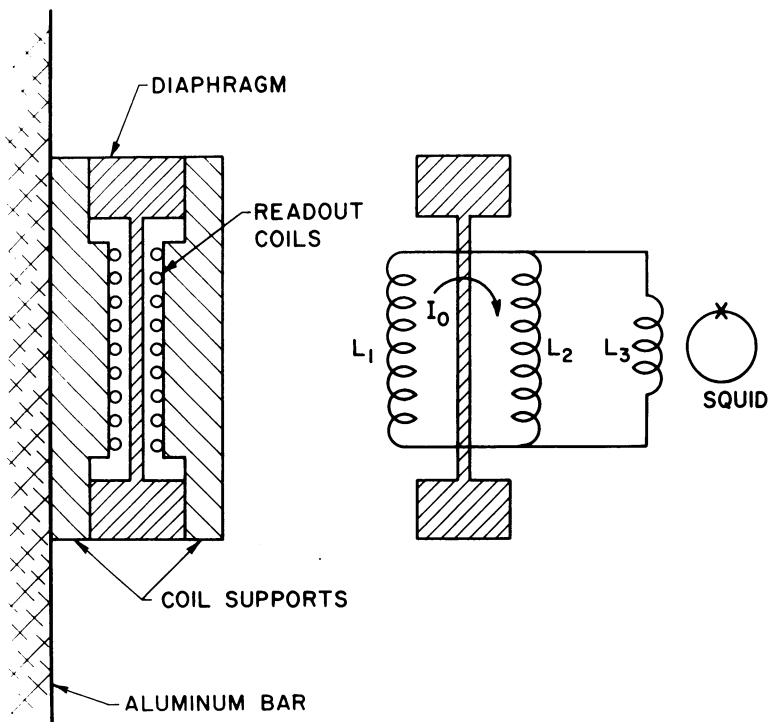

Fig. 1.   Super conducting resonant transducer and SQUID magnetometer.

of the niobium diaphragm. These coils and the circular edge of the diaphragm are rigidly clamped to the end of the aluminum bar. A large persistent current of the order of 5 A is stored in the superconducting loop formed by L_1 and L_2. A third coil L_3 also wound with niobium-titanium wire is connected in parallel with L_1 and L_2 and fed to the SQUID which serves as a parametric amplifier.

As the diaphragm moves back and forth, the inductances L_1 and L_2 are modulated and as a result of flux quantization in the two superconducting loops a net ac current appears in L_3. In turn the magnetic field produced by this current in L_3 is detected by the SQUID magnetometer. The dc current stored in L_1 and L_2 plays the following important roles.

(1) It tends to push the diaphragm away from the two coils L_1 and L_2 thus centering the equilibrium position and allowing the desirable spacing 0.01 cm on both sides of the diaphragm.

(2) The ac energy that appears in the circuit as a result of the diaphragm motion acts as an additional spring by which one can tune the resonant frequency of the diaphragm to the antenna frequency.

(3) A high coupling γ is obtained by means of a large dc current. A persistent current of the order of 5 A should produce $\gamma = 0.95$ and increase the resonant frequency of the diaphragm from 300 Hz to 1350 Hz. We have experimentally confirmed this dependence of the energy coupling and the resonant frequency on the stored dc current.

As is shown by Paik (1972), a high mechanical and electrical Q of the resonant diaphragm is essential in order not to degrade the high Q of the antenna. We have obtained a mechanical Q as high as 3×10^6 after electropolishing the niobium surface and heat-treating it for 10 h at 1800 °C. No dependence of the Q of the transducer on the stored dc current was observed in the low coupling region of $\gamma \lesssim 0.03$. The Q of the transducer remained high when coupled to the SQUID magnetometer amplifier.

It is possible to mount on each gravity wave antenna three resonant diaphragms tuned to the frequencies of the first three longitudinal modes as is indicated in Figure 5. The outputs from the three transducers can be fed into three separate magnetometers. Because of its quadrupole character, a gravitational wave will excite only odd harmonics whereas seismic and most other disturbances will excite all the modes within the frequency spectrum of the pulse. Equation (1) shows that the cross section for the nth mode is reduced by $1/n^2$ from the value for the fundamental mode. So our detector should still be sensitive to these higher modes and give additional information on the pulse shape of a signal.

The magnetometer sensor (SQUID) to be used in our tuned detectors is a toroidal cavity cut between two solid niobium blocks with a weak link at the center. The noise temperature of a SQUID magnetometer has been measured to be less than 1 mK (see Zimmerman, 1972; Giffard et al., 1972). For details of the principles of operation and present state of the art of 30 MHz SQUID magnetometers see the above article and the article by Silver and Zimmerman (1967).

3.2 Single axis superconducting accelerometer

We have also constructed a uniaxial accelerometer which has sufficient sensitivity to detect the Brownian motion of the detector bar at 2 K and which should, when the temperature is reduced, detect the bar motion at 3 mK. The detector diagram is shown in Figure 2.
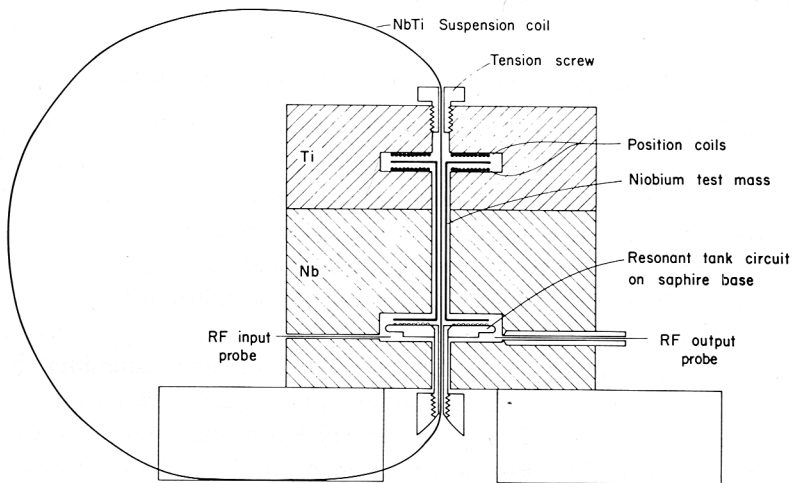

Fig. 2.   Non-resonant superconducting transducer.

A superconducting wire carries a persistent current whose magnetic field acts to levitate the niobium spool. The spool then is tightly bound in directions perpendicular to the wire and can move without friction along the wire. If the accelerometer case is bounded to the end of the bar with the wire perpendicular to the bar, the case will move with the bar while the spool maintains a fixed position in inertial space. A superconducting inductance is mounted on the case and its inductance is then modulated due to relative motion of the case and the niobium spool. The position of the spool with respect to the inductance can be adjusted by the position coils at the back of the spool.

The sensitivity of this accelerometer is determined by the accuracy to which a small change of inductance can be measured. The inductance can be made a part of a resonant circuit so that the resonant frequency changes with the motion of the bar. The use of superconducting circuits allows this sensitivity to be very high because of the high Q which can be obtained for superconducting circuits.

We have constructed a prototype model of this accelerometer and obtained a Q in excess of 10^4 for the varied inductance which enables us to measure bar deflections as small as 10^{-15} cm at 2 K. This calculated sensitivity has not yet been directly measured because the lack of vibration mounting on the prototype caused an excessive mechanical noise level. This situation is being improved and new measurements are underway. We have also constructed a low noise MOSFET amplifier which works while immersed in liquid helium and are using this to detect the amplitude

change of the tuned circuit when it is driven by a constant current generator. Detailed calculations of the performance of this detector when mounted on the 3 mK gravitational antenna indicate a sensitivity 30 dB below kT providing that the oscillator noise can be effectively reduced or balanced out. This sensitivity is comparable to that of the resonant detector already described. The position coils can also be actuated so as to resonate the spool at the mechanical frequency of the bar.

4. Magnetic Support and Superconducting Shield

The magnetic support system for the antenna consists of a set of persistent superconducting coils and a layer of superconducting Nb–Ti on the surface of the aluminum bar. Interaction of the current in the coils with image currents in the Nb–Ti provides the supporting force. Because the coils maintain constant magnetic flux linking them, increasing the height of the bar decreases the currents flowing in the support coils and consequently the supporting force until at the equilibrium height the support force balances the weight of the bar.

Extensive studies of the support system have been made on an aluminum bar 23 cm long and 15 cm in diameter. This bar and the support system are shown in Figure 3. Piezoelectric crystals are attached to the bar which is coated with a 0.04 cm layer of plasma-sprayed Nb–Ti. This assembly is inserted into a cradle which is fitted with a persistent levitation coil made of 0.06 cm × 0.13 cm copper-clad Nb–Ti wire. Another coil is mounted above the bar to simulate the effect of a heavier bar. These studies showed that the system was capable of supporting a 40 cm diameter bar with a considerable safety margin. Further, the mechanical Q of the bar while supported was observed to be unaffected by the Nb–Ti layer. At low temperature the observed Q in a vacuum environment was 6×10^5.

PERSISTANT TOP COIL

POSITION SENSORS (CAPACITIVE)

PIEZOELECTRIC SENSOR

STABILIZING END COIL

ALUMINUM BAR
15 cm dia x 24 cm LONG
COATET WITH
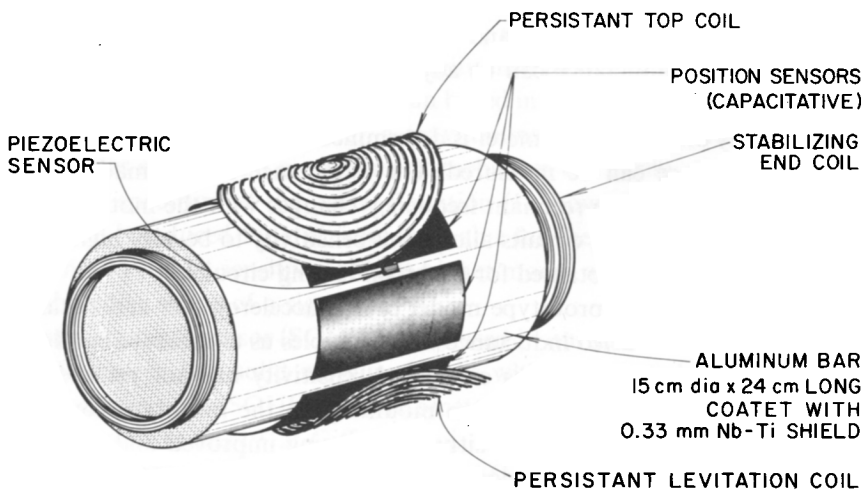0.33 mm Nb-Ti SHIELD

PERSISTANT LEVITATION COIL

Fig. 3. Superconducting magnetic levitation system for test bar.

The field required to support a 40 cm diameter aluminum bar is about 2400 G; hence, the requirements on the superconducting coils are quite modest. We use 0.06 cm by 0.13 cm rectangular wire with a low field current capacity of 700 A, while only ~125 A are required to create a 2400 G field. For comparison a 1 m diameter bar requires a supporting field of 3400 G and a current of 170 A. Further experimentation with plasma spray technique has now enabled us to construct a shield which will exclude fields in excess of 3400 G and could thus be able to support a 1 m diameter bar.

The magnetic support has a natural resonant frequency associated with it which can be explained as follows. The magnetic flux is essentially trapped between the magnet coils and the surface of the bar. Any change in the height of the bar compresses the flux and increases the field strength at the surface of the bar. This in turn increases (or decreases) the force on the bar. The change in force F is $\Delta F \simeq F\, \Delta x/x$ where x is the distance from the bar to the coils. Hence there is an effective spring constant $K = F/x$. The resonant frequency is $\omega = (K/M)^{1/2} = (Mg/Mx)^{1/2} = (g/x)^{1/2}$. If $x \sim 1$ cm then $\omega \sim 30\ \mathrm{s}^{-1}$ or $\omega/2\pi = 5$ Hz $(g = \text{gravitational acceleration} \sim 10^3\ \mathrm{cm\ s}^{-2})$.

The magnetic support just described provides a number of important advantages over other means of support. Excellent mechanical isolation from vibrations at the 1350 Hz resonant frequency of the bar is achieved because of the low resonant frequency (approximately 5 Hz) of the support system and the absence of a direct acoustical path for higher frequency vibrations. Because the support forces are distributed along the bar, there is a relatively small coupling between the support coils and the bending modes of the bar. Distributing the support forces also minimizes acoustic emission arising from stresses induced in the bar by the support. Finally the magnetic support system provides thermal isolation to allow further cooling of the detector.

In addition to the magnetic support system, a cryogenic environment allows us to employ a superconducting Pb shield around the entire liquid helium dewar. This will provide excellent isolation from low frequency electromagnetic disturbances from outside the dewar. In particular this will make the antenna immune to changes in the Earth's ambient magnetic field. High frequency isolation is achieved automatically by the metal vacuum jacket of the entire system.

5. Cryogenic System

Figure 4 shows an end-on schematic view of a system to cool the prototype gravitational wave antenna to 1.2 K. Such a system is being assembled at Stanford.

The gravitational antenna consists of an aluminum bar 40 cm in diameter and 2 m long. The bar is coated with niobium titanium and floated on a superconducting magnet as was described in Section 4. The superconducting magnet is supported on a cylindrical aluminum container which contains liquid helium between two concentric aluminum cylinders. The helium container is supported by springs and acoustical filters in the vacuum system from an external beam which is supported by
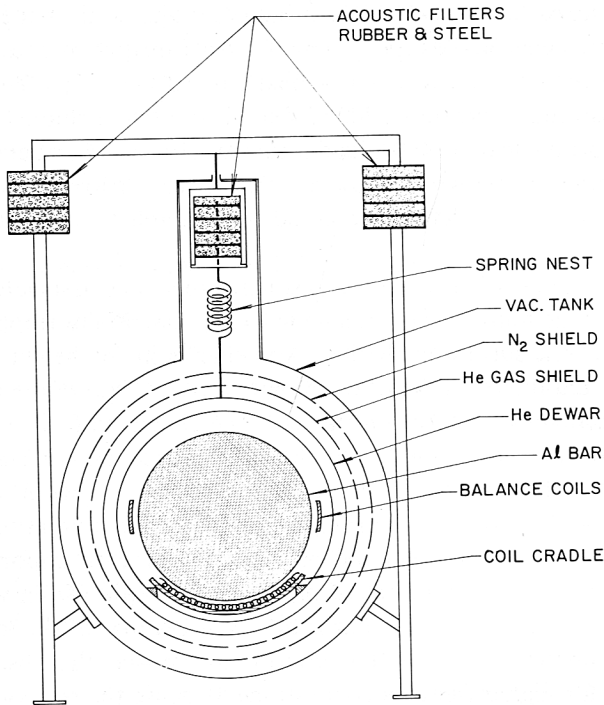
ACOUSTIC FILTERS
RUBBER & STEEL

SPRING NEST
VAC. TANK
N$_2$ SHIELD
He GAS SHIELD
He DEWAR
Al BAR
BALANCE COILS
COIL CRADLE

Fig. 4. Schematic of 1.2 K gravitational wave detector showing dewar and support system.

acoustic filters consisting of alternate layers of rubber and iron. The helium container is surrounded by a gas cooled shield which is cooled by the evaporating helium gas. This in turn is surrounded by a thermal shield cooled by liquid nitrogen. Between each set of shields is superinsulation consisting of several layers of aluminized mylar. Surrounding the helium dewar and in contact with it is a superconducting lead shield.

The dewar for this antenna system is 7 m long and 1 m in diameter on the outside and 60 cm in diameter on the inside. It is a modified superconducting accelerator dewar designed and built for the Stanford superconducting accelerator. Two gravitational wave antennas will be mounted in the single 7 m dewar.

Figure 5 is a schematic diagram of the ultra-low temperature part of the large 3 mK system which is being installed. The gravitational wave antenna consists of an aluminum bar 3 m long and 90 cm in diameter which weighs 5000 kg. This is coated with a superconducting niobium titanium layer about 0.4 mm thick. The bar is supported by a magnetic field of about 3400 G produced by a superconducting magnet. This provides an ideal isolation for vibration and for heat leaks. The bar is surrounded by a thermal shield cooled to 50 mK with a He^3–He^4 refrigerator. Surrounding the 50 mK shield is a shield cooled to 1.2 K by liquid helium. Surrounding the 1.2 K shield is a gas cooled shield, a liquid nitrogen cooled shield and a room temperature vacuum tank as shown in the 1.2 K detector in Figure 4.

The 5000 kg aluminum detector is cooled below 50 mK by a paramagnetic salt in

the form of a toroid surrounded by a toroidal superconducting magnet and a super-conducting shield. The magnet is turned on when the bar is in thermal contact with the He^4 bath. The heat of magnetization is removed at this temperature. He^4 exchange gas provides thermal contact between the He^4 bath and the He^3–He^4 cooled shield (50 mdeg shield). When it is desired to cool the 50 mK shield below the He^4 bath temperature the He^4 exchange gas is pumped out. He^3 exchange gas provides
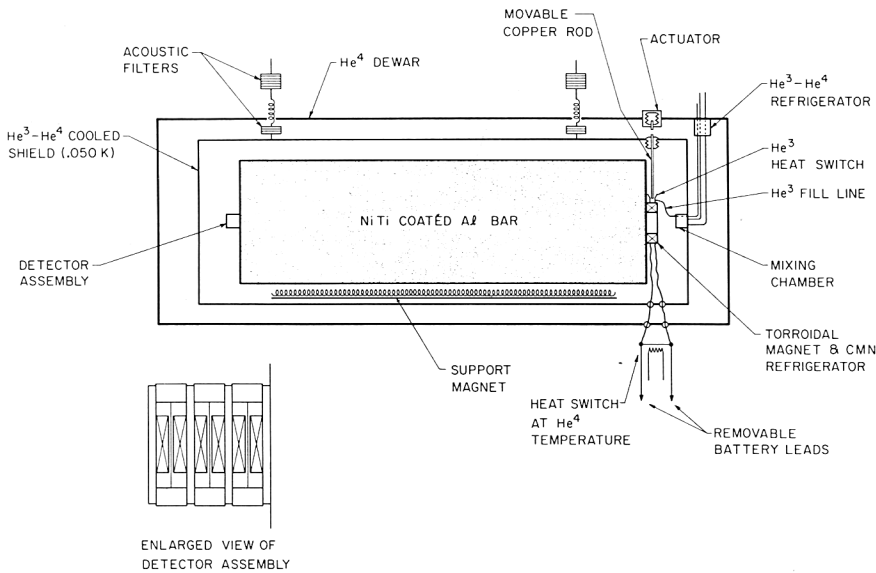

Fig. 5.   Schematic of 3 mK gravitational wave detector and ultra low temperature part of dewar system.

thermal contact between the 50 mK shield and the aluminum bar. When the shield is cooled below 0.2 K by the He^3–He^4 refrigerator the He^3 exchange gas condenses out providing an effective heat switch. In order to cool the aluminum bar and salt below 0.2 K a mechanical He^3 heat switch is used as shown in Figure 5. A copper rod connects the 50 mK shield with the paramagnetic salt via a pool of He^3 into which the rod is pushed. When the bar and salt are cooled to 50 mK, the copper rod is withdrawn from the He^3 providing an effective heat switch. To cool further the magnet is slowly degaussed by means of heating a switch in the He^4 bath on the superconducting magnet. This thermal switch allows the superconducting magnet to decay slowly, cooling the salt and the aluminum bar. The salt may consist of cerium magnesium nitrate thermally mixed with liquid He^3 or it may consist of solid metallic paramagnetic salt which can be soldered to the container for good thermal contact. The salt when it is cold provides a large thermal reservoir to keep the bar cold for a calculated time of the order of 1 month.

Calculations on the amount of refrigeration required to cool the 5000 kg gravitational wave antenna may be of interest. Using only the latent heat of the liquid ni-

trogen it takes about 7000 l of liquid nitrogen to cool the dewar and bar to 63 K, the triple point of nitrogen. To cool from 63 K to 4 K using the heat of vaporization of liquid helium plus the specific heat of the helium vapor assuming perfect heat transfer requires 600 l of liquid helium. To cool from 4 to 1 K requires approximately 1 l of liquid helium. To cool from 1 K to 50 mK requires the removal of 137 joules with He^3–He^4 refrigerator plus the heat required to cool the paramagnetic salt. The He^3–He^4 refrigerator is designed to remove 10^5 ergs s^{-1} at 1 K, 5.5×10^4 ergs s^{-1} at 0.5 K and 500 ergs s^{-1} at 50 mdeg. Therefore it will take a few hours to cool from 1 K to 50 mK. To cool the aluminum bar from 50 mK to 3 mK requires a negligible amount of paramagnetic salt, less than one gram. The large amount of cerium magnesium nitrate which will be used (the order of 20 kg) will provide a larger thermal reservoir to keep the bar cold for an extended period of time.

The calculated heat leak into the 3 mK detector is dominated by cosmic rays. Assuming the dewar is surrounded by 15 cm thick lead shield, the heat leak into the bar from cosmic rays is about 0.8 ergs s^{-1}. The heat leak from radiation from the 50 mK shield is approximately 10^{-6} ergs s^{-1} assuming an emissivity of 0.05. The calculated heat leak from the leads connecting the magnetometer and the superconducting magnet with the external system via the 50 mK shield is also negligible. Preliminary experiments with a superconducting support lead us to believe that the heat leak from the magnetic support will also be negligible. If this should turn out to be the case then the total heat leak will be less than 1 erg s^{-1}. Under these conditions 30 kg of cerium magnesium nitrate would provide a thermal reservoir of sufficient heat capacity to keep the antenna below 5 mK for the order of 1 month. At this point the superconducting magnet would be turned on, the heat of magnetization removed and the salt again demagnetized to 3 mK. The turn around time for this operation will be limited by the capacity of the He^3–He^4 refrigerator and should be only a few hours. The thermal time constant for the aluminum bar at 1 K and below is calculated to be only a few milliseconds. Thus thermal equilibrium times are not limited by the large antenna but by the thermal boundary resistances between the paramagnetic salt and the antenna. Either cerous magnesium nitrate immersed in liquid He^3 as a heat transfer agent or a metallic paramagnetic refrigerant such as praseodymium copper 6 ($PrCu_6$) which can be soldered for thermal heat transfer could be used.

In summary, it appears theoretically possible to cool even a large antenna of 5 tons to a few millidegrees and keep it cold for long periods of time providing the ideal vibration isolation required for the gravitational wave experiments is realized.

6. Conclusion

We have considered the advantages of cooling a gravitational wave antenna to very low temperatures and have shown that it is theoretically possible to increase the sensitivity by 10^6 over room temperature detectors, while at the same time achieving ideal electrical and mechanical isolation. We have outlined the technique for cooling

and have attempted to show that cooling to a few millidegrees and maintaining that temperature appears completely feasible.

It appears possible with this increased sensitivity to observe predicted events with sufficient signal-to-noise resolution to enable phase measurements to be made. Such measurements made simultaneously at each of the three locations at which the antennas are being built would enable an interferometric determination of the direction of the source. This might make possible a correlation between gravitational events and astronomical events in the electromagnetic spectrum, providing a basis for a new gravitational wave astronomy.

Acknowledgements

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