

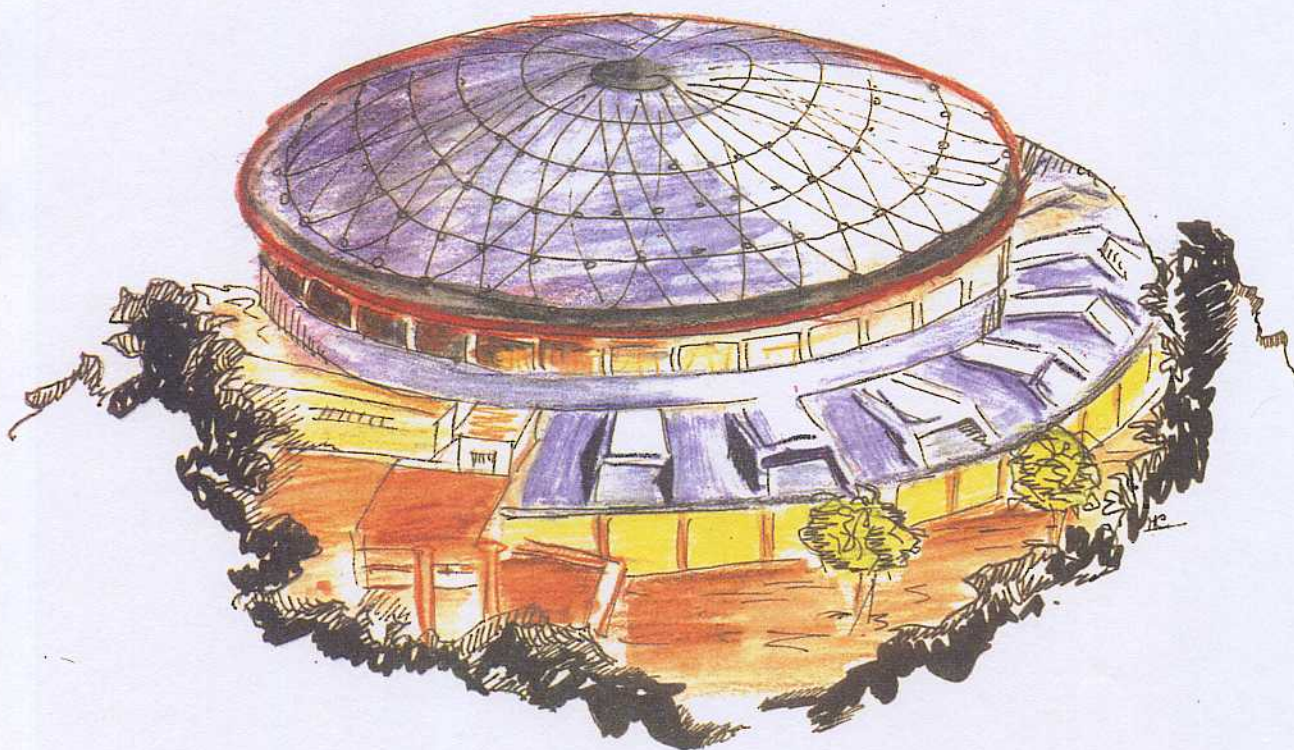
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"NAUTILUS" THE FIRST ULTRACRYOGENIC GRAVITATIONAL WAVE DETECTOR

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"NAUTILUS"
THE FIRST ULTRACRYOGENIC GRAVITATIONAL WAVE DETECTOR

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ABSTRACT

We report on the ultralow temperature resonant gravitational wave antenna NAUTILUS of the Rome group. The goal of this antenna is to detect bursts of gravitational radiation from sources located at distances up to the Virgo cluster of galaxies.

In the first cryogenic test of this detector at ultralow temperatures, performed in 1991, the M=2350 kg, Al 5056 cylindrical bar has been cooled to a temperature of 95 mK.

The detector is now installed at its operating site in the Frascati INFN Laboratories, where it has been placed on a special rotating platform. NAUTILUS is equipped with a resonant capacitive transducer and a dc SQUID preamplifier and is completed with seismic, electromagnetic and cosmic ray veto systems. It should start operating in 1993.

INTRODUCTION

The goals of a gravitational wave (g.w.) experiment are to verify directly the existence of gravitational radiation and to use this new tool for astronomical observations. The strongest detectable effects are thought to be burst events generated by supernovae explosions (SN) and coalescing close binaries [1]. The achievement of a reasonable rate of detected events implies to extend the observing range beyond our Galaxy and the Local Group of galaxies. In particular the aim of the detectors being presently developed is to observe events occurring at distances up

to the Virgo Cluster (2500 galaxies at $\sim 10\text{Mpc}$), with a rate of several events per month. The expected g.w. amplitude in these cases is of the order of $h \sim 10^{-21}$.

After many years of tests, developments and observations with sensitivities of $h \sim 10^{-18} - 10^{-19}$ [2,3], two types of g.w. observatories are in preparation, one type using large laser interferometers and the other one using ultralow temperature resonant antennae.

We recall here that a resonant antenna consists of a carefully suspended resonant mass object, usually a cylindrical bar, whose vibrational normal modes having the appropriate symmetry should be excited by g.w. bursts of extraterrestrial origin [4].

A resonant detector measures the Fourier transform $H(\omega)$ of the metric tensor perturbation $h(t)$ at the frequency of the observed vibrational mode ω_0 . According to the classical cross section theory [5], the sensitivity of the first longitudinal mode of vibration of a cylindrical bar can be expressed [6] by

$$H_{\min} = \frac{L}{v_s^2} \left(\frac{kT_{\text{eff}}}{M} \right)^{1/2}$$

where

M is the mass of the bar,

L its length,

v_s is the speed of sound in the bar material and

T_{eff} is the detector effective temperature, representing the effective energy fluctuation of the observed mode.

In a simplified form T_{eff} can be written as [7,8] :

$$T_{\text{eff}} = \frac{T}{\beta Q} + 2 T_n$$

where

T is the bar thermodynamic temperature,

Q is the mode quality factor,

β is the ratio of the electromagnetic energy in the vibration transducer to the antenna total energy,

T_n is the noise temperature of the electronic amplifier connected to the transducer.

The low thermodynamic temperature is necessary to reduce the thermal fluctuations in the antenna (brownian noise). Moreover at low temperature it is possible to take advantage of the steep increase of the quality factor Q for aluminium alloys [9], and also to use very low noise parametric amplifiers based on the Josephson effect (SQUIDs).

The strategy of the Rome group to obtain a strain sensitivity of the order of 10^{-21} (which means an energy captured by the antenna as low as 10^{-31} J) implies the use of the highest Q aluminium alloy as antenna material (Al 5056), the use of a resonant capacitive transducer [10] with $\beta \sim 10^{-2}$, the development of a dc SQUID amplifier [11] with noise temperature near to the quantum limit ($T_n \sim \hbar \omega_0 / k \sim 10^{-7} \text{ K}$) and the cooling of the bar below 0.1 K.

In the years 1982–1984 a feasibility study was conducted to establish the technical possibility of the cooling of a multiton Al 5056 bar to milliKelvin temperatures [12]. In 1986 INFN financed the Rome group project of an ultralow temperature antenna, NAUTILUS. In 1989/91 the detector, constructed in Italy, was assembled and tested to ultralow temperatures in the CERN laboratories [13].

This detector is now installed in its operating site at LNF and is ready to start a first period of observations.

THE CRYOGENIC SYSTEM

A layout of the cryogenic apparatus is shown in Fig. 1. The relevant feature of the cryostat is its central section, which is shorter than the cylindrical bar antenna (hereafter indicated as the bar) itself. This section contains two helium gas cooled shields, the liquid helium (LHe) reservoir (2000 liters of capacity), three OFHC copper massive rings and, through the top central access, a special ^3He - ^4He dilution refrigerator [14]. End caps are fastened at each stage of the cryostat to complete the seven shields surrounding the bar. The shields are suspended to each other by means of titanium rods and constitute a cascade of low pass mechanical filters. The overall mechanical vibration isolation at the bar resonant frequency (about 900 Hz) is of the order of -260 dB.

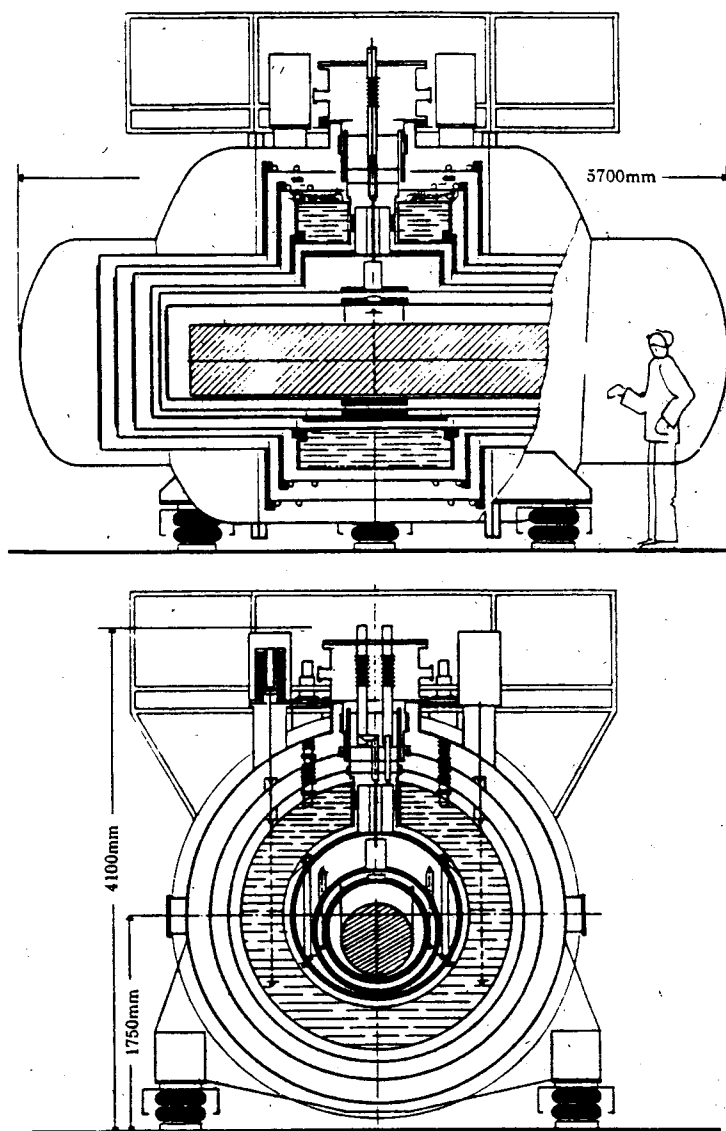


FIG. 1 - Layout of the NAUTILUS apparatus.

The first copper shield is thermally anchored to the 1 K pot of the refrigerator. The intermediate and inner shields are in thermal contact with two step heat exchangers of the

dilution refrigerator; the mixing chamber [15] cools the bar by means of an OFHC copper rod wrapped around the bar central section. The thermal path in these cases is constituted by soft multiwire copper braids, in order to minimize the transmission of mechanical vibrations to the bar (see Fig. 2). We recall here that the bar has a mass of 2350 kg, length of 3 m and diameter of 0.6 m.

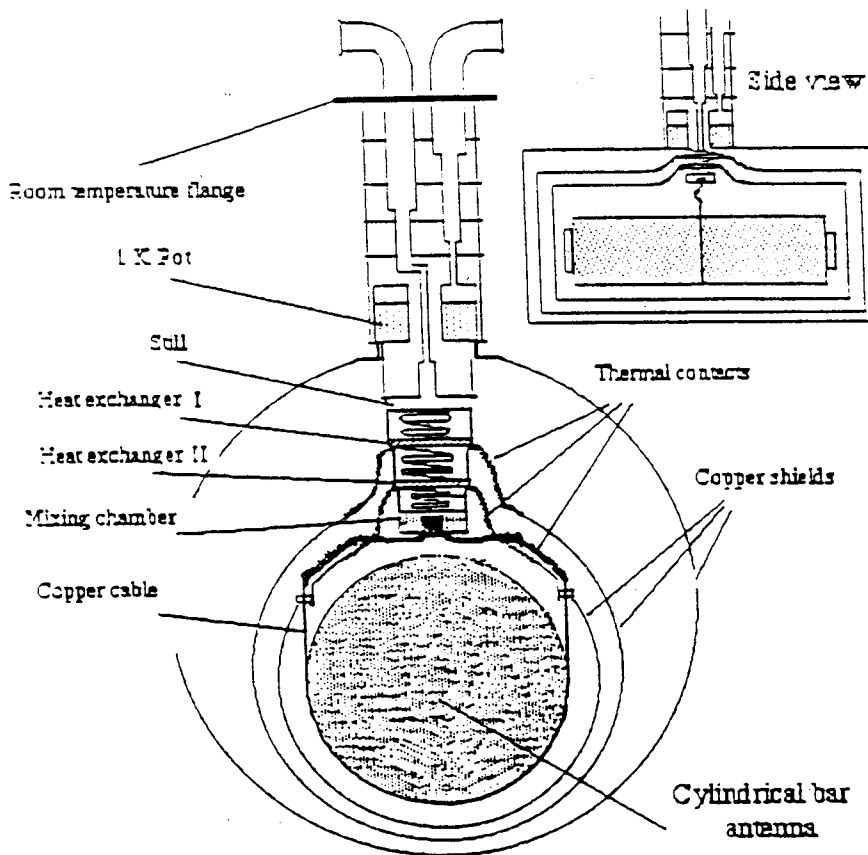


FIG. 2 – Schematic layout of the dilution refrigerator and its connections to the cylindrical bar and to the three copper shields. The shields are suspended each other and are cooled by different stages of the refrigerator. The external shield (2090 Kg) is cooled to 1.3 K by the 1K pot, the heat exchanger I cools to about 350 mK the intermediate shield (860 Kg) and the heat exchanger II cools to about 180 mK the internal shield (800 Kg) surrounding the bar, which (2350 Kg) is cooled to below 100 mK by the mixing chamber, via the copper cable suspension.

Fig. 3 shows the bar temperature during the first cool-down. About three weeks were needed to reach 77 K, using 8000 liters of liquid nitrogen, and about one week to achieve 4.2 K, using about 5000 liters of LHe. We then kept the bar temperature in the range 4.2–8 K for about two weeks, to perform various tests.

On February 18, 1991, we started the ultralow temperature cooling. The initial temperatures of the bar and of the three copper shield were about 8 K. We filled the 1 K pot with LHe at low pressure and started to condense and circulate the ^3He – ^4He mixture in the dilution refrigerator. After three days the calibrated Ge thermometers indicated a temperature of 95 mK on the bar end face and of 63 mK on the mixing chamber. As far as we know, it is the first time that such massive bodies are cooled to these very low temperatures.

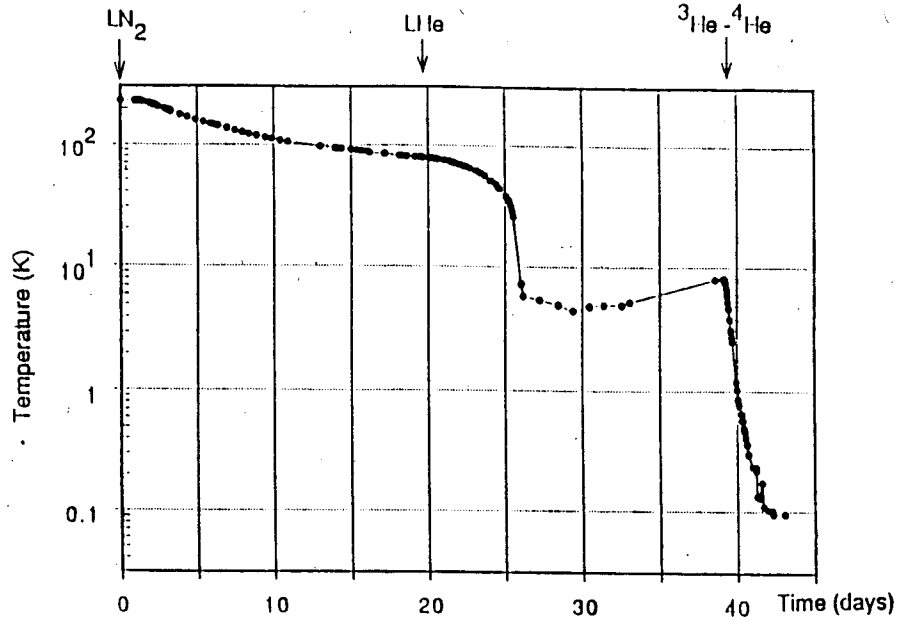


FIG. 3 – Temperature of the cylindrical bar versus time during the first cryogenic test. The arrows indicate the main cryogenic operations, described in the text.

The observed features of the cooling agree with an earlier model [16]. From the measured thermal gradient between the mixing chamber and the bar end (about 30 mK) we deduce an upper limit of $10\mu\text{W}$ for the antenna heat leak (corresponding to $1.7\mu\text{Wm}^{-2}$).

The overall LHe evaporation rate at regime was 50 litres/day.

We remark that in this run we could not optimize the ^3He flow, because of an electrical short in the still heater, so that all of the above results were obtained with a reduced refrigerator cooling power. We think that a bar temperature of about 50 mK is possible.

NAUTILUS AT LNF

NAUTILUS has been moved in the late spring 1992 to LNF, where a large cryogenic facility has been activated.

In this new site (41.5N, 12.4E) the detector is placed on a specially designed platform which can rotate for the proper orientation of the detector with respect to either an array of detectors or even a fixed source.

The detector is completed with seismic, electromagnetic and cosmic rays veto systems.

The need for a cosmic rays detector is due to the fact that extensive air showers or energetic single particles (muons or hadrons) interacting in the antenna may produce signals with rates which increases with the increasing sensitivity of the antenna to g.w. [17,18,19]. For instance with a NAUTILUS sensitivity of $T_{\text{eff}} \sim 1\text{ mK}$, about 1 cosmic ray event per day is expected. This rate increases to 10^3 when $T_{\text{eff}} \sim 1\mu\text{K}$ and to 10^5 if the quantum limit $T_{\text{eff}} \sim \hbar\omega_0/k \sim 0.1\mu\text{K}$ is reached.

The veto system consists of two layers of streamer tubes for a total of 102 counters. The first layer is located on the top of the cryostat, the dimension are $6 \times 6\text{ m}^2$. The second layer is under the cryostat, the dimensions are $6 \times 2.5\text{ m}^2$. The system detects about 50% of the single track events leaving in the antenna more than 10 Gev (corresponding to $T_{\text{eff}} \sim 1.5\mu\text{K}$). For extensive air shower the efficiency is almost 100%.

The general layout of the experiment is shown in Fig. 4.

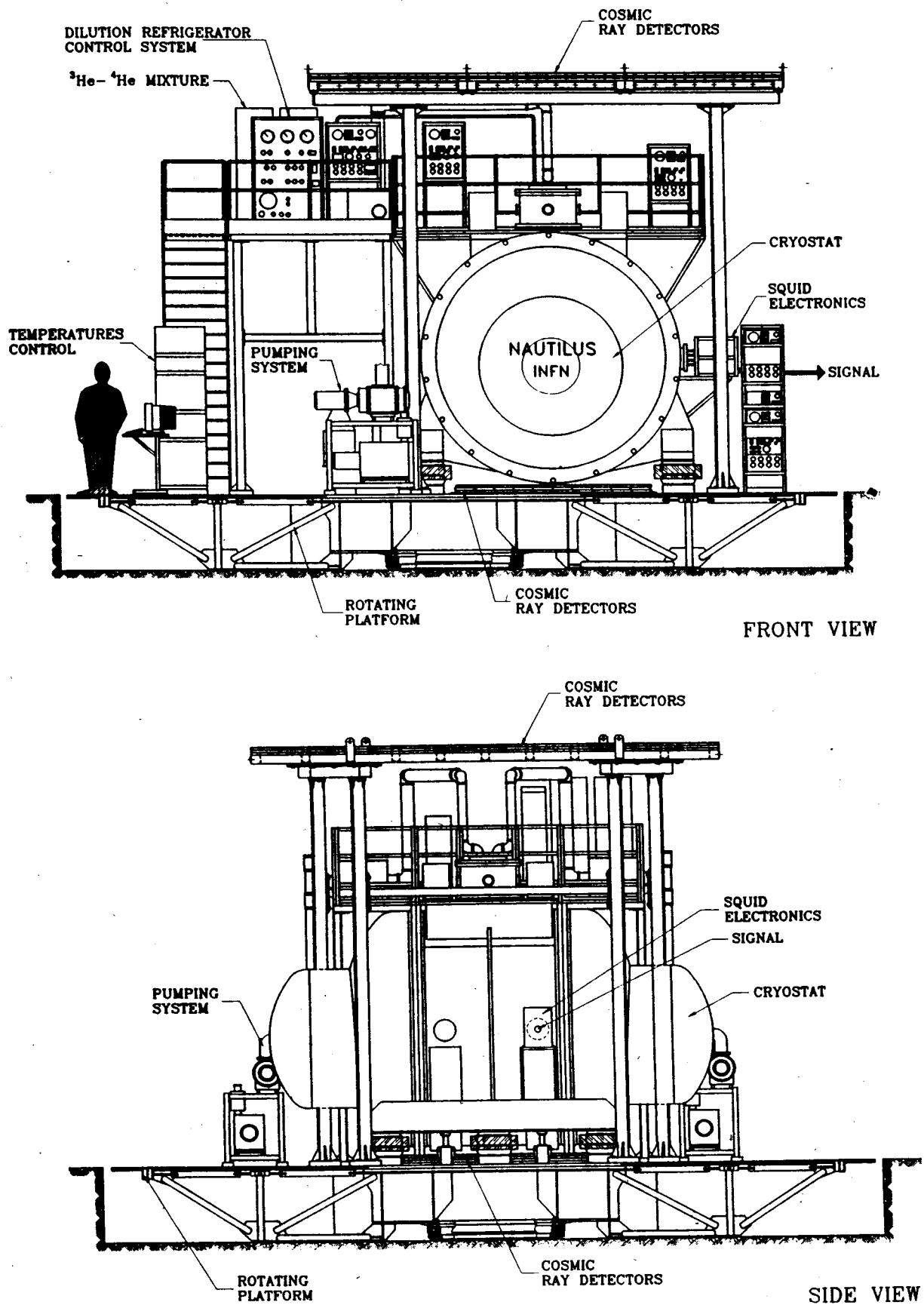


FIG. 4 - General layout of the NAUTILUS detector installed in the experimental Hall 8 at LNF.

NAUTILUS is equipped with a resonant capacitive transducer and a dc SQUID amplifier, following the electronics configuration developed for the EXPLORER detector, presently in operation at CERN [2,3]. We recall (see Fig. 5) that the vibrations of the bar are converted into electrical signals by the capacitive transducer, resonating at the antenna frequency in order to improve the energy transfer from the bar to the electronics. Bar and transducer form a system of two coupled oscillators. The signals are applied to the input coil of the dc SQUID amplifier by means of a superconducting transformer, which provides the required impedance matching. The output signal from the SQUID instrumentation contains the informations on the vibrational state of the antenna and can be properly processed [20].

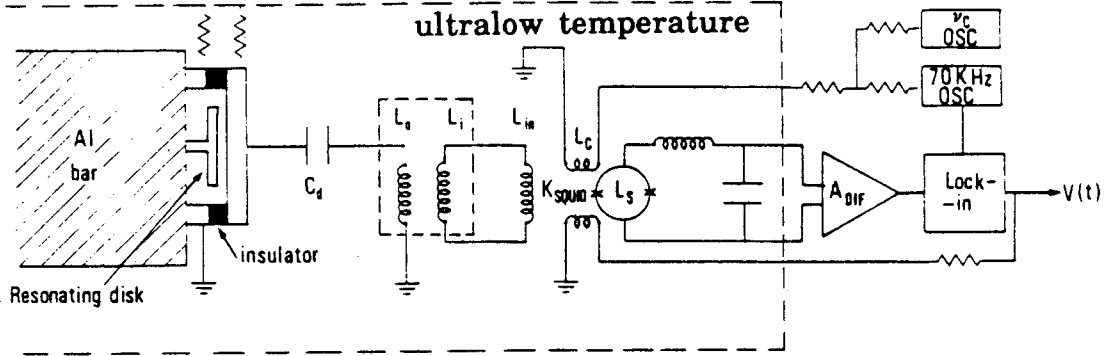


FIG. 5 – Electrical scheme of the experimental apparatus. The vibrations of the bar are converted into electrical signals by a capacitive transducer, resonating at the antenna frequency in order to improve the energy transfer from the bar to the electronics. Bar and transducer form a system of two coupled oscillators. The signals are applied to the input coil of a dc SQUID amplifier by means of a superconducting transformer, which provides the required impedance matching. The output signal from the SQUID instrumentation contains the informations on the vibrational state of the antenna and can be properly processed.

The effective temperature in the first run, planned at the beginning of 1993, should be of the order or less than 1 mK.

In Fig. 6 the pulse sensitivity (one sinusoidal cycle) of the detector at the quantum limit is shown.

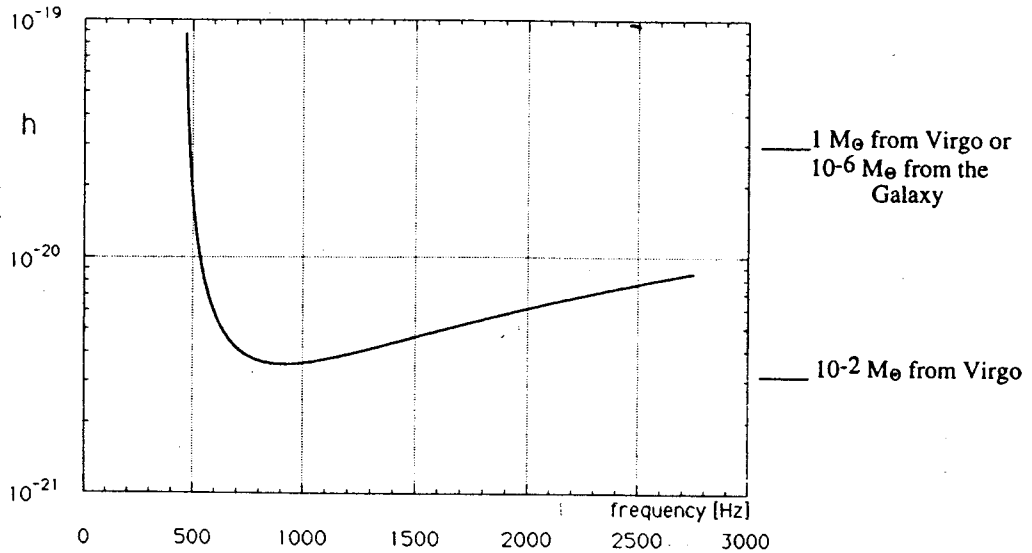


FIG. 6 – Planned sensitivity of NAUTILUS to g.w. pulses. It is assumed that the pulse consists of one sinusoidal cycle with the frequency reported on the abscissa. On the right we report the expected g.w. amplitudes at the Earth corresponding to the conversion of solar masses into g.w. isotropically emitted from the indicated distances.

It is crucial for the unequivocal detection of gravitational waves that various detectors operate in continuous and well coordinated coincidence. In particular it is natural to plan in the near future measurements in coincidence with the similar ultralow temperature antenna AURIGA in preparation at LNL (INFN Laboratori Nazionali di Legnaro, near Padova) and with the antenna in preparation at the Stanford University.

ACKNOWLEDGEMENTS

The NAUTILUS experiment has been the natural last step of an experimental activity started in 1970 for initiative of Edoardo Amaldi. We wish to remind here his important role in this research.

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We thank Franco Bronzini for his contribution to the design of the cryogenic apparatus. We thank Antonino Aragona, Bruno Dulach, Sergio Faini and their collaborators of LNF for the precious contributions to the installation of the experiment.

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