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Cabling for cryogenic Virgo

R. Poggiani [1]

[1] *University of Pisa and INFN Pisa*

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VIRGO - A joint CNRS-INFN Project
European Gravitational Observatory, Via E.Amaldi, 56021 S.Stefano a Macerata - Cascina (Italy)
Secretariat: Telephone (39) 50 752 325, FAX (39) 50 752 550, e-mail virgo@ego-gw.it

1 Introduction

The large number of sensing and control systems in cryogenic Virgo will require thousands electrical connections. Cryogenic Virgo will include sensing wires with negligible current, but also coils and actuators with high current and larger heat load. An excessive thermal load can lead to high wire temperatures and risk of insulation damage.

Electrical connections must fulfill the standard mechanical and vacuum requirements of Virgo:

- high flexibility
- low hydrocarbon contamination

But also:

- low thermal conductivity, to reduce heat budget from external environment
- low electrical resistivity, to reduce heat injection via Joule heating
- capability to resist to large thermal contractions
- ability to operate for years at temperatures as low as 4 K, with thermal cycling

Addressing the cabling in cryogenic Virgo will require a detailed study to define several parameters: definition of electrical connections (signal cabling, power cabling etc); electrical parameters; maximum allowed thermal dissipation; mechanical stiffness; maximum allowed contamination.

2 Some guidelines for design

We will focus on the thermal and electrical constrains on cryogenic leads cooled by conduction. For sake of simplicity, we will consider an homogeneous wire with constant cross sectional area A and length L, resistivity $\rho(T)$, thermal conductivity $k(T)$, where T is the temperature, assumed to be a function of axial position only. The axial position x is measured starting from the cold end. We will assume that the wire ends are at temperatures T_L and T_H, with $T_L < T_H$. The wire current is I.

Heat budget due to thermal conductivity is proportional to the cross section and inversely proportional to the length, favoring long thin wires with low thermal conductivity. There will be also an ohmic contribution due to Joule heating. For this process, heat budget is reduced by choosing thick and short wires with low electrical resistivity.

The steady energy balance equation for conduction cooled leads is:

$$\frac{d}{dx}\left(kA\frac{dT}{dx}\right) + \rho\frac{I^2}{A} = 0 \tag{1}$$

with the boundary conditions $T(0) = T_L$, $T(L) = T_H$.

The heat Q_L at $x = 0$ will be:

$$Q_L = \sqrt{Q_H^2 + I^2 \int_{T_L}^{T_H} 2\rho(T)k(T)dT} \tag{2}$$

where Q_H is the heat at $x = L$. The quantity is minimized when $Q_H = 0$:

$$Q_L^{minimum} = I\sqrt{\int_{T_L}^{T_H} 2\rho(T)k(T)dT} \tag{3}$$

The optimal wire dimension is given by:

$$\frac{L}{A} = \int_{T_L}^{T_H} \frac{k(T)dT}{\sqrt{Q_H^2 + I^2\int_T^{T_H} 2\rho(\tau)k(\tau)d\tau}} \tag{4}$$

In the special case $Q_H = 0$ the expression becomes:

$$\frac{L}{A}(Q_H = 0) = \frac{1}{I}\int_{T_L}^{T_H} \frac{k(T)dT}{\sqrt{\int_T^{T_H} 2\rho(\tau)k(\tau)d\tau}} \tag{5}$$

The optimal dimension depends not only on material properties, but also on the current, the end temperatures and Q_H. Optimization is achieved for a single operating current, with $Q_L^{minimum} \propto I$ and $L/A \propto I^{-1}$.

For insulated wires, coaxial cables and ribbons heat conduction occurs not only through conductors, but also through insulation. On the other hand, Joule heating occurs at the conductor only. Thus the combination of conductor and insulant must be optimized. We will now discuss some issues about conductor and insulation materials.

The thermal conductivity of several materials is summarized in Fig. 1 a) and b) for reference.

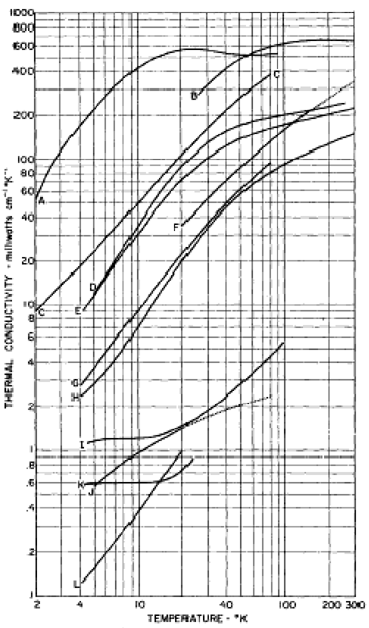


FIGURE 10.8. Low-temperature thermal conductivities of some solids with relatively low conductivities. A, 50-50 lead-tin solder [44]; B, steel, SAE 1020 [39]; C, beryllium copper [44]; D, constantan [39]; E, Monel® [39]; F, silicon bronze [42]; G, Inconel® [39]; H, type 347 stainless steel [39]; I, fused quartz [39]; J, polytetrafluoroethylene (Teflon®) [41]; K, polymethylmethacrylate (perspex) [39]; L, nylon [44].

(a) Solids with relatively low conductivity

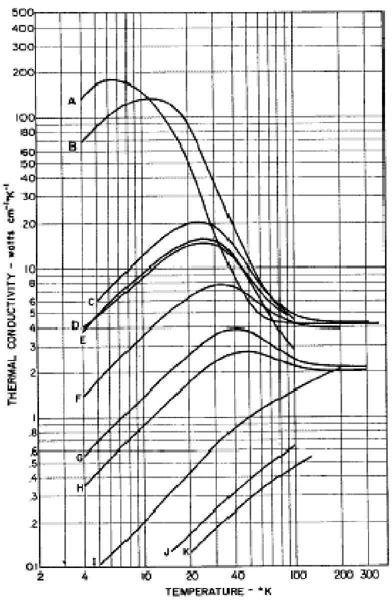


FIGURE 10.7. Low-temperature thermal conductivities of some metals having relatively high conductivities. A, silver 99.999% pure [39]; B, high purity copper [42]; C, coalesced copper [42]; D, copper, electrolytic tough pitch [42]; E, aluminum single crystal [43]; F, free-machining tellurium copper [42]; G, aluminum, 1100 F [43]; H, aluminum, 6063-T5 [43]; I, copper, phosphorus deoxidized [42]; J, aluminum, 2024-T4 [43]; K, free-machining leaded brass [42].

(b) Solids with relatively high conductivity

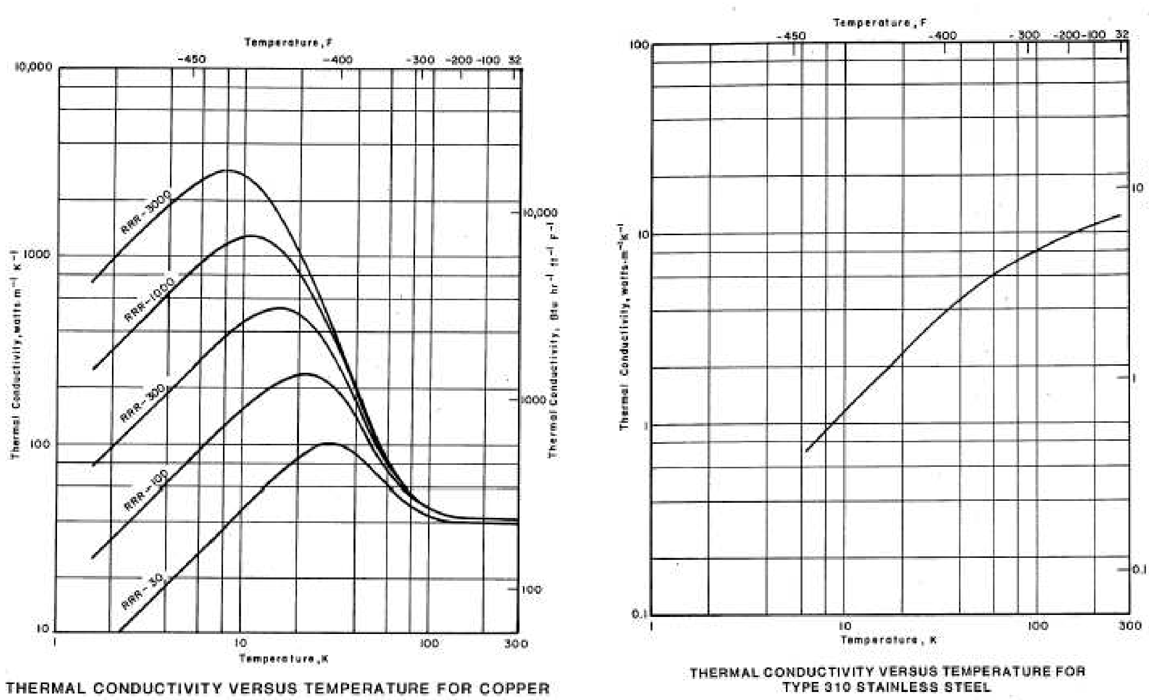
Figure 1: Thermal conductivity of solids with relatively low and relatively high conductivity

3 Conductor materials

The requirements of low thermal conductivity to reduce external heat injection and of low electrical resistivity to reduce Joule heating are in contrast. The electrical resistivity of metals decreases by two orders of magnitude from room temperature to 4.2 K; the thermal conductivity has a maximum at one twentieth of the Debye temperature and a linear decrease below. The electrical resistivity of alloys is weakly decreasing from room temperature to a few Kelvin, while thermal conductivity decreases by one or two orders of magnitude.

The standard conductor materials for cryogenic operation are: stainless steel, constantan, manganin, brass, copper.

The thermal conductivity of copper and stainless steel is detailed in Fig. 2 a) and b).



(a) Copper

(b) Stainless steel

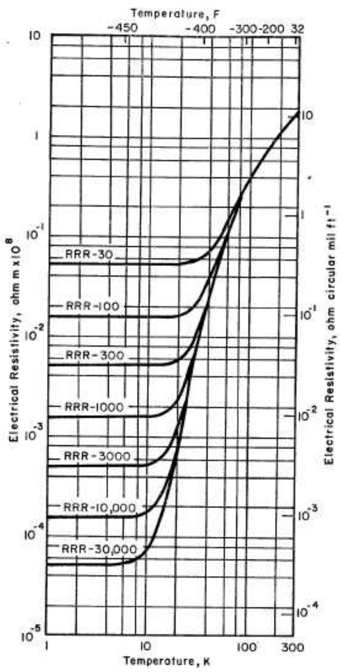
Figure 2: Thermal conductivity of copper and stainless steel [2]

The electrical resistivity of brass, constantan, manganin at 295 and 4.2 K is summarized in Table 1.

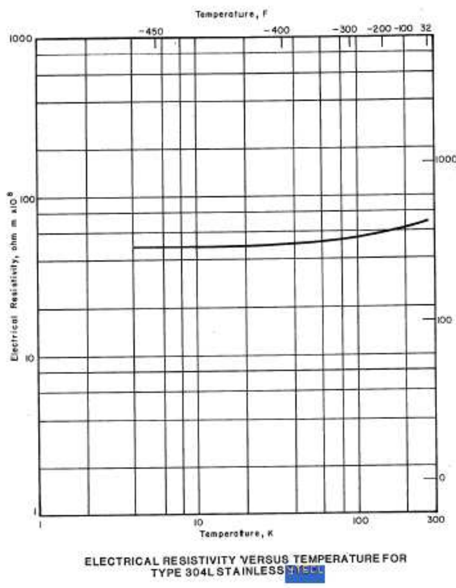
Material	$\rho(\mu\Omega\cdot$ cm) at 295 K	ρ ($\mu\Omega\cdot$cm) at 4.2 K
Brass	7	4
Constantan	52.5	44
Manganin	48	43

Table 1: Resistivity of brass, constantan and manganin at 295 and 4.2 K [1]

The resistivity of copper (strongly dependent on the purity grade) and stainless steel is shown in Fig. 3 a) and b).



(a) Copper



(b) Stainless steel

Figure 3: Electrical resistivity of copper and stainless steel at cryogenic temperatures [2]

Constantan and manganin are good choices for signal wires because of their low thermal conductivity and the weak dependence of electrical resistivity on temperature. Compared to constantan, manganin offers higher electrical conductivity, but also higher thermal conductivity. For large currents, copper is sometimes preferred because of its better electrical conductivity, despite its high thermal conductivity: large diameters to reduce Joule heating and some intermediate heat sinking are required.

4 Insulation materials

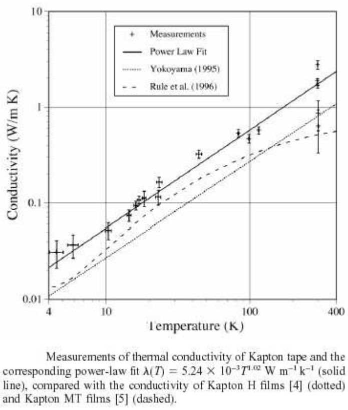
The main challenge of insulation at cryogenic temperatures, in addition to the standard requirements of electrical insulation, is the resistance to mechanical stresses induced by thermal contraction and thermal cycling during operation. The intrinsic mechanical stress can lead to faults. The standard shock test before operation is performed by immersion in liquid nitrogen.

Some low outgassing samples that are quoted to be usable at low temperatures have been studied in the context of Virgo investigations about contamination:

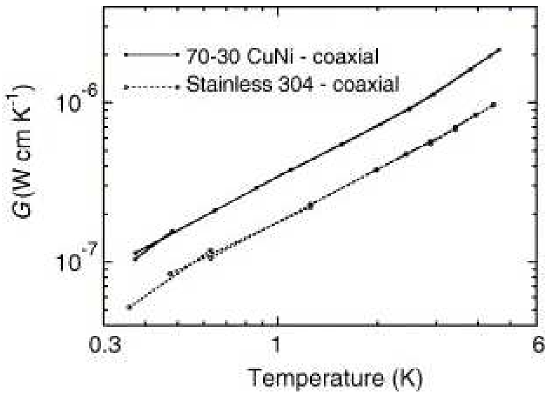
- wires with Pyre–ML insulation [3]; Pyre–ML is a Dupont aromatic polyimide that can undergo also high temperature baking
- ribbons with Gore–Tex insulation [4]; Gore–Tex is an expanded polytetrafluoroethylene

- alumina insulated wires [5]

Some of them could be used for coils or signal connections. Kapton, a traditional choice for ultra high vacuum cabling, is also a standard for cryogenic insulation. Pyre–ML is very similar to Kapton, from the point of view of thermal and mechanical properties. The VIRGO contamination measurements have found that Kapton nominal insulation is often not pure Kapton. Kapton insulated cables have shown emission by FEP layers [6]. Kapton ribbons from different manufacturers have shown emission by adhesives used to seal the various layers [7], [8]. The additional components were not observed in the emission of Pyre–ML. As a reference, the thermal conductivity of Kapton tape between 5 and 300 K is $5.24\times10^{-3}\ T^{1.02}$ W m^{-1} K^{-1} [9], see Fig. 4, a).



(a)



(b)

Figure 4: a) Thermal conductivity of Kapton tape at cryogenic temperatures [9]; b) Coax Co., LTD: thermal conductivity of miniature coaxial cables [10]

From the point of view of thermal and mechanical properties, but not from the point of view of outgassing, Gore–Tex is very similar to Teflon, whose thermal conductivity is shown in Fig. 1, a). Coax Co., LTD, produces semi-rigid cables for low temperature operations, with different conductors: stainless steel (SUS304), Cupronickel, Niobium, Oxygen-free copper and silver. The thermal conduction between 0.3 and 4.5 K of miniature coaxial cables (cross section 8.6×10^{-4}cm^2) by Coax Co., LTD, has been measured by [10]. The cables were made of 70-30 CuNi and stainless steel 304, with PTFE insulation (Fig. 4, b)). The low temperature properties of Gore–Tex in the form of woven fabric has been investigated in [11], where it was shown that it is a strong and flexible material at low temperatures. The Planck IR telescope collaboration has recently considered ribbons with flat conductors on Kapton and on Gore–Tex to replace the traditional cryogenic coaxial cables with stainless steel conductors [12].

5 Commercial solutions

Flexible ribbons able to work down to 0.5 K are commercially available. The typical insulation is Kapton, with several choices for conductors (manganin, copper, constantan, stainless steel, brass). An example are the ribbons developed for the Herschel mission, with Kapton insulation and brass or steel conductors.

Caburn offers stainless steel cryogenic instrumentation wires with Kapton type F insulation for use down to liquid helium temperature (Fig. 5).

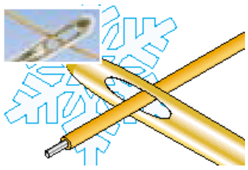


Figure 5: Caburn: cryogenic wire

Tayco Engineering offers some products that can be used down to liquid nitrogen or liquid helium temperatures. The ultra miniature ribbon cable provides high flexibility at low temperatures (Fig. 6, left). The ribbon includes 9 gold plated nickel conductors and an outer thin gold layer for shielding. The ribbon is very light and can be baked up to 200 ^{0}C. It is used for interconnection of detectors on satellites and has been qualified for Mars missions and others. The same factory offers also a cryogenic shielded twisted pair ribbon cable (Fig. 6, center), with 24 twisted pairs of 40 AWG manganin wire and vacuum deposited aluminium shielding. This product has been used for instrumentation of Cryogenic Telescope Assembly (CTA) and is NASA Space Flight Qualified. The cryogenic focal plane ribbon cable (Fig. 6, right) is available with straight or twisted conductors and has been qualified for NASA Space Infrared Telescope Facility (SIRTF), Mars Missions, MAP and other missions.

Figure 6: Tayco Engineering: ultra miniature ribbon cable (left); shielded twisted pair ribbon cable (center); focal plane ribbon cable (right)

STAR Cryoelectronics provides wires and cables with copper, phosphor–bronze, niobium conductors and Poly–Nylon, Formvar insulation and flexible cryocables (Fig. 7), with braided stainless steel shield and 10 or 14 pin LEMO end connectors. The CBL–C2 cryocable standard wiring includes multiple twisted pairs of phosphor–bronze or copper wire with polyimide insulation. The warm side connector is vacuum sealed.

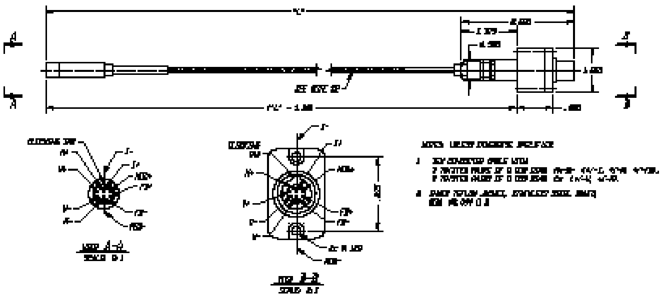
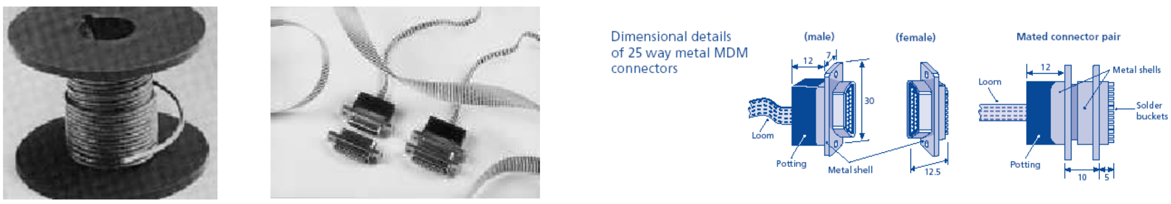


Figure 7: Star Cryoelectronics: CBL–C2 cryocable

Oxford Instruments offers sub–miniature coaxial cables (Fig. 8, left), with conductor and shields made of stainless steel or copper and Teflon insulation. Cryogenic ribbon cables are available (Fig. 8, center), with twisted pairs of constantan wires and polyester insulation. Ribbons are available without or with connectors. In the last case, the low temperature MDM connectors (Fig. 8, right) are potted to the cable.



(a) (b) (c)

Figure 8: Oxford Instruments: a) stainless steel coaxial cable; b) ribbon cable; c) MDM metal connectors

Lake Shore offers phosphor–bronze cryogenic wire with Formvar or polyimide insulation, twisted pairs (phosphor–bronze with polyimide insulation) and ultra miniature coaxial cables (Fig. 9), with copper or 304 stainless steels conductors.

Figure 9: Lake Shore coaxial cables

6 Conclusions

Issues related to cabling has been discussed in view of a possible use in the cryogenic version of Virgo. As a starting point, it has been shown that some commercial options are currently available.

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