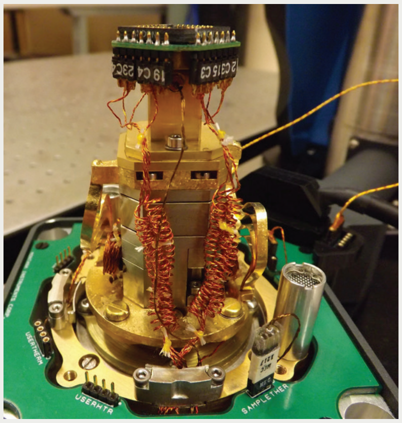
TEN THINGS YOU NEED TO KNOW

USER GUIDES:
WIRING FOR CRYOSTAT

Many cryogenic experiments rely on electrical connections from the lab environment to a sample under test in the low temperature world of a cryostat. When these connections are needed, understanding how to install them without increasing sample temperatures requires careful considerations of many factors.



HEAT LOSS ALL WIRES CONDUCT HEAT FROM THE OUTSIDE WORLD TO YOUR SAMPLE.

THE FORMULA FOR HEAT FLOW IS: $Q = k * A * \frac{(T_2 - T_1)}{L}$

Where Q is the heat flow in Watts

k is the conductivity of the material and is measured in W/(m*K)

A is the cross-sectional area of the wire (m2)

L is the length of the wire(m)

(T2-T1) is the temperature gradient across the wire

The goal is to minimize this heat flow out of your sample. In order to do this, examine each aspect of the equation.

1

WIRE GEOMETRY (Area/Length) The cross sectional area referenced as gauge (AWG), and length of the wire can greatly affect the heat loss. As you can see, the heat loss is proportional to the area and inversely proportional to the length; therefore a thin, long wire will reduce the sample heating. Thin wires can break easily, so select the wire gauge with robustness in mind. Similarly, long wires need to be managed, so they don't tangle and get in the way. Also thin, long wires have higher electrical resistance which may impact the circuit function. Some examples are shown below.

2

WIRE MATERIAL choice determines the "k" in the equation above. This affects both thermal conductivity and electrical resistance. For low temperatures, instead of copper, consider Manganin, or Phosphor Bronze. First, determine the thermal losses. The table at the right shows the conductivity of a few common wire materials at three temperatures.

THERMAL CONDUCTIVITY (W/(M * K))

Wire Type	300K	30K	4K
Copper (C110)	400	1000	300
Phosphor Bronze	48	12	1.6
Manganin	22	6	0.5

Compared to ordinary copper wires (C110), Manganin and Phosphor Bronze wires are about 10% the conductivity at room temperature and less than 1% at low temperatures. So you can drop the heat losses by 90% by just changing out the copper wires.

But let's also look at electrical performance. The table on the following page shows the electrical conductivity of these materials at two temperatures.

ELECTRICAL CONDUCTIVITY (OHMS /M)

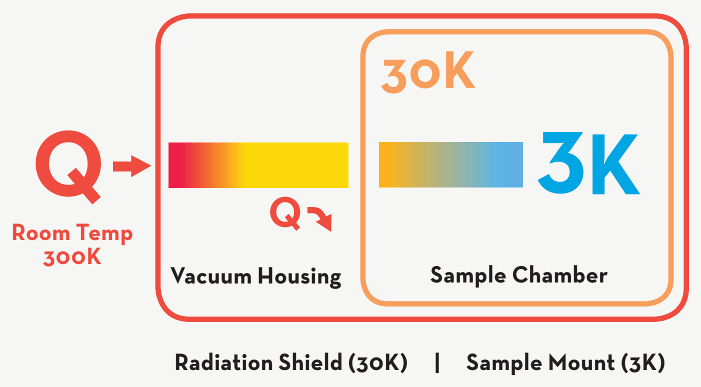
Wire Type	AWG	Resistance (Ohms/m) 300K	Resistance (Ohms/m) 4.2K
Copper (C110)	30	.32	.003
Copper (C110)	34	.81	.0076
Phosphor Bronze	32	4	3.3
Phosphor Bronze	36	10	8.6
Manganin	30	9.7	8.6
Manganin	36	39	35

These alternate wires have much higher resistance. If you are running at significant current levels (amps), these wires may introduce a voltage drop to the internal devices, or even generate heat in the wire itself. If the current level is low, or if you are operating a thermometer bridge, this may not matter.

As you see, there are a number of tradeoffs. If you need very low resistance, you may need to use copper, at the cost of higher sample temperature. If you are moving piezo stages, then Phosphor Bronze may be sufficient if your wires are short. If you are doing temperature measurement, Manganin may be the least cnoductive of these choices. Below are some practical examples.

3

THERMAL LAGGING or "thermalizing" is a process of thermally connecting conductive elements to an intermediate temperature so excess energy is pulled out at that point, rather than traveling onto your sample. If a wire is connected directly from room temperature to the sample all the energy coming through the wire will pass through to the sample. If that wire is sufficiently thermally connected to a 30K portion of the cryostat, then most of the energy coming through the wire will be diverted to the shield and much less energy will come from the shield to the sample. Normally wires are lagged as they pass through the radiation layer. Consider the diagram at right:



FOR ELECTRICAL RESISTANCE:

Wire Material	AWG	300-30K leg, 0.1m long resistance (ohms)	30-3K leg, 0.1m long resistance (ohms)	Total resistance (ohms)
Copper (C110)	34	0.08	0.01	0.1
Phosphor Bronze	36	1	0.87	1.9
Manganin	36	3.5	3.7	7.2

FOR CORRESPONDING THERMAL LOSS:

Wire Material	AWG	Diameter (mm)	Thermal load on shield (mW) 300-30K leg, 0.1m	Thermal load on sample (mW) 30-3K leg, 0.1m long
Copper (C110)	34	0.16	26.7	3.5
Phosphor Bronze	36	0.127	1.03	0.02
Manganin	36	0.127	0.48	0.01

By connecting your wire to an intermediate "radiation shield", the temperature of the wire at that boundary is close to the radiation shield temperature (~30K) and the sample is only exposed to that temperature through the wire.

To analyze the conductivity completely, one would calculate the integral of the thermal and electrical resistance for the wire length based on the temperature at each point on the wire. To simplify that, you can assume that the resistance is roughly linear and the result will be approximately right. On the left is a table of the electrical resistance and thermal loss, based on a 4" wire segment from room temperature to the radiation shield and another 4" from the radiation shield to your sample.

If your circuit can tolerate a 2 ohm electrical resistance per wire, then using Phosphor Bronze wire will introduce only 20 microwatts of heat per wire. Note that if the wire was not lagged, then there would be over 1mW of heat load on the sample (the sum of the two loads).

HERE IS AN EXAMPLE OF A GOOD FOUR CONDUCTOR WIRE THAT IS EASY TO USE:

4

LAG IT AT THE SAMPLE (3K) as well. If you can lag your wires at the sample mount, then your wires are heating the mount, and not the sample. Be aware these are different. Often the sample has a different emissivity than the gold sample mount, or generates its own heat from the optical port or RF input. There is usually a slight gradient from the face of the sample where your experiment is going on, to the back of the sample, where it is mounted. This might only be 0.1mm, but if you have a glass or semiconductor sample, you will have a thermal gradient across this. While this may be difficult to model, it is best not to load down your sample any more than necessary.

PRACTICAL CONSIDERATIONS

5

VACUUM FEEDTHROUGHS

As the wires enter the cryostat, make sure the electrical connector is hermetically sealed, or there will be gas leaks through the connector. Some people use vacuum compatible epoxy to seal connectors, but these can crack and is not recommended.

6

USE TWISTED PAIRS, even at low frequencies. Twisted pairs of wires provide a degree of immunity to the magnetic interference that could induce a noise component into the circuit. In a four wire sensor, for example, use a pair for the current (I) lines, and another pair for the voltage (V) lines. Twisted pairs also help with the structural integrity of the bundle, as the wires help support each other.

7

COAX ISSUES - High frequency circuits often require coax cables and connectors. The same issues of length, materials, and lagging apply to coax, plus additional issues of heat loss through the core and bandwidth. The problem with coax is that while one can lag the outer shield, the inner core is difficult to pull the heat out of. Try to lag the shield over some length and select cable with very thin insulation material between the core and shield. There are some very tiny coax cables available. Usually the high frequency lines have a solid (non-braided) shield, so they can be fragile, easy to pinch and tough to solder to. The table on the next page shows some coax lines used in cryogenic systems and some relevant parameters.

Consider if the circuit requires the shield on the coax to be separated from earth ground. Ground often has significant noise levels on it due to EMI and RFI from other lab equipment. In extreme cases, triax cable may be warranted.

Also note that there are frequency losses at each connection. If the cable has a connector at the vacuum feedthrough, then another to transition the semi-rigid to a flex cable, there will be losses at each boundary. As a rule of thumb, count on about 1dB loss at each connection.

CABLE TYPE	FLEXIBLE CABLE	SEMI RIGID	SEMI RIGID
Dimensions			
Center conductor – AWG (diameter)	38 (0.119 mm)	37 (0.1143 mm)	29 (0.29mm)
Jacket outer dimension	0.43 mm [0.017 in]	0.51 mm [0.02 in]	0.64mm [0.025 in]
Material			
Center conductor	Copper	Carbon Steel	Silver plated Stainless
Dielectric/insulating material	PFA	Teflon® PTFE	Teflon® PTFE
Shield	Copper tape braid dual	304 stainless steel	304 stainless steel
Attenuation (dB/ft)			
1 GHz	1.12	1.9	0.82
20 GHz	–	8.6	3.8
Thermal Loss			
Thermal Loss per cable (K)	0.03	0.025	0.025
Cable length for loss calculation (cm)	70	30	30

When working with coax, do not exceed the minimum bend radius, especially for semi-rigid cable. This can damage the cable and greatly reduce the voltage and frequency performance of the assembly. Normally the cable specs will be valid as long as the minimum bend radius is respected.

8

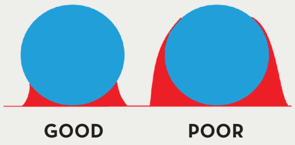
INSULATION ISSUES - Before picking a random cable from your electronics room, consider if it will outgas and contaminate your sample? NASA has some great tables on this at: http://outgassing.nasa.gov/ Do a Search, and look at the value in the table for CVCM (Collected Volatile Condensable Materials). This is the percentage of the cable that will leave the cable and settle on places like windows and samples. For comparison, Belden PVC wire insulation has a CVCM of 10%, which would be terrible, and most of the Teflon insulations have a CVCM of 0.01% or below. A good rule of thumb is to select materials with CVCM of less than 0.1%.

Another handy resource is the LIGO Vacuum Compatible Materials List which can be found at: https://dcc-llo.ligo.org/public/0003/E960050/011/E960050-v11%20Vacuum%20Compatible%20Materials%20List.pdf including coax, ribbon and individual wires.

9

SOLDERING AND CONNECTORIZING

There is a proper way to make low temperature soldering connections. Beware that solder can contract differently than the other materials in the cryogenic environment. In the worst case, it might crack or even add enough strain to break small samples. Try to use very little solder, and strain-relieve by twisting wires together where possible. Below is an image of good and poor solder joint, where the solder is applied lightly for connection, and not over applied where it might stress the elements. Remove all flux, as flux will outgas substantially.



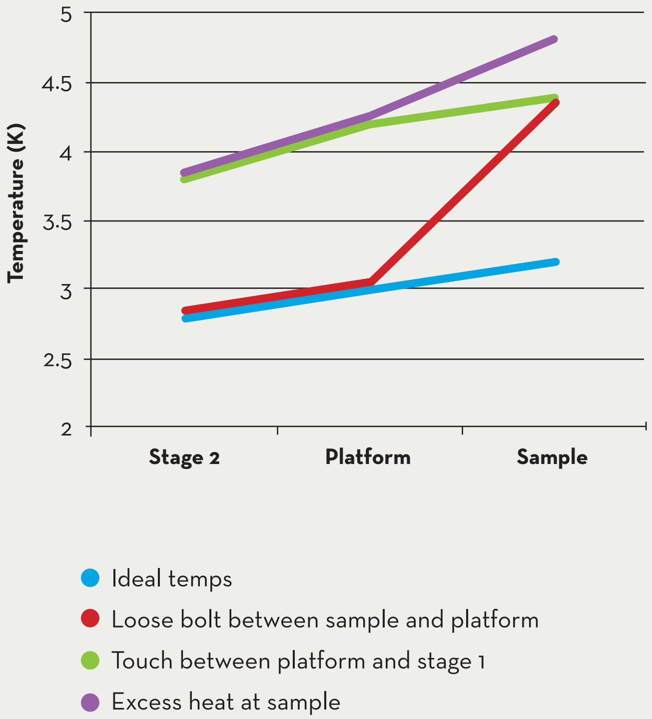
Teflon heat shrink can be used to protect wires from shorting.

Beware that tin lead will superconduct at less than 7K. If you are making sensitive DC measurements, this transition may affect the net resistance of the connecting wires. It may also introduce magnetic anomalies in the areas of the superconductance.

Connectors should be designed for multiple connections and flexible contacts. Some low cost connectors rely on a single sided spring contact. This can be unreliable after several thermal cycles. A multiple contact connector with 2 or preferably more contacts is much better.

10

VERIFYING YOUR PERFORMANCE -Let's say you have made all the intelligent decisions you can during the design process, but the resultant base temperature is not what it should be. You will need to determine the sources of the heat that are raising the sample temperature. You can often individually verify the heat losses of each item by empirically removing the item (wire in this case) and testing its effect. Knowing the heat load map of the cryostat, you can translate a heat power (watts) into a thermal change (Kelvin). The graph below of the temperature measured at three locations in the cryostat showing some typical scenarios:



The blue line is the ideal condition, with slight gradients between each location. If your sample is not cold enough, the temperature of the other locations can help you determine where your losses are. If only the sample is warmer than expected, but the platform is at the proper temperature (red line), then there may be a weak connection in the sample mount, such as a loose bolt or no N-grease between the components. If the gradient between the sample and platform is as expected, and stage 2 is higher, while the platform is even higher, then look for a "touch", possibly from a wire that is thermally shorted to the radiation shield. If all locations are too warm, and the sample is elevated above its mount, there could be a heat source at the sample, possibly from window radiation, or even internally generated. Of course, a combination of problems can make the diagnosis non-trivial. In any case, having more thermometers at key places clue you in to the problem. Cryogenic engineering includes a bit of detective work to get the lowest temperatures.

If you pay attention to these details in wiring within the cryostat, your sample will cool better and you will have lower noise in your measurements. Good luck on your research! If you're a veteran to the field and want to share your tips for optimizing wiring, send us an email; we'd love to hear from you!

Montana Instruments makes closed cycle optical cryostats which can keep your samples at 3K. If you'd like to find out more about us, visit our web site: www.montanainstruments.com (406) 551-2796

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