Introduction

At the detector group meeting in Pasadena in March 2000 an outline concept for the thermal strap from the ^{3}He cooler cold tip to the detectors was discussed. This document formalises that discussion and attempts to place boundary conditions on the implementation of the 300 mK thermal strap in order that its detailed design can be taken further. The same concept can be applied to the 2-K straps and a method for getting these through the 4-K enclosure is also proposed.

The 300 mK Concept

The original concept for the connection between the detector arrays and the cooler cold tip was that thermal straps would emerge from the back of each detector module. These were then connected separately to a thermal control node that was close to, and connected separately, to the cooler cold tip. This arrangement had two disadvantages a) there would be five “holes” into the 2-K environment through which straylight could get in and b) each of the five thermal straps would need to be independently supported – adding to the parasitic load on the cooler.

The concept discussed at Pasadena has two larger thermal “bus bars” connected to the thermal control node one penetrating the spectrometer 2-K box wall and one penetrating the photometer 2-K box wall. Most of the length of the bars then runs inside the 2-K boxes and flexible thermal links (copper wires) are taken directly onto the 300 mK structure of the detector modules. Thus there is only one “hole” into each 2-K box. Figure 1 shows a topographical representation of the thermal interconnects for this concept. Thermal mass is represented as equivalent to an electrical capacitor; thermal impedances, whether due to the A/L of the straps or the contact impedance, are shown as equivalent to electrical resistance.

Figure 2 shows how the light seal at each entrance hole and the mechanical support of the bus bars might be achieved. The bar itself is supported on two (TBC) mounts similar in concept to the scheme used for the cooler and detectors. Here a Titanium frame is used to support two kevlar strings that are wrapped around the bar itself. At the light seal end of the bar the support, the mechanical interface to the 2-K box and the 2-K part of the labyrinth are made as a single unit. The connections to the detectors and the cooler cold tip will be made with mechanically compliant material (copper wire (TBC)). It is proposed that there be two bars – one each for the photometer and spectrometer and that the thermal control node is constructed as part of the photometer bar with a compliant link to the spectrometer bar. This will need some detailed modelling to ensure that the needs of both sets of arrays can be met.

For the spectrometer box the simple mechanical layout of the detectors means that a single, straight bar with two supports, one at the entrance to the box and one close to the detectors, will be sufficient. The situation with the photometer box is more complex as the arrays are distributed inside the 2-K structure. Here we could either have two separate bars – one to the “upper” detectors and one to the bottom detector – or run a single bar around the optimum route with extra supports as deemed necessary. Figure 3 indicates how this might be achieved.

Design Specification

The requirements on the thermal straps are that they should provide a good thermal contact between the cooler cold tip and the detector arrays in order that the temperature difference between the cold tip and any array is no more than 25 mK. In order to achieve this, all the contributions to the total thermal impedance of the contact between the cold tip and the arrays have to be accounted for as well as the various thermal loads on the system.

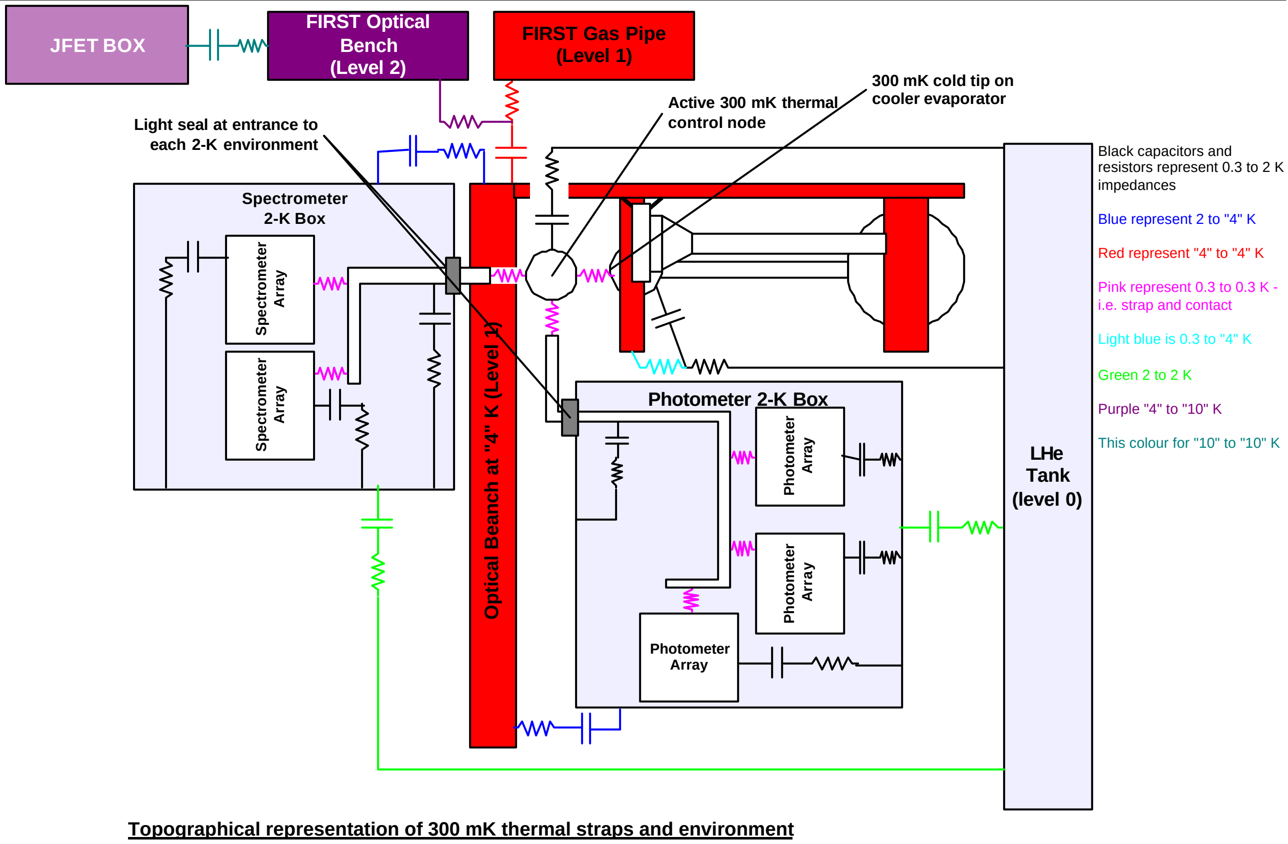


Figure 1: Topographical layout of the thermal connections between the various temperature zones in the SPIRE instrument

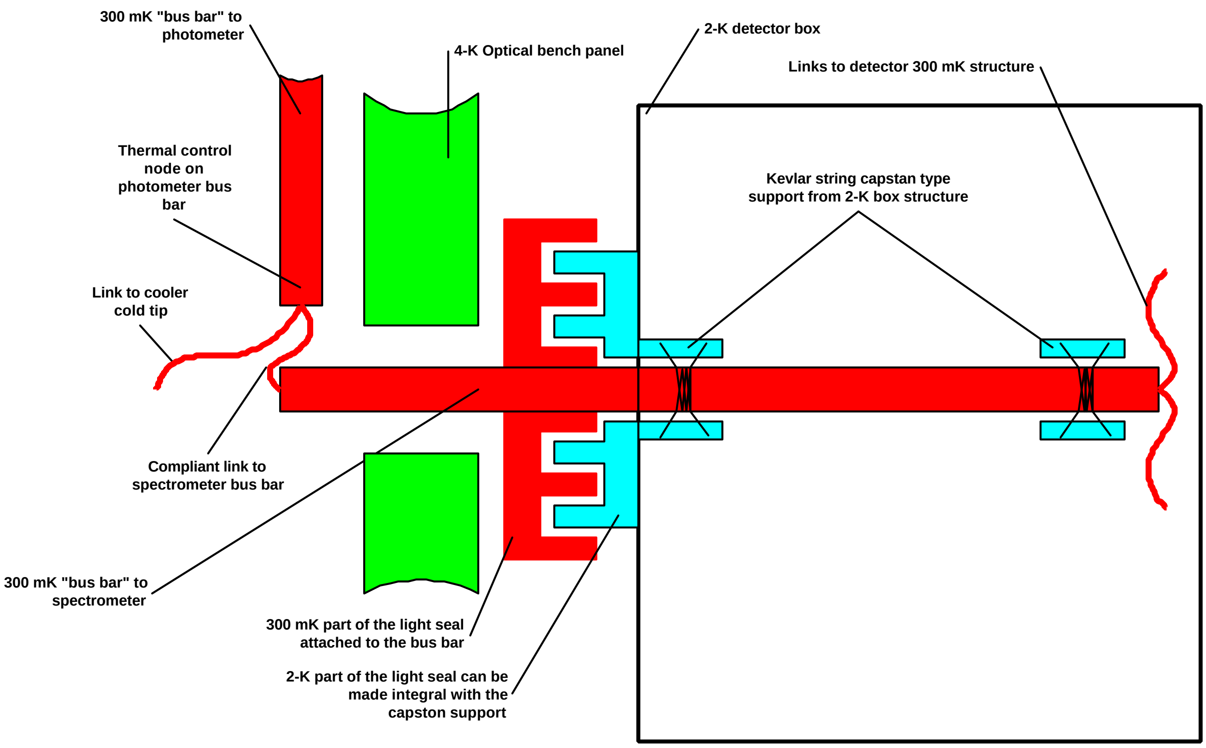
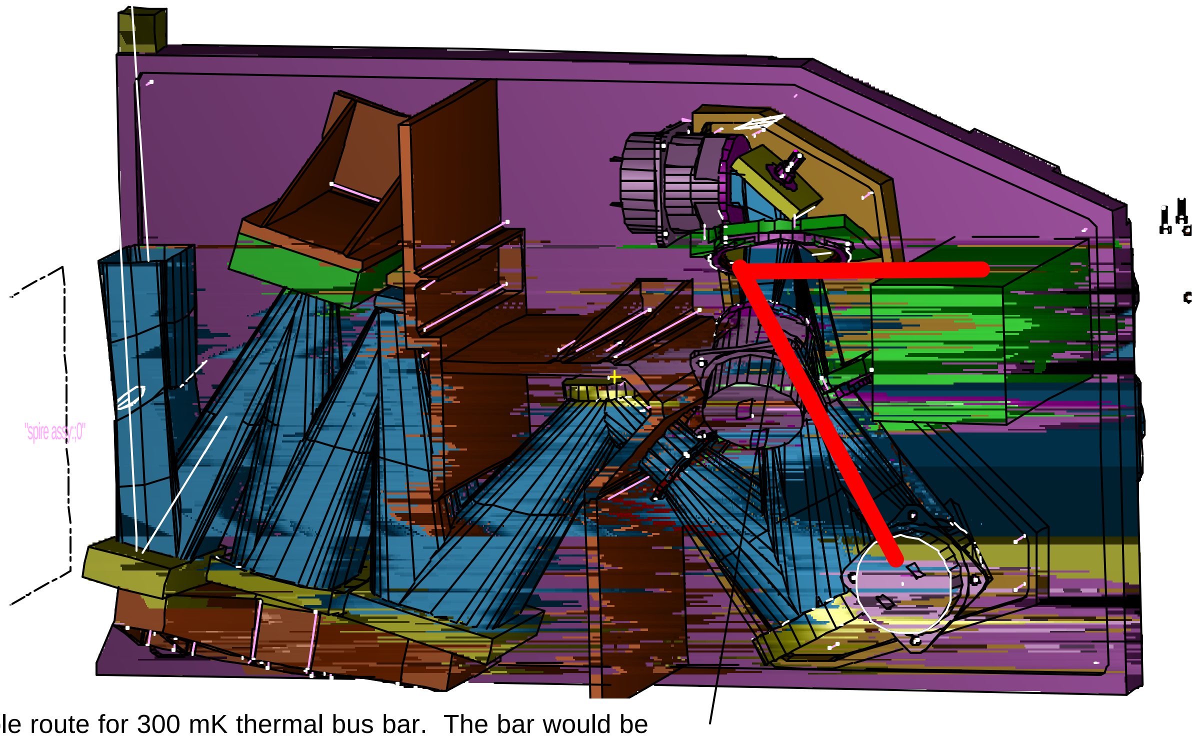


Figure 2: Conceptual implementation of the 300 mK bus bars



Possible route for 300 mK thermal bus bar. The bar would be located on the wall of the 2-K box closest to the optical bench. Support would need to be provided at the corner. The compliant links from the detectors would need to be arranged to avoid the optical beams and the various components. The box may require a "power bulge" to accommodate the bus bar.

Figure 3: Possible photometer side 300 mK strap routing

Each "joint" in the system – i.e. the connecting link from the cooler evaporator to the bus bar will have a joint at each end etc. – will represent thermal impedance, and, therefore, the possibility of a temperature difference between one side of the joint and the other. In order that the specification on the total temperature along the bar is met, the temperature difference across each joint must be small. A specification of 2 mK total is set for each compliant link including joints. The length of the compliant links is not clear but should be no more than 2-3 cm. The lengths of the bus bars are again uncertain but 25 cm for the spectrometer and 40 cm, maximum, for the photometer should be sufficient.

There will also be "heat leak" down the supports from the 2-K structure which will lead to both a temperature increase and additional thermal load on the cooler. Each detector module contributes 1.6 μW to the thermal load; the total net lift of the cooler is 10 μW, therefore the load from the supports must be at very most no more than 2 μW total. In fact some margin is required on the total load so the specification will be set for no more than 1 μW total from the supports. The load from the support from the photometer buss bar is set at 0.6 μW and that from the photometer bus bar at 0.4 μW to reflect the different number of supports likely to be needed. Figure 4 is a graphical summary of the loads and temperature differences specified for the connection between the cooler and the detector arrays. The temperature differentials have been specified to allow for reasonable specifications for the sizes of the bus bars and links.

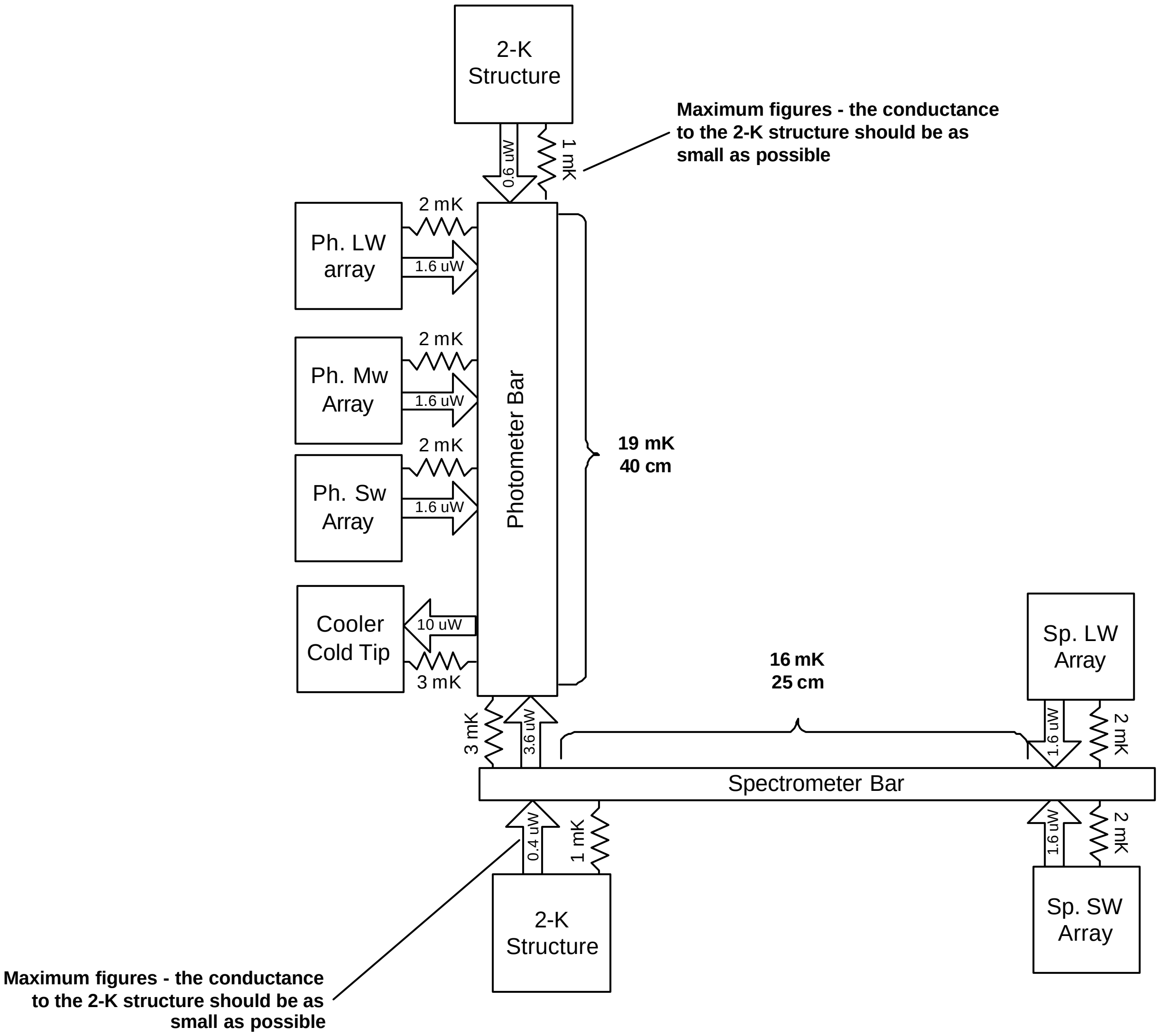


Figure 4: Graphical summary of the thermal specification for the connection between the arrays and the cooler cold tip. The lengths of the bus bars are estimates and the length of each compliant link is TBD.

Estimated size and Mass of thermal connection system

From figure 4 we can estimate the required thermal conductance for the joints and, assuming the bus bars are made from high purity copper ($k_{Cu} \approx 0.18$ W/(K.cm) according to Lionel – however see appendix), we can estimate the required diameters and therefore their masses.

Conductance and diameter:

1. **Cooler Tip:** The most critical joints will be those at the cooler tip itself as this is where the heat flow is the greatest. If the length of the link is taken as 2 cm and we assume a temperature drop across the link of no more than 8 mK, then the diameter of the link has to be at least:

$$D \geq 2\left(\frac{Q.L}{\pi.\Delta T.k_{Cu}}\right)^{1/2} \qquad (1)$$

$D_{L1} \geq 0.14$ cm

The compliance of the link will have to be carefully thought about to avoid placing loads on the cooler. It may be possibly to achieve sufficient compliance by putting a loop in the link. It may also be possible to have better quality material with higher conductivity.

If we allow no more than a 2 mK temperature difference across each of the joints, then the conductance of each of the two joints must be greater than:

$$k_j \geq \frac{Q}{\Delta T} \qquad (2)$$

$k_{j1,j2} \geq 0.005$ W/K

Suomi et al (1968) report on the thermal impedance of bolted copper to copper contacts in the 0.02 to 0.2 K temperature region. They find that for tapered threads the contact impedance is $<2\text{x}10^{-5}$ K/(erg/s) i.e. a conductance of >0.005 W/K. In fact they could not measure the impedance in their experiment, however with due diligence a conductance of this order appears to be readily achievable.

2. **Bus bar link:** Here the temperature drop allowed is the same – 1 mK for the link and 1 mK for each joint, but the heat flow is lower – 3.6 μW compared to 10 . If the length of the link is kept at 2 cm, the required diameter and joint conductance are:

$D_{L2} \geq 0.22$ cm
$k_{j3,j4} \geq 0.0036$ W/K

3. **Array links:** These will be the same for all detectors. The total temperature drop must be less than 2 mK and the heat flow is 1.6 μW for all detectors. If the temperature drop is divided equally between the two joints and the link itself, and the link is 2 cm long, then the diameter and joint conductance requirements are:

$D_{DET} \geq 0.18$ cm
$k_{jDET} \geq 0.0024$ W/K

4. **Bus bars:** Here we need only to consider the required diameter. The heat flow down the bars is a little complicated as it is “injected” at different points along the bar. The most conservative requirement is set assuming that all the heat flow is injected at the very end of the bar. For the photometer the total heat flow will be (3x1.6)+(0.6) = 5.4 μW along a 40 cm bar with a required temperature difference of no more than 9.5 mK. The spectrometer it is (2x1.6)+(0.4)=3.6 μW along a 25 cm bar for temperature difference of no more than 7 mK. Using the same assumptions as above the diameters are:

$D_{PHOT} \geq 0.4$ cm

and,

$D_{SPECT} \geq 0.3$ cm

5. **Bus bar supports**: The problem here is slightly different as we wish to set a requirement on the maximum allowed conductance per support. If we assume three supports for the photometer bus bar and two for the spectrometer bus bar each with a ΔT of 0.5 mK and Q=0.2 μW then the maximum conductance per support will be:

   $k_{supp} < 0.0004$ W/K.

   Comparing the design values for the support structure for the cooler evaporator (see Lionel's reports for the ESA contract) this figure would seem to be achievable using a combination of TAV6 alloy and Kevlar cord. A detailed design study would be required to ensure this.

Mass

Taking all the figures together we can specify a single link design of 2 cm long and 0.2 cm diameter with welded tabs at each end taking (say) M3 brass bolts. The mass of the links and bolts will be ~2 g each. The mass of the bus bars will be 45 g for the photometer and 16 g for the spectrometer.

Tony Richards (2000) gives the formulae for calculating the size and volume of various baffle designs. If we assume a four section baffle with a vane height of 12 mm, then the total diameter will be about 54 mm and the total height about 18 mm (see figure 5). The total volume is about 20 cm^{-3}. If we employ the combined light seal and support structure at the wall of the box we can assume that one half of the light seal is made from TAV6 (density ~4.5 g cm^{-3}) and the other half aluminium (2.7 g cm^{-3}). Adding 20% to the TAV6 component for the extra material required for the support structure, this gives a baffle mass of (2.7x10)+(4.5x12)=81 g. The other supports can be made much lighter – let us assume no more than 10 g per support.

Component:	Mass (grammes)
Cooler Link	2 (300 mK)
Photometer Bus Bar	45 (300 mK)
Photometer light seal and first support	81 (27 at 300 mK)
Photometer second Support	10 (all at 2 K)
Photometer third Support	10 (all at 2 K)
Phot. SW array link	2 (300 mK)
Phot. MW array link	2 (300 mK)
Phot. LW array link	2 (300 mK)
Photometer Sub total	**154 (80 at 300 mK)**
Photometer Margin (10%)	**15.4 (8 at 300 mK)**
Bus bar link	2 (300 mK)
Spectrometer Bus Bar	16 (300 mK)
Spectrometer light seal and first support	81 (27 at 300 mK)
Spectrometer second support	10 (All at 2 K)
Spect. SW array link	2 (300 mK)
Spect LW array link	2 (300 mK)
Spectrometer Sub total	**113 (49 at 300 mK)**
Spectrometer Margin (10%)	**11.3 (4.9 at 300 mK)**
Grand total	**294 (142 at 300 mK)**

Table 1: Mass breakdown for 300 mK thermal strap.

Table 1 gives the mass breakdown for the thermal strap as a whole. The mass to be supported at 300 mK is represents half the total for the spectrometer and a third for the photometer. Some effort in light weighting suspended portion of the light seal would pay dividends.

Outline drawings:

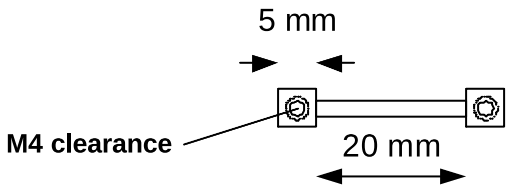


Figure 4a: Thermal link – the link itself is 2 mm diameter copper with tags welded to the ends.

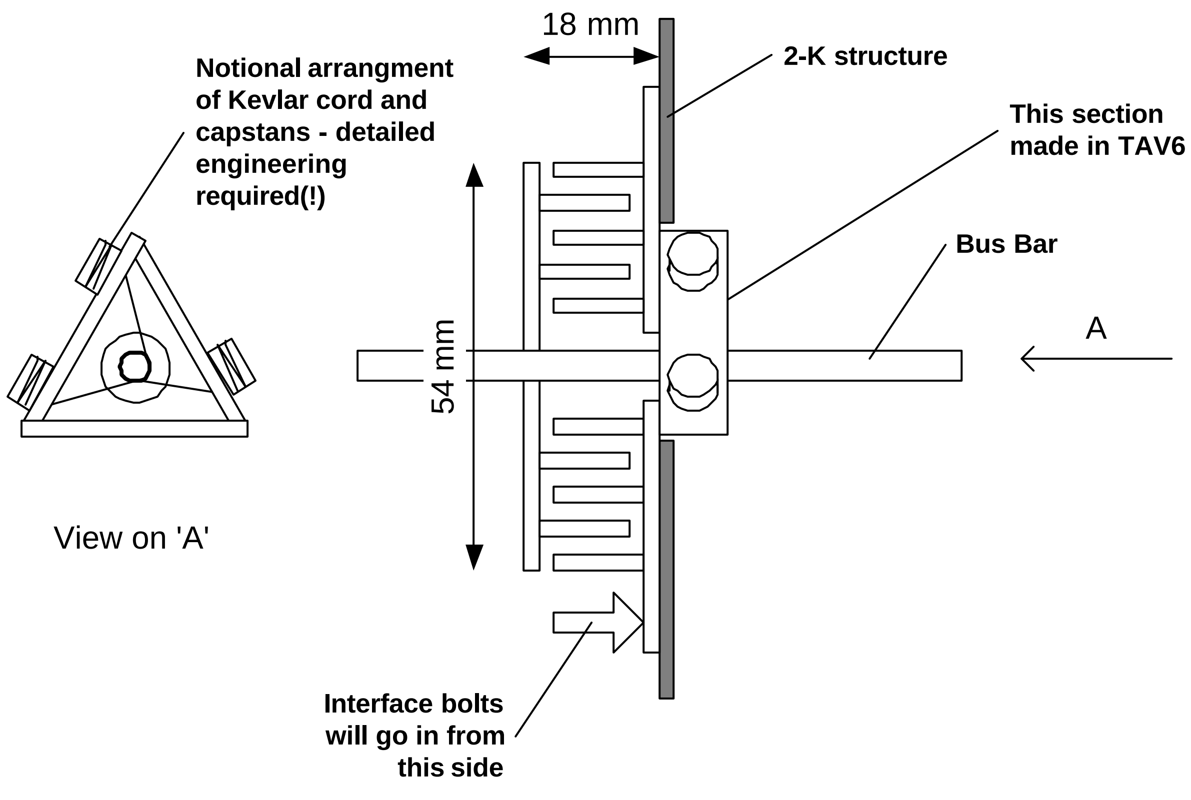


Figure 4b: Combined light seal and bus bar support at entrance to 2-K environment. A 4-section baffle is shown here

Conclusions

A concept has been discussed for the 300 mK thermal strap based on solid copper bus bars with compliant links between separate bars for the photometer and spectrometer; the cooler cold tip and the bars and between the arrays and the bars. The concept does not appear to have any technical difficulties preventing its implementation, although there are still many engineering details to be worked out. The specification for the bus bars; the thermal links and the support structures have been given based on conservative assumptions about the conductivity of the copper and the bolted connections. The mass of the whole system as proposed will be less than 300 g.

A detailed engineering design for the supports is now required to ensure that they will be capable of providing the correct mechanical performance at the same time as giving the necessary thermal isolation. Also a thermal model of the performance of the temperature control circuit based on the specification given in this note is required to ensure that the strap concept will allow the necessary stability to be achieved with a single control node.

Appendix:
Thermal conductivity of copper: The figure quoted by Lionel (0.18 W/(K cm)) appears to be on the conservative side for 300 mK. Dupré et al (1964) made measurements of the thermal conductivity of different purity copper samples and found conductivities up to 13 W/(cm deg^2) below 1 K – this translates to 140 W/(K cm) at 300 mK! There is clearly a very wide range of performance and we will have to a) choose the purity of the copper carefully and b) measure its performance.

References:

Suomi et al (1968) Physica **38** pp 67-80
Dupré et al (1964) Physics Letters **8** pp99-100
Richards (2000) SPIRE-RAL-NOT-000344