FERMILAB INPUT COUPLER HEAT CALCULATIONS

Tom Peterson
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INTRODUCTION

A fortran program originally written by Karl Koepke, Fermilab, for current leads for magnets, was modified to calculate the heat generated and conducted through copper-coated stainless steel carrying a 1.3 GHz oscillating electric current. The program divides the conductor into segments and performs an energy balance on each segment. Given a heat leak "guess" for the cold end, a temperature at the warm end is calculated. By iterating until the specified warm end temperature is obtained, heat flow to the cold end is found.

Skin depth in the copper coating, electrical resistivity of the copper, and thermal conductivity of the copper and stainless steel are found for each segment as a function of temperature. The "anomalous skin effect" in the copper at low temperatures is approximated by treating the copper as if it had a RRR = 20 for the purpose of calculating the surface resistance.

The purpose of the calculations was to find stainless steel and copper-coating thicknesses which would minimize the heat into the various low temperature levels, given the physical constraints on the lengths of each segment, to check the optimal position of the 5 K intercept, and to find the static and total heat loads to each temperature level.

The following assumptions were used in the program: copper RRR = 40, coax impedance = 50 Ohms, RF frequency = 1.3 GHz, peak RF power = 208 KW, pulse length = 0.0016 sec, rep. rate = 10 Hz.

See also reference 1, the paper "TESLA Input Coupler Development", by M. Champion, et. al., for more information about the input coupler design. The coupler configuration is per the 16 Dec 92 drawings from Fermilab.

RESULTS FOR THE COUPLER WITH THERMAL INTERCEPTS AT 5 K AND 70 K

Calculations were made separately on the following parts of the coupler (see figure 1): the niobium stub (the Fortran program was not used for this), the 2 K to 5 K segment of copper-coated stainless steel outer conductor, the 5 K to 70 K segment of the outer conductor, the 70 K to 300 K segment of the outer conductor, the lower inner antenna (at 70 K), the 70 K to 300 K segment of the inner conductor, and the 300 K length of inner conductor.

Niobium stub.

Since it would be convenient to use the flange which connects the outer conductor of the coax to the RF cavity as the 5 K intercept, a check of the heat load to the 2 K level through the niobium stub on the beam pipe was made. Since the "5 K" intercept will have some temperature gradient to the 4.5 K fluid, a flange temperature of 6 K was used in this calculation.

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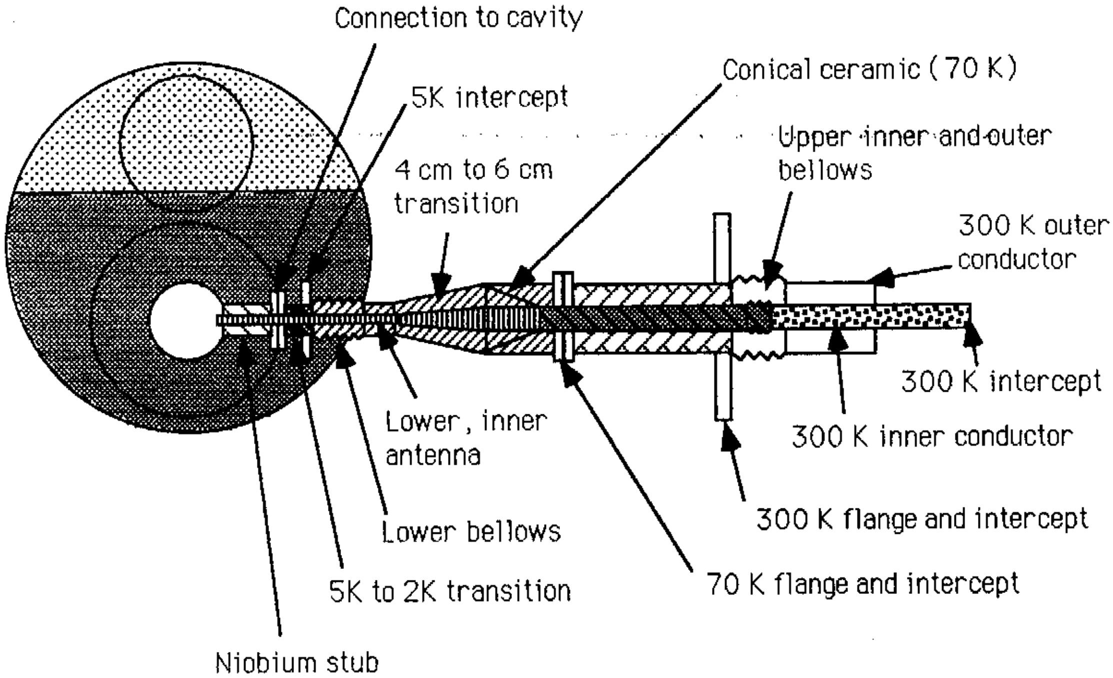
FIGURE 1

FERMILAB INPUT COUPLER SKETCH
SHOWING COMPONENTS FOR THERMAL ANALYSIS



Niobium stub, entirely at 1.8 K to 2.0 K

Copper coated stainless steel, 5 K to 2 K transition

Lower bellows, cylindrical, conical, and cylindrical tube form 5 K to 70 K outer conductor.

70 K to 300 K outer conductor, anchored at 300 K by a support flange

Lower, inner antenna, at 70 K to 80 K, cooled via conduction through the ceramic to the 70 K intercept on the outer cond.

70 K to 300 K inner conductor

300 K inner conductor, thick-wall copper to sink the top of the inner bellows at 300 K

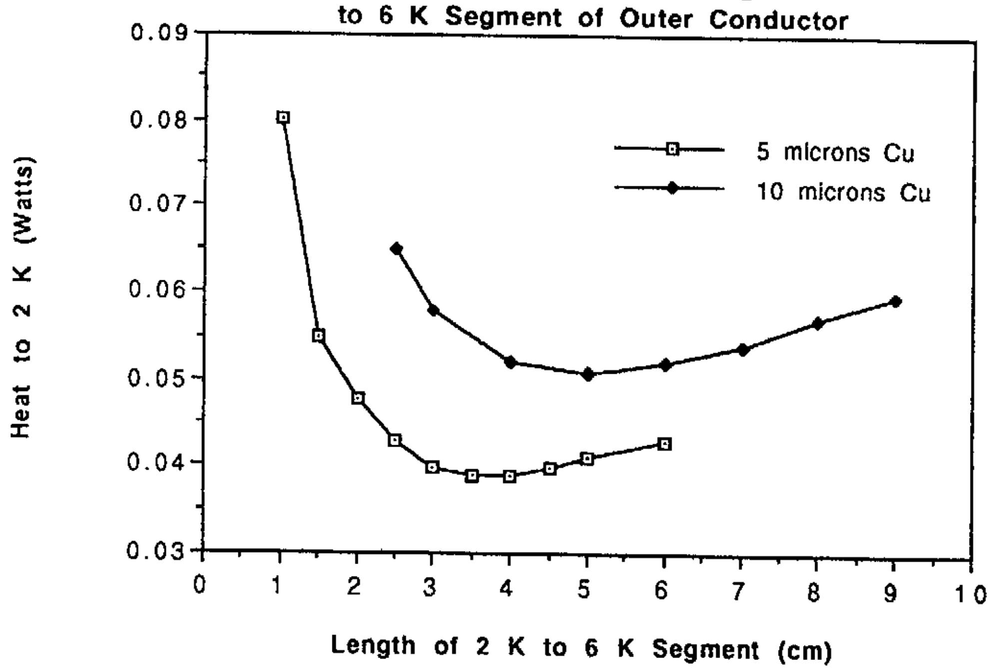
A thermal conductivity integral for untreated niobium between 2.0 K and 6.0 K was estimated from data presented in a TESLA Seminar on 13 November 1992, by H.-G. Kuerschner of Uni. Wuppertal (reference 2). The thermal conductivity ranges from 0.8 W/mK at 2 K to 75 W/mK at 6 K for un-heat-treated niobium with a RRR in the range 120 to 160. The thermal conductivity integral from 2 K to 6 K is 0.87 W/cm. For a tube of niobium 41 mm long and 40 mm diameter with a 2 mm wall, this results in a heat flow of 0.56 Watts. Since our niobium is specified as RRR = 300 or more, and it may be heat treated, this is a lower limit for the conductive heat load to 2 K for each coupler when the 5 K intercept in on the lower connecting flange. (I have not accounted for the resistance to heat flow due to the conductivity of the beam tube on which the coupler is mounted, but with its larger diameter and thickness that would be a small effect.)

Copper-coated stainless 2 K to 5 K transition.

Since 0.56 W to 2 K at each input coupler is too much, calculations were made for a 5 K thermal intercept just above the flange, set off from the flange by some length of the copper-coated stainless steel outer conductor of the lower section of the input coupler. The fortran program calculates the amount of heat generated in the copper conductor and conducted via the stainless and copper layers to 2.0 K. The result is that the stainless steel conducts very little heat, and its thickness within the possible ranges of values for the lower, outer conductor does not matter.

Figure 2 shows the results for various 2 K to 6 K lengths (since again a 6.0 K intercept temperature was used for the purpose of making a conservative calculation).

Figure 2
Plot of Heat to 2 K versus Length of 2 K to 6 K Segment of Outer Conductor



The electrical skin depth at room temperature for 1.3 GHz is 1.8 microns. Due to the porosity of platings and surface irregularities one should plate 3 to 5 times the calculated skin depth (reference 3), so conservatively 10 microns is as thin as we should go at room temperature. At 70 K the skin depth is only 0.6 microns, so one could plate only 5 microns on conductor which will only see high power at 70 K or colder. Hence, in order to reduce the heat load, 5 microns are recommended here for conductor at 70 K or below, such as this section from 2 K to 6 K. However, due to the difficulty of obtaining a uniform 5 micron coating, and in order to make the thermal load estimates conservative, heat load estimates in the final summary will be based on a 10 micron copper coating on all conductors.

For a 5 micron thick coating of copper, the optimum length from the thermal intercept to the flange is 4.0 cm, with a heat load of 0.04 Watts. This optimum is a broad one, so the location of the intercept is not critical, but could be 3.0 to 5.0 cm for about 0.04 Watts. With a 10 micron thick coating of copper the optimal length to the intercept is 5.0 cm, with a heat load of 0.05 W. Again, the length is not critical, but may be anywhere from 4.0 to 7.0 cm for a heat load of less than 0.055 W.

These values for the heat load are about 10 times less than the best we would do with the intercept at the end of the high-quality Niobium stub, on the flange. Therefore, it looks like the 5 K intercept should be moved up onto the lower, outer conductor of the input coupler by about 4 or 5 cm. This intercept must be below the bellows in the case of the Fermilab design, since the bellows is almost the entire 70 K to 5 K thermal resistor.

We can then conservatively estimate the 2 K heat load under full power to be about 0.06 W, perhaps as low as 0.04 W with a 5 micron coating, safely less than the 0.15 W in Table 4.2 of the April, 1992, proposal (reference 4). "Static" (zero power) heat to 2 K using the 4 cm length is calculated to be 0.03 W.

5 K to 70 K outer conductor.

The 5 K to 70 K outer conductor consists primarily of three segments: a bellows, a conical 4 cm to 6 cm transition, and a 6 cm diameter cylinder. The dimensions are: a 0.015 cm (0.006 inches) thick stainless bellows with an 18 cm thermal length, then a 0.17 cm (0.065 inches) thick stainless cone with a 10 cm length, and thirdly a 0.09 cm (0.035 inches) thick stainless cylinder with a 2 cm length. There should be a 5 micron copper coating on the ID of each section.

This results in (for 5 microns copper):
0.20 Watts heat to 5 K (no power),
0.33 Watts heat to 5 K (with full power).

Table 1 is a sample of the fortran program output for the 5 K to 70 K outer conductor. Figure 3 is a plot of the temperatures along that conductor from the output in table 1. Almost all the delta-T is in the bellows; the conical and upper cylindrical segments are entirely within 1 K of 70 K.

With 10 microns copper the heat loads are:
0.33 Watts heat to 5 K (no power),
0.49 Watts heat to 5 K (with full power).

Figure 4 is a plot of full power heat to 5 K versus copper coating thickness for this conductor.

Table 1

Fortran program output for the 5 K to 70 K outer conductor with 5 microns copper on bellows, conical, and cylindrical sections.

STEADY STATE COUPLER TEMPERATURE DISTRIBUTION

COPPER RESISTIVITY RATIO RRR	=	20.0
COPPER THERM. COND RATIO RRRC	=	40.0
COLD AND WARM END RADII CM	=	2.00 3.00
COLD TO WARM COPPER WIDTHS CM	=	0.00050 0.00050 0.00050
COLD TO WARM SS WIDTHS CM	=	0.015 0.170 0.090
COLD CYLINDER LENGTH CM	=	18.00
CONICAL LENGTH CM	=	10.00
WARM CYLINDER LENGTH CM	=	2.00
TOTAL GUIDE LENGTH CM	=	30.00
COAX IMPEDANCE OHMS	=	50.00
FREQUENCY	=	0.13E+10
PEAK POWER WATTS	=	0.21E+06
PULSE LENGTH SEC	=	.0016
REP RATE HERZ	=	10.00
HEAT LEAK INTO 4K WATTS	=	-0.33

WAVELENGTH (CM)	=	0.23E+02
X INCREMENT (CM)	=	0.30E+00
INITIAL DT/DX (K/CM)	=	0.20E+02
PEAK CURRENT SQUARED (A*A)	=	0.83E+04
AVG PEAK CURRENT SQUARED (A*A)	=	0.13E+03

N	T(N) (K)	AVGRES (Ohm-cm)	THERMC (W/cm-K)	WATTS	DTDX (K/cm)	SURF. RES. (Ohms)
1	10.0	0.78E-07	0.65E+01	-0.33	7.81	0.20E-02
10	23.6	0.80E-07	0.12E+02	-0.30	3.70	0.20E-02
19	32.8	0.87E-07	0.12E+02	-0.27	3.17	0.21E-02
28	41.3	0.10E-06	0.11E+02	-0.24	3.12	0.23E-02
37	49.8	0.13E-06	0.84E+01	-0.20	3.25	0.25E-02
46	58.3	0.16E-06	0.71E+01	-0.17	2.96	0.29E-02
55	65.6	0.21E-06	0.63E+01	-0.12	2.34	0.33E-02
64	69.4	0.23E-06	0.59E+01	-0.08	0.37	0.35E-02
73	70.1	0.24E-06	0.58E+01	-0.03	0.14	0.35E-02
82	70.3	0.24E-06	0.58E+01	0.01	-0.02	0.35E-02
91	70.1	0.24E-06	0.58E+01	0.04	-0.14	0.35E-02
100	69.3	0.23E-06	0.59E+01	0.07	-0.40	0.35E-02

Figure 3
Temp vs Position for Coupler 4 K to 70 K
Outer Conductor with Bellows and Cone

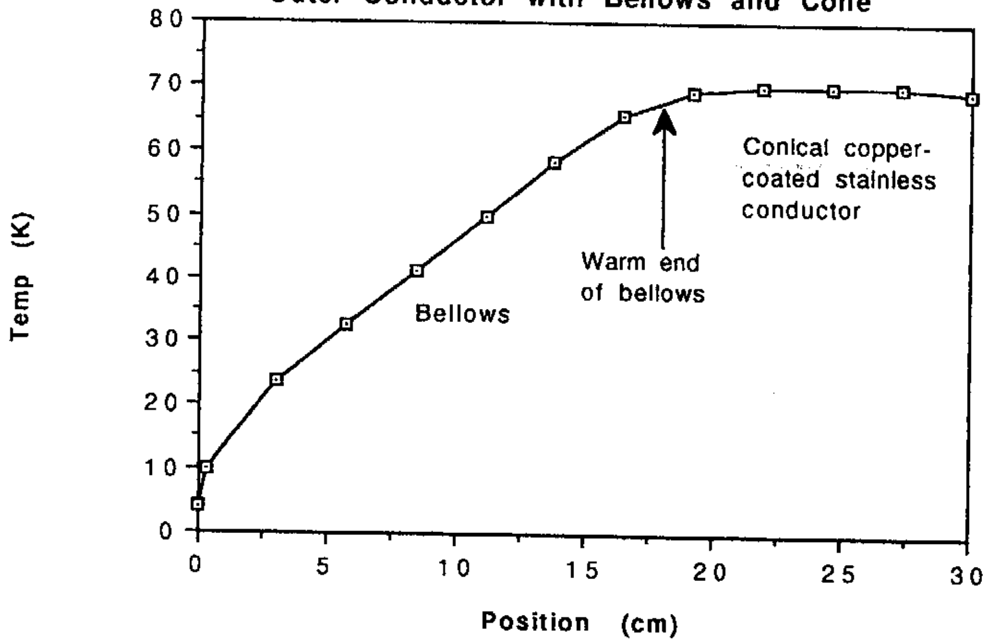
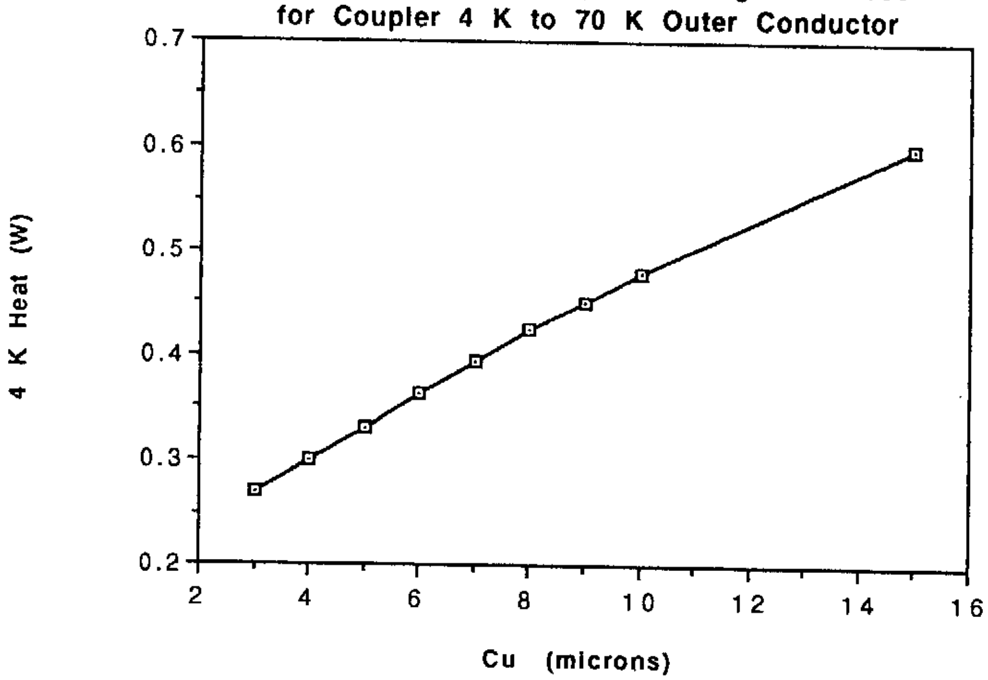


Figure 4
4 K Heat versus Copper Coating Thickness
for Coupler 4 K to 70 K Outer Conductor



70 K to 300 K outer conductor.

The dimensions for the upper outer conductor in this calculation are: 0.050 cm (0.020 inches) thick stainless steel, 20 cm long, and 10 microns copper plating.

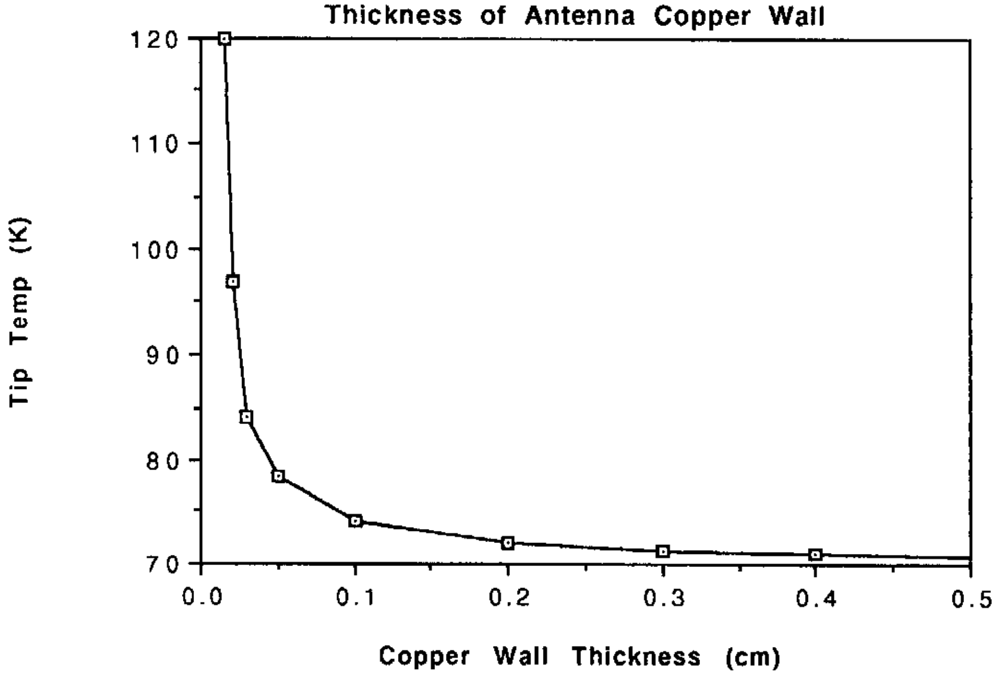
The resulting calculated heat loads are:
2.0 Watts to 70 K (no power),
2.4 Watts to 70 K (with full power).,

This section of conductor is a little shorter than optimum. That can be seen in the similar static and total loads. Conduction of heat from the warm end is larger than it would be in a more nearly optimum geometry. But the inner conductor between 70 K and 300 K is longer than optimum (described below) due to its smaller diameter and long reach to the doorknob. Therefore, there is no advantage in trying to stretch out the length of this part of the coupler, but material should be used for this outer conductor which is as thin as practical. Stainless steel 0.050 cm (0.020 inch) thick is safe against collapse. For comparison, 0.014 cm (0.035 inch) wall implies 3.0 W to 70 K with full power, and 2.6 W with no power.

Lower, inner conductor.

The result for the lower, inner conductor is 1.1 Watt of heat to 70 K. This is just the heat generated in the antenna. A minimum 0.10 cm (0.040) inches thick copper gives a tip temperature of 74 K. See figure 5 for a plot of antenna tip temperature as a function of the antenna copper wall thickness.

Figure 5
Temp of Lower, Inner Antenna Tip versus
Thickness of Antenna Copper Wall



As the thickness of copper decreases below 0.10 cm the temperature of the tip increases rapidly. A solid rod could be used, and has the advantage of no internal vacuum space to pump out, but the disadvantage of a large mass resulting in possible mechanical support and vibration problems. Thermally just copper tube at least 0.10 cm thick is sufficient.

300 K to 70 K inner conductor.

The dimensions for the inner conductor between 70 K and 300 K are: a 0.165 cm (0.065 inch) wall stainless tube, 22 cm long, and a stainless steel bellows with a 0.015 cm wall and an effective thermal length of 15 cm. There should be 10 microns copper coating on the outer surfaces.

The resulting heat loads are:
2.0 Watts to 70 K (with full power),
0.6 Watts to 70 K (no power).

This section of conductor is a little longer than optimum. There is a peak temperature in the bellows of about 315 K, and heat flows out of it in both directions, toward the 70 K intercept and toward the 300 K end. The heat toward the 300 K end of the bellows is 0.37 Watts.

300 K inner conductor between bellows and doorknob.

Due to the length of the upper, inner conductor, it is advantageous to use a length of good thermal conductor from the warm side of the bellows to the doorknob in order to prevent overheating of the bellows area. The dimensions for the upper, inner conductor between the inner bellows and doorknob are: 13 cm long, and 0.140 cm (0.055 inch) wall (or thicker) copper. There is 1.0 Watt of heat generated in this tube. It removes the 1 Watt of its own heat generated plus the 0.37 W from the bellows end with a total delta-T over the length of the tube equal to 2.4 K.

SUMMARY FOR THE COUPLER WITH THERMAL INTERCEPTS AT 5 K AND 70 K

2 K to 5 K outer conductor -- 5 microns copper on approximately 0.1 cm (0.049 inch to 0.065 inch) thick stainless steel. 5 K thermal intercept should be about 4 cm above the flange.

5 K to 70 K outer conductor -- 5 microns copper on 0.015 cm (0.006 inch) wall bellows, and 5 microns copper on approximately 0.17 cm (0.065 inch) thick wall stainless cone.

70 K to 300 K outer conductor -- 10 microns copper on 0.050 cm (0.020 inch) wall stainless.

Lower, inner conductor -- pure copper, minimum 0.10 cm (0.040 inch) thick, possibly solid piece.

70 K to 300 K upper, inner conductor (including bellows) -- 10 microns copper on 0.165 cm (0.065 inch) wall stainless, 10 microns copper on a 0.015 cm (0.006 inch) wall bellows.

300 K inner conductor above bellows -- pure copper, minimum 0.140 (0.055 inch) wall.

Table 2 summarizes the heat loads to the various temperature levels with and without power, assuming all copper coatings are 10 microns thick.

Table 2

Coupler Heat Summary Table
for 2.0 K, 4.5 K and 70 K Temperature Levels

No power, and **208000 Watts peak power (25 MV/ m)**

	2.0 K Watts	4.5 K Watts	70 K Watts
2 K to 5 K outer conductor	*0.03* **0.06**	*-0.03* 0	0 0
5 K to 70 K outer conductor	0 0	*0.35* **0.49**	*-0.4* **-0.1**
70 K to 300 K outer conductor	0 0	0 0	*20* **24**
70 K lower, inner antenna	0 0	0 0	0 **1.1**
70 K to 300 K inner conductor	0 0	0 0	*0.6* **2.0**
SUM	*0.03* **0.06**	*0.32* **0.49**	*22* **5.4**
Room temperature cooling power	*24* **48**	*80* **123**	*31* **76**

Room temperature cooling power is calculated as 800 W/W times 2.0 K Watts, 250 W/W times 4.5 K Watts, 25 W/W times 40 K Watts, and 14 W/W times 70 K Watts. Total room temperature power required per coupler is 135 Watts with no power and 247 Watts under full power.

Table 3

Coupler Heat Summary Table
for 2.0 K and 40 K Temperature Levels

No power, and **208000 Watts peak power (25 MV/ m)**

	2.0 K Watts	40 K Watts
2 K to 40 K outer conductor	*0.19* **0.32**	*-0.2* 0
40 K to 300 K outer conductor	0 0	*25* **27**
40 K lower, inner antenna	0 0	0 **0.7**
40 K to 300 K inner conductor	0 0	*0.6* **2.0**
SUM	*0.19* **0.32**	*29* **5.4**
Room temperature cooling power	*152* **256**	*73* **135**

Total room temperature power required per coupler is 225 Watts with no power and 391 Watts with full power.

40 K INTERCEPT AND ELIMINATION OF THE 5 K INTERCEPT

Since in TESLA we may have a 40 K to 60 K helium gas shield, a check of the coupler using the same stainless and copper dimensions was made to see if a 40 K intercept might eliminate the necessity of the 5 K intercept. Table 3 summarizes the results for the coupler with just a 40 K intercept at the location of the present 70 K intercept. Interestingly, there are some advantages of a 40 K intercept, for example in reducing the heating of the lower, inner antenna. The total heat to 40 K under full power is about the same as to 70 K, and heat to 2 K with the 40 K intercept is less than the total of 5 K and 2 K with the 70 K intercept. But the room temperature cooling power per coupler is still reduced by 37% with the use of 5 K and 70 K intercepts as compared to 40 K alone. We should plan to incorporate a 5 K intercept in the coupler design even with a 40 K intercept.

AN ENTIRELY 4 CM COUPLER VERSUS THIS DESIGN

At Fermilab there have been some discussions of whether expanding to 6 cm coax, as opposed to an entirely 4 cm coupler, results in larger heat loads to the low temperatures. Calculations indicate that only at 70 K is there a heat load penalty, and it is not significant.

In the coupler design presented in figure 1 and described in this paper, the 2 K to 5 K segment, and the bellows in the 5 K to 70 K segments are 4 cm coax. Since calculations show that the bellows is the primary thermal resistor from 70 K to 5 K (figure 3), an entirely 4 cm coupler of this same basic design is calculated to have the same heat loads to 5 K and 2 K as are presented here for the 4 cm to 6 cm design.

Calculations for the 70 K level of a 4 cm coupler show that the 70 K to 300 K outer conductor, which is constrained to be shorter than optimum due to other considerations in this tapered design, is better in a 4 cm coupler. But the 70 K to 300 K inner conductor, which is already a little longer than optimum in the this 6 cm design, is becomes more of a problem in the 4 cm design. In particular, the bellows on the inner conductor in a 4 cm design would tend to run warmer. The net result is about 0.6 W less to 70 K under full power, which does not look important. In conclusion, thermal considerations do not favor an entirely 4 cm coupler over this tapered 4 cm to 6 cm design.

REFERENCES

1. M. Champion, et. al., "TESLA Input Coupler Development", presented at the 1993 PAC and part of TESLA Report #93-33.

2. H.-G. Kuerschner, "Theorie der Waermeleitung in sl Niob, Messung der Waermeleitfaehigkeit, Modellrechnungen", presented at a TESLA seminar, DESY, 13 November 1992.

3. Stephen F. Adam, "Microwave Theory and Applications", Hewlett Packard.

4. TESLA collaboration, "A Proposal to Construct and Test Prototype Superconducting R.F. Structures for Linear Colliders", DESY, April 1992.