LCLS-II Technical Note

RF cables for LCLS-II 3.9 GHz Cryomodule

LCLS-II TN-17-11

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1. Introduction

The 3rd (3.9 GHz) harmonic cryomodule is currently under development for LCLS-II project. Again, the RF cables to be used in the cryomodule needs a special consideration similar to the 1.3 GHz cryomodules, since the power flow out of HOM ports can be significant due to the continuous wave operation of the machine.

2. Scope of the Study

The scope of study is to investigate and analyze the heating in the RF cables for LCLS-II 3.9 GHz cryo-modules. Two different lengths for the HOM cables are considered; 2m and 3m with intercepts at 2K, 5K, 50K, and room temperature distributed at equal distance along the cables in both cases Fig. 1 shows the basic geometry of a 3m long LCLS-II RF cable to be used on the higher order mode (HOM) coupler ports.

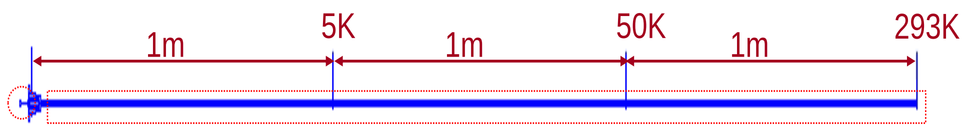
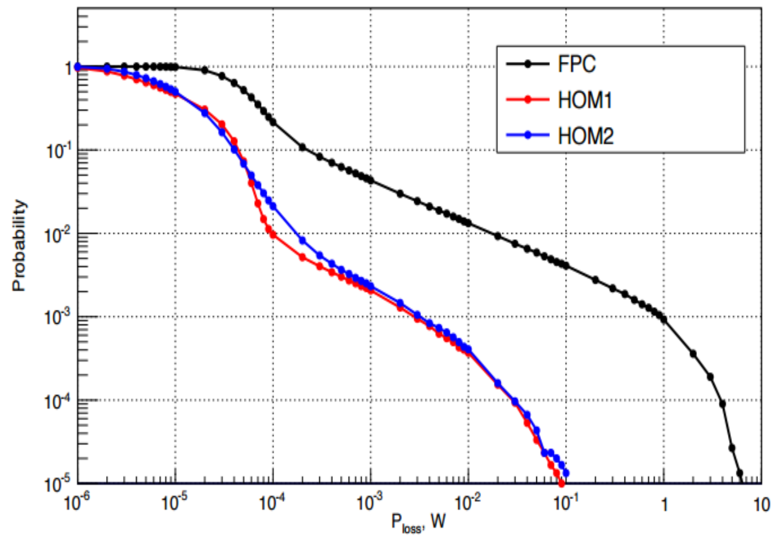


Fig. 1. Geometry of the ILC Cavity.

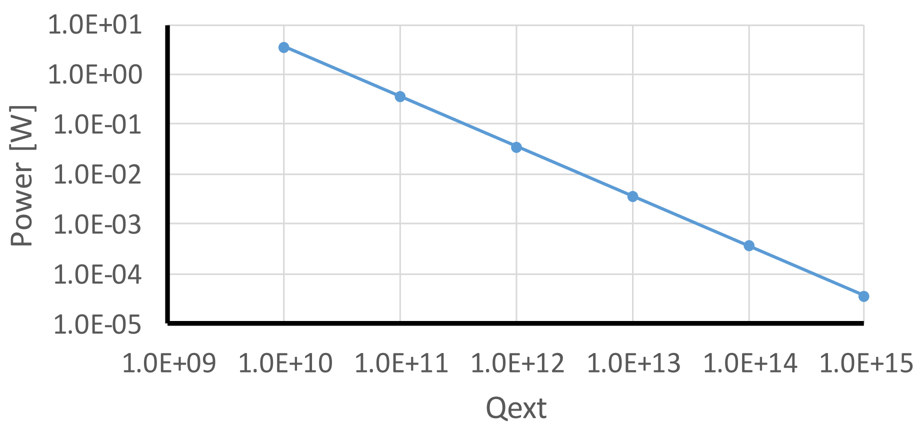
3. Expected Power Flow out of the Cryomodule HOM Ports

There are basically two sources for the power coming out of the HOM ports at each cavity in the cryomodule:

- The first source of power is the beam induced higher order modes excited inside the cavity structure and coupled to HOM antennas to get it removed from the cryo-module and dumbed outside. Earlier analysis has shown that several watts of power can flow out of the HOMs ports but recently a refined analysis based on more realistic statistical model demonstrated that only 0.1 W are expected to accumulate due to HOM excitations with a fairly low probability (1e-5) [1].
- The second source of power is the leakage from fundamental mode. Proper tuning of the HOMs should minimize this leakage but sometimes if the notch frequencies are off, the leakage could be significant. Figure 2(b) illustrates the amount of power leakage in W versus external quality factor of the HOM ports for the 3.9 GHz 9-Cell cavities (R/Q=751, Eacc=14.9MV/m, and Leff=0.346m). The leaked power can be up to 3.5 W in case of Qext=1e10.



(a)

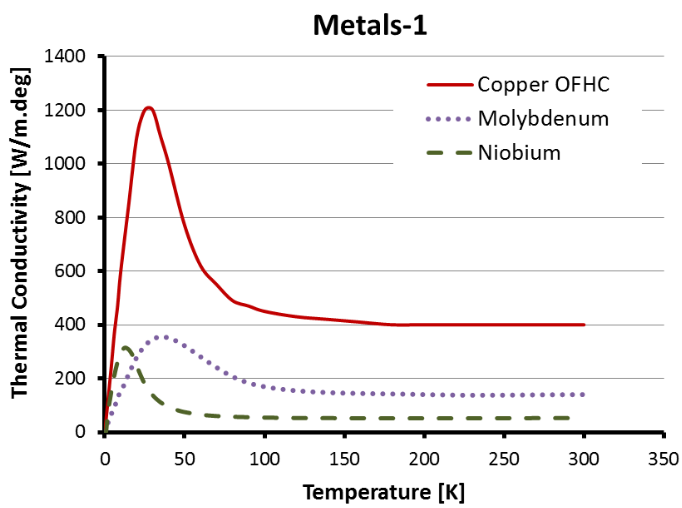


(b)

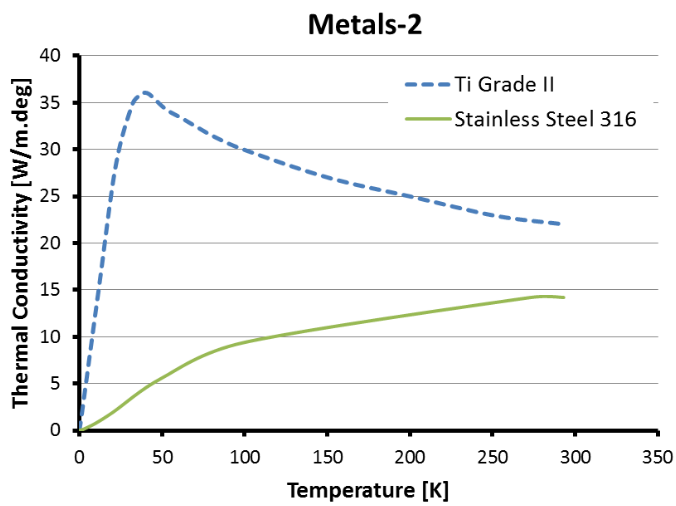
Fig. 2. Sources of power coming out of the Higher Order Mode (HOM) ports. (a) Probability versus amount of HOM power induced by the beam instabilities [1]. (b) Power leaking from the fundamental operating mode as a function of external quality factor of the HOM coupler.

4. Material Properties

In order to accurately model the thermal flow in the RF cables from the cavity through the HOM ports, it was inevitable to represent the thermal conductivity of each metal or dielectric in the cable assembly as a function of temperature. Fig. 3 shows the thermal conductivity of metals [2] to be used in the cable assembly separated in two categories Metals-1 for the relatively good thermally conductive metals in (a), and Metals-2 for the relatively poor thermally conductive in (b). Similarly, the thermal conductivity of ceramics [3] to be used in the assembly is shown in Figure 4, again separated in two categories; Ceramics-1 in (a) for the relatively good conductive ceramics, and Ceramics-2 for the poor ceramic in (b).



(a)



(b)

Fig. 3. Thermal conductivity as a function of temperature of the metals used in cable and coupler assembly.

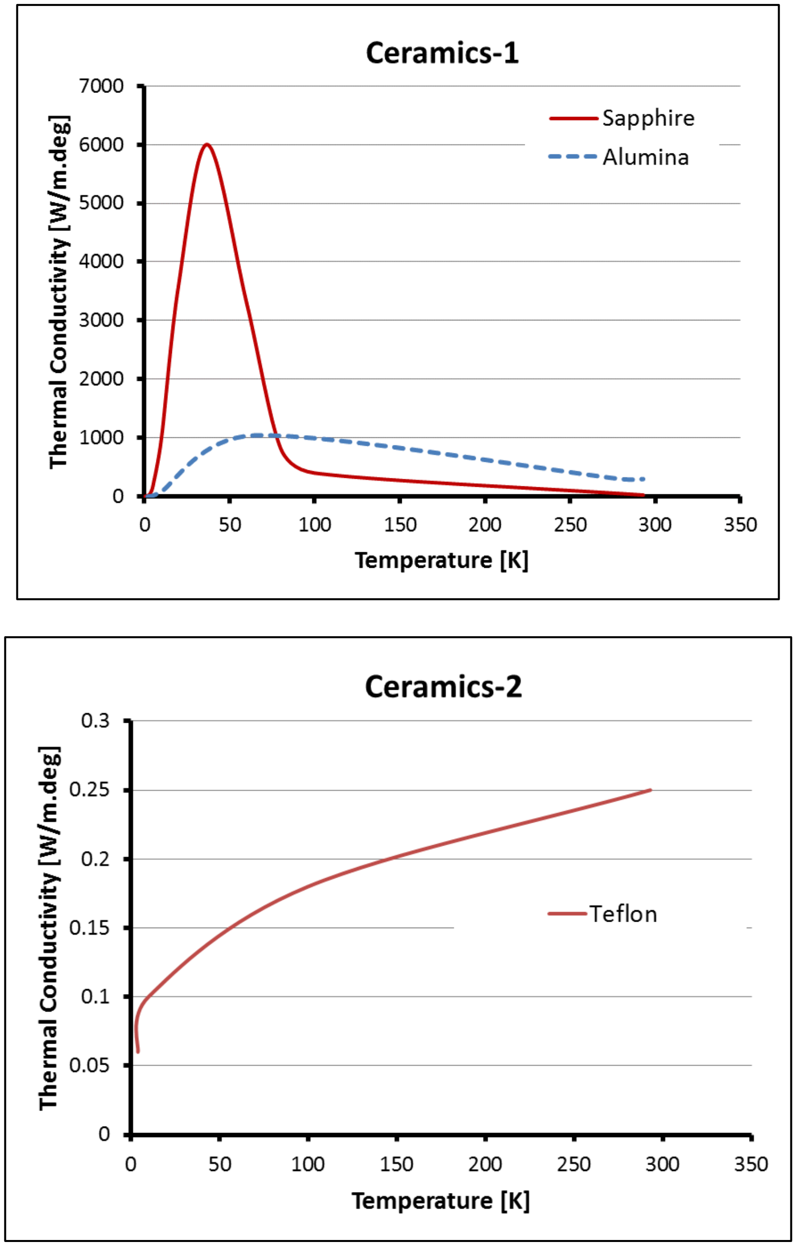


Fig. 4. Thermal conductivity as a function of temperature of ceramic used in cable and coupler assembly.

On the other hand the cable losses would vary also with temperature and has to be taken into account. Figure 5 depicts the cable attenuation as a function of temperature normalized to its rated value at room temperature (300K), where we have assumed a simple linear scaling up to 40K. Below 40K changes in cable loss was assumed to be negligible.

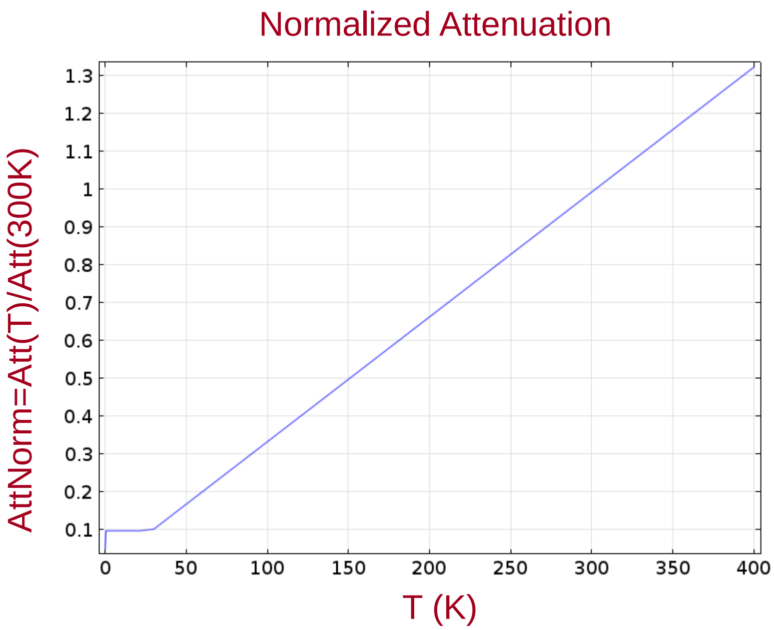


Fig. 5. Normalized cable attenuation as a function of temperature

5. Cable Specification

Based on the requirements of LCLS-II, we set the specifications that the RF cables should fulfill as listed in Table 1.

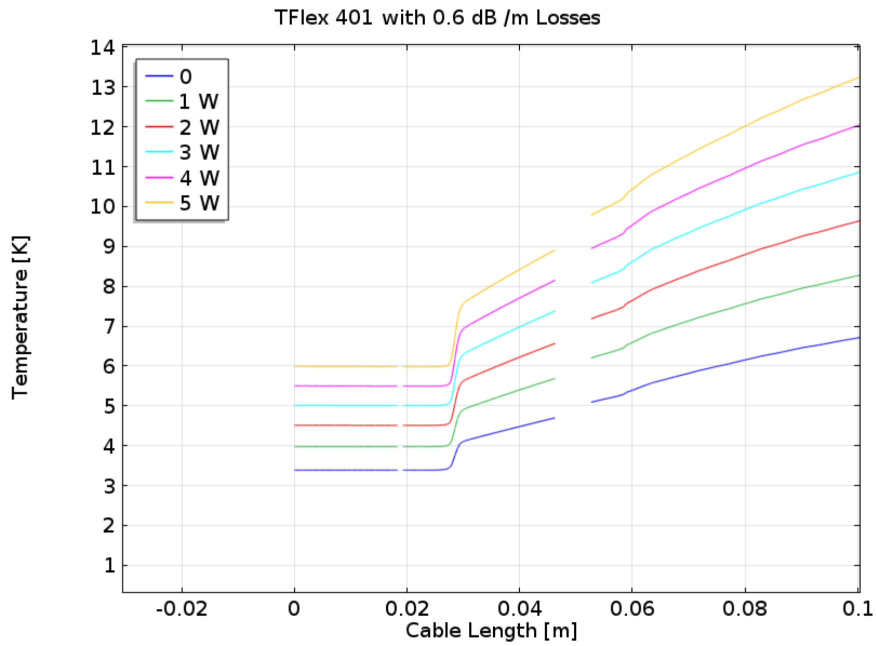
Table 1. Specification for the RF Cables of the3.9 GHz Cryomodule

Specification	Value	Implication
Rigidity	Flexible	
Impedance [Ohm]	50	
Diameter [in]	<0.3	
Length [m]	2.0 (HOM1), 3.0 (HOM2)	
RF Losses at 3000 MHz [dB/m]	**< 0.5 dB/m**	
RF Losses at 6000 MHz [dB/m]	**< 1 dB/m**	
Temperature Range [C]	-100 to +200	Fluorin Based Dielectric (FEP, FPTE)
Dynamic Heat Load [W]	**7**	Conductors have to be copper
Radiation [Rad]	1e5	
Static Bend Radius [mm]	30	
Dynamic Bend Radius [mm]	50	
Connector #1	Nonmagnetic Male N-Type	Brass, Beryllium Copper or similar
Connector #2	Nonmagnetic Male N-Type	Brass, Beryllium Copper or similar
Shielding Effectiveness	>100 dB	
Operating Frequency [GHz]	**10**	
Intercepts	2K, 5K, 50K	

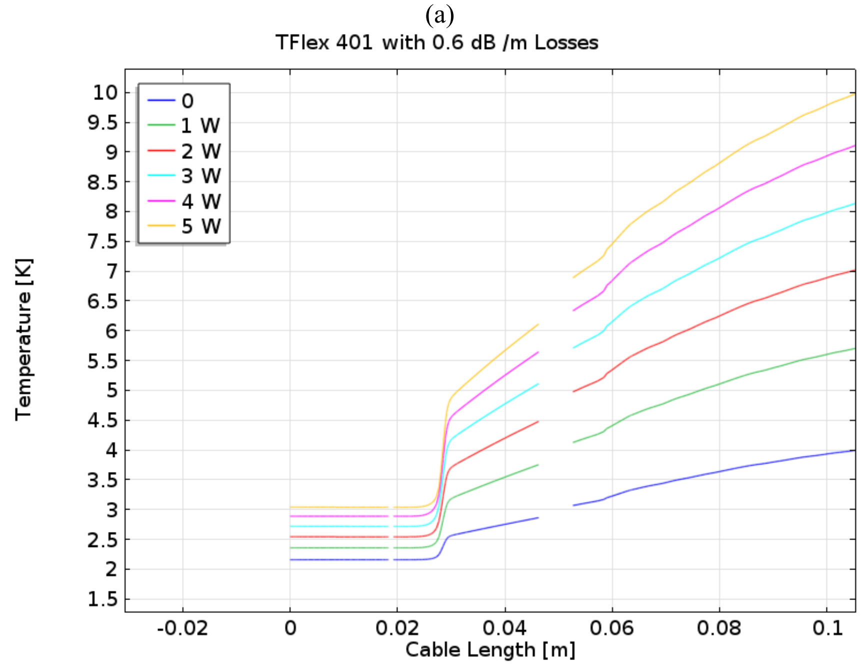
6. Thermal Analysis

We have analyzed the cable performance for the 3.9 GHz cryomodule assuming two different lengths for the HOM cables; 2m and 3m with intercepts at 2K, 5K, 50K, 293K distributed at equal distance along the cables in both cases.

At the beginning, we evaluated two options for the thermal intercepts; one is narrow of cross section 2.5 mm x 2.5 mm and the other is wide of cross section 2.5 mm x 10 mm. Figure 6 shows close-up pictures for the thermal profile along the cable axis nearby the HOM antenna. The purpose of this analysis is to check how high the antenna tip temperature can raise due to deposited heat from the HOMs and leaked fundamental mode power. The antenna tip reached a temperature of 6K in the narrow leads (2.5 mm x 2.5 mm) case, while it is significantly lower (3K) using the wide leads (2.5 mm x 10 mm). Based on this, it was decided to use the wide leads in order to secure enough cooling for the HOM antenna tip, preventing any potentially induced quench.



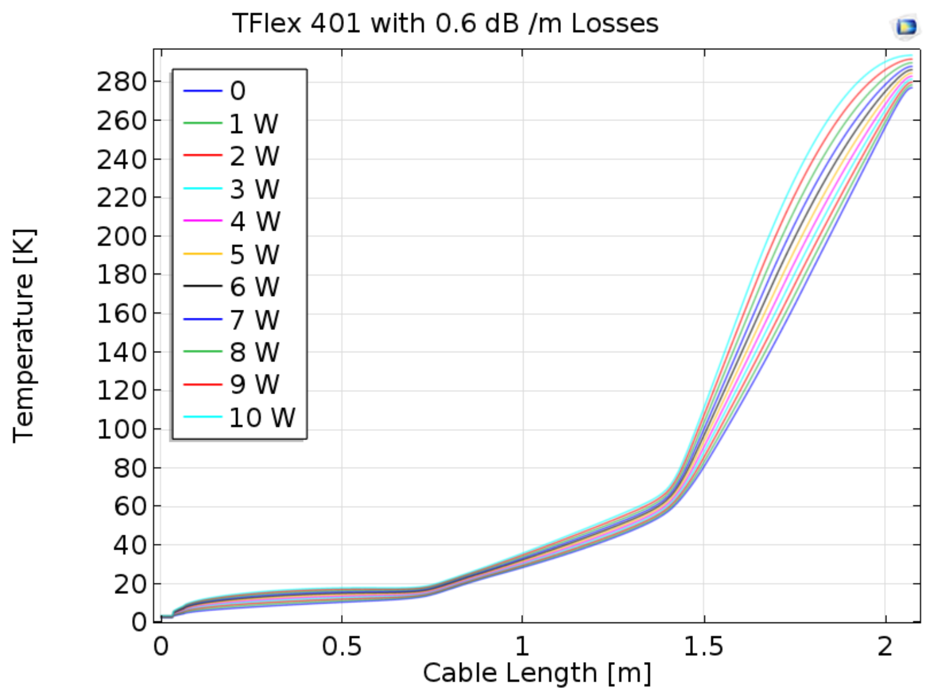
(a)



(b)

Fig. 6. Thermal profile of a 2m Copper cable (0.6dB/m at 3 GHz), leads intercepts every 0.67m. (a) With narrow (2.5 mm x2.5 mm) leads intercepts. (b) With wide (2.5 mm x10 mm) leads intercepts.

Figure 7 demonstrates the temperature profile along the cable axis for the 2m, and 3m length cases in (a) and (b), respectively. As shown in Figure, the cable can handle up to 10W of power flow in the case of the 2m long cable, while it can bare 8W for the 3m long cable while barely exceeding the 75°C criteria



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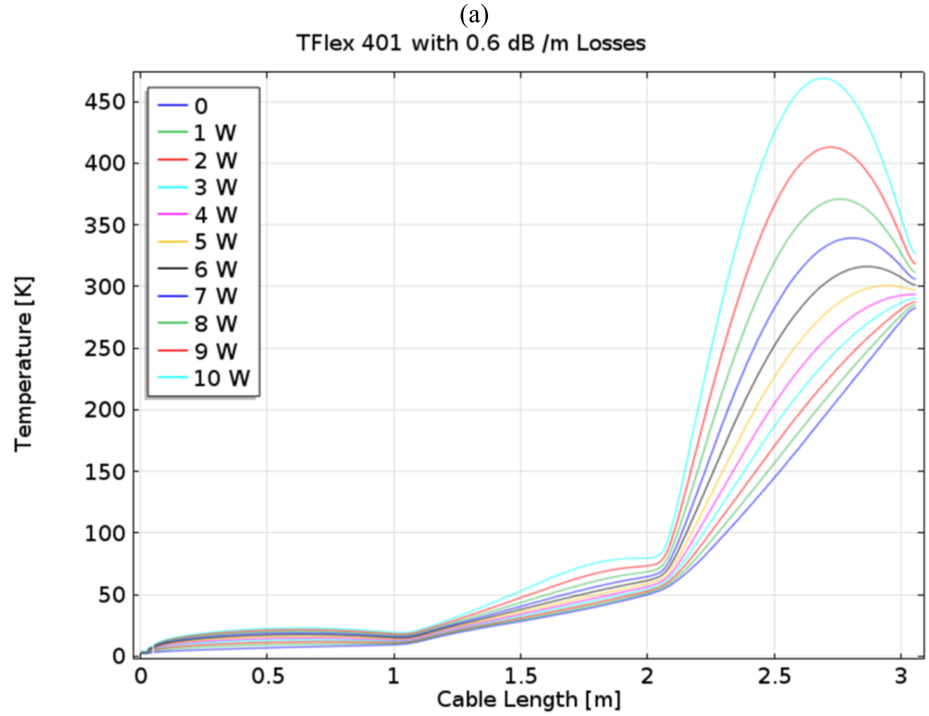
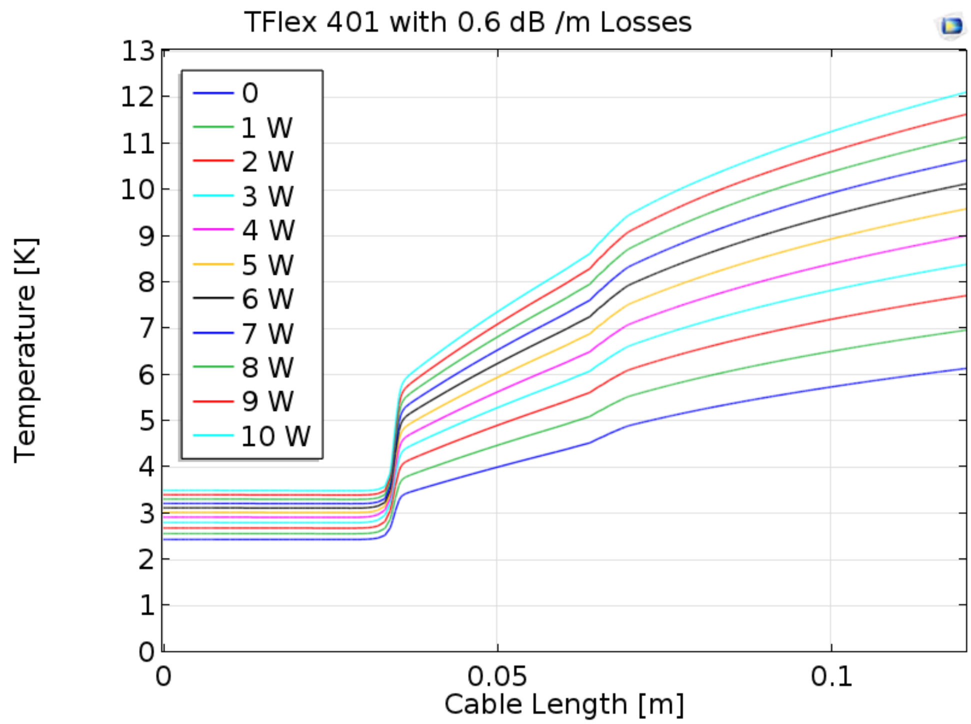


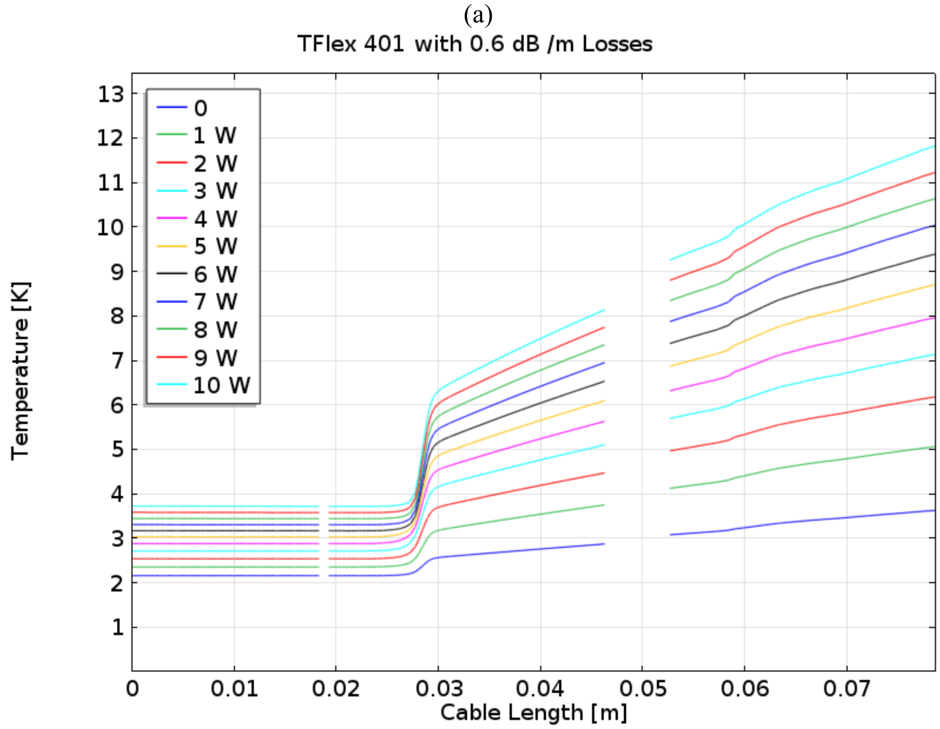
(b)

Fig. 7. Thermal profile of a Copper cable (0.6dB/m at 3 GHz). (a) 2m long with wide leads intercepts every 0.67m. (b) 3m long with wide leads intercepts every 1m.

A close-up for the thermal profile along the two cable length cases is shown in Fig. 8 to demonstrate the maximum temperarure along the tip, which is will not exceed 3.5K at 10 W in case of the 2m long cable, and 4K at 8W in case of the 3m long cable.



(a)



(b)

Fig. 8. A close-up for the thermal profile of a Copper cable (0.6dB/m at 3 GHz). (a) 2m long with

The static heat load was found to be 27.4 mW (2K), 286.7 mW(5K), 405.7 mW(50K), and 719.8 mW(293K) for the 2m cable as listed in Table 2, while it is 9.3 mW (2K), 164.8 mW(5K), 242.8 mW(50K), and -416.9 mW(293K) for the 3m long cable, as listed in Table 3.

On the other hand, the dynamic heat load at 10W power flow for the 2m long cable is 119.6 mW (2K), 484.5 mW(5K), 998.5 mW(50K), and 5.81 mW(300K), while at 8W power flow for the 3m long cable the dynamic heat load is as follows, 113.7mW (2K), 422 mW(5K), 1223.6 mW(50K), and 708.6 mW(300K).

The project decided to use 2.5 m cables based on this analysis as a compromise to balance the static and dynamic heat loads.

Table 2. TFlex401 cable (2m) performance for 3.9 GHz cryomodule with wide leads intercepts

Power Flow[W]	**2K [mW]**	**5K [mw]**	**50K [mW]**	**293K [mw]**
0	27.38	286.73	405.68	-719.78
1	36.28	305.48	451.59	-659.64
2	45.24	324.38	499.85	-597.26
3	54.29	343.43	550.63	-532.50
4	63.43	362.65	604.18	-465.16
5	72.65	382.10	660.71	-395.06
6	81.93	401.80	720.51	-321.97
7	**91.27**	**421.82**	**783.86**	**-245.64**
8	100.64	442.26	851.06	-165.78
9	110.09	463.14	922.47	-82.08
10	119.63	484.52	998.51	5.81

Table 3. TFlex401 cable (3m) performance for 3.9 GHz cryomodule with wide leads intercepts

Power Flow[W]	2K [mW]	5K [mw]	50K [mW]	300K [mw]
0	9.27	164.76	242.83	-416.87
1	21.91	193.01	313.60	-326.02
2	34.61	221.87	393.03	-226.41
3	47.43	251.44	483.14	-116.22
4	60.39	281.94	586.51	6.86
5	73.47	313.74	706.51	145.86
6	86.67	347.22	847.86	304.90
7	**100.05**	**383.02**	**1017.10**	**489.75**
8	113.67	422.00	1223.63	708.57
9	127.78	465.89	1481.52	973.22
10	142.70	517.64	1812.94	1301.92

7. Conclusion and Recommendations

RF cables are one of the critical components in cryo-moules. A failure in a cable would impede the use of the cavity connected to that cable. Excessive heating is the imminent threat for cable failures. Using low loss cables is the only option to avoid excessive heating on cables given the relatively large amount of power flow (7 W) in CW operation. Copper cables are the only viable solution in this case because the dominating dynamic loads in CW operation. Stainless steel cables despite being popular in previous projects with pulsed operation, where static load is dominating, can't be used as the poor thermal conductivity of stainless steel will trap the heat inside the cable causing catastrophic heating failures beyond 0.5W power flow. We recommend using cables with less than 0.6 dB/m at 3 GHz in order to ensure that the maximum temperature along the cable won't exceed 75ºC. Wide (2.5 mm x 10 mm) lead intercepts should be used to secure enough cooling for the HOM antenna tip. Two different lengths were considered for the RF cables; 2m and 3m. Based on our study , we decided to use 2.5 m cables to balance the static and dynamic heat loads. PTFE dielectric is favored (seems to be the only choice) in this case to ensure the low loss performance for the cables. Using a high radiation resistive jacket for the cable like TEFZEL or Halar (~100 MRad) should resolve the issue of limited radiation hardness of PTFE.

References

[1] Resonant Excitation of High Order Modes in the 3.9 GHz Cavity of LCLS-II Linac LCLS-II TN-16-05

[2] Margerita Mario, Material Properties for Engineering Analyses of SRF Cavities, Fermilab Specification: 5500.000-