LCLS-II Technical Note

RF Cables for LCLS-II Cryomodules: Issues and Remedies

LCLSII-TN-15-44

[Publish Date]

Mohamed Hassan, Timergali Khabiboulline, Darryl Orris, and Nikolay Solyak

April

TABLE OF CONTENTS

1. Introduction

The fact that LCLS-II is a continuous wave Linac puts quite a bit of pressure on the considerations of RF cables for the cryo-modules. Due to the continuous wave nature of the proposed machine, the HOM cables is required to remove a significant amount of RF power up to 10 W. In contrast to XFEL which is based on a pulsed Linac, the amount of HOM power to be removed in LCLS-II is more than an order of magnitude higher than XFEL. In order for the RF cable to survive the expected 10 W power flow, the cable has to be of low loss and cooling intercepts have to be carefully designed. Available low loss cables in the RF market are Teflon based which exhibits ultra-low loss but is poor from radiation resistance perspective. As a matter of fact, LCLS-II cryo-modules are required to bare a relatively high radiation dose over their life time, which mandates that Teflon-based components should be avoided as much as possible inside the cryomodule. In this technical note, we present the challenges posed on the selection of the RF cables and how we finally managed to meet both the RF loss and radiation hardness requirements.

2. Scope of the Study

The scope of study is present the investigation and analyses carried out to set criteria for the RF cables of LCLS-II cryo-modules. Fig. 1 shows the basic geometry of an LCLS-II RF cable to be used on the higher order mode (HOM) coupler ports. The HOM cables are either 3 m or 2 m in length with thermal intercepts at 2K, 5K, 50K, and room temperature, as shown in Figure 1.

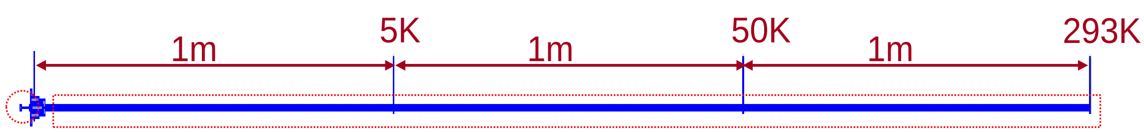


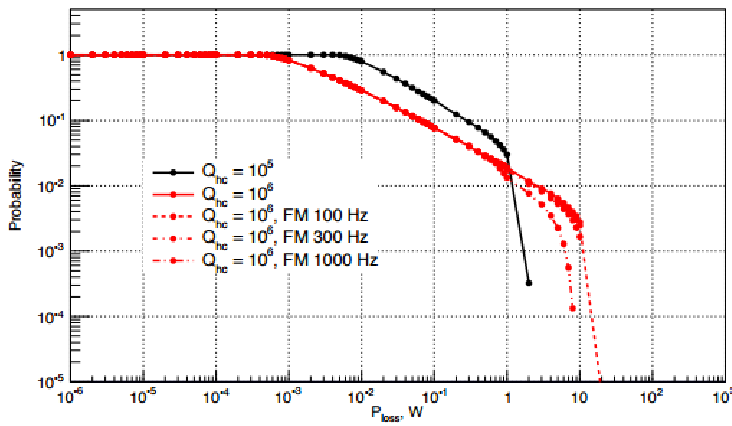
Fig. 1. Geometry of the ILC Cavity.

3. Expected Power Flow out of the Cryomodule HOM Ports

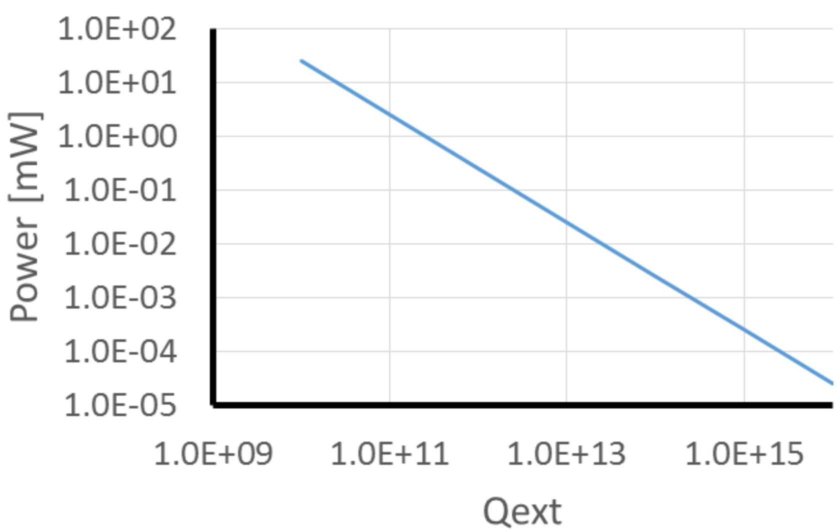
There are basically two sources for the power coming out of the HOM ports at each cavity in the cryo-module:-

- 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. Analysis has shown that there is 1/100 chance to get an accidental 1W, and ~1/1000 chance that we get accidental 10W of power because of this beam induced HOMs [1]. Figure 2(a) demonstrates the probability of having different levels of HOMs power for various external quality factors [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 mW versus external quality factor of the HOM ports.



(a)

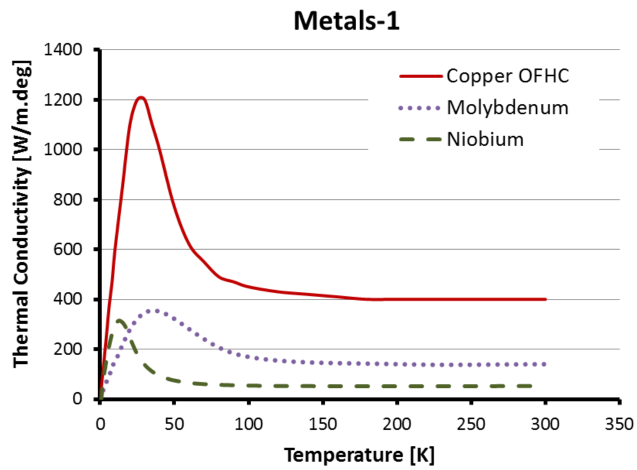


(b)

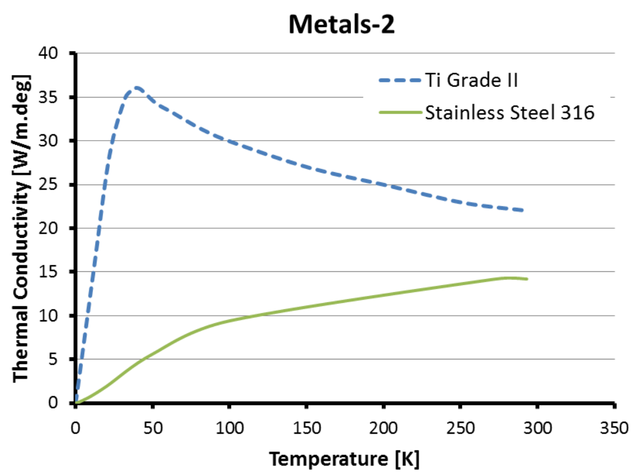
Fig. 2. Sources of power coming out of the Higher Order Mode (HOM) ports. (a) Probability versus amount of HOM power induced by the beam instabilities [1]. (b) Power leaking from the fundamental operating mode as a function of external quality factor of the HOM coupler.

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.

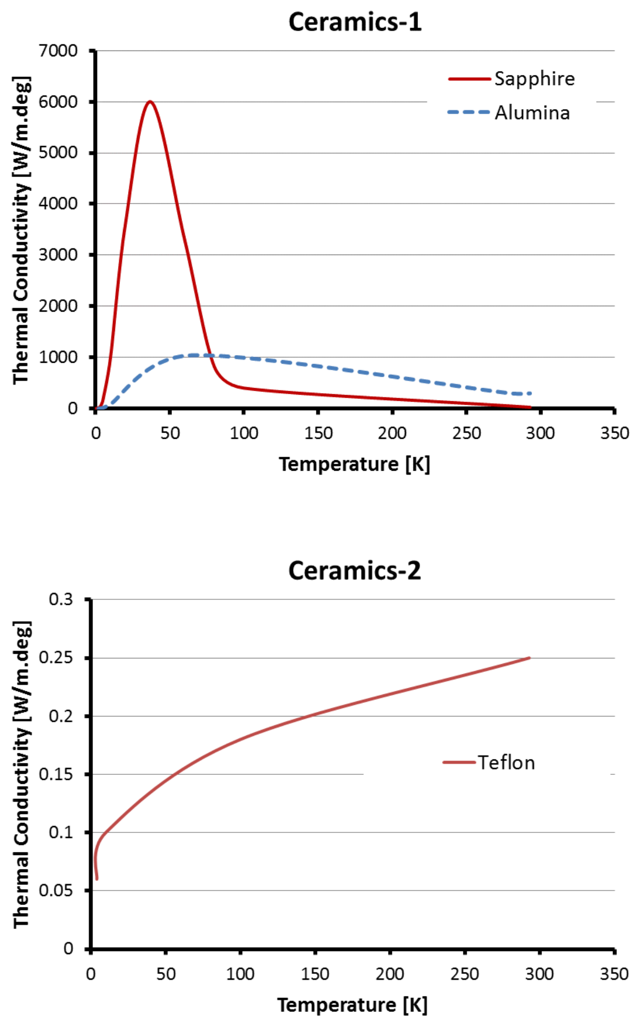


Fig. 4. Thermal conductivity as a function of temperature of ceramic used in cable and coupler assembly.

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.

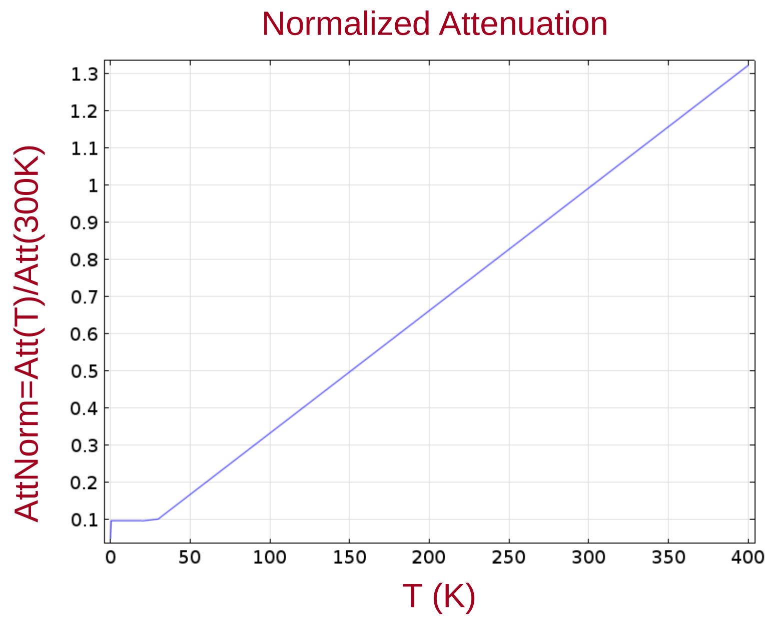


Fig. 5. Normalized cable attenuation as a function of temperature

5. Thermal Analysis

We have investigated the performance of several RF cables under various scenarios in terms of the material of the cable conductors and the amount of power flowing along cable, based on the configuration shown in Figure 1, with four thermal intercepts at 2K, 5K, 50K, and 300K.

We have started by analyzing the performance of an all stainless steel cable of 0.2" OD and has a loss rating of 0.42 dB/m at room temperature. Stainless steel cables were used before in ILC pulsed cryo-modules that was built at Fermilab (CM1, and CM2). Figure 6 shows the temperature along the cable axis. Clearly the cable won't stand more than 0.5 W of continuous wave power flow. As expected, the poor thermally conducting stainless steel cables are not suitable for cryo-modules to be operated in the continuous wave regime.

On the contrary to stainless steel, copper has a very good thermal conductivity and represents a viable option for use in such continuous wave cryo-modules. Figure 7(a) shows the performance of the cable upon just changing the material of inner and outer conductors from stainless steel to copper. As shown in Figure, the cable can handle up to 10W of power flow but the temperature will increase up to 350K in case of the 10W power flow at the last section of the cable between the 50K and 300K intercepts. Since we really want to lower the maximum temperature on the cable to even lower values, we would need to use a better cable in terms of RF losses. For instance, figure 7(b) shows the performance of the cable in case of loss value of 0.2 dB/m. In this case, maximum temperature on the cable will not exceed room temperature.

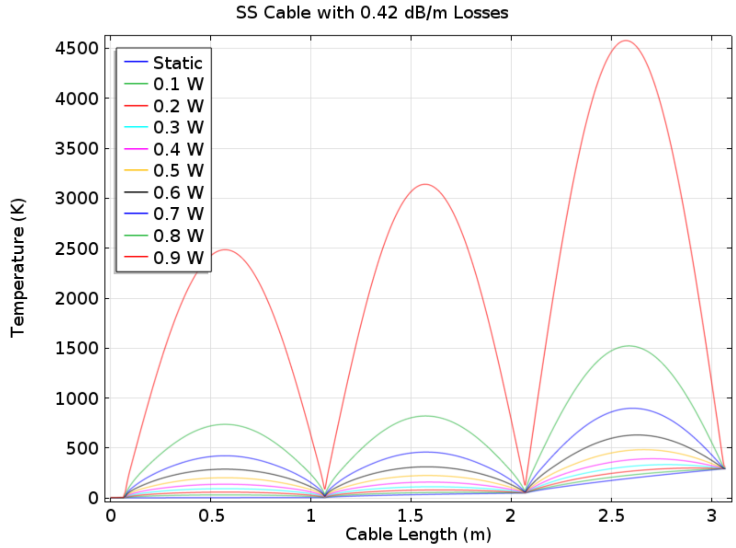
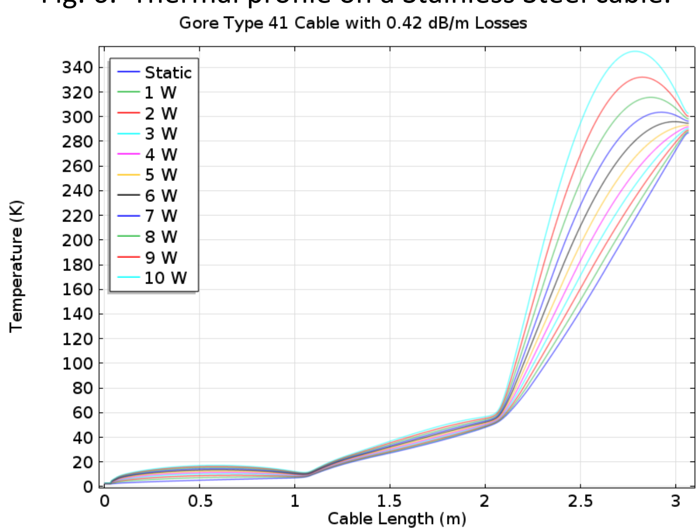
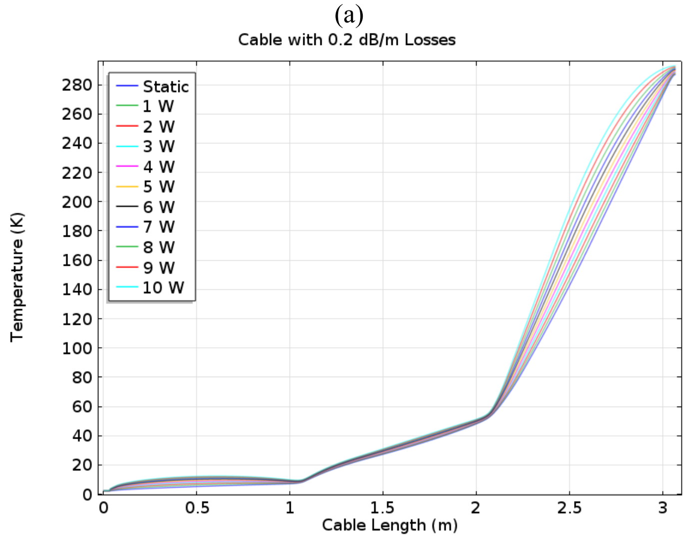


Fig. 6. Thermal profile on a Stainless Steel cable.



(a)



(b)

Fig. 7. Thermal profile on a Copper cable. (a) Cable loss 0.42 dB/m. (b) Cable loss 0.2 dB/m

6. RF Loss Requirements for Cables

In order to ensure a proper performance for the cable without excessive heating we sat a limit on the maximum temperature on the cable to not exceed 75ºC. In this case, and based on the thermal analysis presented in the previous section we need a cable with loss value of less than 0.3dB/m at 1 GHz.

Figure 8 demonstrates the performance of a Times Microwave TFlex 401 cable, one of the candidates for LCLS-II cryo-modules under various power flow conditions. The TFlex401 cable has a 0.3dB/m loss at 1GHz.Table 1 lists the intercepted power in mW by the cooling leads at 2K, 5K, 50K and 300K, respectively. Maximum temperature on cable at the 10 Watt maximum expected power flow won't exceed 30ºC.

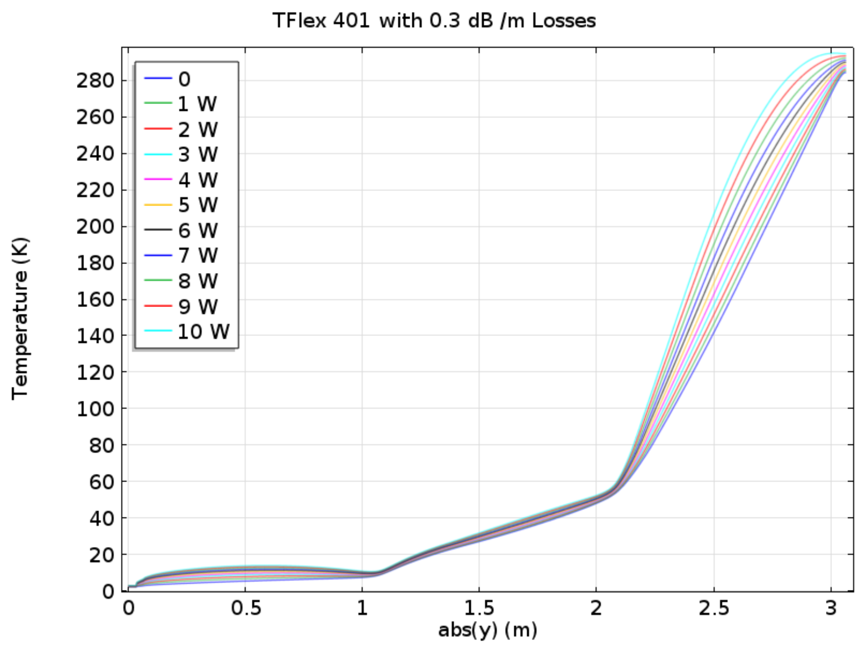


Fig. 8. Thermal profile on a Copper cable. (a) Cable loss 0.42 dB/m. (b) Cable loss 0.2 dB/m

Table 1. Intercepted Power at the Cooling Leads for TFlex401

Tflex401 0.3 dB/m				
Power [W]	**2K [mW]**	**5K [mW]**	**50K [mW]**	**300K [mW]**
0	6.30	189.88	287.86	-484.04
1	12.38	204.31	323.62	-438.61
2	18.46	218.83	360.99	-391.48
3	24.55	233.44	400.10	-342.50
4	**30.64**	**248.16**	**441.10**	**-291.53**
5	36.73	263.00	484.19	-238.40
6	42.83	277.96	529.54	-182.92
7	48.95	293.05	577.40	-124.88
8	55.09	308.28	628.01	-64.05
9	61.25	323.66	681.64	-0.16
10	67.42	339.23	738.62	67.10

7. LCLS-II Radiation Hardness Requirements for Cables

The radiation requirements in LCLS-II stems from the expected dose to be accumulated over the life time of the cryo-module due to dark currents flow. Figure 9 shows the dose equivalent in [mrem/h/10nA] (normalized to 10 nA of dark current flow) [4]. Based on this map we estimate the radiation dose that the cables may receive to be in the order of 100 MRad in 20 years at 1nA/CM. This sets the radiation hardness requirements on cables to be at the 100 MRad level.

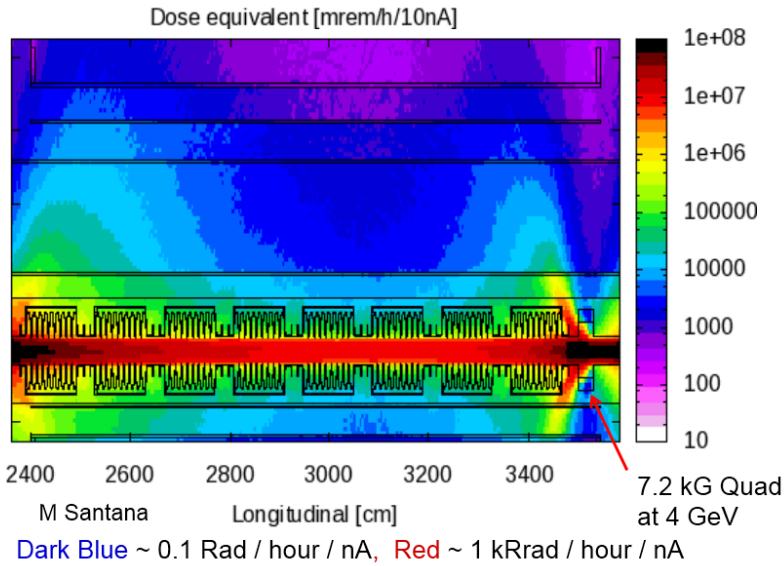


Fig. 9. Simulated dose equivalent in mrem/h per 10 nA of dark current for LCLS-II cryo-module [4].

8. Radiation Resistance of Commonly Used Dielectrics

Different dielectrics reacts differently to radiation doses. Figure10 presents the approximate radiation limit in Air at room temperature for different dielectrics commonly used in cables. Kapton is clearly the best from radiation perspective as it can bare up to 1e9 Rad, followed by Halar and TEFZEL which can bare up to 1e8, then ETFE at 2e6, FEP at 5e5. Finally PTFE is the lowest in terms of radiation resistance at 2e4, which is expected because it is a Teflon compound. It is worth noting also that the radiation resistance generally gets better upon going from room temperature to cryogenic temperature 4K. Figure 11 shows the radiation resistance of PTFE both at room temperature and 4K. Fortunately, the radiation resistance gets improved by an order of magnitude at cryogenic temperature.

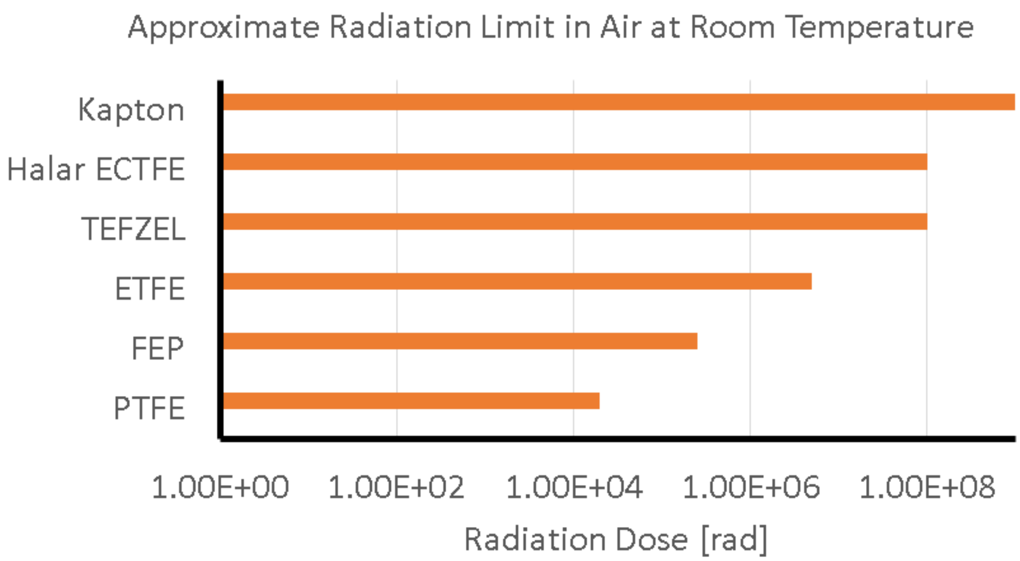


Fig. 10. Approximate radiation limit in Air at room temperature

	In Air	In Vacuum
Threshold	$2\text{-}7 \times 10^4$	$2\text{-}7 \times 10^5$ or more
50% tensile strength	10^6	10^7 or more
40% tensile strength	10^7 or more	8×10^8 or more
Retain 100% elongation	$2\text{-}5 \times 10^5$	$2\text{-}5 \times 10^6$

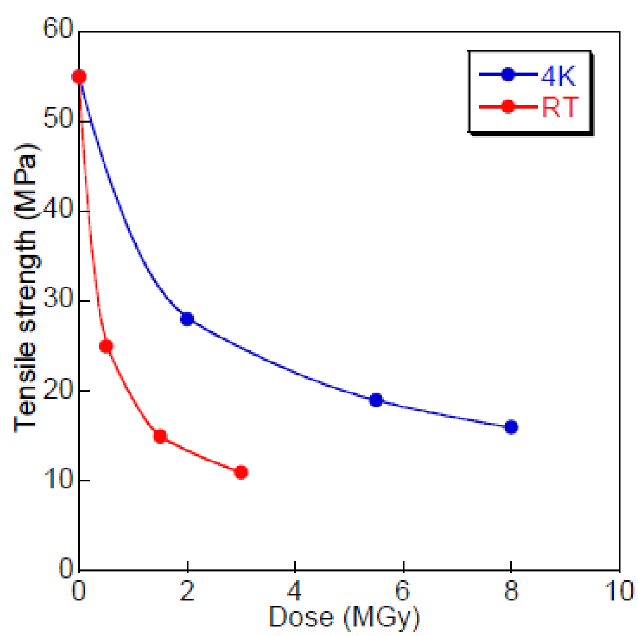


Fig. 11. Comparison between the radiation resistance of PTFE at room temperature and 4K

9. Remedies

Obviously, there is a conflict between the RF loss and radiation hardness requirements. From RF loss perspective, PTFE is favored as a cable dielectric in order to meet the 0.3 dB/m at 1 GHz loss requirements however, it doesn't meet the radiation hardness requirements. In order to resolve this conflict we decided to use a high radiation resistive material only for the cable jacket, like TEFZEL or Halar, while still use PTFE for the cable inside dielectric. Even if some damage happened to the inner dielectric of the cable because of radiation, the jacket will hold the cable together and no significant performance changes are expected. This way we meet both the RF loss and radiation requirements.

10. 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 (10 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. Cable section between thermal intercepts should be kept relatively short (~<1m) to avoid excessive heating. We recommend using cables with less than 0.3 dB/m at 1 GHz in order to ensure that the maximum temperature along the cable won't exceed 75ºC. PTFE dielectric is favored (seems to be the only choice) in this case to ensure the low loss performance for the cable meeting the 0.3 dB/m requirements. 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. Even if some damage happens to the inner dielectric, the jacket will hold the cable together and no significant performance degradation should incur given that no flexing or movement is expected on the cables after installation. Moreover, our experience from testing a cable with PTFE inner dielectric and FEP jacket with a radiation dose of 500 MRad, indicated that the cable survived that large amount of radiation with relatively tolerable damage (see Appendix)

Appendix1: Exclusion of Kepton

Kepton is often suggested as dielectric material for the cable because of it is relatively high radiation resistance (~1e9 rad), but unfortunately it doesn't exhibit the same superior performance from the RF loss perspective. Table 2 compares the loss tangent of several dielectrics commonly used in RF cables. Clearly, the Kaptorn is inferior to other dielectrics with the PTFE being the best exhibiting a loss tangent of less than 0.0003 at 3 GHz. To further demonstrate the difference in performance between a Kapton vs PTFE based cables, Table 2 presents the loss performance of different sample cables at 1 GHz and 3 GHz. The Kapton cable exhibit about 1.8 dB/m loss at 1 GHz ,which is far from the required 0.3 dB/m loss criteria we have established for LCLS-II. The only dielectric that can meet this loss requirements is PTFE, which has a relatively poor radiation resistance (2e4 rad).

Table 2. Dielectric Loss Tangent of Commnly Used Dielectrics

Material	**Dielectric Constant**	**Loss Tangent**
PTFE	2.0-2.1	0.00028 at 3GHz *
FEP	2.1	0.0007 at 1MHz
TEFZEL	2.6-2.3	0.0007 - 0.0119
PE	2.26	0.00031 at 3GHz
Kapton 100	3.9	0.0036 at 1kHz #
Kapton 150	2.9	0.001 #

* http://www.rfcafe.com/references/electrical/dielectric-constants-strengths.htm

http://www.dupont.com/

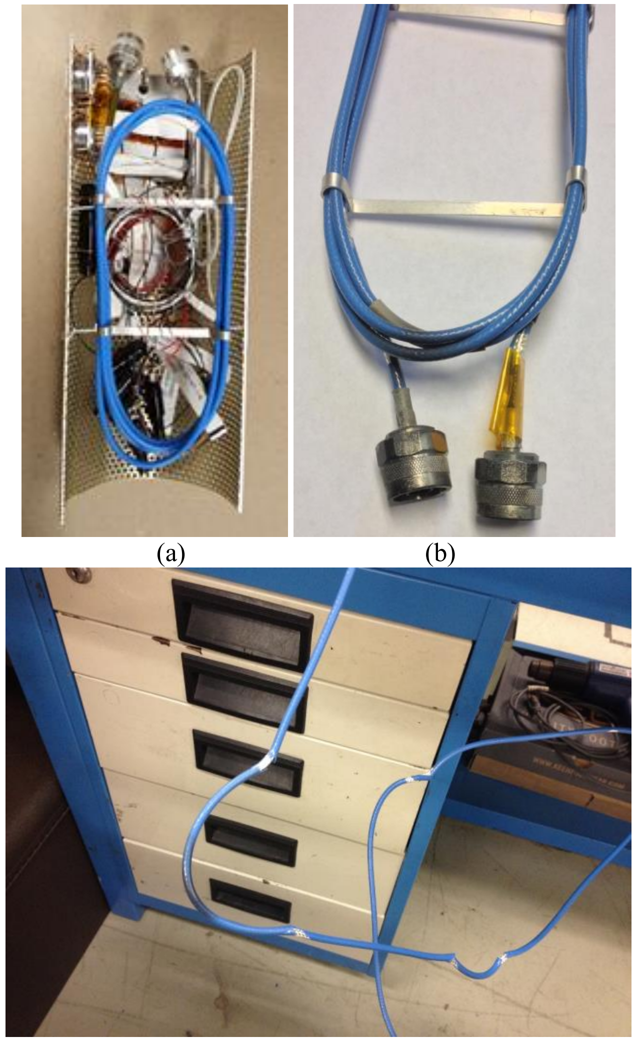
Table 3. Sample Cables Loss Performance

Room Temperature Measurements							
Cable Type	**Dielectric**	**Length [m]**	**OD [in]**	**Loss [dB] 1GHz**	**Loss [dB] 3GHz**	**Att [dB/m] 1GHz**	**Att [dB/m] 3GHz**
Gore Type 41	ePTFE	1	0.19	0.35	0.55	0.35	0.55
Gore Type 42	ePTFE	1	0.29	0.23	0.45	0.23	0.45
Times MW LMR 200	PTFE	3	0.195	1.18	2.15	0.39	0.72
Times MW LMR 240	PTFE	3	0.24	0.91	1.50	0.30	0.50
Times MW LMR 300	PTFE	3	0.29	0.64	1.15	0.21	0.38
AccuGlass AWG 20	Kapton	3	0.13	5.45	15.00	1.82	5.00

Appendix2: Radiation Test of Times Microwave (PTFE Based) Cable

One of the procured cables (Times Microwave TFlex402) has been subjected to a radiation test at Sandia in an inert gas purge at room temperature, where it was exposed to 500 MRad of gamma irradiation over a period of 7 days. The cable was exposed folded and held by metallic bracket as shown in Fig 12(a). After exposure the cable was measured in as is position, as shown in Fig 12(b) and then unfolded, as shown in Fig. 12(c). The jacket got cracked while unfolding the cable, which is expected because of radiation damage.

Table 4 compares the loss performance of the cable before and after radiation test at both 1GHz and 3GHz. The increase in loss is approximately 30% after this relatively large 500 MRad radiation dose, which is will beyond LCLS-II expected dose of 100 MRad. It is worth noting here the cable jacket here is FEP which has a radiation resistance of only 5e5 Rad at room temperature.



(a) (b) (c)

Fig. 12. Radiation test of TFlex402 RF cable. (a) Cable in folded fixture before radiation test. (b) Cable (still folded) after radiation test. (c) Cable unfolded during RF measurements after radiation test.

Table 4. TFlex402 cable performance before and after radiation test.

	Before Test	**After Test**
Loss [dB/m] at 1GHz	0.41	0.55
Loss [dB/m] at 3GHz	0.73	0.95

References

[1] A. Sukhanov, Resonance Excitation in 1.3 GHz Cavity, Technical note #
[2] Margerita Mario, Material Properties for Engineering Analyses of SRF Cavities, Fermilab Specification: 5500.000-ES-371110.
[3] Pobell, Frank. Matter and methods at low temperatures. Vol. 2. Berlin: Springer-Verlag, 1996.
[4] Chris Adolphsen's Talk