



# **CLIQ & K-MOD Feeders**

## **Dimensioning of electrical conductors**

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# CLIQ and K-MOD Current Feeders

The current feeders, are the in and out segments of these electrical circuits that link the vacuum vessel wall at ambient temperature to the HL-LHC triplet cold masses at  $\sim 1.9\text{K}$ .

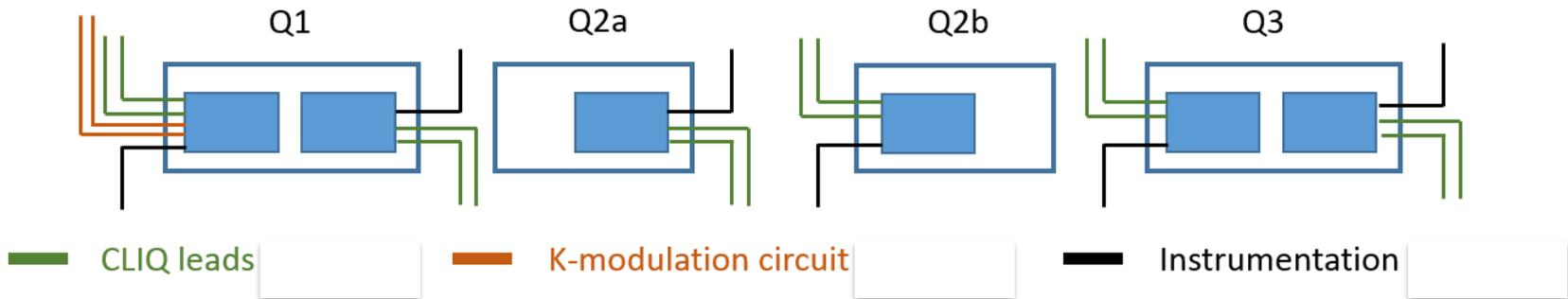
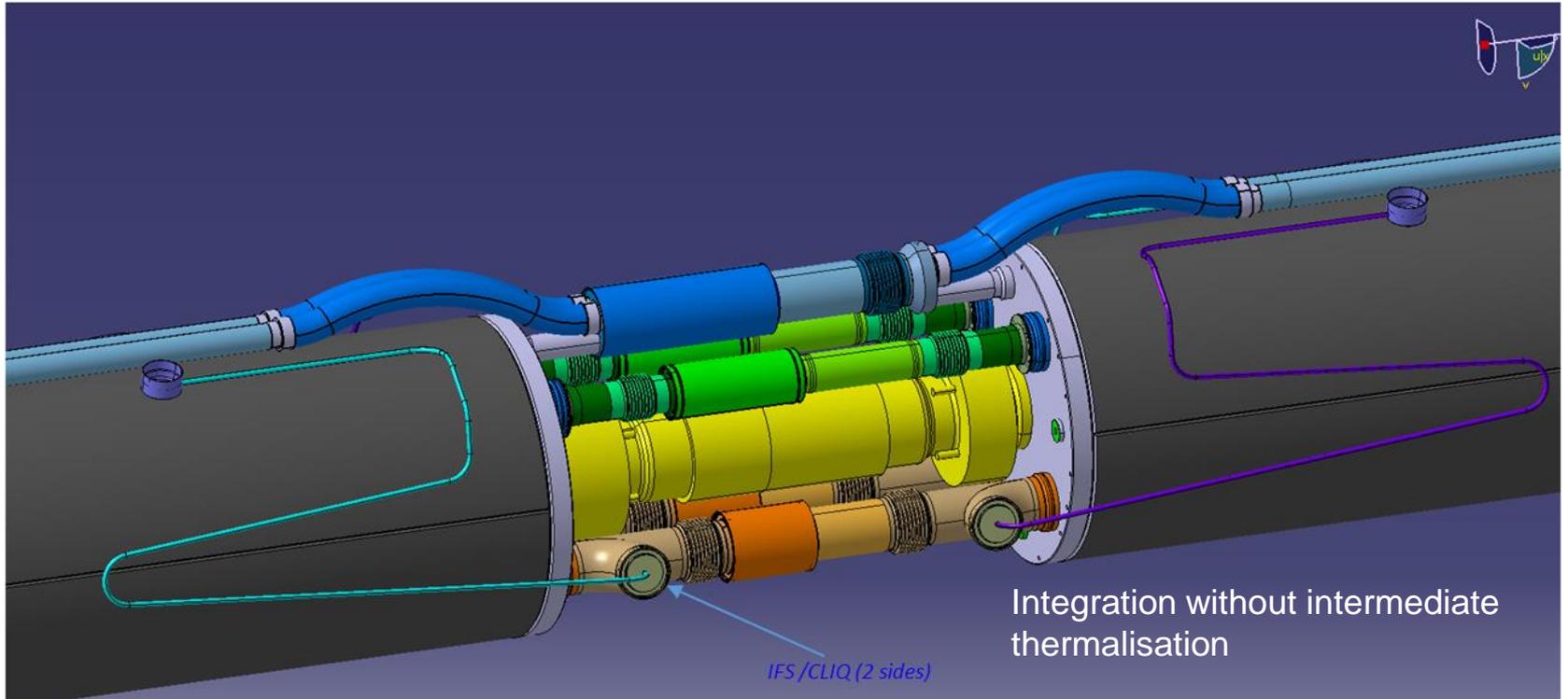
The objective is to provide **effective, robust and reliable** current feeders as part of the CLIQ and K-MOD electrical circuits and to do so at reasonable capital and exploitation costs.

A design trade-off is required between values adopted for the key governing parameters

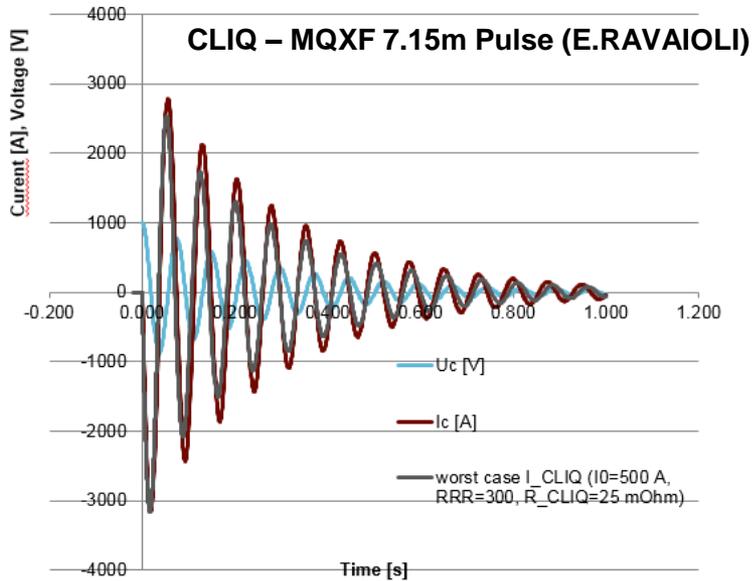
# Key Design Parameters for CLIQ and K-MOD

- The dimensioning of the electrical conductor cross section depends on the following key design parameters:
  - The maximum allowable resistance of each feeder conductor
    - To ensure adequate pulse transmission to the magnet (CLIQ and K-MOD)
    - To ensure stability against thermal runaway under 35A continuous current (K-MOD)
  - The maximum allowable feeder conductor temperature after transmission of the CLIQ or the K-MOD electrical pulse.
  - Maintain the feeder warm (vacuum vessel) end always at temperatures above the dew point of the LHC tunnel ambient air
  - The maximum heat loads to 1.9K that can be tolerated by the refrigeration system
- From these can be selected or determined the following physical parameters:
  - Conductor material
  - Conductor cross-section
  - Conductor length

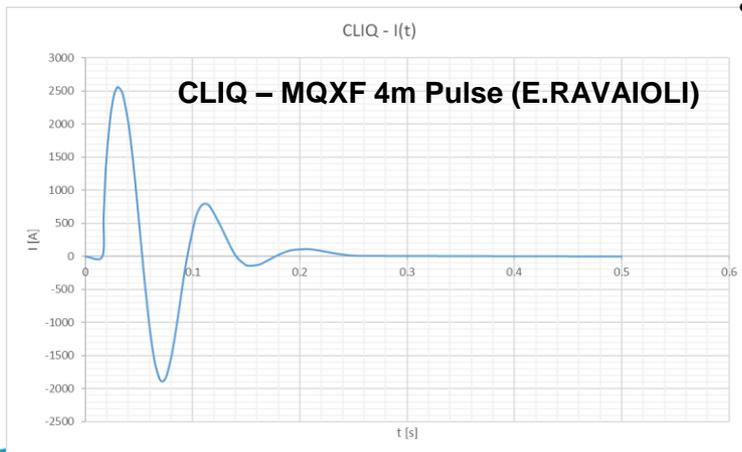
# Schematic Layout



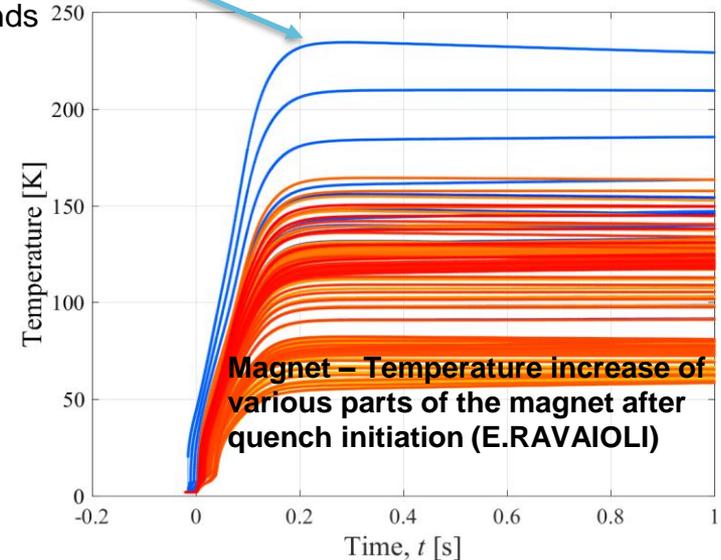
# CLIQ Input Parameters



CLIQ Unit - Parameters		
No CLIQ units (Select only 1 or 2)	1	
Charging Voltage $U_0$ [V]	1000	
Capacitance $C$ [mF]	40	
CLIQ circuit resistance $R_{CLIQ}$ [m $\Omega$ ]	25	<-----
CLIQ Wire - Parameters		
Initial temperature of CLIQ lead [K]	293	
Maximum allowed temperature in the CLIQ lead [K]	350	<-----
Coil Parameters - MQXF 7.15 m		
Equivalent Inductance $L_{eq}$ [H]	0.0035	
CLIQ Wire - MQXF 7.15 m		
Peak Current [A]	3169	
Minimum cross-section of the CLIQ lead [mm $^2$ ]	8.69	
Coil Parameters - MQXF 4 m		
Equivalent Inductance $L_{eq}$ [H]	0.0020	
CLIQ Wire - MQXF 4 m		
Peak Current [A]	2493	
Minimum cross-section of the CLIQ lead [mm $^2$ ]	5.27	



Cable temperature 225K max  
after ~0.2 seconds



# Some important conditioning comments

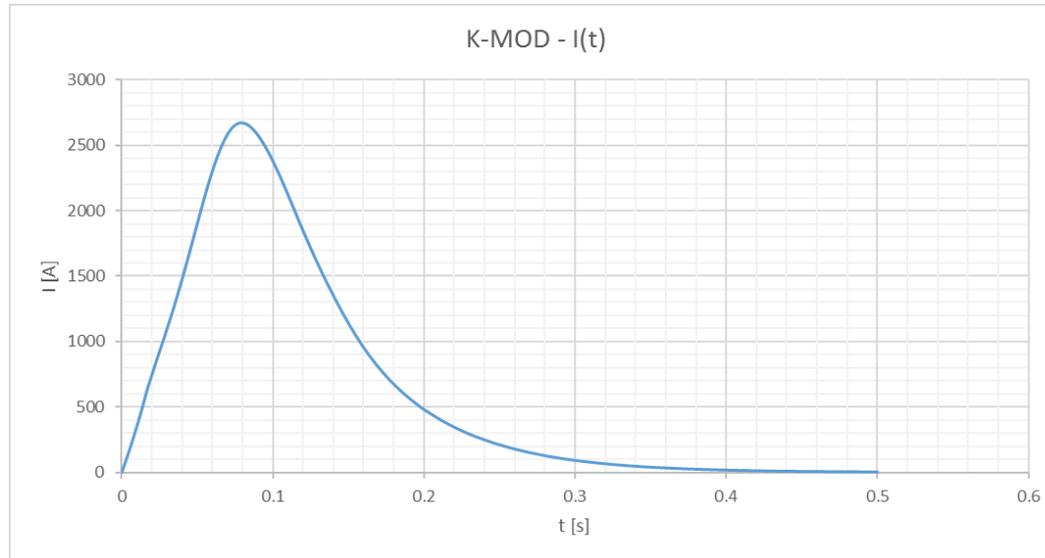
- Felix and I agree that overcoming the comfortable limit of 350 K seems to add unnecessary risk.
- After discussing with Felix, we think the parameters for the highest thermal load that the CLIQ lead can see are: very low initial magnet current (500 A, no coil resistance); CLIQ circuit resistance: 25 mOhm
- The minimum cross-section obtained from these assumptions is 8.7 mm<sup>2</sup>.
- The value of 5 mOhm would be exceeded due to heating if the lead cross-section was too small.
- This is not critical since it would occur a bit later in the discharge, but we shouldn't forget about this.

Courtesy: Felix Rodriguez-Mateos, Emmanuele Ravaioli

- To avoid the risk of condensation on the warm end electrical connections to the CLIQ or K-MOD feeders, their warm end temperature should never go below ~288K.

Courtesy: Rob Van Weelderen

# K-MOD Input parameters



## Pulsed Mode

### Continuous direct current mode

Assuming **35 A DC current**, this imposed a limitation on the maximum amount of resistance that the lead can have without eventually having a thermal runaway.

For the copper lead with **RRR = 100**, the maximum resistance is 1.3 mOhm after thermal stabilization at 35 A, which corresponds to a maximum resistance of **0.86 mOhm** after thermal stabilization at **0 A**.

For the brass lead (with RRR = 2.0, resistivity at room temperature =  $4e-8$  Ohm\*m) the corresponding numbers are a maximum resistance of 1.4 mOhm after thermal stabilization at 35 A, which corresponds to a maximum resistance of 1.3 mOhm after thermal stabilization at 0 A.

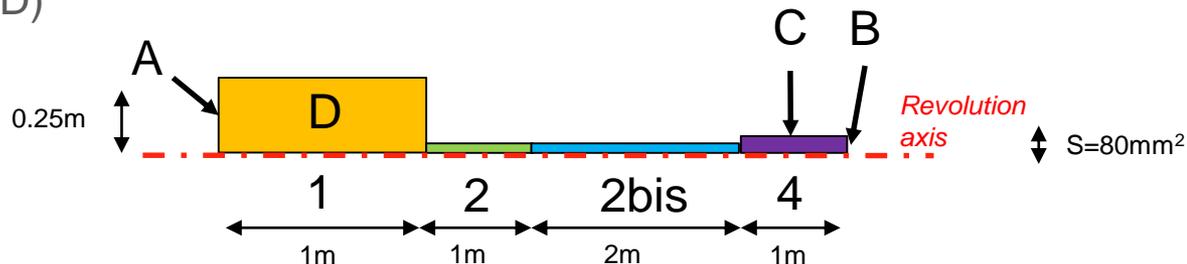
## A more detailed thermo-electric study

- Check the influence of the non linear properties ( $k(T)$ ,  $C(T)$ ,  $\rho(T)$ ,  $\rho_{elec}(T)$ ) and their transient effects on the temperature increase of the CLIQ and K-MOD feeders when using a more detailed FE model (when compared to an adiabatic model).
- Provide data to allow selection of the conductor materials and cross-sections of the CLIQ and K-MOD feeders.

Note: all calculations performed for conductor material: Cu RRR100.

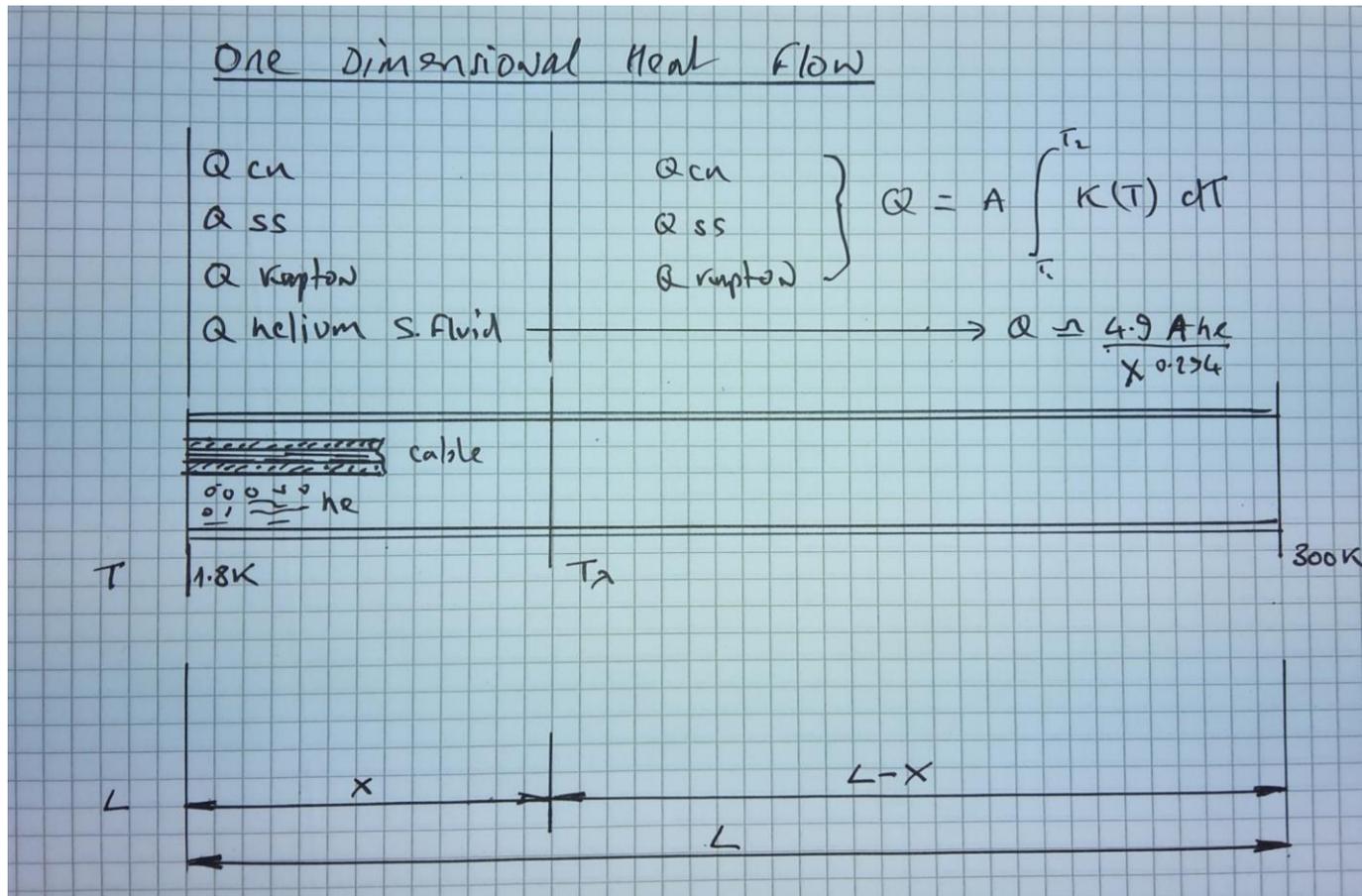
# Transient detailed Model

- The transient FE model is composed of 4 connected zones (axisymmetric model):
  - The magnet, 1 (not real volume, aim: Volume magnet  $\gg$  volume cable to be conservative)
  - Connection cable length, **part 2**, inside the cold mass, (L=1m),
  - **The feeder length, feeders part 2, between the cold mass and the vacuum vessel connection (L=2m), 2 bis  $\rightarrow$  object of this study**
  - The cable outside the vacuum vessel connected to the feeder (conductor cross section  $80\text{mm}^2$ , L=1m), 4
- The boundaries conditions are:
  - Voltage, A: 0V
  - Intensity signal, B: CLIQ and K-MOD **MQXF 4m** pulse
  - Convection from the supply cable, at C:  $2\text{W}/(\text{m}^2\cdot\text{K})$  , natural convection
  - Temperature of the magnet, D: 0 to 225K (200ms for CLIQ, instantaneous for K-MOD)



# One dimensional heat flow model

## Polyimide insulated copper Cables inside a stainless steel tube with helium



# Calculated and interpolated cable parameters - electrical and thermal

The temperature increases of the adiabatic models and the finer (more detailed) models are compared below. For the more detailed model the point where the final maximum temperature is located on the feeders is given. (not at the warm extremity)

**Results per single feeder unless otherwise stated**

					CLIQ Calculated values MQXF 4m																		
S	r	Ri	Rf	Qcu	CLIQ Adiabatic		CLIQ Finer Model		Diff.	Icliq	K-MOD Adiabatic			K-MOD Finer Model			Diff.	Lfeeder	Q(1 triplet)	Q (1 triplet)			
					Ti	Tf	ΔT	Ti	Tf	ΔT	ΔT	lmax	Ti	Tf	ΔT	Ti	Tf	ΔT	ΔT	L	Qcu	Qtotal	
[mm <sup>2</sup> ]	[m]	[Ω]	[Ω]	[W]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[m]	[W]	[W]		
		Before q	After q																				
20	2.52E-3	4.80E-04		1.92	295.15	297.84	2.69	264.39	266.51	2.12	0.57	2500	295.15	302.21	7.06	263.64	269.69	6.05	1.01	2			
18	2.39E-3	5.33E-04		1.73	295.15	298.48	3.33	267.20	269.84	2.64	0.69	2500	295.15	303.88	8.73	266.44	274.03	7.59	1.14	2			
16	2.26E-3	6.00E-04		1.54	295.15	299.36	4.21	270.05	273.43	3.38	0.83	2500	295.15	306.22	11.07	269.29	279.02	9.73	1.34	2			
14	2.11E-3	6.85E-04		1.35	295.15	300.67	5.52	272.93	277.40	4.47	1.05	2500	295.15	309.67	14.52	272.17	285.08	12.91	1.61	2			
12	1.95E-3	8.00E-04		1.15	295.15	302.68	7.53	275.09	282.02	6.93	0.60	2500	295.15	315.06	19.91	275.09	293.03	17.94	1.97	2			
10	1.78E-3	9.59E-04		0.96	295.15	306.03	10.9	278.05	288.21	10.16	0.72	2500	295.15	324.24	29.09	278.05	304.56	26.51	2.58	2			
9	1.69E-3	1.07E-03		0.87	295.15	308.64	13.5	279.54	292.23	12.69	0.80	2500	295.15	331.48	36.33	278.77	312.73	33.96	2.37	2			
8	1.60E-3	1.20E-03		0.77	295.15	312.3	17.2	281.05	297.30	16.25	0.90	2500	295.15	341.90	46.75	280.27	324.14	43.87	2.88	2			
7	1.49E-3	1.37E-03		0.67	295.15	317.76	22.6	282.57	304.90	22.33	0.28	2500	295.15	357.73	62.58	281.79	340.76	58.97	3.61	2			
6	1.38E-3	1.60E-03		0.58	295.15	326.34	31.2	284.10	313.86	29.76	1.43	2500	295.15	383.68	88.53	283.31	367.1	83.79	4.74	2			
5	1.26E-3	1.92E-03		0.48	295.15	341.18	46	285.64	329.65	44.01	2.02	2500	295.15	430.03	134.88	284.85	413.98	129.13	5.75	2			
4	1.13E-3	2.40E-03		0.38	295.15	370.37	75.2	287.19	359.39	72.20	3.02	2500	295.15	516.11	220.96	285.61	501.73	216.12	4.84	2			
					CLIQ Calculated values MQXF 7.15m																		
8.6	1.69E-3	1.12E-03	2.32E-03	0.83	295.15	342.15	47	279.96	319.7	39.7		3169								2	Qcliqcu x12	Qcliqtot x12	
					CLIQ Interpolated values MQXF 7.15m																		
8.6	1.69E-3	2.24E-03	4.65E-03	0.415	295.15	342.15	47	~286	~326	40		3169								4	4.98	5.18	
8.6	1.69E-3	2.40E-03	4.99E-03	0.38	295.15	342.15	47	~287	~327	40		3169								4.37	4.56	4.74	
					K-MOD Interpolated values																		
																					Qkmodcu x2	Qkmodtot x2	
8.6	1.69E-3	2.24E-03	4.65E-03	0.415																4	0.83	0.87	
10.75	1.91E-3	8.60E-04	3.72E-03	0.518																4	1.04	1.09	
11	1.96E-3	8.59E-04	3.60E-03	0.53																4	1.06	1.1	

# Results comparison of adiabatic vs a more detailed model

- With the assumptions made concerning boundary conditions the finer more detailed model does not return significant differences in warm end maximum temperatures. An adiabatic model is precise enough to conservatively evaluate the temperature increases caused by the CLIQ and K-MOD electrical pulse.
- Nevertheless, we can observe that the temperature at the warm extremity of the feeders (part 2) requires detailed study, with a realistic steady state model, to ensure that the conductor selected does not cause condensation/freezing at the extremities.

# Parameter list functional updated

Parameter (Specified)	CLIQ	K-MOD	Source
Warm end minimum temperature (K)	~288	~288	Van Weelderen
Discharge at quench (MITs)	0.6	0.6	Ravaioli/Mentink
1 discharge only per magnet per quench	Yes	Yes	HL-LHC MCF Meeting Minutes no. 37
HV Withstand to ground at R.Temp (V)	3680 DC	3680 DC	EDMS1963398
Radiation dose integrated over lifetime (MGy)	30	30	Spec WP3 ch 12 QFX
Steady state temperatures (K)	1.8, ~50, ~290	1.8, ~50, ~290	LHC
Fluids	Helium super-fluid Helium gas	Helium super-fluid Helium gas	LHC
Operational temperature range (K)	1.8 - ~350	1.8- ~350	Williams
Assembly after cryostating	?	?	

# Parameter List (suggested or calculated) updated

Parameter (Suggested or calculated)	CLIQ	K-MOD	Source
Intermediate thermalisation	No	Maybe	Williams
Conductor material	Copper RRR100	Cu85Zn15 brass?	Williams
Conductor resistance maximum (m-ohm)	5 max at 0A	0.86 max at 0A 1.3 stable at 35A	Mentink/Ravaioli
Max feeder temperature after discharge (K)	~350	~350	Ravaioli/Rodriguez-Mateos
Conductor materialisation	Twisted pair? multi-strand? extruded polyimide (kapton)	Single solid polyimide wrapped polyimide (kapton)	Williams
Conductor length (m)	~4	~4	Discussions TE- MSC-CMI/Williams
Forces between cables	694.8 N/m (@2493A)	~1122.9 N/m? (@3169A)	Mentink
Zero maintenance in the tunnel	yes	yes	Williams
Lifetime (years)	25	25	Williams

# Conclusions (1)

## CLIQ

- The principal limits determining the material length and cross section of the CLIQ conductor are:
  - Maximum allowable feeder resistance: fixed at 2.5 m-ohm per feeder at 0A
  - Maximum allowable warm end temperature: ~350K
  - Absence of condensation at the warm end connections: temperature not lower than 288K
- A conductor ~4m long of cross section of 8.6 mm<sup>2</sup> in OHFC copper ~ RRR100 can satisfy these conditions.

# Conclusions (2)

## K-MOD

- The principal limits determining the material length and cross section of the K-MOD conductor are:
  - **In pulse mode:**
    - Maximum allowable warm end temperature: ~350K
    - Absence of condensation at the warm end connections: temperature not lower than 288K
  - **In 35A continuous current mode:**
    - Maximum allowable warm end temperature: ~350K
    - Absence of condensation at the warm end connections: temperature not lower than 288K
    - For a copper lead with  $RRR = 100$ , the maximum resistance is 1.3 mOhm after thermal stabilization at 35 A, which corresponds to a maximum resistance of **0.86 mOhm** after thermal stabilization at **0 A**.
    - For a brass lead (with  $RRR = 2.0$ , resistivity at room temperature =  $4e-8 \text{ Ohm}\cdot\text{m}$ ) the corresponding numbers are a maximum resistance of 1.4 mOhm after thermal stabilization at 35 A, which corresponds to a maximum resistance of 1.3 mOhm after thermal stabilization at 0 A.
- It appears that a copper conductor cannot satisfy the continuous current mode conditions (runaway stability) and the condensation temperature limits. It may be necessary to conduct detailed studies to dimension a conductor in malleable brass e.g CU85-Zn15 as was specified for the LHC 60A trim feeders.
- Dimensioning should also take into account the transition from continuous current mode to pulse mode



***Thank you***

# Service Temperature limits of Polyimide film (when used as an electrical insulator)

**Table 2 – Thermal Properties of DuPont™ Kapton® HN Film**

Thermal Property	Typical Value	Test Condition	Test Method
Melting Point	None	None	ASTM E-794-85 (1989)
Thermal Coefficient of Linear Expansion	20 ppm/°C (11 ppm/°F)	-14 to 38°C (7 to 100°F)	ASTM D-696-91
Coefficient of Thermal Conductivity, W/m-K $\frac{\text{cal}}{\text{cm}\cdot\text{sec}\cdot^\circ\text{C}}$	0.12 2.87 x 10 <sup>4</sup>	296K 23°C	ASTM F-433-77 (1987)
Specific Heat, J/g•K (cal/g•°C)	1.09 (0.261)		Differential calorimetry
Heat Sealability	not heat sealable		
Solder Float	pass		IPC-TM-650 Method 2.4.13A
Smoke Generation	D <sub>m</sub> < 1	NBS smoke chamber	NFPA-258
Shrinkage, % 30 min at 150°C 120 min at 400°C	0.17 1.25		IPC-TM-650 Method 2.2.4A; ASTM D-5214-91
Limiting Oxygen Index, %	37-45		ASTM D-2863-87
Glass Transition Temperature (T <sub>g</sub> )	A second order transition occurs in Kapton® between 360°C (680°F) and 410°C (770°F) and is assumed to be the glass transition temperature. Different measurement techniques produce different results within the above temperature range.		

# Dew Point

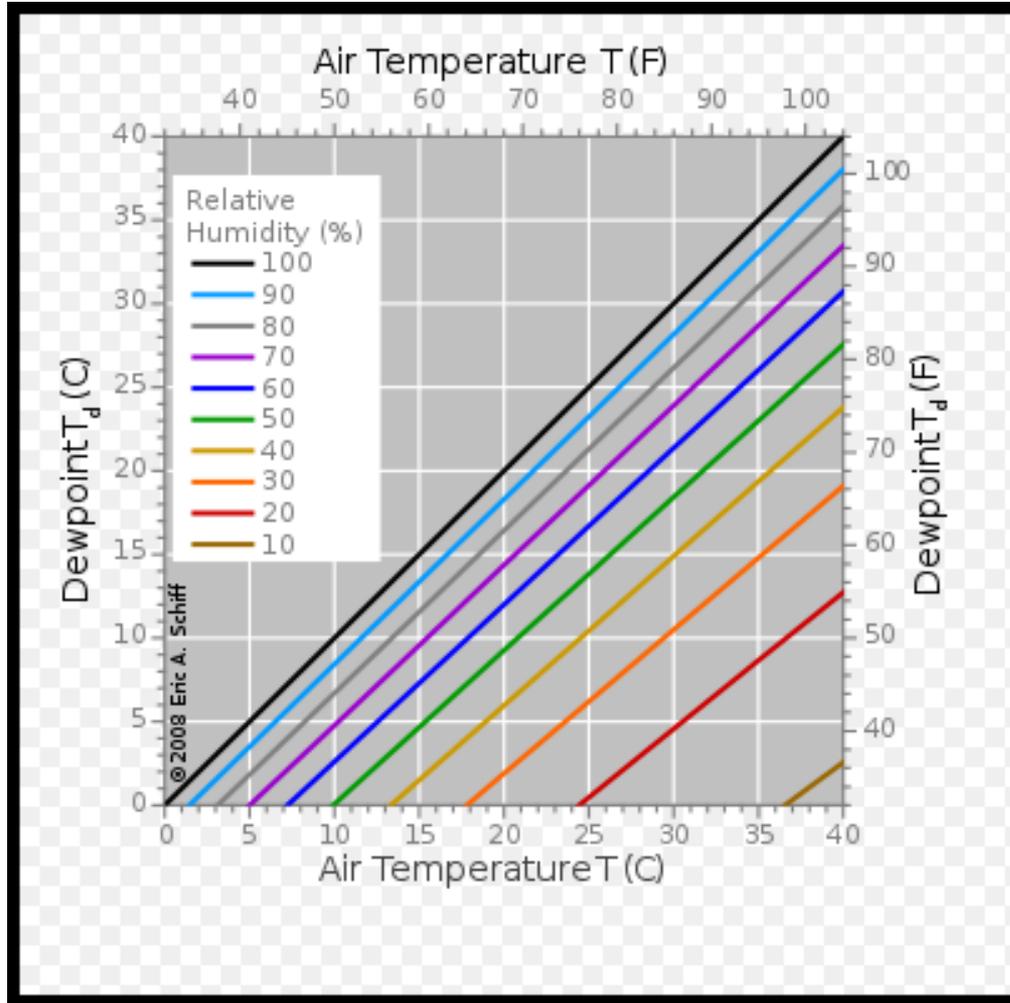


Table 8.7: Indoor conditions per tunnel sector

<b>Tunnel sector</b>	<b>Total heat Dissipation [kW]</b>	<b>Dry bulb temperature, even input [°C]</b>	<b>Dew point at the even input [°C]</b>	<b>Dry bulb temperature odd output<sup>4</sup> [°C]</b>
1-2	125	18 ±1	< 10	23 ±6
2-UJ32	41	18 ±1	< 10	20 ±2
UJ32-4	233	18 ±1	< 5	25 ±7
4-5	111	18 ±1	< 10	22 ±6
5-6	118	18 ±1	< 10	23 ±6
6-7	117	18 ±1	< 10	23 ±6
7-8	109	18 ±1	< 10	22 ±4
8-1	117	18 ±1	< 10	22 ±6