# CLIQ & K-MOD Feeders Dimensioning of electrical conductors

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With very important input from:
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# CLIQ and K-MOD Current Feeders

The current feeders, are the in and out segments of these electrical circuits, together with their electrical and mechanical connection features, that link the vacuum vessel wall at ambient temperature to the HL-LHC triplet cold masses at ~1.9K.

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

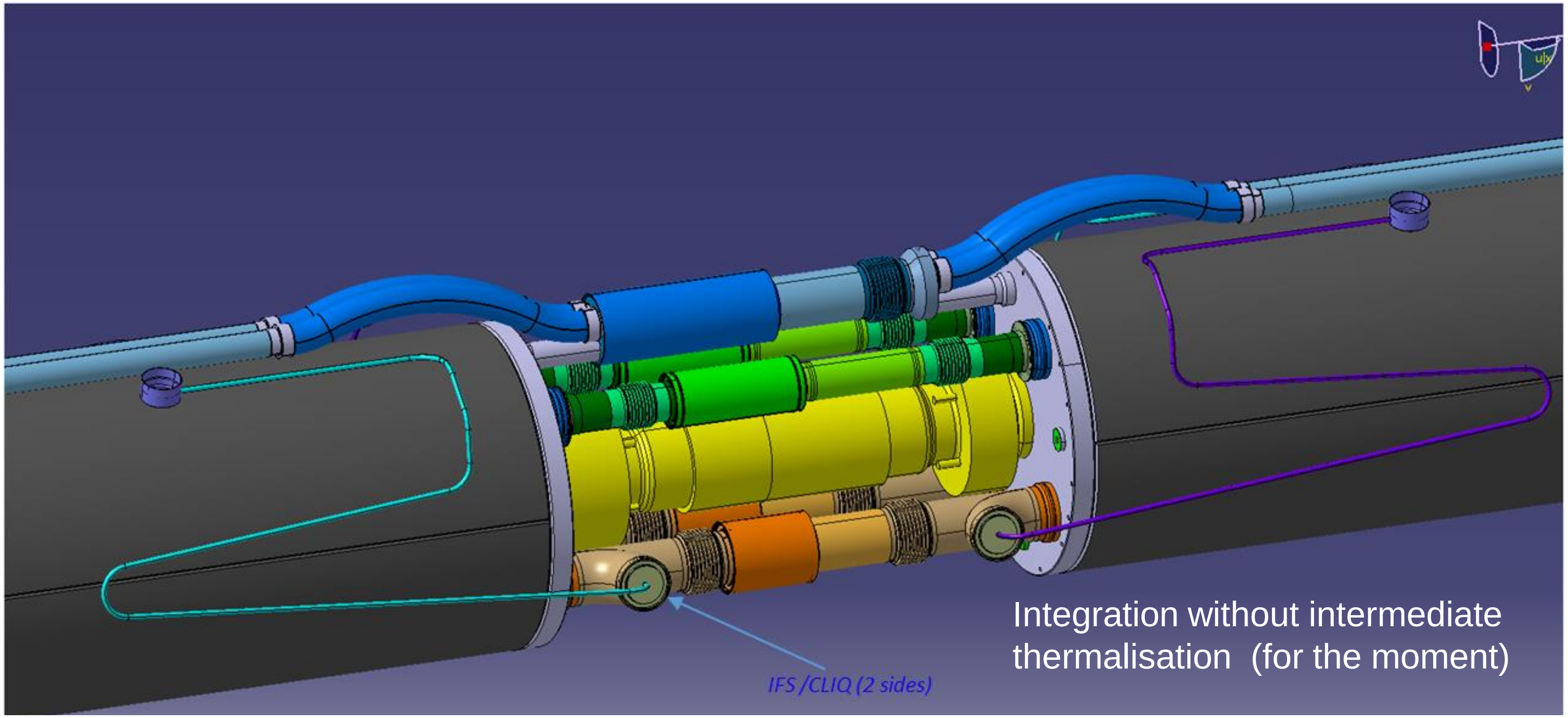
# Key Design Parameters for CLIQ and K-MOD

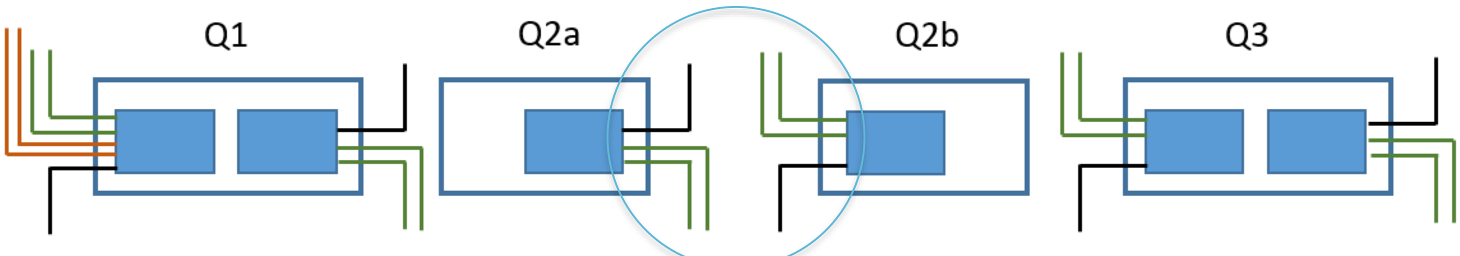
- The dimensioning of the electrical conductor cross section depends on the following key design parameters:

  - 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 <u>maximum</u> allowable feeder conductor temperature after transmission of the CLIQ or the K-MOD electrical pulse.
  - The <u>minimum</u> allowable feeder conductor temperature to maintain the feeder warm (vacuum vessel) end 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 interdependent physical parameters:
  - Conductor material
  - Conductor cross-section
  - Conductor length

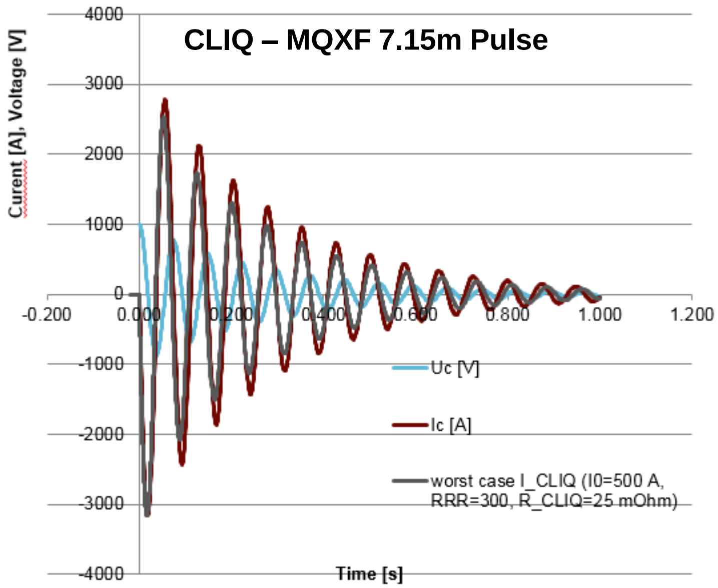
# Schematic Layout




CLIQ leads   K-modulation circuit   Instrumentation

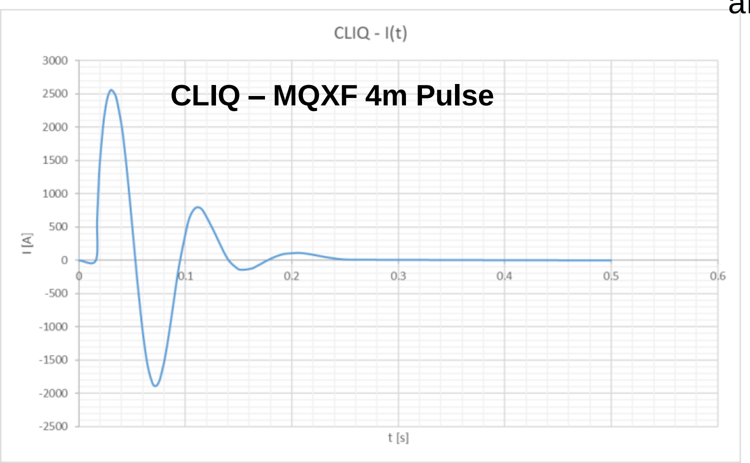
# CLIQ Input Parameters



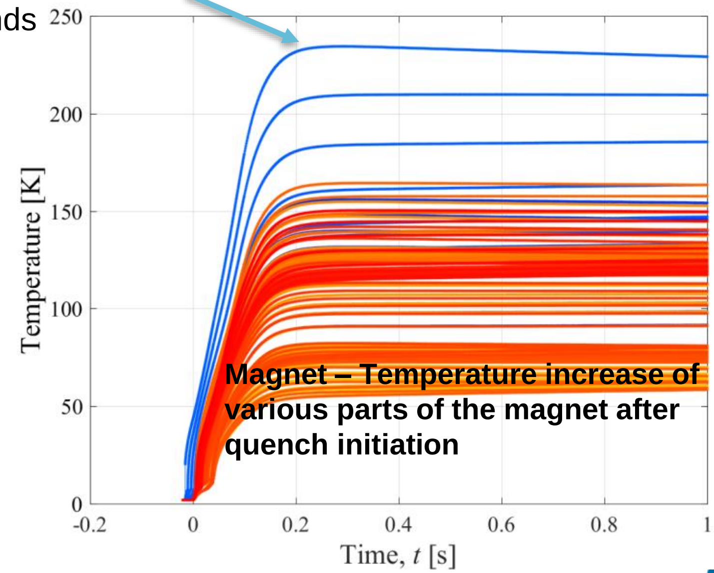

| CLIQ Unit - Parameters | | |
|---|---|---|
| No CLIQ units (Select only 1 or 2) | 1 | |
| Charging Voltage U0 [V] | 1000 | |
| Capacitance C [mF] | 40 | |
| CLIQ circuit resistance R_CLIQ [mΩ] | 25 | <----- |
| **CLIQ Wire - Parameters** | | |
| Initial temperature of CLIQ lead [K] | 293 | |
| Maximum allowed temperature in the CLIQ lead [K] | 350 | <----- |

| Coil Parameters - MQXF 7.15 m | | |
|---|---|---|
| Equivalent Inductance Leq [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 Leq [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




Courtesy E. Ravaioli

# Some important conditioning comments

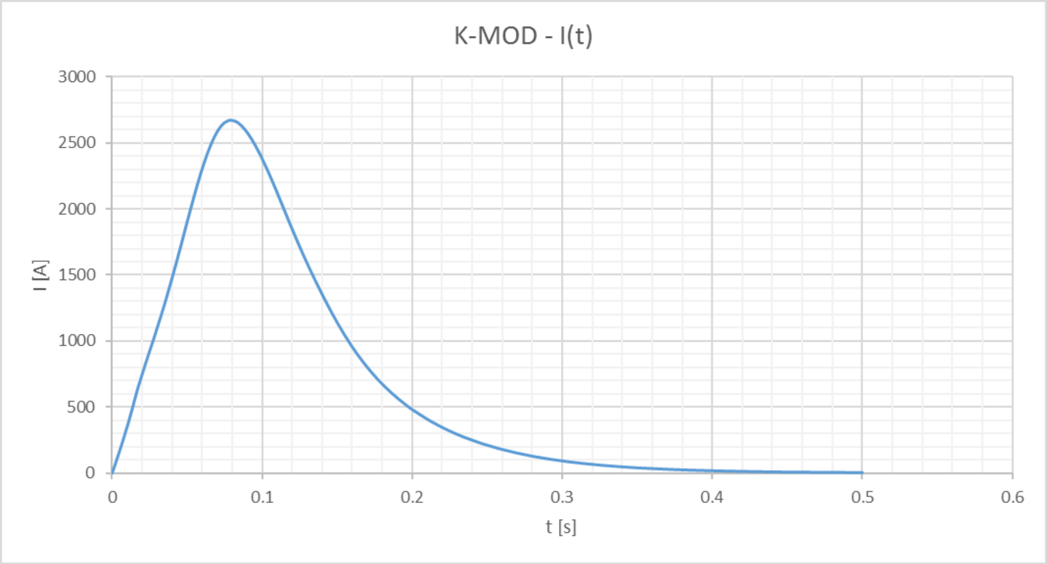
- Felix and I agree that overcoming the comfortable limit of 350 K seems to add unnecessary risk.
- After discussing with Felix, we think the parameters for the highest thermal load that the CLIQ lead can see are: very low initial magnet current (500 A, no coil resistance); CLIQ circuit resistance: 25 mOhm
- The minimum cross-section obtained from these assumptions is 8.7 mm^2.
- 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.

Courtesy M.Mentink

# A more detailed thermo-electric study

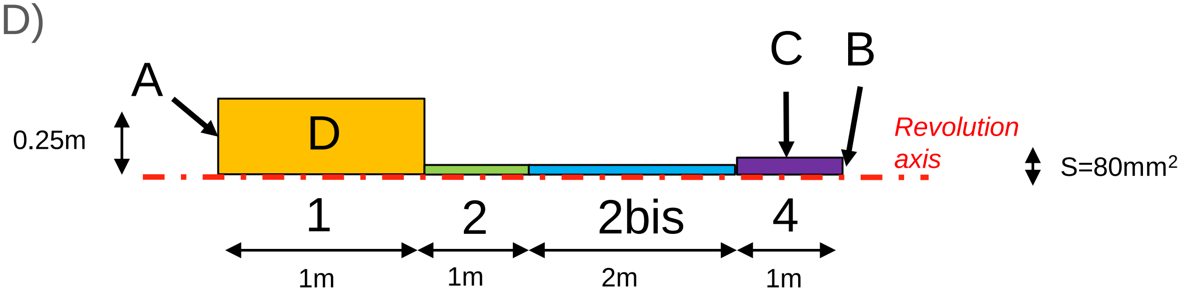
- Check the influence of the non linear properties (k(T), C(T), ρ(T), $\rho_{elec}$(T)) and their transient effects on the temperature increase of the CLIQ and K-MOD feeders with heat transfer simulated at the feeder ends and compare results with an adiabatic model.

- Provide data to help with the  selection of conductor materials, lengths and cross-sections of the CLIQ and K-MOD feeders.

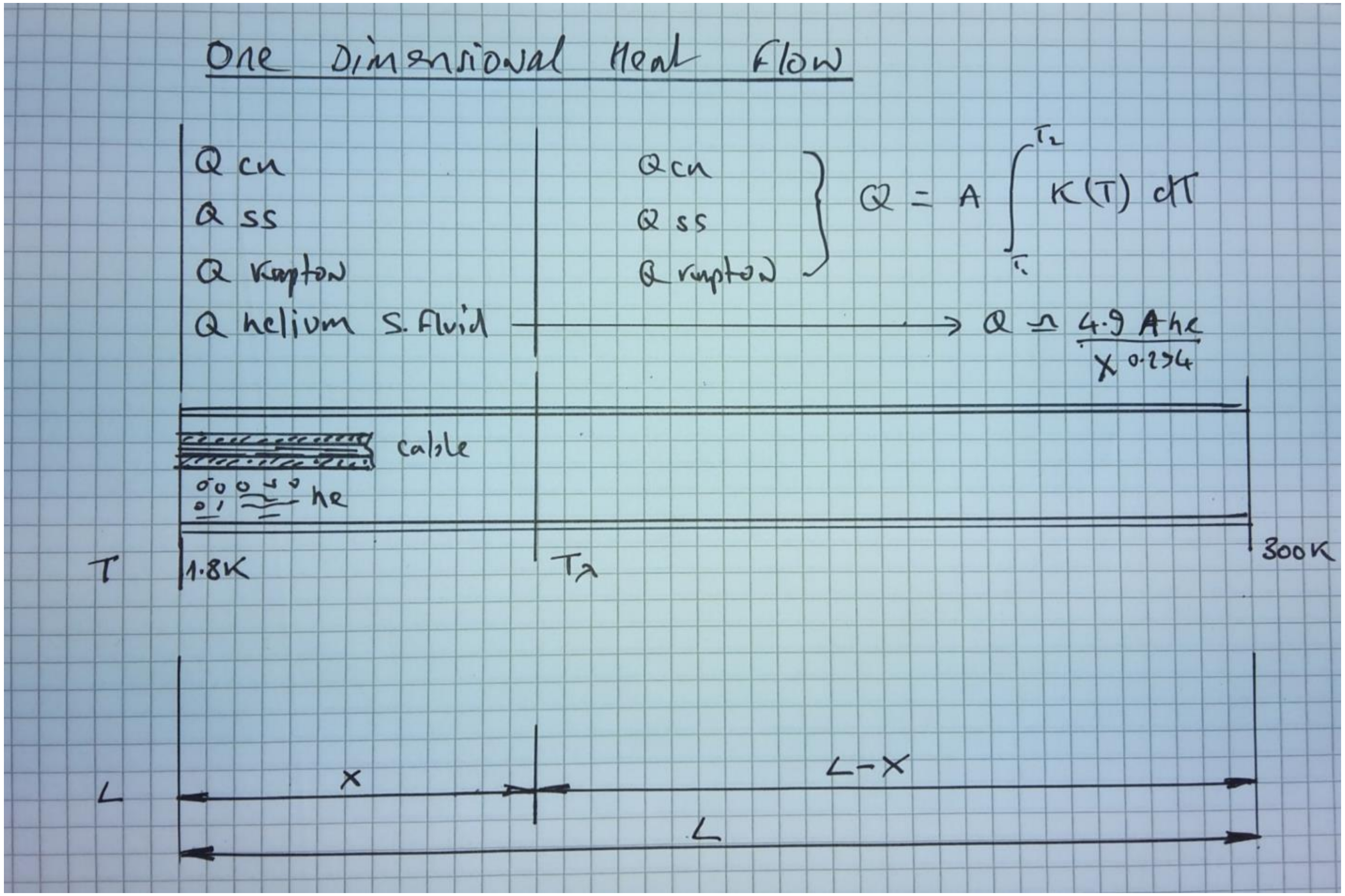
Note: all calculations performed for conductor material: Cu RRR100.

# Transient detailed Model

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

Parameters calculated from adiabatic models and the finer (more realistic) models are compared below. The more realistic model gives a warm end temperature at zero current (Ti) before current discharge and a final maximum temperature (Tf) after current discharge that is not constrained to be at the warm extremity.

**(Results per single feeder unless otherwise stated)  Cu RRR100**

| | | | | | CLIQ Calculated values MQXF 4m | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *CLIQ Adiabatiq* | | | *CLIQ Finer Model* | | | *Diff.* | *Icliq* | *K-MOD Adiabatiq* | | | *K-MOD Finer Model* | | | *Diff.* | Lfeeder | Q(1 triplet) | Q (1 triplet) |
| S | r | Ri | Rf | Qcu | Ti | Tf | ΔT | Ti | Tf | ΔT | ΔT | Imax | Ti | Tf | ΔT | Ti | Tf | ΔT | ΔT | L | Qcu | Qtotal |
| [$mm^2$] | [m] | [Ω] | [Ω] | [W] | [K] | [K] | [K] | [K] | [K] | [K] | [K] | [A] | [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 | | | | | | | | | | | | | | | | Qcliqcu x12 | Qcliqtot x12 |
| 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 | 9.96 | 10.36 |
| | | | | | 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 | | | | | | | | | | | | ~286 | 326 | 40 | | 4 | 0.83 | 0.87 |
| ~22 | 2.60E-3 | 8.60E-04 | 2.20E-03 | ~2.0 | | | | | | | | | | | | ~263 | ~269 | ~6 | | 4 | ~4.0 | ~4.15 |

# 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 2bis) requires detailed study, with a realistic steady state model, to ensure that the conductor selected does not cause condensation/freezing at its warm extremity.

# Parameter list updated (1)

| Parameter | CLIQ | K-MOD | Source |
|---|---|---|---|
| Warm end minimum temperature (K) | ~288 | ~288 | Van Weelderen |
| Discharge at quench (MIITs) | 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<br>Helium gas | Helium super-fluid<br>Helium gas | LHC |
| Operational temperature range (K) | 1.8 - ~350 | 1.8- ~350 | Williams |
| Assembly after cryostating | ? | ? | |

# Parameter List updated (2)

| Parameter | CLIQ | K-MOD | Source |
|---|---|---|---|
| Intermediate thermalisation | No | ? tbc | Williams |
| Conductor material | Copper RRR100 | Cu85Zn15 brass? | Williams |
| Conductor resistance maximum (m-ohm) | 5 max at 0A | 0.86 max at 0A<br>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 |

Confirming that these parameters constitute the functional specification will allow the detail design to converge most rapidly

# 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 mm2 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 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.
- 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
- Intermediate thermalisation (perhaps along the lines of that provided for the LHC 60A trim feeders) may be needed.

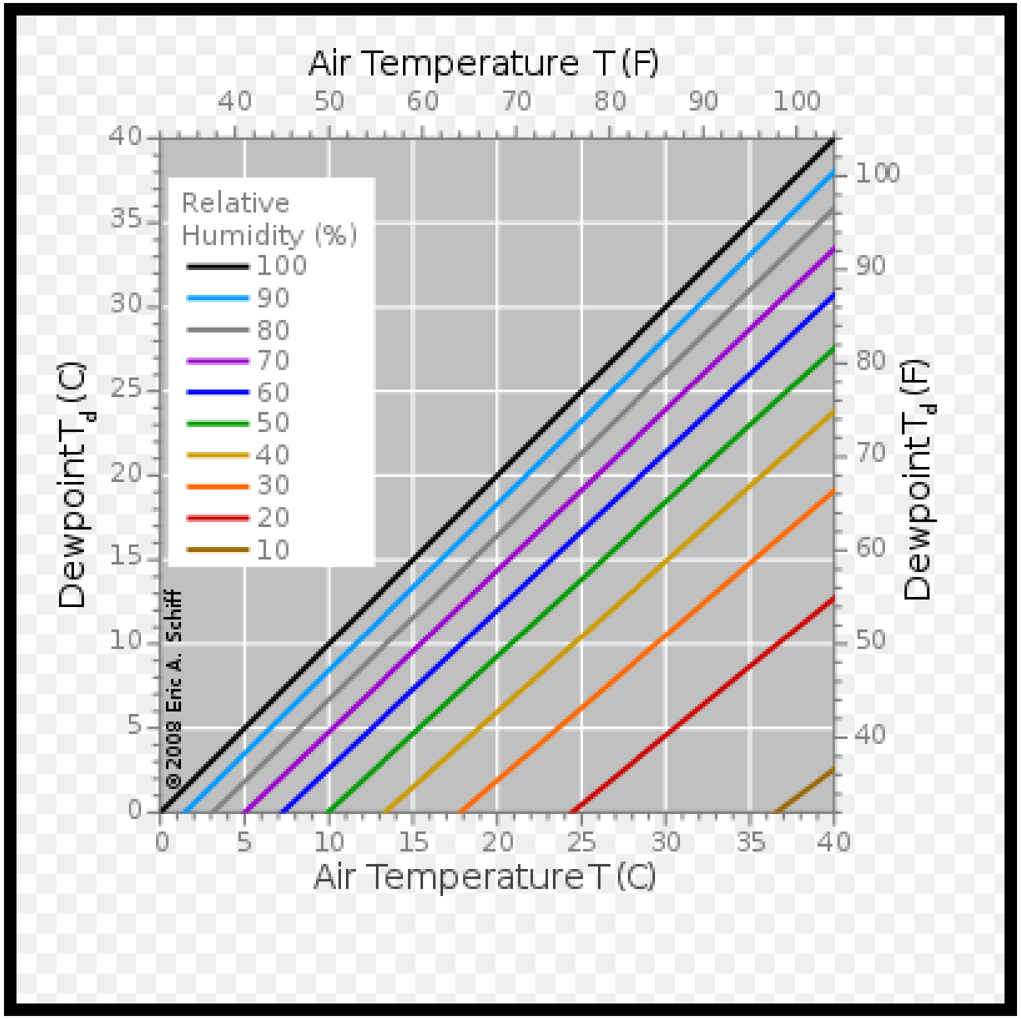
***Thank you***

# 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<br>(11 ppm/°F) | -14 to 38°C<br>(7 to 100°F) | ASTM D-696-91 |
| Coefficient of Thermal Conductivity, W/m-K<br>$\frac{cal}{cm \cdot sec \cdot °C}$ | 0.12<br>$2.87 \times 10^{4}$ | 296K<br>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 | $D_m$=<1 | NBS smoke chamber | NFPA-258 |
| Shrinkage, %<br>30 min at 150°C<br>120 min at 400°C | <br>0.17<br>1.25 | | IPC-TM-650 Method 2.2.4A;<br>ASTM D-5214-91 |
| Limiting Oxygen Index, % | 37–45 | | ASTM D-2863-87 |
| Glass Transition Temperature ($T_g$) | 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



Air Temperature T (F)
40
50
60
70
80
90
100
Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
Dewpoint $T_d$ (C)
Dewpoint $T_d$ (F)
© 2008 Eric A. Schiff
Air Temperature T (C)
0
5
10
15
20
25
30
35
40

Table 8.7: Indoor conditions per tunnel sector

| Tunnel sector | Total heat Dissipation [kW] | Dry bulb temperature, even input [°C] | Dew point at the even input [°C] | Dry bulb temperature odd output[4] [°C] |
|---|---|---|---|---|
| 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 |