The Thermo-Electric Design of the Electric Current Feeders of the HL-LHC Triplets

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Abstract

The HL-LHC Project currently undertaken by CERN that provides an upgrade to the existing LHC accelerator, is designed to increase the luminosity of the colliding particle bunches by a factor of at least five. Part of this upgrade will require the replacement of the existing groups of three superconducting LHC triplet magnets situated on each side of the ATLAS and CMS detectors with similar groups of four higher field HL-LHC triplet magnets of a new design that exploit coils manufactured with cables in Nb3Sn superconducting alloy. The HL-LHC triplet magnets require dedicated electric current feeders linking their cold masses to their cryostat vacuum vessels, thermo-electrically optimised and specifically designed to separately feed their quench protection, beam tuning and instrumentation systems with electric current. The HL-LHC instrumentation feedthrough system is similar, though containing a larger cable inventory, to that mounted on existing cryo-magnets in the LHC accelerator whereas the quench protection and beam tuning systems, both present new requirements calling for a substantially different design approach. Installed in a highly activated zone of the LHC, all three systems consequently exploit only natural heat convection to prevent the formation of condensation at their warm ends. This paper describes the functional design and thermo-electrical optimisation achieved for each of these current feeder systems.

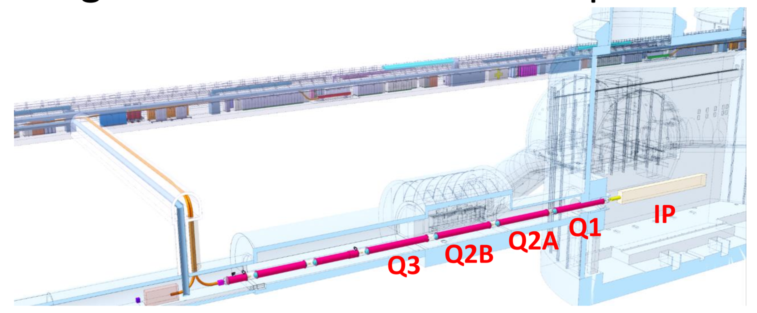

Figure 1. HL-LHC Triplet magnets in the insertion regions of LHC.

Feeders mounted on the HL-LHC triplets:
- The Instrumentation Feedthrough System (IFS)
- The K-modulation (K-mod) beam tuning system
- The Coupling Loss Induced Quench (CLIQ) protection system

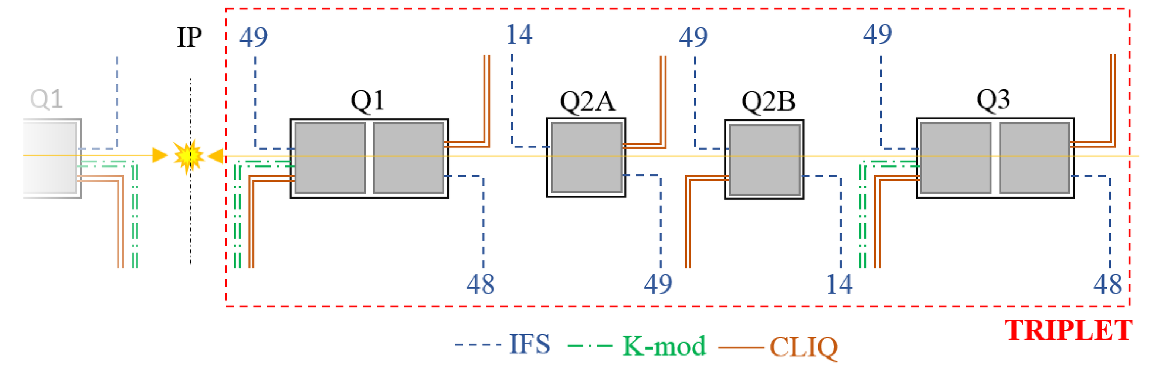

Figure 2. Layout of electric current feeders in an HL-LHC triplet.

Design parameters

The feeders' design process respects several specified requirements which are mainly thermal and electrical, see table 1.
For the CLIQ and K-mod feeders, the electrical currents that can occur through them, has also to be considered for the design, see table 2.

Table 1. Design requirements.

	Requirements		
	Thermal	Electrical	
K-mod	Temperature maximum: 350K No condensation of parts in contact with ambient air: ΔT (Tair-Tsurf)<2k	Electrical insulation: 5kV	
CLIQ			Resistance of one feeder < 2.5mΩ
IFS			

Table 2. K-mod & CLIQ electrical currents.

Feeder	Purposes	Nominal Current	Highest Current
K-mod	Beta function measurement For accuracy at interaction point	35 A sinusoidal (8 h)	4 kA in case of Quench (0,5s)
CLIQ	Quench protection system	3 kA sinusoidal pulse (1s)	3 kA sinusoidal pulse (1s)

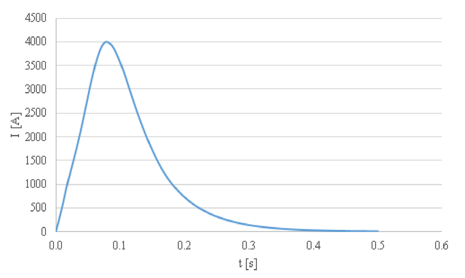

Figure 3. K-mod electrical pulse.

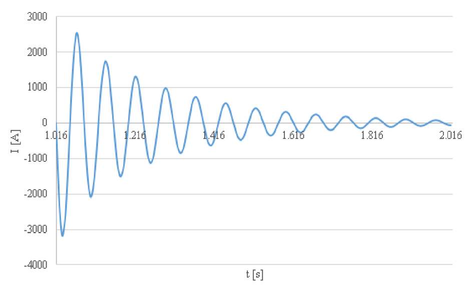

Figure 4. CLIQ electrical pulse.

Design methodology

The design of feeders involves a compromise between intrinsic and external interdependent parameters, see figure 5. In practice, several iterations are needed to reach the optimum design that respect the electrical, thermal and environment requirements.
Because of the nonlinearities of the material, properties as a function of temperature, an finit elements ANSYS model is used to design the feeders, see figure 6.

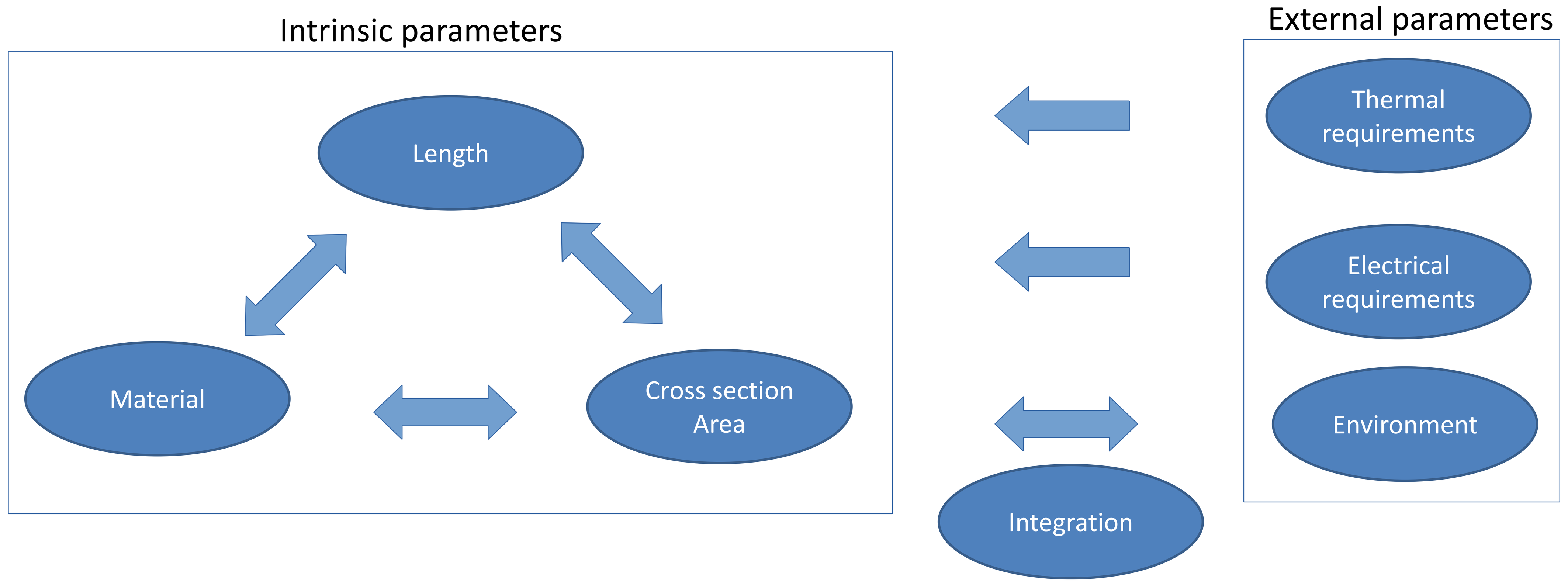

Figure 5. Design diagram.

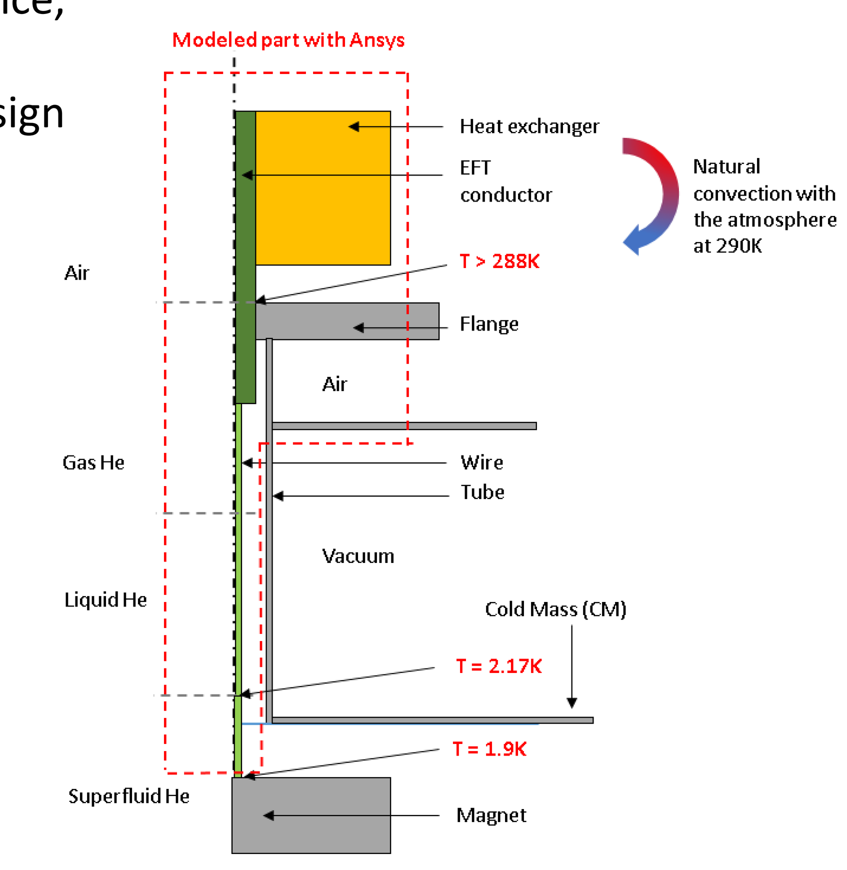

Figure 6. Ansys model.

Results

The results obtained with the aforementioned methodology are presented here.
The physical dimensions of the feeders are presented in the table 3, and the integration on figure 7 and 8.

Table 3. Feeders dimensions.

	Material	Cable/tube	Tube [mm] OD/ID	Cable Length [m]	Cross Section Area [mm2]
IFS	Copper OFHC RRR60-100	48 or 49	14/12	4.4	20
		14	8/6	4.4	2
K-mod		1	8/6	2.1	10
CLIQ		1	8/6	2.9	10

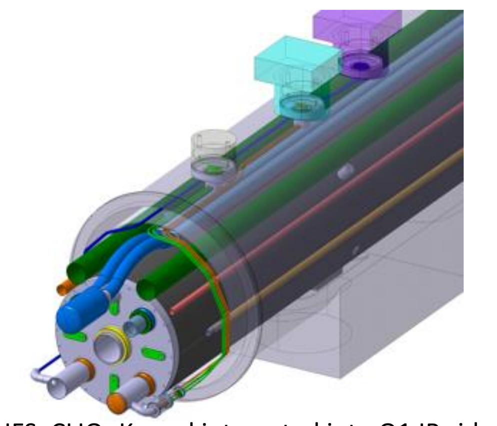

Figure 7. IFS, CLIQ, K-mod integrated into Q1 IP side.

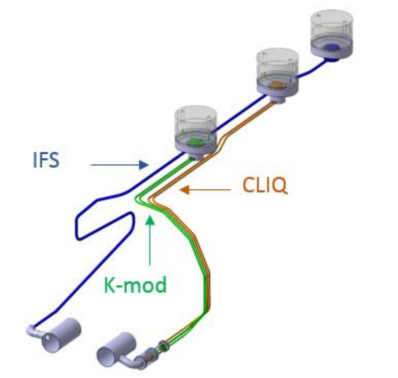

Figure 8. IFS, CLIQ & K-mod feeders extracted for clarity.

After 8 h at 24.8 A RMS the maximum temperature towards the warm end of the K-mod conductor reaches 283 K (initial temperature: 273 K) and after the 4 kA peak pulse rises again to 347 K, figure 9.
The maximum temperature reached by this OFHC (RRR100) copper conductor after the CLIQ pulse is 307 K (maximum initial temperature: 284 K), figure 10.

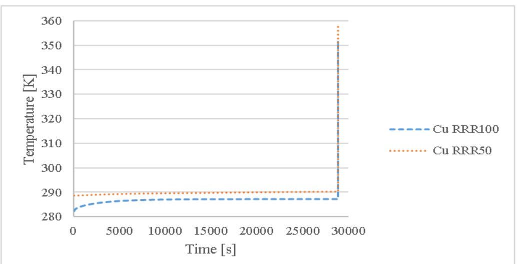

Figure 9. Temperature max of K-mod conductor.

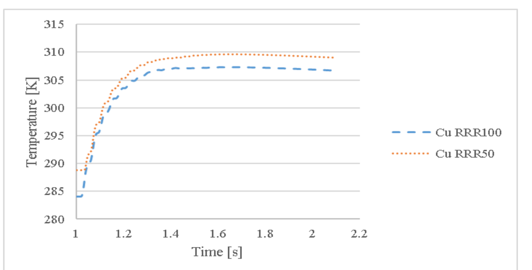

Figure 10. Temperature max of CLIQ conductor.

The material chosen for both K-mod and CLIQ is OHFC copper with an RRR cited in literature of 100. However commercially supplied multi-strand cables in OHFC copper are certified to an RRR of 60. Calculations show the effect of this difference on maximum conductor temperature is not large, figure 9 and 10.

One major aim of this study is to ensure the absence of condensation at the warm end of the feeders exposed to ambient air.
Therefore, a heat exchanger is needed at the warm end of the K-mod and CLIQ feeders, figure 11.
Each CLIQ feeder branch requires a heat input of 0.89 W, requiring a heat exchanger of H 115 mm x L 189 mm x W 100 mm, and each K-mod feeder branch a heat load of 0.65 W, calling for a heat exchanger of H 70 mm x L 189 mm x W 100 mm.

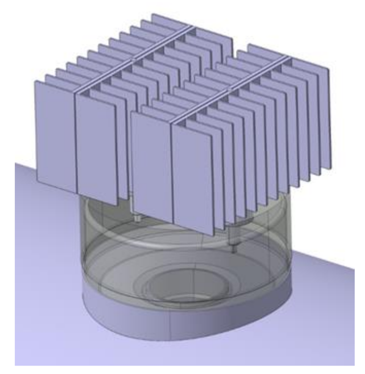

Figure 11. Heat exchanger to enhance heat input to the CLIQ and K-mod warm extremities.

The expected heat loads in the triplet's magnets are presented in the table 4.

Table 4. Heat load in watts to 1.9K due to the electric current feeders for 1 triplet.

Feeder	Qty feeders Q1 or Q3	Qty feeders Q2A or Q2B	Heat/feeder [W]
IFS 49	1	1	0.88
IFS 48	1	0	0.87
IFS 14	0	1	0.16
CLIQ	4	2	0.68
K-mod	2	0	0.94

Total Q1 or Q3 [W]
6.34
Total Q2A or Q2B [W]
2.4
Total/triplet [W]
17.48

Conclusion

The functional design and thermo-electrical optimization, together with the integration of the IFS, K-mod and CLIQ systems into their respective cryo-magnets has been completed. To benchmark the degree to which the numerical model is conservative, experimental thermal performance studies will be carried out in autumn 2019. The design of the HL-LHC triplet IFS, K-mod and CLIQ feeders is now moving from the conceptual to a detail phase. First units for assembly to HL-LHC triplets will be available in the first quarter of 2020.