Thermo-Electric Design of the Protection and Diagnostic Feeders of the HL-LHC Triplets

F. Pasdeloup, H. Prin, L. Williams
CERN, CH1211 Geneva 23 Switzerland
florian.pasdeloup@cern.ch

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 electric current feeder systems.

1. Introduction
The Large Hadron Collider (LHC), the flagship accelerator at CERN, commissioned in 2010, has since then, been operating at beam energy and integrated luminosity progressively increasing to the 13 TeV centre of mass and 192.5 fb\(^{-1}\) attained before being shut down at the end of 2018 for a 2-year period for routine maintenance and upgrades. To extend its discovery potential, HL-LHC will provide the LHC with a major upgrade in the time window 2021-2026, to increase its luminosity by a factor of at least five and extend its physics production lifetime until 2035. The HL-LHC project comprises a staged series of equipment upgrades to the LHC accelerator of which a cornerstone part is the replacement of the insertion region magnets, comprising the triplet final focus chain immediately to the left and right of the Interaction Point (IP) of experiments ATLAS and CMS, (figure 1).
These triplet magnets will be equipped with feeders supplying electric current for diagnostics and control functions, quench protection and β function measurements as explained below.

1.1. The Instrumentation Feedthrough System (IFS)
The Instrumentation Feedthrough System of the HL-LHC Triplet magnets contains instrumentation wires for magnet diagnostics and control and feeder cables for the conventional Quench Heater (QH). It shares the general characteristics of systems previously installed in the LHC arcs [1].
The design challenge of the HL-LHC Triplet magnets IFS centres on the wire inventory with 40% more channels than an LHC dipole, corresponding to a more than 3 times higher copper cross-section.

1.2. The Coupling Loss Induced Quench (CLIQ) protection system
A conventional Quench Heater (QH) for superconducting magnets relies on heat generated in resistive heaters in intimate thermal contact with the magnet coils. The effectiveness of this system depends on the heat diffusion rate through the electrical insulation and into the coils, enough to initiate resistive transition and quench. The longer this diffusion takes, the hotter become the hot-spot temperatures in the magnet.

The CLIQ[2] system uses a capacitive discharge to initiate a few rapid oscillations with a peak value of 3170 A (absolute value) in the magnet supply current, (figure 2). The consequent rapid change in local magnetic field in the coils causes high inter-filament and inter-strand coupling losses that dissipate directly into the coil volume generating enough heat to quench completely a magnet typically within a few tens of ms, far more rapidly than a conventional QH.

The HL-LHC Triplets are equipped with both a conventional QH and a CLIQ protection system.

1.3. The K-modulation (K-mod) beam tuning system
The $\beta^*$ function at the interaction point determines the beam size and therefore the luminosity and performance of a collider and fine tuning of the $\beta$ function is fundamental. Currently the preferred method to measure the $\beta$ function in the LHC and its future upgrades is based on K-mod of the Q1 quadrupoles, those closest to the interaction point. With K-mod, the gradients of the quadrupoles are modulated, and the induced tune shifts are measured to determine the $\beta$ function at the interaction point.

The K-mod circuit allows a factor 2 improvement in the accuracy of the $\beta$ measurements [3]. K-mod requires the injection of a 35 A peak continuous sinusoidal input with a period varying between 60 and 30 s for typically 15 minutes in every 30, during a period of up to 8 hours. In the case of a magnet quench, an over-current pulse would pass through the K-mod feeder leads, for a few tenths of a second, with a peak value of about 4 kA, (figure 2).

2. Design requirements concerning all feeder types

2.1. Electrical requirements.
In addition to carry the current presented in §1.3 & 1.2, all equipment is required to be insulated to a high voltage withstand level to ground of 5 kV, with leakage currents below 15 $\mu$A, in line with general requirements for LHC [4], [5]. For correct function of the CLIQ system, the CLIQ feeders must present a total resistance per conductor branch linking cold mass to vacuum vessel lower than 2.5 m$\Omega$, or 5 m$\Omega$ in total.

![Figure 1. Layout of electric current feeders in an HL-LHC triplet.](image1)

![Figure 2. CLIQ and K-mod electrical pulses during a quench.](image2)
2.2. Thermalisation
Conduction cooled resistive current leads are operational in the LHC to supply up to 60 A to power closed orbit dipole corrector magnets [6], where efforts to minimize the heat loads to 1.9 K through the 1504 installed leads were of paramount importance. Intermediate temperature heat sinks at 50 K and 20 K were implemented through thermalisation blocks, designed to compress the solid brass Kapton®-insulated conductor-in-tube system and thus maximize the conductive heat transfer.

In contrast, HL-LHC Triplet magnet feeders are characterised by being few and having little impact on the overall LHC heat-loads to 1.9 K allowing a total heat load, deposited on the cold masses, of up to 20W per triplet. In addition, thermalisation as implemented on the LHC 60A dipole corrector leads is inherently less effective when applied to multiple wires (IFS) or to a multi-strand cable (CLIQ and K-mod). Multi-strand cable are used for flexibility so that the cable warm ends can be tightly coiled up and protected during the assembly of the cold mass into its cryostat: the feeders need to be assembled and pressure (25 bara) and leak tested (≤ 1.10-10 Pa.m3/s) on their cold masses before these are assembled into their cryostats.

Consequently thermalisation has not been implemented meaning therefore that the feeders described here must be self-protecting and designed to be thermally stable during resistive heating.

2.3. Maximum temperature that polyimide insulated conductors may attain in LHC
The pseudo glass transition temperature of Kapton HN® polyimide insulating material is situated between 630K and 680K. The generally accepted maximum conductor temperature for feeders linking superconducting accelerator magnets to room temperature in the LHC is about 350 K.

2.4. Condensation
Correct function under high voltage is crucial to the effective and safe operation of HL-LHC triplet magnets in an activated zone of LHC. Operational experience at CERN shows that to prevent condensation, the temperature of any parts in contact with ambient air should not be lower than 288 K for a nominal tunnel air temperature of 290 K. This rule is confirmed by analysis of the dew point data obtained for one sector in the LHC tunnel over one complete year, where a minimum temperature above the dew point of 2.6 K has been measured.

2.5. Radiation
The at least five times increase in luminosity at the interaction points 1, ATLAS and 5, CMS that will be provided by the HL-LHC Triplets, leads to a roughly equivalent increase in activation of all LHC machine equipment on each side of these interaction points. All HL-LHC equipment in the long straight sections to the left and right of ATLAS and CMS must withstand an integrated dose of 1 MGy.

2.6. Integration requirements.
The IFS, CLIQ and K-mod feeders design, have been largely adapted to an existing cryo-magnet layout and this has constrained the minimum integrated lengths and therefore the cross-sections of the conductors.

Because all three types of feeders are mounted to the cold mass (see §2.2), several integration stages must therefore be considered; integration into the containment vessel for pressure and global leak testing, the integration during assembly of the cold mass into its cryostat and finally the integration and ease of access in the LHC tunnel.

3. Design
3.1. IFS.
IFS feeders of 2 types, containing either 50 or 14 cables are installed on the HL-LHC triplet, (figure 1). The IFS feeder is composed of a glass-cloth sleeved cable bunch in one tube of diameter 14/12 mm, 4 m long for 50 cables and of diameter 8/6 mm, 3 m long for 14 cables. In each case the complete bunch
of instrumentation wires, with sufficient over-length, is brought uninterrupted out of the cold mass and is fed through the IFS feeder tube while straight. The tube is then welded in place to the cold mass and there formed to final shape as shown in figure 3 and figure 4.

3.2. CLIQ and K-mod.
The CLIQ and K-mod feeder’s conductors are each tightly contained in a separate tube, this allows the use of tubes of smaller diameter, more easily formable where the insulated conductor can be tightly adjusted to the tube inner diameter so minimizing the superfluid contribution to heat in-leaks. The stainless-steel tubes are diameter 8/6 mm, 2.45 m long for CLIQ and 1.7 m long for K-mod.

Both CLIQ and K-mod feeders will be formed separately and mounted on to their cold masses at one of the last assembly stages, they are terminated with cable ends to be electrically and mechanically connected to those of the cold mass via a combined connection box providing the required high-voltage reliability. Their final formed shapes are shown in figure 3 and figure 4.

4. Conductor
A conductor is defined by its material, its Cross-Sectional Area (CSA), its length and the number of strands that it is composed of.

Avoiding skin effect due to alternating currents (see §4.3.3) and providing adequate flexibility determines the number of strands. The material, length and CSA are interdependent, define the thermal and electrical conductance of the conductor, and therefore, the temperature the conductor reaches due to the continuous or momentary passage of electric current.

![Figure 3. Feeders integrated into Q1 IP side.](image1)

![Figure 4. Feeders extracted for clarity.](image2)

4.1. Methodology to select a material, the length and the CSA
A first parameter, generally the conductor material, must be selected. After fixing the maximum temperature the conductor may reach, a minimum CSA can be defined from an adiabatic thermal calculation relating the temperature increase of the conductor to the Joule effect of the circulating current, a valid approximation, since both CLIQ and K-mod are subjected to short duration current pulses.

The length is selected in accordance with the design requirements: maximum electrical resistance, minimum conductor warm extremity temperature and the maximum conductor temperature in its length when carrying current continuously as in the case of K-mod. If current is passed for more than a few seconds, the increase of temperature due to transient electro-thermal effects is important. In this case the CSA will also influence the conductor temperatures reached.

Furthermore, the convective boundary conditions at the warm end and the current flow both vary with time, and the problem presents numerous nonlinearities, in particular the variation of the material properties with temperature. A finite element (FE) analysis has been conducted with ANSYS® software on a representative model, (figure 5). Initial analysis calculates the conduction through the feeder system of ambient heat transferred to its warm end by natural convection giving the static heat inlet in the absence of any electrical current. The effects of current flow (both continuous and pulsed) are calculated using the same model enhanced with the time varying electrical signal as an additional boundary

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condition. Some requirements are opposed, for example for CLIQ, a maximum electrical resistance and a maximum thermal conductance further limit the design possibilities.

4.2. IFS design

4.2.1. Composition and material. The wires in the IFS are serving three categories; thermometers, voltage-taps, and power supplies for quench heater and for cryo-heaters, they employ standard polyimide insulated commercial OFHC multi-strand copper wires.

4.2.2. CSA and Length. For each function, the wire CSA retained is that of the same function serving the LHC arc dipoles. Connected at the warm end of the feeder, a cover flange, (figure 6), equipped with commercially available helium leak-tight electrical feedthroughs (EFT), one per channel, has been modelled. Analytically evaluated convection coefficients for the surrounding air have been applied as a boundary condition to the cover flange and the operating temperature of the cold mass, has been imposed at the cold extremity of the wires.

Figure 5. Heat-flow model.  

Figure 6. Temperature on the EFT’s ambient air exposed part.

This FE model, applied to a technologically manageable IFS length of 4 m, shows a distinctive gradient of temperatures on the cover flange. Some temperatures of outer extremities of leak-tight feedthroughs (those connected to the wires with larger CSA) were calculated and shown to be below the design limit of 288 K.

A very similar configuration was on test at CERN with the number of wires and the total CSA of the conductor being close to that of the triplet IFS50. Temperature measurements of the cover flange and on the air side extremities of its feedthroughs were carried out and in parallel a FE analysis of the IFS under test was made.

The same FE model applied to the configuration under test also returned results showing a temperature gradient on the cover flange and temperatures below the dew point temperature of 288 K on some upper extremities of the leak-tight feedthroughs with an ambient temperature of 290 K, (figure 6). However, temperature measurements made with a thermal camera showed the temperatures of the IFS cover flange and its leak-tight feedthroughs to be almost totally homogeneous and close to the temperature of the ambient air in the test hall.

The FE model is therefore conservative, where radiative and convective heat transfer phenomena, in and around the cover flange, bring additional heat to the conductors at the warm end. In particular, radiation heat exchange from the cover flange at 300 K to the 400 mm or so of extra length of instrumentation wiring coiled inside it may account for the difference between the calculated results and the physical measurements.
The FE model will be refined after bench-marking from heat-load measurements due to be carried out on a complete representative system, in the cryogenics laboratory at CERN.

4.3. CLIQ and K-mod design

CLIQ and K-mod, are new type of leads and so require a dedicated study.

4.3.1. Material. The material chosen for both CLIQ and K-mod 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 7 and figure 8). However, the actual RRR value of the commercial product will be validated by tests at CERN in late 2019.

Another candidate material, brass Cu90Zn10, with a higher electrical resistivity and a lower thermal conductivity, has been studied for K-mod. Simulations were conducted and have shown several advantages linked to the use of this material; lower heat load to the cold mass and a lower peak temperature during the K-mod pulse. However, when comparing 2 conductors, one in OFHC copper the other in Cu90Zn10 brass of the same 2 m length, but of CSA selected so that both conductors attain a maximum temperature of about 350 K after 8 hours of continuous 35A current flow and the final peak of 4kA during quench, the brass conductor heats more rapidly, attaining 327 K, with the temperature still rising, whereas the copper CURRR100 reaches temperature stability at 287 K, (figure 7).

The higher CSA required for thermal stability of the brass conductors, leads to a more rigid conductor to be lodged in a tube of larger diameter so complicating integration into the cryostat. Uncertainties appeared in achieving reliable splicing at the cold connection between the cold mass cables, 10 mm² CSA in copper, to the feeder cables, 25 mm² CSA in brass. For the four K-mod feeders in the triplet, two in Q1 and two in Q3 (the ones in Q3 are not powered), the heat load reduction of 2 W per triplet, (0.95 W for one copper conductor and 0.45 W for one brass conductor) does not justify the use of brass.

For CLIQ with an upper resistance limit 2.5 mΩ for each branch of this feeder, a CSA of 40 mm² would be needed in brass. With such a CSA, the heat load reduction on 12 CLIQ feeders is 1.8 W per triplet, (0.63 W for one copper conductor, 0.48 W for one brass conductor). Once again, the heat load reduction obtained does not justify the use of brass.

4.3.2. CSA & Length. The CSA of the K-mod conductor has been determined as a function of its length, of the order of 2.1 m, determined by the formed shape required to integrate the cable in tube into the assembled cryo-magnet. The length defined, a simulation was launched, considering in a first step, the heating effect of the uninterrupted 35 A peak sinusoidal (24.8 A RMS), current flow during 8 hours,
followed at the end of this period by that of the K-mod pulse of 4 kA peak, (figure 2). Results have validated a section of 10 mm² in OFHC copper where after 8 h at 24.8 A RMS the maximum temperature towards the warm end of the conductor reaches 283 K (initial temperature: 273 K) and after the 4 kA peak pulse is applied, rises again to 347 K, (figure 7).

The CLIQ conductor length of the order of 2.9 m is also determined by the as-formed shape required to integrate the cable in tube into the assembled cryo-magnet. Not to exceed 350 K anywhere in its length while carrying its sinusoidal pulse, (figure 2), a minimum CSA of 6.5 mm² is required in OFHC copper. With such a CSA, and the length needed for integration, the resistance of 2.5 mΩ per branch is at the upper limit specified. To favour common components in the triplet magnets, a CSA of 10 mm², the same as for K-mod, has been selected for CLIQ where the resistance of the conductor drops to 1.5 mΩ. The maximum temperature reached by this OFHC (RRR100) copper conductor after the CLIQ pulse is 307 K (maximum initial temperature: 283 K), (figure 8). The parameters selected and presented here do not therefore represent an optimal thermo-electric design.

4.3.3. Number of wires that compose the conductor. The CLIQ pulse has been checked for the skin effect at a frequency of 10 Hz. The skin depth of the current, 21 mm at 300 K and 2 mm at 2 K, larger than the strand diameter of 0.39 mm, does not therefore determine the number of wires in the cable.

4.3.4. Lorentz forces. Circulating currents during CLIQ and K-mod pulses may occur separately or simultaneously. Magnetic forces have been evaluated between these feeders that run in separate dedicated tubes, with, in places, only 20 mm between conductor centres. A repulsive force per unit length between two K-mod conductors, the worst case, of 160 N/m has been calculated. Mechanical links are foreseen between the tubes to limit their displacements due to this force.

5. Heat exchanger

5.1. IFS
As explained in §4.2.2, the FE model used to dimension the feeders is conservative when compared to measurements of temperature made on a similar system. Nevertheless, the IFS feeder at the warm end is designed so that fins may be added from the outside to enhance heat transfer to the cover flange if first performance tests show it to be necessary.

5.2. CLIQ and K-mod
FE calculations on an initial design have shown that the heat transfer to the leak tight feedthroughs from the ambient air under natural convection conditions will be insufficient to prevent condensation in the least favourable atmospheric conditions in the LHC tunnel. A heat exchanger, composed of vertical parallel fins, in aluminium alloy and mechanically attached in close thermal contact with the air-side end of the conductor of each leak-tight electrical feedthrough has been optimised dimensionally (number of fins, spacing and surface area) making use of the Elenbass correlation [7] with, as design parameters, the minimum temperature difference available of 1.5 K to the surrounding air, the surface area of the fins and the heat power required to keep the conductor warm end above the dew point in the LHC tunnel.

Each CLIQ feeder branch requires a heat input of 0.65 W, requiring a heat exchanger of H 70 mm x L 189 mm x W 100 mm, and each K-mod feeder branch a heat load of 0.89 W, calling for a heat exchanger of H 115 mm x L 189 mm x W 100 mm.

6. Electrical Insulation
Optimum electrical insulation properties maintained over the operational lifetime of the HL-LHC triplets are critical for the functional reliability and safety of the LHC accelerator.

Polyimide is well known for its excellent electrical insulation properties, for its radiation resistance and for its suitability for use at helium cryogenic temperatures, it has therefore been retained for this design.
6.1. IFS
The wires composing the HL-LHC triplet bundle are commercially supplied with a polyimide insulation guaranteed for a voltage rating of 1000 V AC. However, these polyimide-insulated wires have been tested successfully to 5 kV and have been installed and given satisfaction in the LHC machine in large numbers of LHC arc cryo-magnets presenting very similar high voltage requirements.

6.2. CLIQ and K-mod
A search for 10 mm² CSA commercially available multi-strand cables with extruded polyimide insulation, was launched. A candidate product, with a configuration otherwise corresponding to that required, but with a minimum achievable extruded polyimide insulation radial thickness of 1 mm, has been assessed. Although of excellent quality, its rigidity is too high and its associated minimum bending radius of 100 mm too large, particularly for the cable routing inside the cover flange where it would apply unacceptably large forces to the helium-side ends of the leak-tight feedthrough conductors.

The feeder cable electrical insulation will be obtained from two commercially available polyimide tubes, each tube is composed of three wrapped and glued layers of 25 μm and one layer of 50 μm. These tubes are assembled one inside the other before sliding them both over the conductor.

7. Predicted Results
The calculated static heat loads to 1.9 K due to the feeders assembled to the HL-LHC triplet magnets are summarized in the table 1. The total static heat load for 1 triplet composed of one each of Q1, Q2A, Q2B and Q3 is 17.48 W which is acceptable given the limit value of 20W.

| Feeder  | Qty feeders Q1 or Q3 | Qty feeders Q2A or Q2B | Heat/feeder [W] | Total Q1 or Q3 [W] |
|---------|----------------------|------------------------|----------------|-------------------|
| IFS 50  | 2                    | 1                      | 0.88           | 6.35              |
| IFS 14  | 0                    | 1                      | 0.16           |                   |
| CLIQ    | 4                    | 2                      | 0.68           |                   |
| K-mod   | 2                    | 0                      | 0.94           |                   |

|                | Total Q2A or Q2B [W] | 2.4                  |
|----------------|----------------------|----------------------|
|                | Total/triplet [W]    | 17.5                 |

8. Conclusions and future Work
The functional design and thermo-electrical optimization, together with the integration of the IFS, CLIQ and K-mod 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, CLIQ and K-mod 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.

9. References
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