

Operational experience in the use of 18 kA HTS current leads for Edipo

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Abstract. In spring 2013, the Edipo facility of CRPP was commissioned. The dipole is powered via two 18 kA HTS current leads, designed and manufactured at CRPP. As part of the Edipo commissioning framework, the operational parameters of the leads were implemented in the control system. The in-situ tests were found to be in good agreement with the tests performed without a background field in 2011. The leads consist of a conduction cooled HTS module, made of AgMgAu/Bi-2223 stacks, and a wire bundle heat exchanger. The heat exchanger is cooled by forced flow helium gas, the inlet temperature of which was measured to vary between 65 K and 85 K. During operation with field, the mass flow rate is a function of current (2.05 g/s per lead at full field, 12.35 T, 17.2 kA). Reduced cooling investigations showed that 0.31 g/s per lead is suitable for overnight standby and 0.2 g/s per lead for longer periods. For detection of and protection against quench in the HTS module, a threshold of 10 mV was found to be appropriate. The heat exchanger has a voltage protection threshold of 120 mV. The temperatures of the heat exchanger, the HTS, and the helium inlet temperature were monitored in order to provide a further layer of protection.

1. Introduction

The European Dipole (Edipo) is a new facility, hosted by CRPP, for the testing of high current force flow conductors in a high field [1]. In order to reduce the cryogenic load, the dipole is powered by two CRPP designed HTS current leads [2]. The conduction cooled HTS module consists of AgMgAu/Bi-2223 stacks soldered on a stainless steel support, similar designs have been successfully used for particle accelerators [3] and magnets for fusion [4]. The resistive part of the lead is a wire bundle heat exchanger that is cooled by forced flow helium. The helium inlet temperature is 75 K, which was measured to vary between 65 K and 85 K. The leads were commissioned in 2011 without a background field [5]. The first cool-down of the Edipo coil assembly lasted 50 days with a subsequent cool-down lasting only 24 days. In both cases the leads were cooled down together with the dipole and did not limit the overall cool-down rate. The leads are actively cooled once the dipole temperature is less than 10 K. No problems with the leads were observed during cool-down.

2. Operation with field

During operation with field, the leads are independently operated with the mass flow rate ($\dot{m}$) controlled as a function of current (figure 1). A minimum mass flow rate of 0.38 g/s per lead is activated at the same time as the power supply in order to prevent quenches at low current. The control system has an option to automatically increase the flow and ramp down the field in the event of too high a temperature. Furthermore, the temperature differences between redundant sensors in the same



locations are also over-watched by the control system. Temperatures and flow rates for a ramp to the full Edipo field of 12.35 T, corresponding to 17.2 kA, are shown in figure 2. The cooling of the leads was found to be sufficiently stable both during current ramps and flat tops to allow successful operation with field. Variation of the helium inlet temperature did not cause any problems.

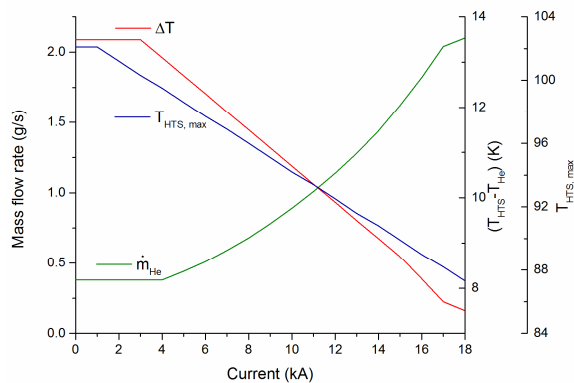


Figure 1. Mass flow rate as a function of current used to control the HTS leads. Also shown are the maximum allowable HTS temperature ($T_{HTS, MAX}$) and the maximum allowable temperature difference between HTS and He inlet ($T_{HTS} - T_{He}$).

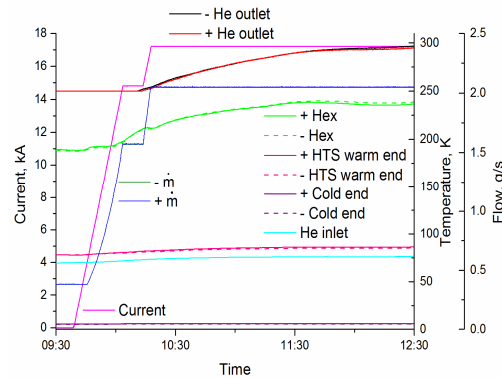


Figure 2. Temperatures and flow rates for the two leads during a current ramp and subsequent stable operation at 17.2 kA. Above 4 kA mass flow is a function of current. The thermocouples for the helium outlets have a lower temperature limit of 250 K.

During commissioning of the leads in 2011, the mass flow was set as a function of the temperature difference (ΔT) between the HTS (T_{HTS}) and the helium inlet (T_{He}). However, it was found that ΔT control was not suitable for use with field due to variations in T_{He} . Control with $\dot{m}(I)$ necessitated the use of a higher flow than with $\dot{m}(\Delta T)$. After commissioning the temperature sensors had 0.4 mm thick glass/epoxy insulation on both sides, previously they were not insulated. Overall, the temperatures during operation were in agreement with the prior measurements (table 1).

Table 1. Comparison between commissioning and operational values. With field; control was $\dot{m}(I)$ and the temperature sensors were insulated. Commissioning; control was $\dot{m}(\Delta T)$, there was no insulation.

Parameter	Commissioning (no field)	Operation (12.35 T)
I (kA)	17	17.2
$\dot{m}$ (g/s)	1.84	2.01
T_{HTS} (K)	84	85-86
T_{He} (K)	76.2	76.4
ΔT (K)	7.8	8.6-9.6

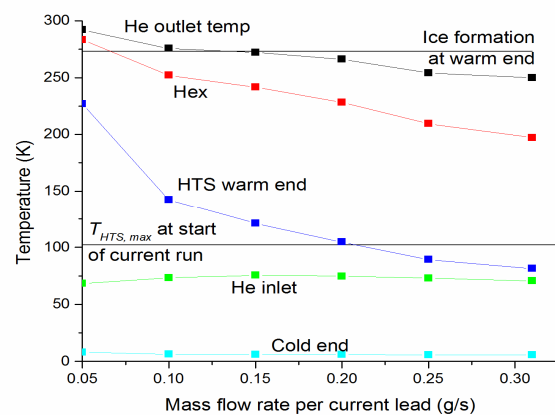


Figure 3. Current lead temperatures as a function of the mass flow rate at zero current. Presented temperatures are an average of all sensors installed in each location and each lead. The allowable $T_{HTS, MAX}$ to start current from zero is 102 K. Ice formation line is at 273 K.

3. Standby operation

The nominal standby mass flow rate is 0.31 g/s per lead, when the power supply is not energized. This cools the leads sufficiently enough that operation with current can start immediately. During commissioning, the helium outlet temperature was ~ 270 K. However, once installed with the complete facility, and with longer periods of standby, this was measured to sink to ~ 250 K resulting in the formation of ice on the room temperature end of the leads. The variation of the leads' temperatures, at zero current, with different mass flow rates is shown in figure 3. For longer standby the helium mass flow rate is reduced to 0.1 g/s per lead. A mass flow rate of 0.1 g/s per lead was found to be appropriate to avoid ice or moisture formation. However, this leads to a temperature ~ 130 K at the warm end of the HTS module and so a subsequent re-cooling is required before operation with current. The re-cooling duration is less than one hour. For longer periods of standby (weekends or more) a standby $\dot{m}$ of 0.1 g/s is used, for overnight standby 0.31 g/s is retained with the resulting ice being none or minimal. Fans were installed to enhance air circulation over the leads and other feed throughs.

4. Helium inlet temperature stability

The ~ 30 year old CRPP cryoplant [6] provides supercritical helium at ~ 4.5 K and helium gas with a nominal temperature of 75 K. The cryoplant utilizes a 750 kW base load motor and an additional 250 kW motor to produce 1.2 kW at 4.4 K. The cryoplant is shared with the Sultan [7] test facility and there is sufficient cooling power for one facility to be in standby whilst a high field test is performed in the other facility. In standby only one compressor is required; if either facility is operating with field then both compressors are needed.

A particular feature of this configuration is the 75 K helium gas that is used for cooling the current leads and the thermal shields. This temperature was measured to vary between 65 K and 85 K and the temperature is weakly linked to pressure (figure 4), but there is a large amount of scatter. The variation is unavoidable and is due to a variety of factors, including pressure drop over the filters, external temperature, and number of compressors in use. The high helium inlet temperature results in an HTS warm end temperature of ~ 80 K, significantly higher than that used for other HTS leads. For comparison the LHC leads have an HTS warm end temperature of 48-52 K [8] [9]. This high temperature with a potentially large variation necessitated a large safety factor to be used for the specification of the amount of HTS material [2]. However, the resulting robust design has been proved to allow safe operation of the leads over a variety of helium inlet conditions.

5. Operational aspects of quench and thermal runaway

A voltage based system is used to protect the HTS module against quench and the resistive heat exchanger against thermal runaway (e.g. in case of loss of flow). Protection of the current leads is integrated within the complete Edipo quench detection system (QDS), the development and commissioning of which is reported elsewhere [10] [11]. For detection of quench in the HTS module, the proposed threshold of 10 mV was found to be appropriate. This was a compromise between the relatively high noise (± 3 mV) and a high HTS temperature if too high a threshold is specified (~ 50 mV at 17 kA: ~ 127 K). Whilst a constant voltage threshold is generally suitable for protecting a superconducting component against quench; it is less suitable for protecting the resistive heat exchanger against thermal runaway- at low current a much higher temperature rise is experienced before the voltage is over-threshold. A temperature based protection system could be used, but in practice a significant lag time between thermal runaway and a sensor's response arises due to the electrical insulation. The heat exchanger is adequately protected at full current with threshold of 120 mV, lower than the 150 mV used for commissioning at 18 kA. To improve the protection of the heat exchanger at low currents; a current dependent voltage threshold could be used, or the heat exchanger temperature could be integrated into the QDS.

During commissioning of the dipole the negative current lead was quenched at low current (720 A). The quench voltages are shown in figure 5. The quench occurred ~ 72 s after the start of the current ramp and was due to an insufficiently cooled lead. Although the HTS temperature was decreasing, the

rate of decrease was not sufficient when compared to the rate of current increase (10 A/s). The control logic was subsequently updated so that the minimum cooling when the power supply was energized was raised from 0.31 g/s to 0.38 g/s per lead; i.e. constant mass flow rate beneath 4 kA and $\dot{m}(I)$ at higher currents. There were no further low current quenches.

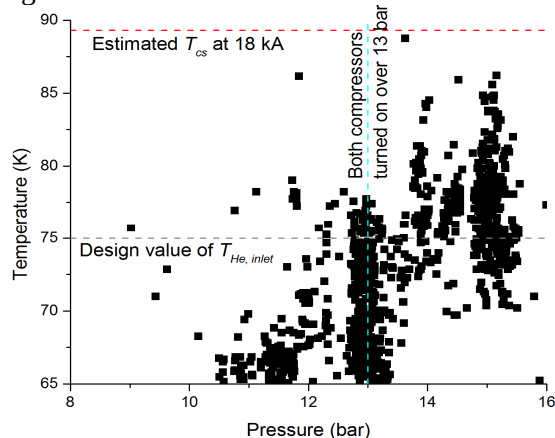


Figure 4. Variation of the helium inlet temperature as a function of the pressure. Above 13 bar, both of the cryoplant compressors are required. The estimated T_{cs} was presented in [5].

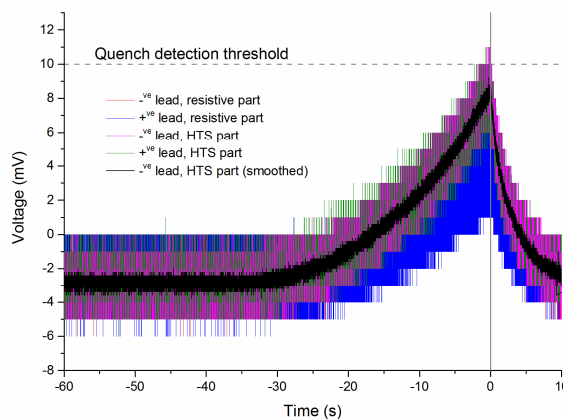


Figure 5. Quench voltages at ~720 A. Quench was detected first on the HTS part of the negative lead; a 5 point smoothing of this signal is shown.

6. Conclusion

The current leads functioned well during the commissioning of the Edipo facility and allowed operation at high field (12.35 T, 17.2 kA) for extended periods of time. During the several weeks of operation with and without field the operational parameters of the leads were refined and were implemented in the control system. Reduced cooling parameters were established for long standby periods in order to prevent ice formation at the warm end of the leads. Due to a robust current lead design, the high helium inlet temperature (75 K) and its large variation (± 10 K) did not lead to problems during operation. The quench detection system was shown to adequately protect the leads.

References

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