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CRYOGENICS IN HIGH-CURRENT BUSBARS – SOLUTIONS AND REQUIREMENTS

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ABSTRACT

In superconducting high-current busbars the major cooling demand is generated in the current leads. To minimize these current lead losses we developed a novel multistage cooled current lead. Depending on the amperage from 20 kA in chlorine electrolysis up to 500 kA in aluminium plants one can choose from a limited variety of cooling machines. Most effective are refrigeration plants based on the Claude-cycle providing cooling power on different temperature levels. But these systems are only available for higher cooling demands i. e. amperages around and above 200 kA.

To reduce the required quantity of high-temperature superconductor, the superconductor inside the busbar should be cooled by sub-cooled liquid nitrogen at a temperature between 65 and 70 K. For long-distance transmission lines it is recommended to reduce the busbar temperature down to 20 K and to use helium gas as coolant.

Keywords: Cryogenics, High-temperature superconductor, Current lead, High-current busbar.

1. INTRODUCTION

The use of high-temperature superconductors (HTS) has big advantages especially in high direct current applications. Relevant industrial applications can be found in chlorine, zinc or copper electrolysis and aluminium plants (Morandi, 2015). Within the scope of the installation of a demonstration model in a chlorine electrolysis we are building two current leads and a 25 m long superconducting busbar for 20 kA DC. A transmission line with similar technical data (current of 20 kA, 20 m long) was built by CERN (Ballarino et al., 2014). CERN used MgB_2 and we use 12 mm wide YBCO tapes as superconducting material. While the MgB_2 conductor has to be operated around 24 K the YBCO can run on higher temperature around 70 K.

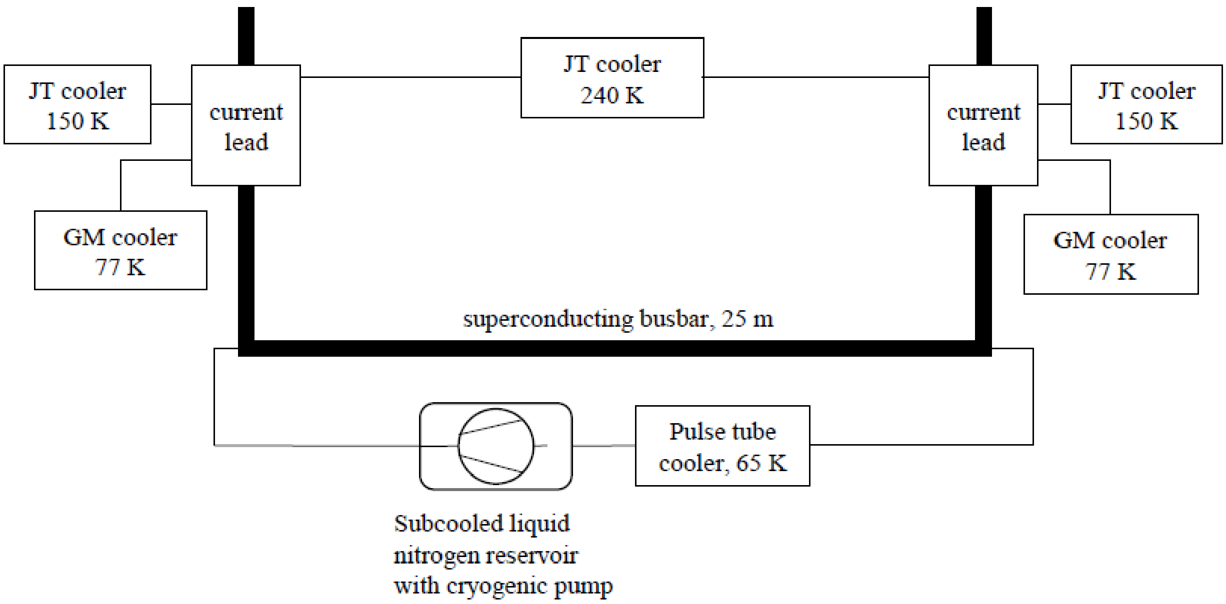


Figure 1 Schematic diagram of demonstrator

2. MAIN SECTION

The 20 kA demonstration model that will be installed in a chlorine electrolysis in the second half of 2017 consists of two main parts: the two identical current leads at both ends and the 25 m long superconducting busbar in between. Figure 1 shows a schematic diagram of the demonstrator. In the actual design both parts are cooled separately and have their own cooling machines. The two current leads only share the cooling machine for the first stage. The cooling water required for all cooling machines is provided on site.

2.1. Current lead

As the major losses are generated in the current leads, we built a novel multistage cooled current lead (Schreiner et al., 2016). The length and cross section of the several parts of the copper path was designed using a 1D model and is optimized for 20 kA. Multistage current leads have been investigated before but to our knowledge never been built in that high current range (Yamaguchi et al., 2013; Bromberg et al., 2010).

2.1.1. Multistage cooling

The warm copper busbar terminal is cooled by ordinary cooling water. Below this level we applied three separate cooling machines based on different cooling principles. The first stage is cooled by a standard Joule-Thompson (JT) cooling machine (@ 240 K) used for freezing systems in food industry in many cases. This machine is equipped with a frequency converter to regulate the cooling power and to save energy. The second stage is cooled by a mixed-refrigerant cooling machine (@ 150 K). Mixed-gas machines are mainly used as a cryo pump working on the Meissner trapping principle e. g. in vacuum coating processes. In the copper-HTS transition zone the superconducting tapes are soldered to T-shaped copper laminates and are cooled by liquid nitrogen at atmospheric pressure. The evaporating nitrogen is recondensed by a single-stage

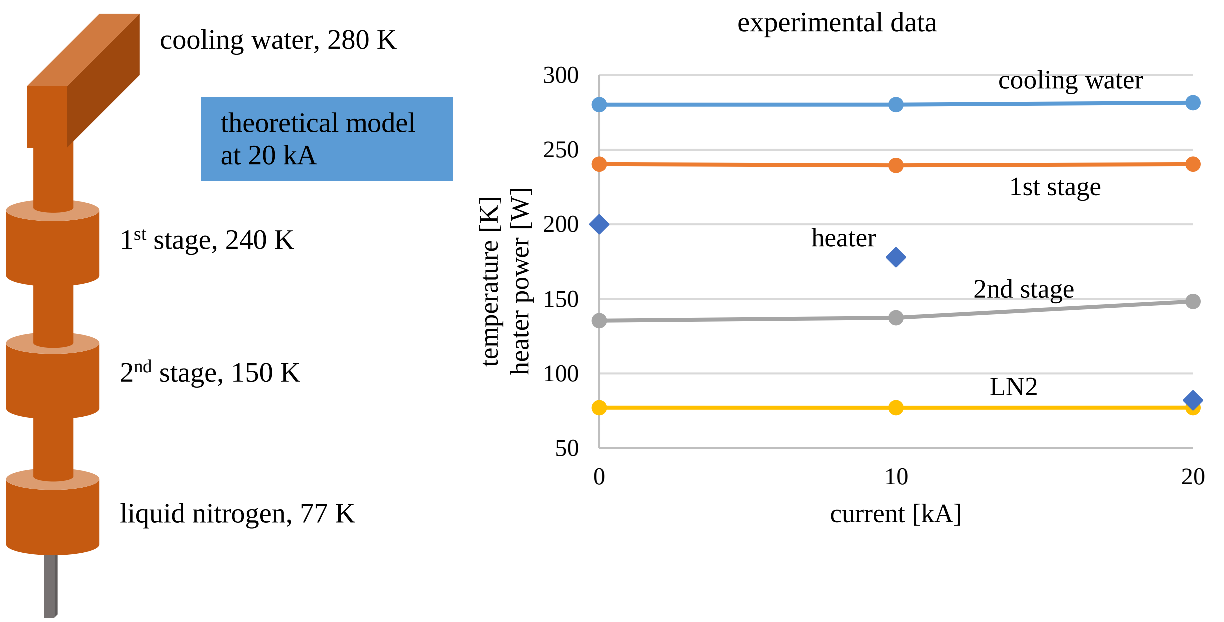
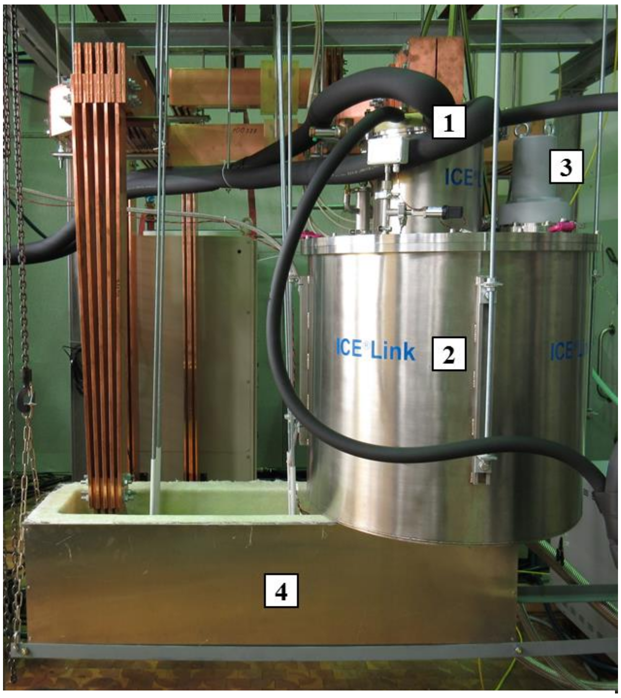


Figure 2: Current path temperatures

Gifford-McMahon (GM) cryorefrigerator at 77 K. As the GM cooler has excess cooling power and is not adjustable yet, we installed a controllable electric heater inside the liquid nitrogen reservoir to maintain constant pressure in the dewar. The selection of cooling machines was based on the following criteria: reliable, good value for money and easily available from the market, worldwide distribution and maintenance.

2.1.2. Test of current lead

The current lead was tested in short circuit at various currents up to 20 kA. The bottom section of the dewar where the superconductors are coming out was dipped into an open liquid nitrogen tank for the test. The superconductors were pressure connected on copper lamellas in the nitrogen bath and the other side was carried out as an ordinary conduction cooled current lead made of copper. The set-up is shown in Figure 3.



1: warm connection
2: vacuum insulated dewar
3: GM cryocooler
4: liquid nitrogen bath

Figure 3: Photo of current lead test rig

For cooling down we start the mixed-refrigerant machine (2nd stage) first to bring the copper rod's temperature down. One can save liquid nitrogen by cooling it down to an intermediate temperature, because the copper rod contains the main part of the thermal mass. As soon as the copper rod achieves 160 K we start the GM-cryocooler and the liquid nitrogen filling. About three hours after the liquid nitrogen meets the target level the nitrogen boil off stops and the pressure starts to decrease. To keep constant pressure in the dewar we apply an appropriate electrical heater power.

Figure 2 shows the comparison between the temperatures derived from the theoretical model and the measured temperature values at two different currents and the no-load situation. Particularly at the rated current of 20 kA the theoretical values match the measurements accurately. As the coolant in the 2nd stage cooling machine is a mixed-refrigerant we have no sharp phase transformation temperature but we have a temperature glide. For this reason temperature is rising with increasing load on the 2nd stage.

2.2. Superconducting busbar

In contrast to cables busbar systems usually consist of discrete system elements. Elements with a length of maximum 12 m fit into a standard 40 foot container which is practical and cost saving. The advantage of this technique is the simple installation especially in industrial plants with limited space. The custom-built

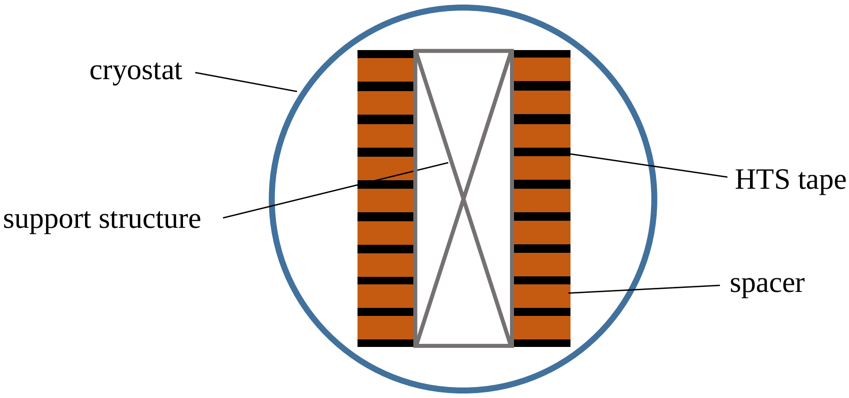


Figure 4: HTS tape arrangement

elements can include vertical and horizontal angels wherever necessary. The disadvantage is the additional heat load from the cryogenic couplings and the resistive losses generated by the contacts of the HTS tapes. The resistive losses are reduced as far as possible by soldering each single tape face-to-face.

2.2.1. Structural design

The need of superconductor can be minimized by increasing the distance of the single HTS tapes. While we have very narrow feed through at the bottom of the current lead, we have much more space in the busbar. As only short pieces of superconducting tapes are required in the current lead it is useless to optimize its design for saving superconducting material. The major part of the superconducting tapes is installed in the busbars. The special design allows the reduction of the number of superconducting tapes by 50 % compared to the number of tapes in the current lead. The spread is realized by copper tapes between the HTS tapes and a support structure fixing the two stacks (see Figure 4).

Our design can easily be modified for higher currents. One option is the increase of the number of tapes.

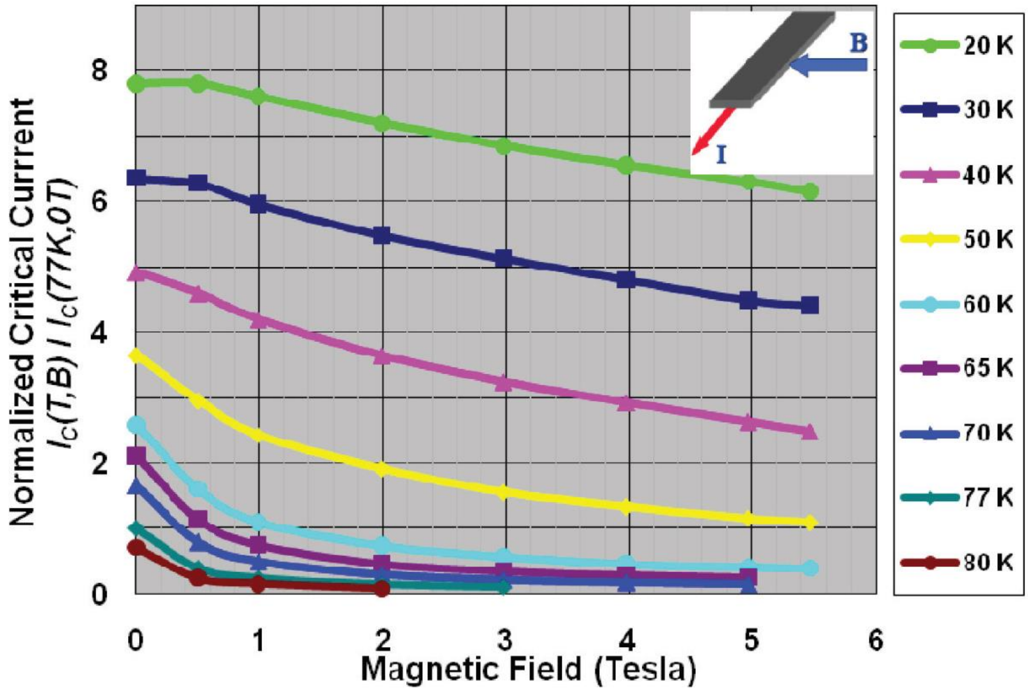


Figure 5: Lift factor of AMSC tape (Performance data courtesy Railway Technical Research Institute, Tokyo, Japan)

More reasonable is lowering the temperature of the superconductors inside the busbar. As nitrogen will freeze below 63 K you have to choose cold helium gas for cooling in this case. The lift factor of a typical YBCO tape is shown in Figure 5. By decreasing the temperature from 77 K to 20 K the critical current can be increased by a factor of almost 8. Higher capital investment in cooling technology is more than compensated by cost savings in superconducting material.

2.2.2. Busbar cooling

The superconducting tapes in the busbar are cooled by sub-cooled liquid nitrogen at a temperature from 65 K to 70 K in a closed loop. The sub-cooled nitrogen is generated by a high-performance pulse tube cooler developed at Institut für Luft- und Kältetechnik (ILK) in Dresden. The circular flow of the liquid nitrogen is supported by a special pump for cryogenic liquids (Binneberg et al., 2008). The expected mass flow rate of 0.1 kg/s can discharge heat output of about 1000 W and is sufficient to keep the temperature of the superconducting tapes below 70 K (see Table 1).

$$\dot{Q} = \dot{m} \cdot c \cdot \Delta T = 0.1\ \mathrm{kg/s} \cdot 2.01\ \mathrm{kJ/(kg \cdot K)} \cdot 5\ \mathrm{K} = 1005\ \mathrm{W}$$

Table 1. Estimated heat load of 25 m busbar

resistive losses due to HTS soldering	7 W per coupling	56 W
cryogenic losses (radiation)	2 W/m²	25 W
additional cryogenic losses at couplings	4 W per coupling	32 W
heat conduction current lead (77 → 70 K)	4 W per current lead	8 W
ripple current (AC losses)	1 W/m	25 W
Total		**146 W**

2.3. Outlook

The 20 kA demonstrator is the first step to prove the suitability of superconductors in industrial environments. Our aim is a range of superconducting busbars of currents from 20 kA up to more than 200 kA and long lengths of several ten metres up to kilometres. Long lengths and very high currents result in higher cooling power requirements, but open the opportunity to significant savings in energy consumption.

3. CONCLUSIONS

With the successful test of the multistage cooled current lead we completed one big part of the demonstrator project. After initial cool down and liquid nitrogen filling the novel multistage current lead achieves zero-boil-off. This feature is advantageous particularly with regard to the industrial application, because in some applications it is not allowed to evaporate huge amounts of nitrogen. Compared to laboratories liquid nitrogen logistic is not available in many industries. The cooling of the busbar is also designed as a closed loop. The parts of the busbar are currently in production and their tests will start soon.

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NOMENCLATURE

$\dot{Q}$	rate of heat flow (W)	C	specific heat capacity (kJ/(kg·K))
$\dot{m}$	mass flow rate (kg/s)	ΔT	temperature difference (K)

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