Building of a Superconductor Busbar at 200 kA for an Aluminium Plant

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Abstract

Superconductors for electric current have reached a level of industrial readiness and today in place there are the first superconducting applications and demonstration projects. Superconductors are conducting direct current with extremely high densities of more than 500 A/mm². Further advantages are loss-free high-power transmission, small dimensions of busbars, and a low carbon footprint.

This paper explains the current steps that had been undertaken to develop an industrial-ready technology into real industrial applications for the aluminium industry. It explains the design of a 200 kA demonstrator at TRIMET Aluminium SE with the target to complement an existing aluminium plant. It covers the following points:

- The current status of superconducting high-current DC development and its applications
- The motivation and an overview of the DEMO200 project at Trimet
- The design of a 200 kA busbar, current lead and associated connections
- The construction and technical layout of currents, magnetic fields and forces, and
- The test program on how to test a 200 kA system

To close, a conclusive status of the project and an outlook for further applications will be provided.

Keywords

Aluminium, Superconductor, Busbar, Efficiency, Green Transformation

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Superconductors – the mysterious material

In the early stages, the industry in general paid little attention to superconductivity because the applications were limited and expensive. Nevertheless, the development was steady and many applications became feasible after the discovery of **high-temperature** superconductivity in 1986. Nowadays, high-temperature superconductors (HTS) can transmit high currents with zero losses, which is the breakthrough. In direct-current (DC) operation, the superconductors show no electrical resistance and only the material itself sets a limit to the current load capacity. For example, a single HTS-Tape has a current carrying capacity of more than 50 kA/cm². The superconductive layer, with a thickness of only 3 µm, is made of sintered ceramic materials and a typical arrangement is shown in Figure 1, with the black arrow indicating the superconducting layer. The remaining layers are used for contacting and stabilization. Compared to conventional conductors or busbars, the amount of material is significantly lower so that existing resources are used more efficiently. Because of its small physical dimensions and versatility, the HTS-technology is space saving and can be installed in restricted rooms. Using individual tapes and arranging them according to their intended purpose, it is possible to manufacture busbars for extremely high currents. Cooling the busbars with liquid nitrogen (LN_2) maintains the operating temperature of HTS within a thermal insulated cryostat. The superconductor busbar system is cooled by standardized refrigeration systems used in many industrial processes and is therefore operationally reliable.

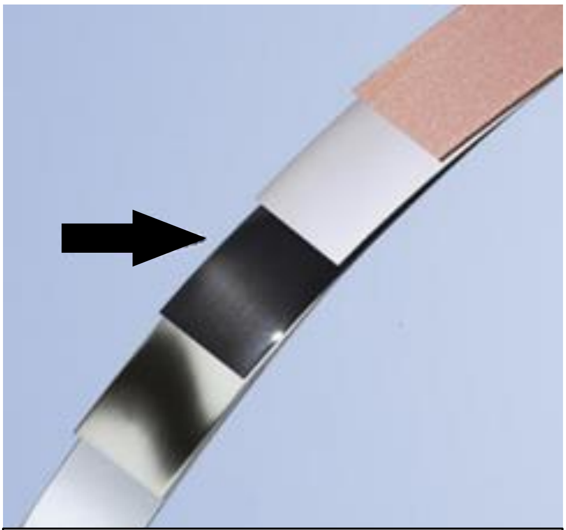

Figure 1: Superconducting tape consisting of different layers

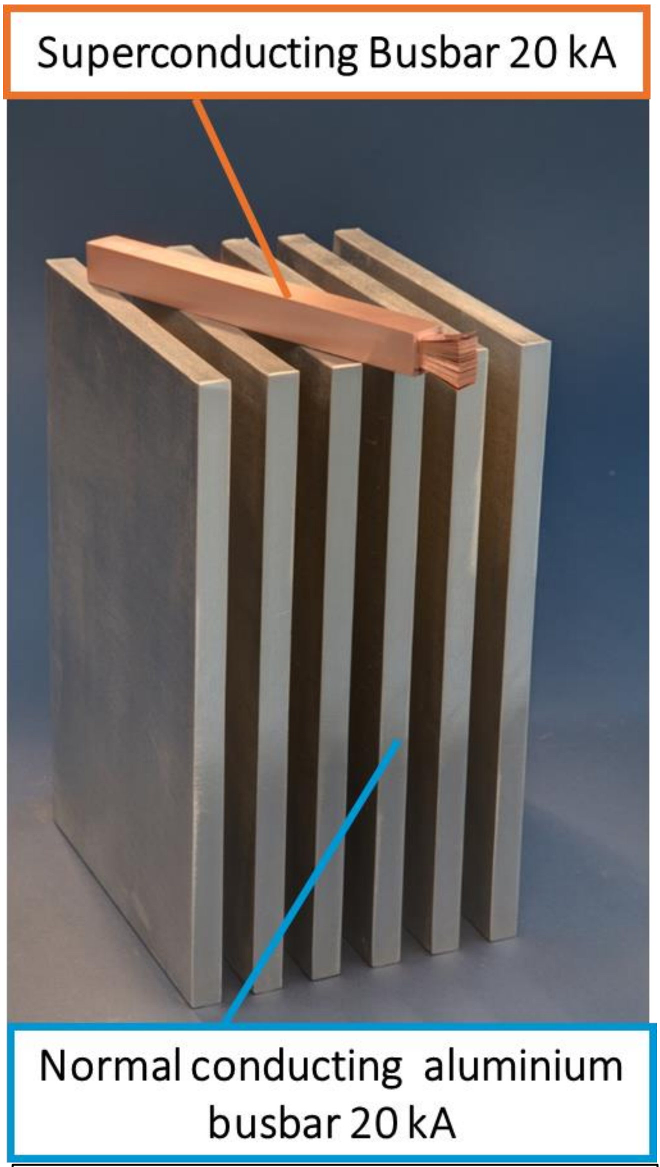

Figure 2: dimension comparison between aluminium and superconductors with a current capacity of 20 kA

Superconductors offer benefits

In many areas of energy intensive industries, high currents are used to produce a wide variety of metals. These high currents are conducted by busbars, cables and overhead transmission lines made of copper or aluminium. However, their technically operated current densities lead to large physical dimensions. Superconducting technology offers decisively more compact solutions. Even after including the refrigeration systems, the operating expense by case is up to 90 % lower than the electric losses of conventional busbars. Using HTS, the savings in material compared by its mass are between

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50 % and 90 % resulting in a decrease of materials in production and transport. This also gives the possibility to have more compact designs and the reduction of auxiliary structures that are needed for aluminium or copper busbars. Hence, superconductors have a very low environmental impact regarding its construction, operation, and recycling.

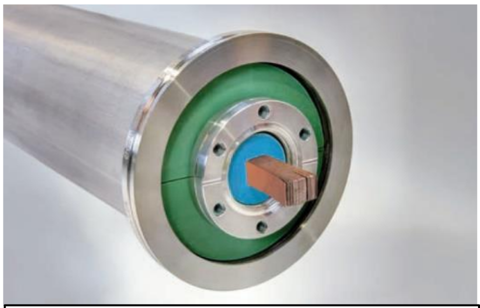

Figure 3; Superconducting module interior view

The operating window is that superconductors need to be operated at a temperature of 77 K (-196 °C) or below. During the last decades, the superconductor industry succeeded to convert the brittle superconducting material into flexible and maintainable formats that can be used for industrial applications. In the case of 3S, a demonstration system in a chlorine plant, the superconductors are encapsulated in a double-walled stainless-steel cryostat for thermal insulation.

The system mainly consists of superconducting busbar modules, the current leads to cool down the current path from the ambient temperature and a set of cooling machines. A further advantage of the modularity and encapsulation is the easy transportation and the IP68 protection, which means no fire load and the highest level of personal safety. Figure 4 shows the system operated in an industrial production plant. Refer to reference [1] for specific use cases for aluminium smelters.

Figure 4: Current lead with connected superconducting busbar

Current status of superconducting high-current DC development (3S)

3S is the first modular superconducting busbar that was installed from 2016 to 2020 in a chlorine electrolysis plant at BASF Ludwigshafen, Germany, for the demonstrating the technical feasibility of a superconducting system in a real production environment. That included the completion of the stringent safety, environment and health audit process.

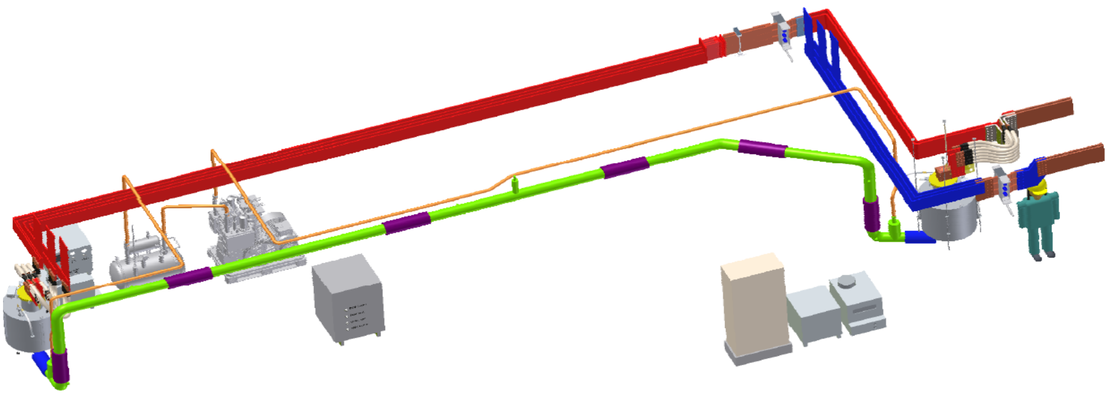

Figure 5: 3S- 20 kA Superconducting Busbar System drawing as installed in a chlorine plant to shortcut a copper busbar system (red)

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The system has a length of 25 m, a nominal current of 20 kA and an operating temperature of 70 K. 3S was funded by the German Federal Ministry for Economic Affairs and Energy and demonstrated that superconducting busbars can be used in industry for production applications providing all benefits including significant reduction of line losses, resource consumption and reducing space requirements for installation room.

Motivation and overview of the DEMO200

DEMO200 is the next step in the development of the technology. It is a demonstration project for 200 kA in an aluminium smelter based largely on the insights and experience taken from the 3S project.

DEMO200 is designed to show the advantages of superconductors to a wider range of high current applications to reduce energy costs and improve the carbon footprint at the same time. Especially aluminium smelters can gain from the benefits of superconducting technologies due to its concept to conduct very high currents without losses in an extremely compact way. TRIMET Aluminium SE is a partner in the DEMO200 project and has identified a specific application for a 200 kA superconducting system.

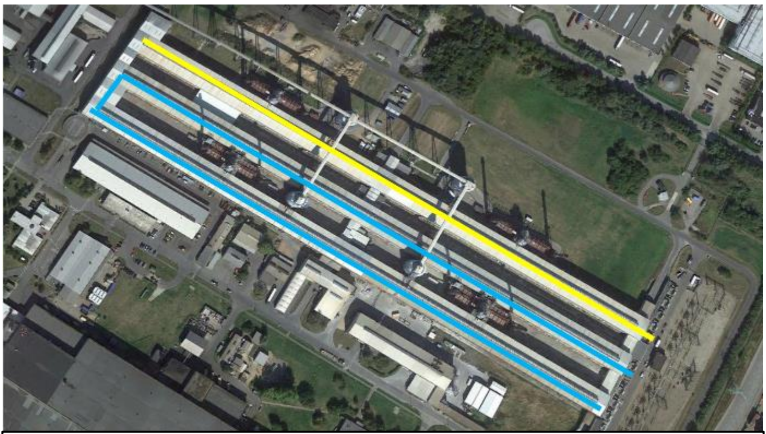

Figure 6: aluminium plant in Hamburg, view from above, yellow line is the 200 kA aluminium return bar

The aluminium plant in Hamburg has a fairly unique situation where there is an aluminium return busbar of 600 m length with a nominal current of 200 kA and a voltage drop of 12 V. Under normal circumstances this results in electric losses of 20.000 MWh per year. A superconducting busbar has the potential to reduce the electric losses by more the 90% [2].

Overview of the DEMO200 project:

To demonstrate the technology superconductor units are used of standard diameter but of shorter length.

Demonstration unit for a superconducting busbar with 200kA line current

- Length: 2-3 m
- Diameter: 30cm
- 10 modules with 20 kA in parallel
- Full scale current leads
- Operation at 70 K (subcooled LN_2)

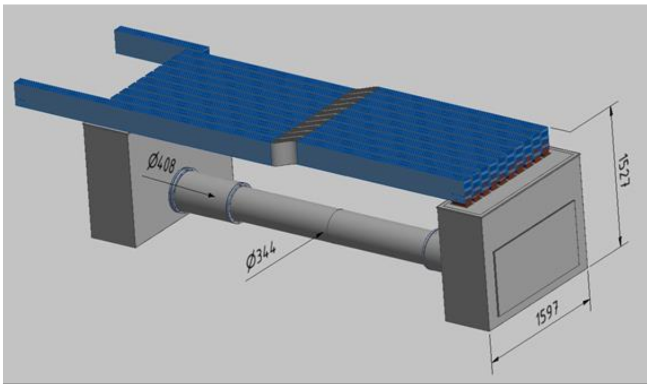

Figure 7: Demonstration Unit with 10 x 20 kA aluminium current return bars (blue)

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Partners of the project:

- Vision Electric Super Conductors GmbH for current leads, power supply, system design and the integration and operation
- Karlsruhe Institute of Technology for superconducting module design
- Messer SE for cryogenic systems

Associated partners are Theva Dünnschichttechnik GmbH for the superconducting tapes and TRIMET Aluminium SE as the host of the project. The project is funded by the Federal Ministry for[Economic Affairs and Energy of Germany.

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Design of the superconducting busbar, currents lead and connections

Geometry of the modular 200 kA busbar system for DEMO200

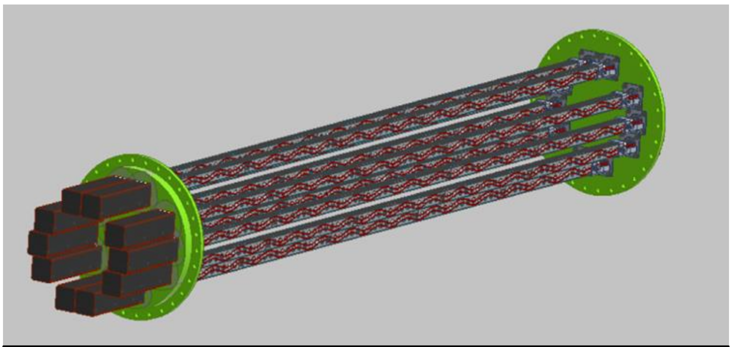

Figure 8: visualization of 20 kA busbars modules arrangement for 200 kA

The 200 kA busbar is composed of ten individual modules of 20 kA to be operated in parallel. The modules with maximum lateral dimensions are arranged in circular fashion as is shown in figure 8. This arrangement allows the horizontal access to all ten modules, which is helpful for the assembly. To test the 200 kA busbar system it is connected to 25 kA power supply that is available. The ten individual modules will be connected one by one with a package of ten aluminium current return bars as shown in figure 7. Thus the currents in the 20 kA superconducting modules are oriented into the same direction conducting 200 kA in total.

An initial subscale test of three modules at 77 K is executed prior to the assembly of the DEMO 200 busbar. The expected critical currents are calculated and confirmed by measurements of the superconducting tapes. Within the scope of the project, several module designs based on different HTS assemblies were tested and validated.

Superconducting Tape Properties

The angular and field dependence of the critical current of the REBCO tapes is a key input parameter to the self-consistent electromagnetic calculation of the critical current of the superconducting busbar system. Therefore, measurements on a 12 mm wide tape used in the subscale test was characterized at both 70 K and 77 K to obtain data at temperatures and fields relevant to the 200 kA.

The line current of 200 kA requires a large number of superconducting tapes in parallel. The optimization of this number therefore is a key focal point with respect to the economic viability of the busbar. For this was developed a simulation tool to analyze the influence of magnetic fields on different tape arrangements. The critical current of the tapes is strongly dependent on temperature and magnetic field and moreover also from the direction of the field. It was therefore important to characterize.

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Several different tape arrangements have been analyzed with this procedure. As expected, the number of required tapes decreases with increasing distance between tapes. The finally selected configuration not only takes the number of needed tapes into account but also its manufacturing aspects. Moreover, it must reflect a series connection of 10 modules. Each module is based on 4 stacks with 15 tapes each. Four stacks are disposed in a rectangular arrangement and to one module. Ten modules are arranged with their centers on a ring of 280 mm diameter. This results in a total outer diameter of 300 mm.

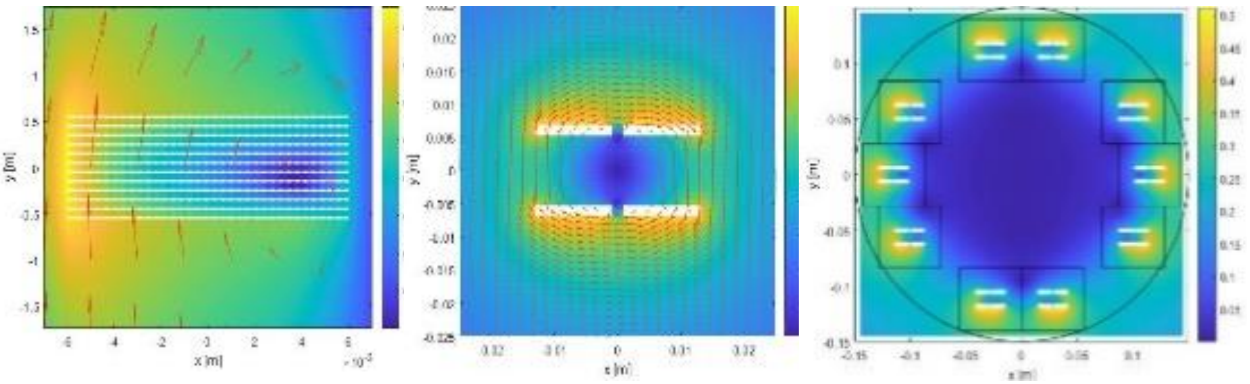

Figure 9: Arrangement of tapes in DEMO 200. Left: single stack, Middle: single module, right: all 10 modules

Superconducting Modules used in DEMO200

The busbar is a stiff structure with a given total length. The thermal contraction of the HTS-tapes when cooled down with liquid nitrogen is expected to be about 0.5%, i.e. 3 m on the target length of 600 m. In the design this contraction is taken into consideration by using a wave shape of the HTS-tapes (Fig. 10). The waves have an amplitude of about 1 cm and a wave length of about 10 cm. They are guided by lamellar steel springs to avoid local compressions.

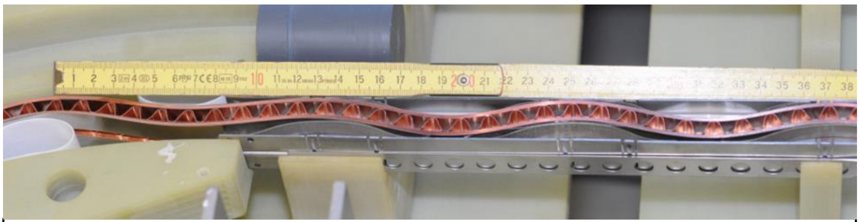

Figure 10: Wave arrangement of HTS-stacks for thermal compensation.

A key challenge of a busbar with currents of 200 kA are the large Lorentz forces, within and between modules. The compressing forces within the modules are compensated by using corrugated copper-tapes, which act as a hard spring. The forces between the modules are considered by mounting the four stacks in a stable steel structure shaped as a H-profile. The thermal contraction of this H-profile is around 0.3% and is compensated by small spring-type incisions.

The H-profile with mounted stacks is housed in a cage of steel sheet provided with holes for LN_2-access (Fig. 10, downside). Overall, the square module has a cross section of 56 mm.

Current Leads

For the connection of a superconducting busbar to copper or aluminium busbars a 200 kA current lead is needed. We designed a nitrogen gas cooled modular current lead consisting of again ten modules of 20 kA each.

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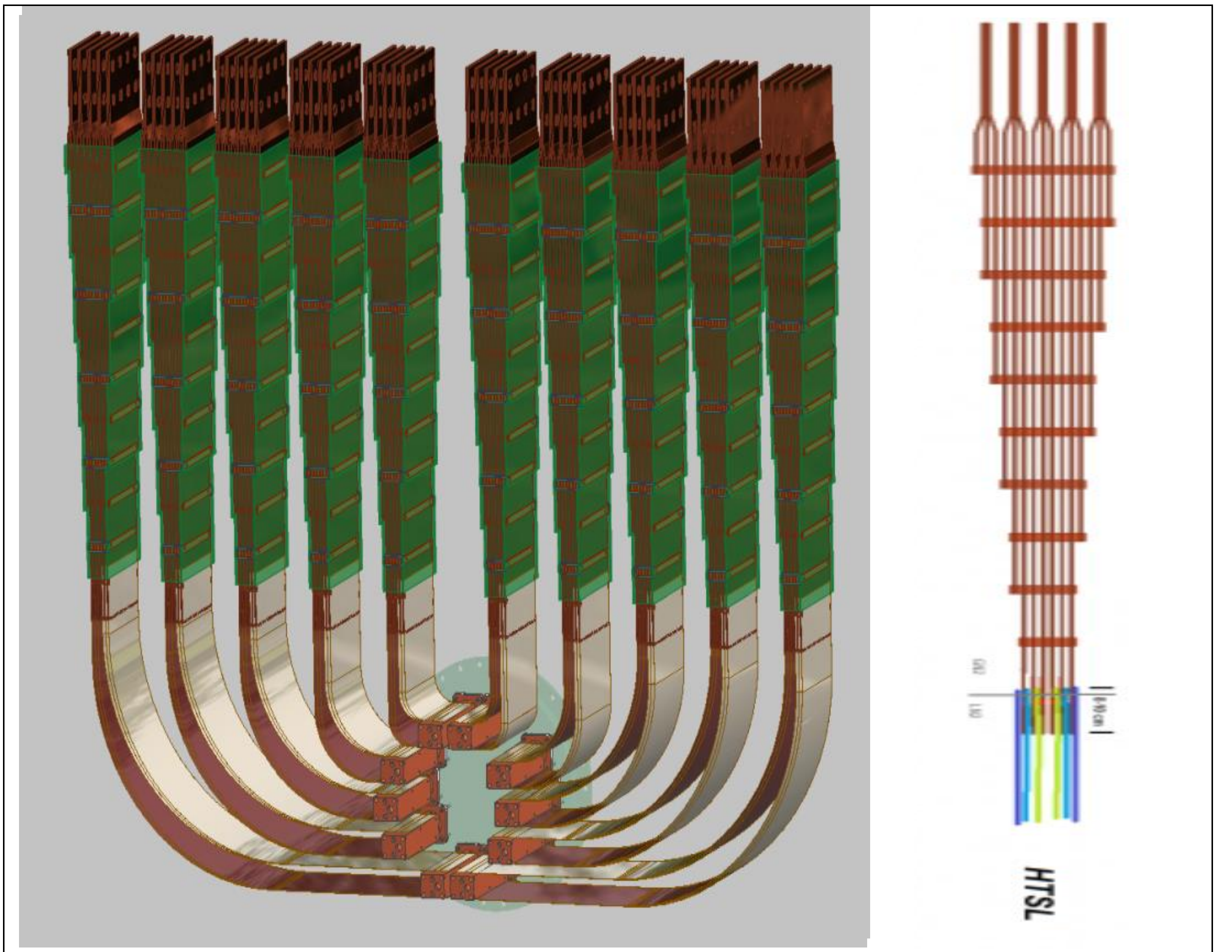

Figure 11: 200 kA Current Lead for DEMO200

Each module is housed in a reinforced plastics cage, which guides the evaporating nitrogen. The number of copper bars diminishes with depth, reflecting the resistance decrease of copper with temperature (Fig. 5). The leads of HTS-tapes are soldered on the liquid nitrogen side. Since the busbar is operated at 70 K while the current leads are at 77 K, the number of tapes of the current leads must exceed the number of tapes in the modules by a lift factor of 1.5.

Overall Design

The final design of DEMO200 comprises of 10 stable modules with quadratic cross sections that are joined in a compact ring arrangement and placed in a tube-shaped cryostat. This cryostat is cooled with an own circuit operated with subcooled liquid nitrogen at a pressure of 5 bar(a) and an entrance temperature of 68 K. The temperature of this circuit is maintained with a heat exchanger.

The front ends of the cryostat are closed with reinforced plastic discs with ten integrated copper contact blocks (Fig. 12). On one side of the copper-block, the HTS-tapes of one module are soldered, on the other side the tapes of the corresponding current lead. The copper blocks are optimized with respect to their ohmic resistance. The current leads are placed in rectangular cryostats and operated with liquid nitrogen at ambient pressure. The evaporating nitrogen yields an effective gas cooling. Figure 12 shows the overall design of DEMO200.

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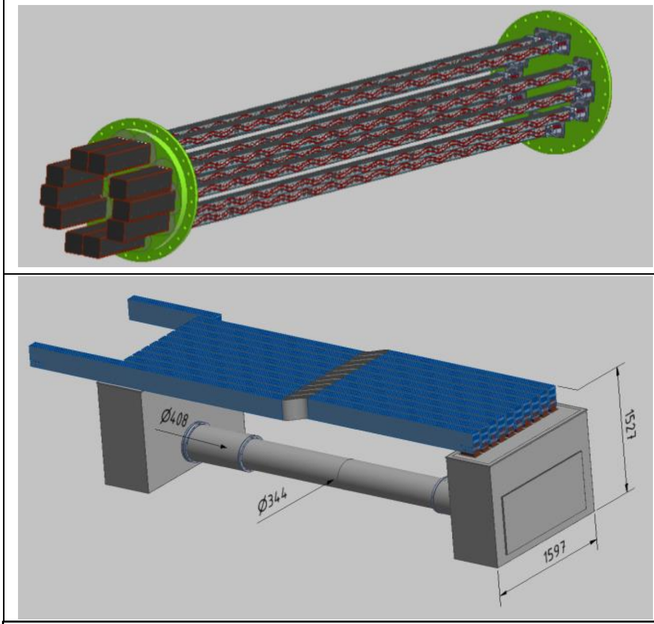

Figure 12: Overall design of DEMO200. Top: busbar with ten modules. Bottom: DEMO200 with tube cryostat, cold boxes and aluminium return bars.

Subscale Test

In a first step we installed a subscale setup with three modules for a functional test under simplified conditions. The modules are identic to the target setup. Three modules are tested.

The tests are performed at T= 77 K immersed in liquid nitrogen in an open bath cryostat. The three modules will be connected in series with return bars to create currents of magnetic fields in the same orientation. There are different aspects of DEMO200 that to be tested including a validation of the nominal current at T= 77 K. Also tested is the stability of our structure with respect to Lorentz forces under pulsed currents at T= 77 K.

Moreover, we intensively test the functionality of our length compensation. For this we use a stable structure at ambient temperature outside the cryostat. This stable structure maintains the superconducting modules at a constant length, such that contraction and dilatation during a cooling cycle is compensated by the wave shape of the HTS-stacks. Figure 13 shows the setup of the subscale experiment.

Finally, also the contacts are tested. For the subscale test the HTS-stacks are simply soldered on copper-blocks which are linked to the current source by flexible copper-braids. The soldering procedures in the subscale test and in DEMO200 are the same. In thorough pretests we achieved contact resistances of 10 nΩ per tape. The modules are integrated in a stable reinforced plastic structure (Fig. 13) with supports. All mechanical parts of the subscale-test are placed in a 5 m long bath cryostat.

Conclusions

DEMO200 is designed to demonstrate the technical feasibility of a superconducting busbar for a DC current of 200 kA like is used in aluminium smelters. All features of a real-life device are addressed to validate the functionality. With its modular structure it can easily be adapted to a wide range of currents. The project will yield a basis for a rigorous cost estimation in order to assess the economic viability of such investments. If successful, the technology can be implemented on industrial scale.

Acknowledgment

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References

[1] Reiser W., Reek T., Räch C., Kreuter D. (2021) Superconductor Busbars—High Benefits for Aluminium Plants. In: Perander L. (eds) Light Metals 2021. The Minerals, Metals & Materials Series.

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[2] Refer to the project website at www.demo200.de.

[3] S. Elschner, J. Brand, W. Goldacker et al., "3S–Superconducting DC-Busbar for High Current Applications", *IEEE Trans. Appl. Supercond*., **28** (4) 4800805 (2018).

[4] W. Reiser, T. Reek, C. Räch, D. Kreuter, "Superconductor Busbars – High benefits for Aluminum plants", in *Light Metals 2021*, Springer (Ed. L. Perander) 2021, ISBN 978-3-030-65396-5, p. 359

[5] V.R.M. Zermeno, F. Grilli, "3D modelling and simulation of 2G HTS stacks and coils", *Supercond. Sci. Technol.* **27** (4), 124013 (2014)

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