# 3S – Superconducting DC-Busbar for High Current Applications

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***Abstract*—Within a German government funded project a superconducting (HTS) high current DC-busbar is under development. The aim is the fabrication of a demonstrator with a length of 25 m and a nominal current of 20 kA for installation and test in an industrial real life application. The concept is a modular system with rigid superconducting elements of arbitrary length, straight or with defined bends, each equipped with own cryostat and premanufactured in the factory. These elements can easily be transported, but have to be joined on the installation site. To manufacture such elements several issues had to be addressed: The arrangement of the superconducting tapes was optimized with respect to minimization of the magnetic self-field effects. The thermal contraction of the busbar had to be balanced and in particular low resistance joints between the superconducting elements had to be developed. These are based on innovative comb-shaped structures with face-to-face soldered tape ends. A first prototype of such an element including two joints was built and tested at $T$=77 K up to an effective current of $I$=20 kA. With a resistance of less than $R$=0.5 nΩ the losses from the contacts are small compared to the cryostat losses.**

***Index Terms*—DC-busbar, superconducting cable, high current cables**

## I. Introduction

Superconducting DC-busbars are particularly well adapted for large current applications as electrolysis, aluminum production [1] or the energy supply of large data centers, with current demands up to 200 kA over distances of several 100 m. With normal conducting techniques the required cross sections for such currents reach 1 m² but can be reduced by more than one order of magnitude using superconducting tapes, cryogenic equipment included. The benefit of superconductors therefore is, beside vanished ohmic losses, also a substantial gain with respect to smaller size, less material weight, reduced costs and more flexibility at the installation site.

Compared to superconducting AC-cables [2] the required current capacity is at least one order of magnitude larger. In contrast to cables for magnet applications, as CORC [3], Roebel [4] or CroCo [5] the main focus of DC-busbars is not on a high engineering current density, but on the absolute current capacity. The economic aspects of cooling are a crucial point, i.e. a cooling medium aside from liquid nitrogen (LN) is hardly acceptable. Especially for very large currents I > 100 kA flexible cable-type solutions, as already successfully put into operation [6], will be difficult to handle. For such large currents, fixed, rigid bus-bar installations are an alternative option. This implies the need of short, transportable elements to be joined on site.

Within the German government funded project 3S (German acronym for SupraStromSchiene) the partners VESC, KIT and ILK have joined to develop a prototype of such a busbar on a medium scale designed for a DC current of 20 kA and a total length of 25 m. It will be installed and tested as a current connection between a rectifier and an electrolysis device at the BASF-site in Ludwigshafen, Germany. It will consist of seven elements with lengths up to 6 m, including several with a bend of 90°. The current leads linking the normal- and superconducting parts of the installation are developed in an independent project [7].

A number of experimental challenges have to be addressed: An appropriate superconducting material had to be selected. In order to reach the required current many superconducting tapes need to be connected in parallel. The arrangement of the tapes (sect. II) is a compromise between compactness, limitation of self-field effects and minimization of AC-(ripple)-losses. Since the busbar will consist of rigid elements in series we had to consider the thermal contraction of the superconducting tapes inside the cryostats. Also considerable Lorentz-forces are expected. For both we found reliable constructive solutions (sect. III). However, the key challenge of the whole project was the development of low-ohmic electric contacts between the busbar elements (sect. IV). To validate the developed concept a prototype busbar was built up and tested in an open bath cryostat at T = 77 K (sect. V). The cryogenic aspects of the project were not subject of this contribution, but a brief estimation of the expected losses is given (sect. VI).

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## II. Tapes and Tape Arrangement

The projected busbar has a nominal current of 20 kA. With a critical current of commercially available standard 2G-YBCO-tapes of e.g. $I_c$ = 500 A at T = 77 K about 40 tapes in parallel are needed, i.e. about 1000 m total tape length.

Standard material, even from different suppliers, is usable. There is no particular requirement on the length, since only piece lengths < 10 m are needed. According to industrial standards the width of the tapes is chosen as 12 mm and the critical current was specified to a minimum value of $I_c$ = 450 A at $T$ = 77 K. In fact we received material with critical currents in a wide range of 450 A < $I_c$ < 700 A. The required copper stabilization strongly depends on the maximum short circuit surges expected at the installation site. In our case these are moderate (max. 33 kA for 100 ms), therefore a stabilization of 2 x 20 µm copper is regarded as adequate to prevent a detrimental heating of the tapes. A material with a small field and angular dependence of the critical current is preferable.

Since the amount of material is the dominant cost factor we decided to operate the busbar in subcooled LN with a maximum temperature $T$ = 70 K. This enhances the critical current by a factor of about 1.8. On the other hand the self field of the cable strongly reduces the local critical current. The arrangement of the tapes should be a compromise aiming a minimization of both, the self field influence and, in opposition, the total cross section. Further, it must allow a good access of LN and must be sufficiently simple for an industrial manufacturing process.

The decision for the arrangement relied on FEM-simulations, based on the H-formulation of Maxwell's equations as described in [8]. The dependence of the critical current on the field and its direction [9] was measured for the selected material and scaled to the guaranteed critical current (single tape) of $I_c$ = 450 A (77 K) rsp. 800 A (70K). For four different tape arrangements, which all fit into a cryostat with an inner diameter of 11 cm, we calculated the number of tapes needed to transport the nominal current (Fig.1):

- one dense stack
- four dense stacks on a rectangular array
- Two stacks with 2.5 mm gap between the tapes and 40 mm gap between the stacks

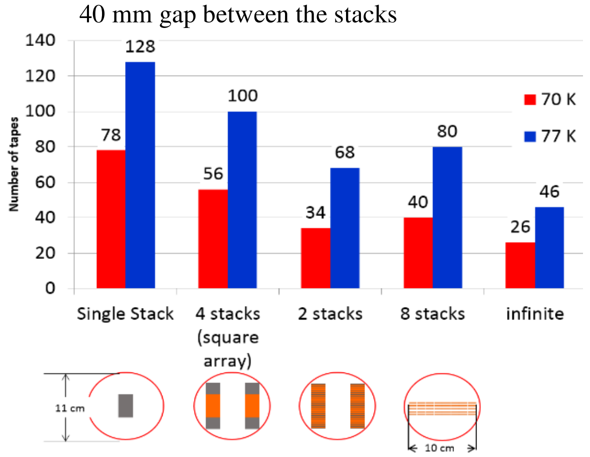


**Fig. 1:** For four different arrangements, the number of tapes needed for the total current $I$ = 20 kA was calculated by numerical (FEM) simulation (see text). Left columns: $T$ = 70 K, right columns: $T$ = 77 K.

- Eight stacks side by side with 2.5 mm gap between tapes.

For comparison, disregarding the mutual magnetic field corresponds to an infinite distance between tapes and gives a lower bound for the sought number.

As result an arrangement with two stacks, 23 tapes in each, with a distance of 2.5 mm between the tapes and 40 mm between the stacks was selected, ensuring a large security margin. The critical current of such a stack in its self field is estimated to about 8 kA if the single tapes have an $I_c$ = 450 A.

## III. Mechanical Structure

In contrast to a cable, a busbar, once installed, is locally fixed. Since the outer wall of the cryostat remains at ambient temperature, the thermal contraction of the superconductor has to be considered. Down to LN a length difference of 0.23 % (Hastelloy) is expected, i.e. 2.3 cm for a 10 m element.

Furthermore a spacer between the tapes which resists to the considerable compressive Lorentz forces but allows a good access of the LN has to be developed.

As a solution we formed the two parallel stacks to a slight wave with a pitch of about 0.5 m and an amplitude of a few mm (Fig.2). The stacks consist of 23 tapes and, as spacers, undulated copper tapes with about 1cm pitch. The wave shaped stack easily absorbs the thermal contraction differences, whereas the undulated copper tapes act as a spring compensating the compressive Lorentz forces (F/l ≤ 125 N/m) and balance the small length differences of the tapes during the cooling procedure.

This tape arrangement has the further advantage that arbitrary angles can easily be realized within the plane of the stack for the prefabricated elements. Even bends perpendicular to the stack-plane are not impossible. If these are requested, the stacks have first to be twisted along their longitudinal axis on a length of e.g. 1m, and again arbitrary angles are possible.

The attracting Lorentz force between the two parallel stacks (F/l ≤ 1250N/m) is hold by a flexible cage type structure.

**Fig. 2**: Stack of 23 superconducting tapes in wave form (overdrawn) with undulated copper tapes as distance holders.

## IV. Electrical Contacts

Since the busbar consists of static elements to be joined on the installation site, a solution for low resistance electrical contacts between the stacks of adjacent elements was a key feature of the project. A current of 20 kA at a resistance of 1 nΩ already generates a heating of 0.4 W.

It soon became obvious, that such resistances can only be achieved with face-to-face (ftf) contacts between the individual tapes of adjacent stacks. For soldered (PbSn) ftf-contacts with 5 cm overlap resistances of 10 nΩ for single tapes are reported [10] and could be reproduced in our experiments. Resistances of back-to-face or back-to-back contacts were at least one order of magnitude larger and thus were rejected.

Each stack is equipped with a comb-shaped copper contact of 75 mm length with 12 teeth (Fig. 5). The pre-tinned ends of the tapes were soldered on both sides of these teeth with their superconducting face outwards, i.e. the orientation of the tapes alternates within the stack. To join the stacks two such comb-contacts are stuck into each other with slight pressure on a length of 50 mm and soldered with PbSn-solder, thus yielding ftf-contacts. 25 mm on each contact comb at first remain free.

This concept alone is only viable if the superconducting material and the quality of the contacts are extremely homogeneous. Since the busbar consists of many elements in series, the critical current of each current path is limited by the weakest tape in the series, if only the ftf-contacts are effective. Current distribution between parallel tapes would scarcely be possible, because the tapes are soldered with their high resistive substrate side on the teeth of the contact. Therefore, we added additional copper combs (‘equalizers’) on the free 25 mm section of each contact comb (Fig. 3). The teeth of these equalizers are then in direct touch with the superconducting sides of the tapes and allow a low ohmic redistribution of current between the tapes of the stack. The resistance via equalizer (SC/solder/Cu/solder/SC) is about one order of magnitude larger than the direct ftf-contact, but acceptable, since normally only a small fraction of the current takes this path.

The undulated copper spacers might also contribute a little bit to balance the currents, however the corresponding resistance is probably too high to make it effective.

The stacks are preliminarily equipped on both ends with such a contact-comb. Their contacting and the deployment of the equalizers are done later in a single soldering procedure. For this purpose a special temperature controlled soldering device was developed which makes sure that the melting temperature (189 C) is reached everywhere, without exceeding the tolerable temperature limit avoiding tape degradation (240 C) [11]. With this equipment, a reproducible contacting procedure, appropriate for the installation on site, was provided.

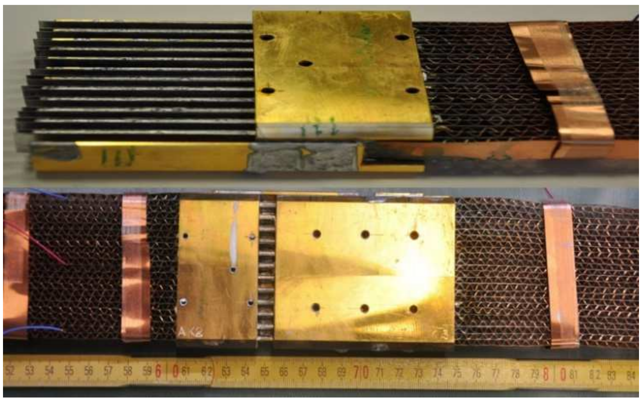

**Fig. 3.** Contacts between stacks (see text). Upper: Stack with contact-comb and equalizer. The tapes were soldered with the substrate side on the teeth of the comb. Lower: Joint between two stacks. Scales are not the same.

The contacts in their final geometry were first tested with a reduced numbers of tapes on the contacts, with open ends, such that all mutual resistances were determined independently. For the direct ftf-contacts we achieved reproducible values of 10 nΩ. Contact resistances between other tapes via the equalizers are about 150 nΩ and without equalizers in the order of 500 nΩ.

## V. Subscale Model

To validate the whole concept a lab model was built up. It already had the full size and capacity, i.e. two strands (A and B). Each strand consisted of three segments with a length of 70 cm each and 23 tapes in parallel. Both strands thus include two full scale contact joints (scheme see Fig. 4). The tapes of the outer segments also terminate on a copper comb but here with the superconducting sides soldered on the copper teeth to inject the current. These outer combs were pressed on large copper blocks, which were linked to the current source by ten 240 mm² copper braid cables. The lab model was fixed on a frp-structure and had overall a length of 2.65 m. It was placed in an open bath cryostat in LN. To have clear experimental conditions both strands are isolated with respect to each other.

Different tests were now possible: The single strands could be energized individually with a DC-current, the two strands could be connected in parallel (the situation in real life) or could be operated in series to ensure equal currents in both strands. In this last case a backwards conductor with sufficient distance to the strands has to be foreseen.

In a first step both strands (A, B) were energized and tested individually. We measured the total current, the overall voltage, and the voltages between all adjacent pairs of equalizers (Fig. 4), which gave us both, the resistances of the contact joints and the voltages along the superconducting segments.

From the graphs in Fig. 5 the resistances of the contacts can be determined. For all four contacts, the voltage taps were placed on the centers of the two equalizers on both sides of the contact. $U_{AJ2}$, $U_{AJ3}$ are the voltages along the joints of strand A, $U_{BJ2}$, $U_{BJ3}$ of strand B. At high currents the voltages increase roughly linearly with voltages of 4.2 µV and 3.9 µV for strand A and 2.2 µV and 10.7 µV for strand B at the specified current of 10 kA in one strand. This yields a heat production of at maximum 0.1 W, i.e. 0.2 W for the two strands in parallel.

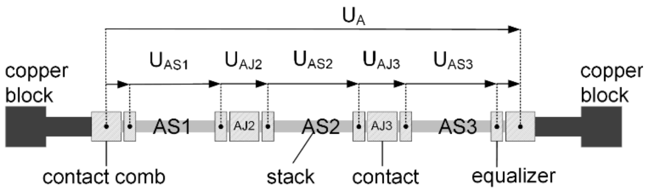


**Fig. 4**. Measuring scheme of strand A of the subscale model (strand B analogous).

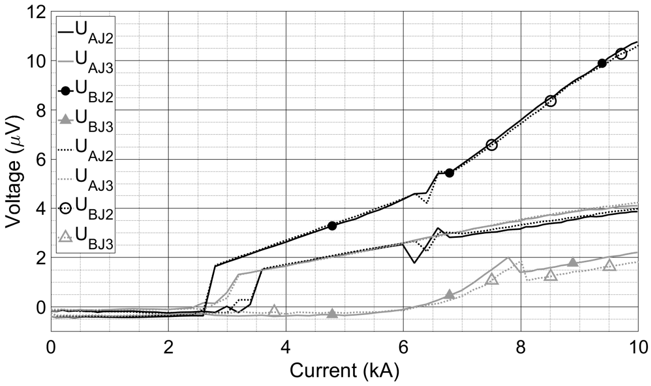


**Fig. 5.** U(I)-characteristics measured between the equalizers on both sides of the contacts ($U_{AJ2}$, $U_{AJ3}$, strand A, $U_{BJ2}$, $U_{BJ3}$, strand B). The strands are energized individually (dashed lines) and in series (straight lines).

For all four contacts we measured (Fig.5) a voltage below the detection limit (0.1 μV) at small currents, followed by a steep increase to the expected ohmic behavior. This effect is reproducible and shows no hysteresis. If the strands A and B are connected in series, the same peculiar steps are again observed (Fig. 5, straight lines). This behavior probably reflects, that the equalizers are not on a defined potential and that for small currents only the outermost tapes carry current, whereas the voltage taps are placed on the centers of the equalizers. However, to the present, these steps are not understood in detail.

Fig. 6 shows the voltages of all six segments. $U_{AS1}$, $U_{AS2}$, $U_{AS3}$ (black lines) and $U_{BS1}$, $U_{BS2}$, $U_{BS3}$ (grey) are the voltages on strands A rsp. B measured between the centers of the equalizers on both ends of the different segments (Fig. 4). The straight lines depict the voltages for the series connection. For all six segments, the series connection yields a slightly larger voltage, reflecting a small additional field effect. But obviously the magnetic field caused by the parallel strand (about 50 mT) does not cause an important reduction of the critical current.

The behavior of the six segments is not homogeneous. The segment BS1 shows a first detectable voltage at 6 kA whereas for the segment AS2 it is at 8.5 kA. We also observe for all six segments a smooth transition line. Both results reflect the large scatter in critical current of the 23 tapes connected in parallel. However, with a measuring length of 55 cm, at I = 10 kA the 1μV/cm-criterion is reached for none of the six segments.

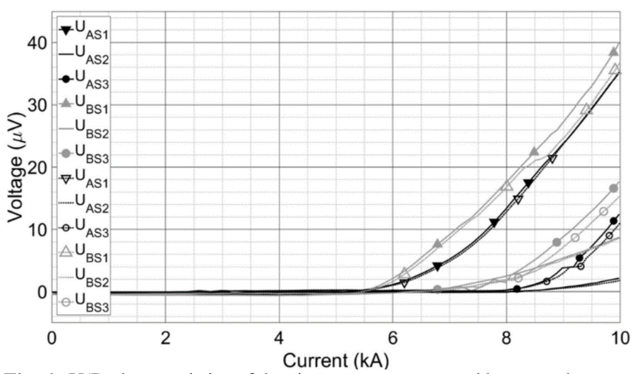


**Fig. 6.** U(I)-characteristics of the six segments measured between the equalizers at their ends (assignment of voltages see Fig.4). The strands are energized individually (dashed lines) and in series (straight lines).

These experiments have shown, that at T = 77 K a current of I = 10 kA is carried in the serial operation mode without reaching the usual 1μV/cm-criterion. This current corresponds to the projected 20 kA in the parallel connection. The contact resistance between 2-strand elements can be kept below 0.5 nΩ with the developed technology.

## VI. Cryogenic Aspects

The superconducting elements of the busbar each have their own cryostat. The cryostats are joined with welded couplings, such that the contacts are accessible for soldering. The system will operate in undercooled LN, which is pumped through the cryostat, and cooled with a pulse-tube-system in such way that the temperature nowhere exceeds 70 K. The 2-cycle-pulse-tube cryo-cooler and the highly effective cryo-pump are developed in the frame of this project by ILK, Dresden. Details of the cooling system will be published elsewhere.

The total losses of the cryostat are expected at 2 W/m. As seen above, the losses at the contacts are about 0.2 W per contact. With six contacts in the projected busbar the corresponding losses remain small compared to the cryostat losses.

Although a DC-application, AC-losses might not be negligible. Most industrial DC-applications use a DC-current with a strong ripple in the output of the rectifier. We evaluated this contribution with a numerical FEM-calculation. To this purpose we used the typical transients of the DC-current at the installation site of our busbar at BASF company. Indeed the amplitudes (pp) of the ripple are in the order of 10%, typical for industrial applications. The calculations in a 2D-model relied on a multiscale meshing [12] and also took into account the orientation and field dependence of the critical current density. The evaluation gave AC-losses in the order of 0.2 W/m, again small compared to the cryostat losses.

The main contributions to the total losses are the current leads. However, these have their own three-stage-cooling system [7] and the fraction of power reaching the 70 K-level is evaluated to be < 20 W.

In total, the heat to be removed by the cooling system remains below 100 W, easily manageable.

## VII. Conclusion

For the projected busbar all critical technical challenges are solved. Reproducible contacts below 0.5 nΩ were achieved, far better than expected, and for the mechanical issues constructive solutions could be found. The next steps include further tests of the subscale model with a larger current source (TOSKA at KIT, 30 kA). Especially a test with the two strands in parallel and short circuit tests are planned.

The distribution of the currents between the parallel tapes in the package due to inhomogeneous material properties and contact resistances was not yet investigated.

The segments of the busbar were manufactured and are actually mounted at the installation site at BASF in Ludwigshafen. The first tests with full current are planned for the next months.

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