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Busbar for the Low Aspect Ratio Device

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Abstract

The high current required to drive the toroidal field coil of Low Aspect Ratio reactor-size devices (due to the single turn design) results in difficult choices for the electrical bus. In this paper, the implications of both superconducting and resistive busbar are investigated. Special attention is given to the possibility of using a high-Tc busbar.

I   INTRODUCTION

The Low Aspect Ratio tokamak [1, 2, 3] is being seriously considered as a alternative concept. It has unique physics capabilities, but also some unique engineering requirements. One of the items that is most unique is its toroidal field coil. Due to the absence of shielding, it is necessary to avoid the use of insulation (either organic or inorganic). This results in a coil with effectively a single turn.

The use of a single-turn TF coil system raises several concerns regarding the electrical system that feeds the toroidal field system. Very high current is required at low voltage. The number of power supplies is large, due to the very high current required. Assuming that an individual power suppy can deliver 25 kA, the total number of power supplies is around 1200. This level of subdivision could be used to optimize the electrical system.

One issue that has to be addressed is the busbar. Very high currents require high cross sectional area and substantial power dissipation. In this paper, the issues of the busbar for the Low Aspect ratio are investigated, and both resistive and superconducting solutions are presented.

II   RESISTIVE BUSBAR

In this section, the implications of using a room temperature busbar for a device that requires a current of 30 MA are summarized.

For a normal conducting busbar room at any given temperature, there is a tradeoff between the size of the busbar and the dissipated power. The cross-section of the busbar can be increased (at increased initial capital expense), while at the same time decreasing the resistive power (therefore decreasing the operating expense).

The tradeoff can be evaluated using present-day costing methods. The total operating cost of the bus can be determined by calculating the present-day operating cost for a given time span in the future, and then integrating over the life of the device. This cost can then be added to the initial capital expense of the bus to get the total cost of the bus.

In this study, it is assumed that the power required for the busbar is not produced by the reactor. If the reactor makes the electricity, then the energy expenditure is a parasitic loss and the revenue losses are approximately at the rate at which the power plant sells its electricity. In any case, the cost of the electricity produced by the reactor has to be comparable to that of the electricity from other sources, and it has been assumed that the cost of the electricity is 50 mills/kWhr.

In Figure 1 and 2 the tradeoffs are shown as a function of the cross sectional area of a room temperature copper busbar. In Figure 1 it has been assumed that the copper in the busbar costs $20/kg and that the busbar is 50 m long. It has been assumed that the plant operates for 30 years with a 80% capacity and the interest rate is 5%. In Figure 2 the length of the busbar was reduced to 25 m. Very high costs are associated with the busbar and dissipated power.
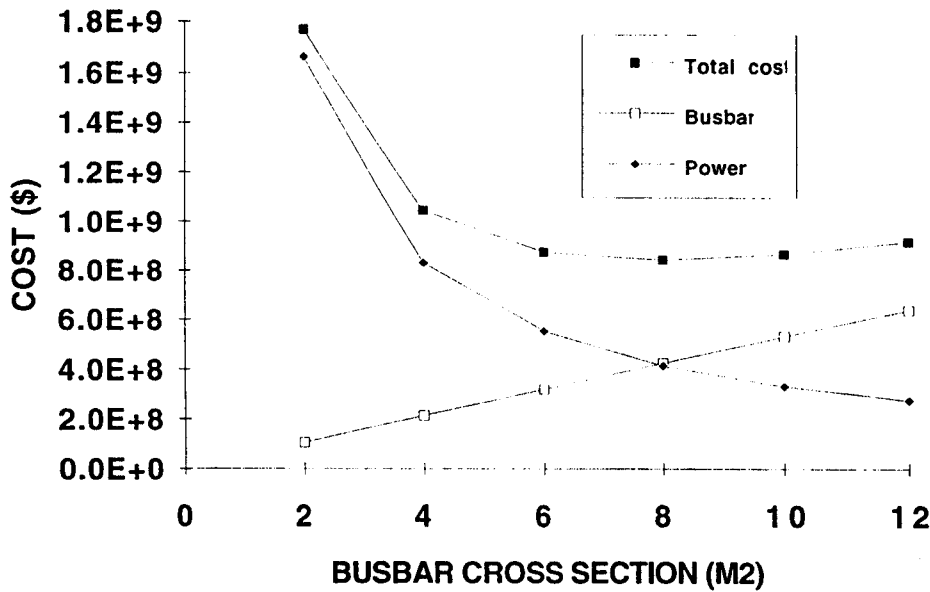
Figure 1: Amortized costs of busbar and power as a function of busbar area, for 50 m busbar, at 50mills/kWhr, 5% interest, and $20/kg copper bar

Due to the nature of the optimization, with one cost (the initial capital cost of the busbar) scaling linearly with the cross-sectional area, and the other cost (the present-day value of the cost of the electricity) scaling linearly inversely with the cross-sectional area, it is simple to demonstrate that the minimum occurs when the two costs are equal. That is, the minimum occurs when the capital cost of the busbar is the same as the cost of the electricity. However, the optimum is quite shallow for values larger than the optimal cross-sectional area. It is, however, sensitive for values of the cross sectional area smaller than the optimum.

The costs associated with the busbar are very large, comparable to the capital cost of the entire plant. The cross-sectional areas are also very large, on the order of 8 m^2 for the entire cross-sectional area of the busbar. The busbar does not have to be in a single section, however. Multiple busbars are actually preferable, in order to match the large number of individual power supplies.

Means of decreasing the cost and the size of the reactor are analyzed in the following sections.

III CRYOGENIC BUSBAR

The conductivity of electrical conductors experiences substantial improvement with decreasing temperature. However, the decrease in dissipated power that accompanies an increase in conductivity needs to be balanced by the increased power in the cooling system, since the conductors require cooling below room temperature. For example, for copper the decrease in resistivity from room temperature to 77 K (liquid nitrogen temperature) is about a factor of 7, which is more or less balanced by a 6 fold increase in total power consumption due to refrigeration efficiencies at 77K. At even lower temperatures, even though the overall balance
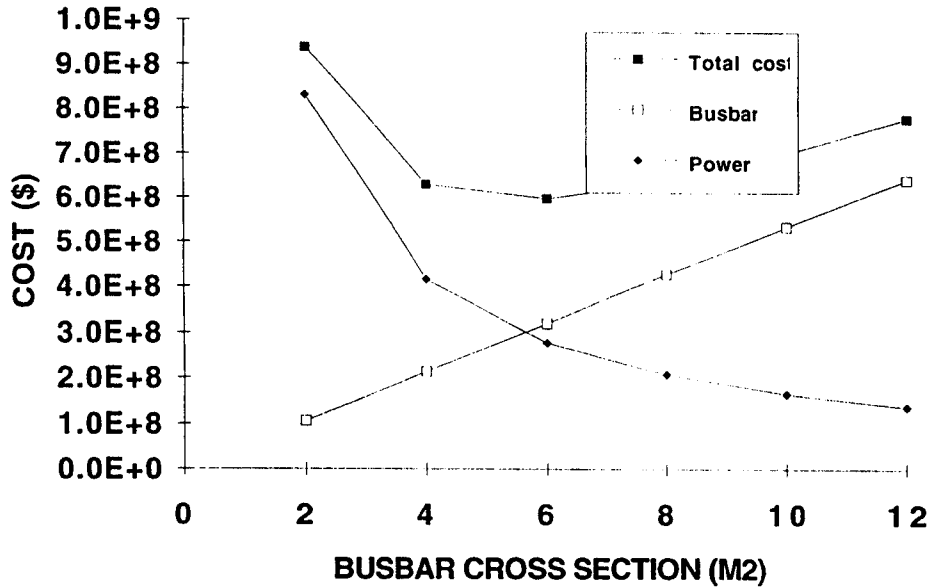
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Figure 2: Amortized costs of busbar and power as a function of busbar area, but for 25 m long busbar.

improves, it does so at the expense of increased complexity of the system.

These advantages are lost in the design of magnet system due to the substantial magnetoresistivity of most materials. However, for busbars with small magnetic fields, it is possible to obtain substantial decrements in total power consumption (ohmic dissipation and cryogenic cooling power) by decreasing the temperature of operation of the busbar, as long as the busbar is broken into a large number of current leads and each lead is placed next to leads with opposite currents, in order to decrease the value of the magnetic field generated by the leads. A large number of concentric leads, of course, satisfies the latter requirement. The largest gains are obtained at neon temperatures with the use of high purity aluminum.

However, as shown in the next section, it is possible to use superconducting busbars at liquid-nitrogen temperatures.

IV HIGH-TC SUPERCONDUCTIVITY

The high-Tc class of superconductors offers many operational and fundamental advantages over low temperature superconductors. The current carrying capability of polycrystalline $Bi_2Sr_2CaCu_2O_x$ (BSCCO) in applied magnetic fields at 20K and below, or at 77 K at small fields, make this the material of choice for many potential bulk applications of high-Tc materials. Operation at high temperatures reduces the complexity of the cryogenic system, providing greater efficiency and reliability over low-temperature superconductors [6].

However, the high-temperature superconductors are ceramic based, and are therefore brittle. It has been suggested that the the problem of brittle material could be solved by fabricating the material in the final form. Bulk materials have been manufactured in large sizes. These materials are either single crystal or multiple crystal, with currents flowing across the grains. In particular, BSCCO 2212 has shown good characteristics at low temperatures and high fields,

and at high temperatures and relatively low fields. This material shows good intergrain current transfer even though the intragrain current density is smaller than that for the YBCO materials. The 2212 material is being fabricated for current leads in superconducting magnets as well as current interrupters [10,11,12] and other applications. The YBCO material has also been used in current leads for both SMES [13] and superconducting magnets [14].

A picture of currently available current leads is shown in Figure 3. The bulk material leads are manufactured in the shape of a hollow cylinder which is a very useful approach since the peak magnetic field is lower than that which would occur in a solid rod with the same cross-sectional area. Also, for coaxial leads it would be necessary that at least one of the leads be hollow.
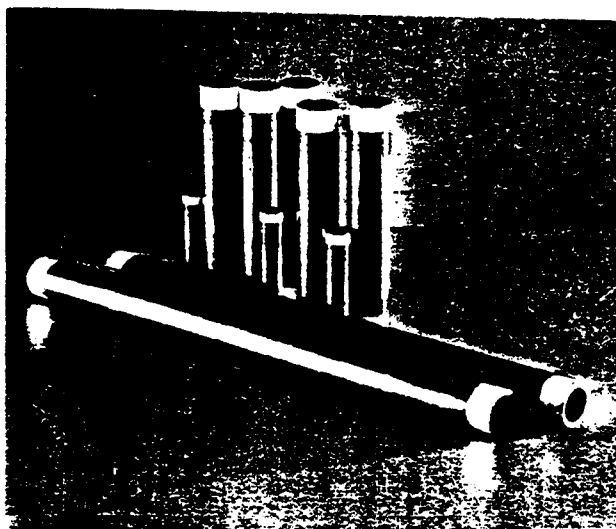

Figure 3: Current lead developed by Hoechst

The advantages of manufacturing superconducting leads using this technique are:
(1) The problems associated with using brittle ceramic superconductors in manufacturing are minimized with this approach, since the superconductor is fabricated in its final shape, requiring little winding or machining.
(2) The superconductor is rigidly held.
(3) Operation at higher temperature ($\leq$ 20 K) offers higher superconductor stability. The temperature and energy margins can be substantially increased with high temperature (20 K) operation with high-Tc materials, as opposed to low temperature superconductors.
(4) The superconducting sections can be individually tested, simplifying the assembly and testing of the busbar.

High-Tc materials can be used to construct efficient, light-weight, low-cost (due to the simplicity of making the winding), compact busbars. The busbar will be considerably lighter and more compact than a comparable room temperature system.
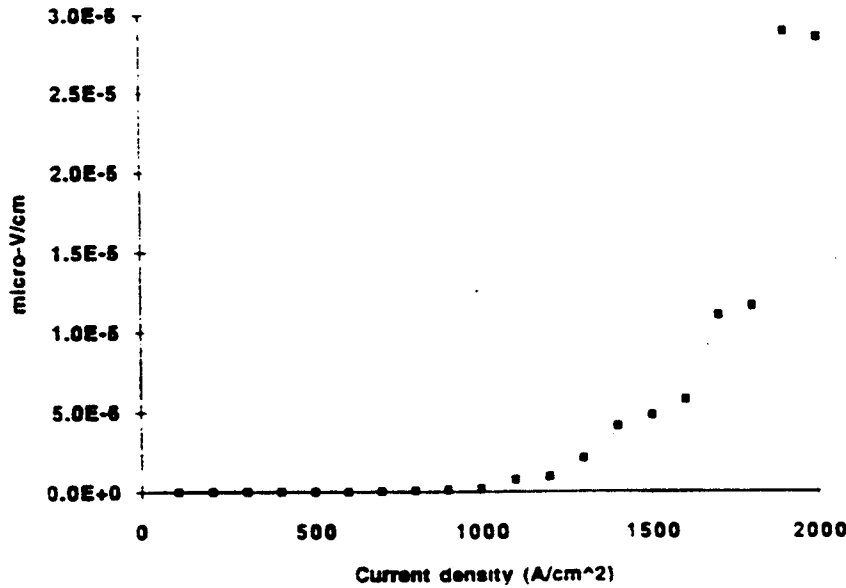
Figure 4: Electric field of high-Tc Superconductor vs current.

V   HIGH-TC SUPERCONDUCTING BUSBAR

Work in progress at MIT with Hoechst, Los Alamos, American Superconductor with Pirelli, and others, indicates that superconducting current leads and transmission lines can be manufactured to operate at 77 K (liquid nitrogen) . A collaboration between MIT and Hoechst in Frankfurth, Germany, has tested superconductors that, at 68 K, can carry up to 16 kA at a current density of 1.5 kA/cm^2 (at self-field). Figure 4 shows the voltage per unit length of a 75-mm outer diameter (OD) hollow cylinders (5 mm thick), tested at 68 K (obtained by pumping on liquid nitrogen). The maximum current of 20 kA is due to power supply limitations.

Due to the higher operating temperature, it is possible to operate at much larger values of the electric field than other low temperature superconductors. Usually, the superconductivity threshold is set to be $0.1 - 1$ μV/cm. However, in this application it is possible to operate with substantially larger electric fields.

If the conductor is carrying a current density of 1500 A/cm^2, and the resulting electric field in the superconductor is about 4 μ/cm, the volumetric dissipation in the conductor is about 6 W/cm^2. For carryring a total of 30 MA over a length of 50 m, the volume of the superconducting bar is about 100 m^3. This corresponds to a total dissipated power in the superconductor of 600 kW, or about 4.2 MW at room temperature.

A. Joints

Hoechst has developed reliable metallurgical bonds between the high-temperature superconductor and the silver contacts. Figure 5 shows a schematic diagram of the analyzed joint.

The resistive losses of the silver/superconductor joints of the sample used above for the current measurements, was determined to be less than 0.4 mW. The specific, resisitive loss of the joints is about 12 mWcm^2. For the current leads that are being discussed, a joint area of
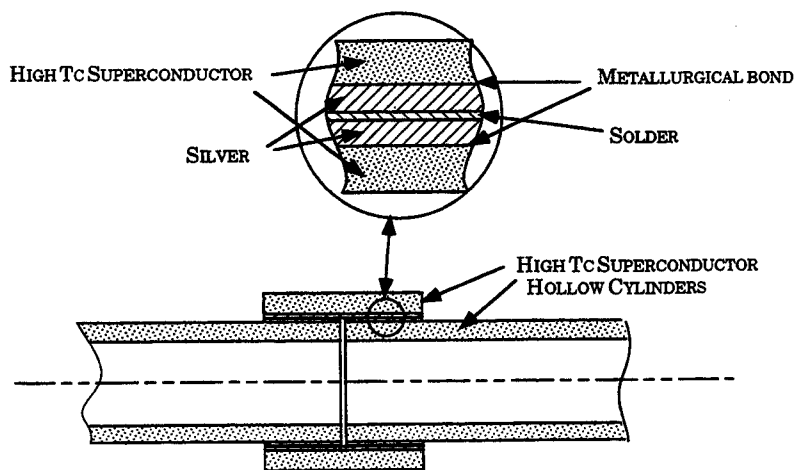
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Figure 5: Schematic diagram of a joint, showing metallurgical and solder bonds.

about 100 cm^2 is feasible by making the conducting region 5 cm long.

A 50-m busbar dissipates less than 1 kW in the joints, and would require a refrigerator of about 10 kW.

VI DISCUSSION

In order to span the distance between the power supply and the nuclear island, several of these cylinders can be connected in series. Currently, the superconducting leads are being investigated as a means of carrying the current from the generator to the transformer in present-day power stations.

Also, in order to minimize self-field, conductors with opposite currents need to be placed near each other. The case that was studied used concentric hollow cylinders, with the magnetic fields exclusively in the region between the tubes. The space between the tubes is used for coolant. If not cooled, the evaporation of liquid nitrogen was determined to be several liters per hour of operation. The overall size of the busbar, even with the gaps for liquid nitrogen, is much smaller than that for normal conducting busbars. Also, the power dissipation is virtually eliminated.

The extrapolated cost of the high-temperature superconductor current leads (hollow cylinders) is $500 for a tube that is 0.4 m long (based on the cost of the superconducting material and the silver required, and the limited processing required). The low-aspect-ratio tokamak strawman requires about 30 MA, and with 25 kA busbar current, 1,200 current lead pairs are needed. The large number of current lead pairs is also necessary in order to minimize the self-field of the busbar. In very large scale manufacturing, it is estimated that the cost of the

leads would decrease by a factor of 2.5 (to 40% of the cost, or $500/m).

The cost of the busbar is on the order of $1.2 M/m, if 0.4 m long sections are used, or $60 M for a 50-m busbar length. These tubes are commercially available now.

In collaboration with Hoechst it has been determined that the hollow cylinders of 2212 BSCCO can be built with lengths on the order of 8 m (30 ft) for about four times the unit price of the 0.4-m lead (the bulk of the cost being the setup/testing time). If 8-m tubes can be manufactured, then the cost of the 50 m busbar is $12M.

VII Conclusions

The LAR busbar could be fabricated using bulk high-Tc material. This process avoids the problems associated with using brittle ceramic materials (for winding applications, for example) because the superconductor is created in its final shape, requiring little winding or machining, and addresses the power dissipation in the busbar system for reactor-size LAR's. Samples with the required properties and dimensions are commercially available today.

ACKNOWLEDGEMENTS

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