Conceptual Design of a 20-kA Current Lead Using Forced-Flow Cooling and Ag-Alloy-Sheathed Bi-2223 High-Temperature Superconductors*

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Abstract— High-temperature superconductors (HTSs), consisting of Bi-2223 HTS tapes sheathed with Ag alloys are proposed for a 20-kA current lead for the planned stellarator WENDELSTEIN 7-X. Forced-flow He cooling is used, and 4-K He cooling of the whole lead as well as 60-K He cooling of the copper part of the lead, is discussed. Power consumption and behavior in case of loss of He flow are given.

I. INTRODUCTION

Usually, a heat sink at a temperature of about 77 K is employed at the transition region between the HTS and the copper part of a current lead. Either a liquid nitrogen (LN) bath or He gas at high pressure lead to a reduction in refrigeration power with respect to a conventional lead [1], [2]. Several prototype HTS leads that used either bulk YBCO or Bi-2212 and were of the 1- to 2-kA class have been designed and tested [3]-[7]. To obtain a higher current density in moderate magnetic fields and to improve thermal stability of the lead, it was suggested [8]-[11] to use Bi-2223 or Bi-2212 that has been electrically and mechanically stabilized by a Ag or Ag-alloy sheath. We use Bi-2223 sheathed with Ag 3 at.% Au alloy in the conceptual design of a 20-kA current lead cooled with forced-flow He. The current of 20 kA has been chosen to make a design feasible for the application to the planned stellarator WENDELSTEIN 7-X [12].

II. CONCEPTUAL DESIGN

There are two versions of the lead, as shown in Fig. 1. In version 1, the lead is cooled by 4-K He at high pressure, whereas in version 2, the copper part of the lead is cooled by 60-K He, and the HTS part is conduction cooled.

The design of the heat exchanger is similar to that of the combined Cu and Nb₃Sn current lead [13], i.e. a central conductor made of phosphorous-deoxidized Cu carries the current and is surrounded by perforated Cu plates that are brazed onto the Cu rod. The inner diameter of the plates must be as large as the largest radial extension of the HTS part, because no clamping or screwing should be made in the transition region between the Cu and the HTS part. This results in a diameter of the conductor of 60 mm. The conductor diameter of the current lead proposed for WENDELSTEIN 7-X (see [14]) is 55 mm.

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Fig. 1. Sketch of HTS current lead.

The superconducting coil will be clamped to a conductor made of electrolytic toughed Cu (E-Cu). The clamp contact has a length of 300 mm, which would result in an electrical resistance of about 25 nΩ. Equipping the E-Cu with a Nb₃Sn insert, as has been done for the POLO lead [15], should reduce this resistance to about 2 nΩ. The connection between the HTS part and the heat exchanger will also be made of E-Cu and will be friction-welded to the phosphorous-deoxidized Cu conductor of the heat exchanger.

The HTS part consists a rigid assembly of 28 modules of Bi-2223 tapes, as shown in Fig. 1. Each tape has a cross section of 8 mm x 0.3 mm, the HTS fraction is 0.65, the stabilizer is made of Ag with 3 at.% Au to reduce the thermal conductivity as proposed in [8]-[10]. 27 tapes are stacked to form a "module". The length of the module is determined during the optimization of the whole lead, together with the length of the heat exchanger. Sockets made of the same Ag-alloy will be rolled onto the ends, and the module will be heat treated. The final module cross-sectional is 8.2 mm x 8.2 mm. A stainless sheet surrounds the entire assembly.

The self field of the HTS part has been calculated by using the computer code EFFI [16]. At 20 kA, the

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maximum magnetic field is 0.25 T, consisting of a self field of 0.16 T with an additional background magnetic field of about 0.09 T from the coil. Following [17], the modules have been aligned to orient the applied magnetic field more parallel to the tape surface. In the calculations, it was assumed that the magnetic field is an average of the field parallel and perpendicular to the surface. The critical current is roughly a factor of two higher than the operation current.

The connections of the HTS part to the heat exchanger and the clamp contact to the coil will be soft soldered because neither welding nor brazing is allowed due to their high temperature, and space restrictions prohibit use of clamping. First grooves will be cut in the Cu of the connection part which must fit the lateral dimension of the HTS part. Then, the HTS rods will be soldered in the grooves. Electrical resistances for the soldered connection of 2.5 n Ω at 4 K and 15 n Ω at 77 K should be possible and are used in the calculations. Figure 2 shows a vertical cut through the HTS part including the connection regions.

Fig. 2. Vertical cut through the HTS part, including connection regions. Dimensions, given in mm, are those used in the calculations and do not represent an engineering design.

Each of the two cooling concepts requires a different length for the heat exchanger and arrangement of cooling inlet. With 4-K He cooling, the inlet will be at the connection region pointing towards the coil. In Fig. 1, the inlet is marked with "version 1". With 60-K He cooling, the inlet will be either at the connection region between HTS and Cu part (marked with "version 2"), or from the coil side. The first possibility requires radial access from the outside, and one has to penetrate the insulation vacuum. The second possibility requires a thermally insulated pipe entering the lead at the connection region between the lead and the coil and bypassing the HTS part. In both cases, there must be a vacuum-tight plate just above the HTS part because the space around this part should be in vacuum.

III. CALCULATION RESULTS

A. General

The calculations were done by means of the computer code CURLEAD [18], [19]. The temperature at the coil end was fixed to 5 K, the warm end with Neumann condition $dT/dx=0$ was 295 K, the corresponding He temperature was 290 K. In both versions, the current lead was optimized, according to [7], by adjusting the length of the Cu heat exchanger and the HTS part for a maximum current of 20 kA. For currents < 20 kA, there is a positive temperature gradient at the warm end, resulting in heat flowing towards the lead, (i.e. the lead is too short). This leads to a mass flow rate that is higher than for an optimized lead at that current. The heat load at the connection region between the HTS part and the superconducting coil is the sum of the thermal conduction from the HTS part and the resistive heat of the contact. Therefore heat load at this location depends on the current. The heat load at the connection region between the HTS part and the Cu heat exchanger is the sum between the thermal conduction from the Cu heat exchanger and the resistive heat of the connection. Therefore it also depends on current. Due to the temperature difference between the conductor and the He at the lower end of the Cu heat exchanger, the heat load at that location can be partly transferred to the coolant and not conducted to the 4-K level of the lead.

B. 4-K Helium Cooling

For a He inlet temperature at 4.5 K, optimization results in $L_{Cu} = 0.50$ m, $L_{HTS} = 0.66$ m, $L_{total} = 1.80$ m (incl. ends), and the He mass flow rate is 0.69 g/s. The upper end of the HTS part was 66 K. Due to poor cooling of the HTS part of the lead, the largest temperature difference between the current carrying part and the coolant was about 60 K, located at the upper end of the HTS part. The temperature at the upper end of the HTS part is not fixed.

As an example for the 20-kA run: A heat of about 325 W is conducted from the Cu heat exchanger, only 12.6 W are transferred to the HTS part of the lead, the main part (about 95%) is taken by the He at the lower part of the Cu heat exchanger. At the HTS part, a heat transfer coefficient of about 3.5 W/m²K has been obtained; a cooled perimeter of 0.18 m leads to a heat transfer of 0.63 W/mK times 60 K = 37.8 W/m. This must be compared to a resistive heat of 5.3 W plus a thermal conduction load of 7.3 W, for a total of 12.6 W, i.e., for a constant temperature difference of 60 K, one needs a length of 30 cm to transfer the heat to the helium. In fact, the temperature difference decreases, and one needs a longer length. In this example, 3.3 W of the 12.6 W are conducted towards the superconducting coil because there is a balance between heat transfer and heat conduction due to the temperature gradient along the HTS part of the lead.

C. 60-K Helium Cooling

The procedure is the same as for the 4-K He cooling, except the He inlet temperature was 60 K, resulting in $L_{Cu} = 1.35$ m, $L_{HTS} = 0.66$ m, $L_{total} = 2.65$ m (incl. ends), and the He mass flow rate is 2.35 g/s. The upper end of the HTS

part was at 70 K. In Fig. 4, the conductor temperature along the current lead is plotted for different currents.

As an example for the 20-kA run: heat of about 44 W is conducted from the Cu heat exchanger, only 0.5 W are transferred to the HTS part of the lead, the main part (i.e. about 99%) is taken by the He at the lower part of the Cu heat exchanger. At the connection area, there is a resistive heat of 6.1 W plus a thermal conduction load of 0.5 W adding up to 6.6 W, (i.e. these 6.6 W are conducted towards the 4-K level).

D. Refrigerator Power Consumptions

Reduction of refrigerator power consumption is the main reason for introducing the HTS into the current lead design. One must distinguish between recooling and refrigeration. Power to cool a lead is related to recooling, whereas power to cool a coil is related to refrigeration. For the calculation of the consumptions, the following relations have been used:

Recooling

$$4.5 \text{ K: } P_w = \dot{m} T_0 \Delta S - \Delta H = \dot{m} 6886 \text{ J/g}$$

$$60 \text{ K: } P_w = \dot{m} T_0 \Delta S - \Delta H = \dot{m} 1343 \text{ J/g}$$

where P_w = power consumption at room temperature (293 K), $\dot{m}$ = mass flow rate, T_0 = Lower temperature, i.e., 4.5 K resp. 60 K, ΔS = entropy difference between 293 K and T_0 , and ΔH = enthalpy difference between 293 K and T_0 .

Refrigeration

$$4.5 \text{ K: } P_w = 352 \text{ W/W } P_c$$

where P_c = power consumption at 4.5 K. The individual P_w is divided by the electrical refrigerator efficiency. For a 4-K refrigerator, an efficiency factor 0.2 has been used whereas for a 60-K refrigerator, a factor 0.3 has been assumed. Using these numbers, the power consumptions for the HTS

lead with 4-K and 60-K He cooling has been computed, as well as the numbers for the combined lead. The results are shown in Fig. 3. The main results are:

1. The recooling power for the HTS lead is strongly reduced in case of the 60-K He cooling. This is due to the higher efficiency.
2. The refrigeration power for the HTS lead is larger than for the combined lead, although a contact resistance of 6 nΩ was used in the calculations (see [14]). The reason is that the heat conduction is negligible for currents larger than zero because of the Nb₃Sn-insert.
3. Compared with a conventional lead, the 60-K He-cooling concept has the largest reduction in refrigeration power. The percentage reduction is essentially independent of current.

E. Effect of Contact Resistance

If the contact resistance at the 60-K level increases by one order of magnitude, at 20 kA the temperature at the lower end of the HTS part increases to 8 K and the heat conducted from the heat exchanger changes sign. This means that the heat exchanger takes most of the heat generated at the contact. The rest is conducted to the 4-K level via the HTS. The temperature at the warm end of the lead also increases because the He temperature also increases. The heat generated at the 4-K level doesn't change the heat conducted from the 60-K level via the HTS but increases the heat load. This result is, of course, the same as for a conventional lead. The resistance at the 4-K level should be kept as small as possible, whereas the resistance at the 60-K level affects mainly the temperature at that location because of the heat exchanger effect.

F. Effect of Higher Temperature of HTS Part

For the 60-K He cooling, the effect of a higher temperature at the upper end of the HTS part has been studied for a current of 20 kA and different temperatures $T_{\text{HTS, top}}$. The length and the mass flow rate of the heat exchanger has been optimized. The main result is that an increase of the temperature of the upper end of the HTS part reduces the recooling rate but enlarges the losses at the 4-K level. To reduce the 4-K heat load, the length of the HTS part was enlarged which results in a decrease of the 4-K heat load. An increase of $T_{\text{HTS, top}}$ leads to a decrease of the temperature margin and reduces the stability of the lead.

IV. TRANSIENT BEHAVIOR FOR LOSS OF HELIUM FLOW

The behaviour of the lead in case of loss of coolant flow was studied numerically for both cooling concepts. Starting from the steady-state solution of the current lead at 20 kA, the helium mass flow was set to zero, and the temperature profiles were computed as a function of time. In case of HTS, the critical temperature was set to 150°C, because the connection between the HTS and the Cu parts were made by soft soldering. The time to reach this temperature is called the "time-of-danger". Figure 4 shows the the temperature distributions of the lead for the 60-K He cooling concept. The results show a different behavior than that for a lead where the HTS part consists of bulk superconductor [7]:

Fig. 3. Total power consumptions for the HTS leads and the combined leads at different currents.

1. The time-of-danger, is much larger, i.e. in our case it is more than 5 minutes. For a rough design using bulk HTS, even with a lower current density of 2.9 A/mm^2 , the burn-out time, i.e. the time to reach 700 K, was only about 1 minute.

2. There is no hot-spot as for bulk HTS, although there exists a peak region in the HTS part of the lead. This is indeed a substantial difference from a combined Cu lead and results from the lower thermal conductivity and the higher electrical resistivity of the HTS.

Fig. 4. Temperature profiles of HTS lead at 20 kA at various times after switching off helium mass flow (60-K He cooling).

3. The broadening of the high-temperature region results in an increase of the temperature of the connection area at the coil side after 4 minutes (60-K He cooling - version 2) resp. 5 minutes (4-K He cooling - version 1). This also indicates the thermally stabilizing effect of the Ag-alloy. There is an interplay between the amount of temperature increase in the HTS part and at the coil side. There seem to be two extreme cases: the Cu lead with no hot-spot region and the bulk HTS lead with no increase of 4-K heat load.

4. When the mass flow stops, there are several minutes before either the "time-of-danger" is reached or the temperature at the bottom of the lead begins to rise. Thus, there is ample time to de-energize most magnets before the lead is damaged and before the magnet quenches.

V. CONCLUSIONS

A conceptual design of a 20-kA current lead consists of a HTS part and a Cu heat exchanger. The HTS part is build up of Bi-2223 tapes stabilized with Ag-alloy sheaths to achieve higher critical current density in applied medium magnetic fields.

If both recooling and refrigeration power are considered, the 4-K He cooling reduces the power consumption to 70%, whereas the 60-K He cooling reduces it to 36%. For the 60-K He cooling, the critical contact resistance is at the 4-K level because it directly changes the heat load and therefore

the refrigeration rate. The resistance at the 60-K-level has a minor effect.

For the 60-K He cooling, an increase of $T_{\text{HTS,top}}$ leads to a decrease of the mass flow rate and therefore of the recooling rate. To get no increase of the heat load at the 4-K level, the length of the HTS part has to be increased. The temperature margin is reduced if $T_{\text{HTS,top}}$ increases, which may affect the thermal stability of the lead.

In case of loss of mass flow, the danger of creating a hot-spot in the HTS part is reduced and the time to reach the critical melting temperature is increased. Here we obtained a time of more than 4 minutes after interruption of mass flow. This is ample time to deenergize most magnets before the lead is damaged and before the magnet quenches.

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