Status of the High Temperature Superconductor Current Lead Development at the Research Centre Karlsruhe

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***Abstract* – The paper describes the status of the high temperature (HTS) current lead development at the Research Centre Karlsruhe (Forschungszentrum Karlsruhe, FZK). After a brief summary of the results for the 70 kA ITER HTS current lead demonstrator, present projects are described: the HTS current leads for the stellarator Wendelstein 7-X, and those for the satellite tokamak JT60-SA.**

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I. INTRODUCTION

The reduction of static heat load in large superconducting magnet systems is of great importance to reduce the necessary refrigeration power which saves capital investment and operational costs. The components that significantly contribute to the heat load are the current leads. In the last decade, the use of high temperature superconductor (HTS) current leads has been investigated by many groups. The reason for using HTS is their capability of carrying an electrical current below a critical temperature without any resistive loss while the thermal heat load is reduced due to the low thermal conductivity of the HTS material. This behaviour results in a drastic reduction of the thermal load towards the low temperature level by about one order of magnitude. On the other hand, the low thermal conductivity causes problems in case of a quench of the superconductor, because the generated heat can not be distributed fast enough leading to hot spots and finally to destruction of the material. Consequently, for safe operation the presence of a normal conducting material which can carry the current during a quench is mandatory. As this will again increase the thermal load one has to choose such material to have a moderate thermal conductivity, *e.g.*, an Ag-alloy. As a result of investigations of many groups, the most promising candidate found are Bi-2223 tapes sheathed with an Ag/Au alloy. Bi-2223 is mostly used because it has the highest critical temperature of all technical HTS materials.

Current leads for transport currents in the range of 10 - 70 kA are needed in many areas of the research community such as particle accelerators, *e.g.* LHC, and thermonuclear fusion experimental devices like ITER, Wendelstein 7-X (W7-X) and JT60-SA.

II. CURRENT LEAD DEVELOPMENT FOR ITER

Within the European Fusion Technology Programme, the Forschungszentrum Karlsruhe (FZK) in collaboration with the Centre Recherches en Physique des Plasmas (CRPP) in Switzerland have developed so called binary current leads for currents up to 70 kA to demonstrate the feasibility for ITER. The binary current lead shown in Fig. 1 consists of a high temperature superconductor (HTS) part covering the temperature range between 4.5 K and 65 K and a conventional heat exchanger in the range of 65 K to room temperature. The HTS part is cooled by heat conduction from the 4.5 K end whereas the heat exchanger is cooled with 50 K He. The HTS material is embedded in a structure made of stainless steel which gives mechanical stability and acts as a thermal heat sink in case of a failure of the cooling system.

One 70 kA HTS current lead demonstrator has been built in 2003. Here Bi-2223 superconductor tapes with an AgAu matrix fabricated by American Superconductor (AMSC) have been used. AgAu has the advantage of a much lower thermal conductivity than pure Ag. In 2004/2005 the current lead was tested in the TOSKA facility of the Forschungszentrum Karlsruhe first with 50 K He and later with 80 K He and finally with liquid nitrogen (LN2) cooling [1-4]. For these tests, no special high voltage requirements need to be fulfilled (the test voltage is 1 kV). So no special design of the electrical insulation system was performed.

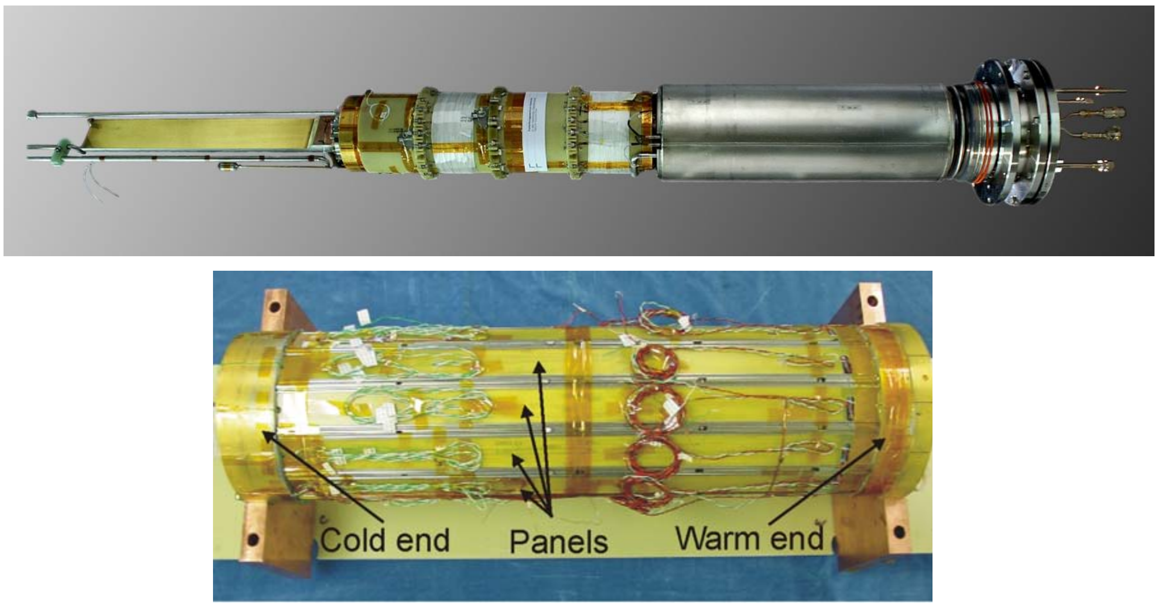

Fig. 1. The 70 kA HTS current lead developed at the Forschungszentrum Karlsruhe has an overall length of 2 m. Top from left to right: clamp to bus bar contact area, HTS part, heat exchanger container, room temperature connector to water cooled bus bar. Bottom: HTS module manufactured by AMSC before assembly with the other current lead parts.

The results led to the following conclusions:

- The 70 kA HTS current lead is very robust and can be stably operated near to its limit. It was operated stable up to 80 kA. Both the dc as well as the quench performance of the HTS module was excellent.
- In the case of a loss of He mass flow through the copper heat exchanger, it took more than 6 minutes from the mass flow interruption until a quench occurred.
- During extended tests, it could be demonstrated that even in case of a quench of the HTS module, an ITER TF-coil could be safely discharged from 68 kA.
- The results demonstrate the high current carrying capacity of the HTS module and achieve a world record for HTS current leads.
- It could be demonstrated that the HTS material used can be reproducibly fabricated by industry with high quality.

- For the ITER current operation duty cycle, the refrigerator power consumption attributable to the HTS current lead is reduced by a factor of 5 compared to the conventional current lead.
- The higher capital cost of the HTS material required for the current leads can be more than compensated by the reduction in cost for the cooling power. Therefore the reduction of operation cost is an extra benefit from the beginning.

The big success of this project has brought ITER to change the current lead design from conventional to HTS type. It is planned now to operate the toroidal field coils (TFC), the central solenoid (CS), the poloidal field coils (PFC) and the correction coils (CC) of ITER with HTS current leads in the current range of 10 kA – 68 kA saving about ¼ of the total cooling power required. As the procurement package “LTS feeders”, which includes the current leads, was given to the Chinese Participant Team, the specific programme in Europe has been stopped.

In the meantime, and also thanks to the big success of the LHC project at CERN where all of the current leads (except the low amperage leads) are using HTS material, other fusion projects, specifically the stellarator W7-X and the Japanese tokamak JT60-SA will use HTS current leads for their magnet systems. The Forschungszentrum Karlsruhe is involved in both projects.

III. CURRENT LEAD DEVELOPMENT FOR WENDELSTEIN 7-X

The stellarator W7-X presently under construction at the Greifswald branch of the Max-Planck-Institute for Plasma Physics consists of 50 non-planar and 20 planar coils with a maximum conductor current of 17.6 kA. The Forschungszentrum Karlsruhe will deliver the current leads for the magnet system. In total 14 current leads are required (I_{max} = 18.2 kA, I_{nom} = 14 kA).

Four main requirements of the W7-X machine dominate the design of the current leads:

- Mounting in upside-down position, *i.e.*, the cold end of the current lead is at the top and the warm end at the bottom side. In conventional leads this may cause cooling problems, because of the large He density gradient between 4.5 K and room temperature (factor 500) which could lead to free convection flow in the opposite direction to the forced convection flow. That would increase the He mass flow rate and the cooling power. The use of conduction-cooled HTS material between 4.5 K and 60 K has the consequence that the He in the heat exchanger has to cover only the temperature range between 50 K (the inlet temperature) and room temperature. This will drastically reduce the free convection process because the density gradient between 50 K and room temperature is now only 6 instead of 500 for conventional designs using no HTS material. The penalty is the higher lead cost due to the HTS material.
- The necessity of using low-Co stainless steel material and the limitation of the amount of silver: due to the design of W7-X, the current leads are located inside the biological shield, very close to the magnet system. Therefore, neutron activation has to be considered and as far as possible, Co and Ag avoided. However, because Bi-2223 is Ag-sheathed, silver cannot be avoided in the design of the HTS current lead.
- The location of the current leads very close to the magnets results in a rather high magnetic stray field: Due to the strong field dependence of the critical current

especially at higher temperatures, a much higher amount of HTS material is needed if the magnetic field increases.

- Paschen[1] tightness and relatively large high test voltage of 13 kV of the current lead and its instrumentation has to be assured.

The design of the binary current lead for W7-X follows the same principles as that of the 70 kA ITER demo current lead described before. It consists of a high temperature superconductor (HTS) part covering the temperature range between 4.5 K and 60 K and a conventional heat exchanger in the range of 60 K to room temperature. The HTS part is cooled by heat conduction from the 4.5 K end whereas the heat exchanger is cooled with 50 K helium. Fig. 2 shows an example of the HTS module. The HTS material used in the current leads is Bi-2223/AgAu tape. As AMSC has stopped the production of first-generation HTS wires in 2006, a material qualification programme was started and different suppliers have been asked to provide samples of single tapes and stacks for electrical, thermal and mechanical testing. At the end of the qualification programme, Bi-2223/AgAu tapes with critical currents >120 A (at 77 K and in self field) became industrially available (European High Temperature Superconductor (EHTS) and Sumitomo). Soldered stacks can also be made in industry (EHTS) [5-6].

Fig. 2. HTS part mock up of the W7-X HTS current lead developed at the Forschungszentrum Karlsruhe.

The performance of heat exchangers (HEX) taking into account the natural convection is presently one branch of general investigations in fluid dynamics. Currently, it is hard to predict how large this effect would be in a current lead heat exchanger. So we decided at an early stage of the project to perform tests with reduced-size HEXs. A series of heat exchanger mock-ups has been installed in normal as well as in upside-down orientation to test the overall performance. Two different HEX types were tested: the perforated plate HEX as it was used in the conventional and HTS-current leads developed at FZK and two different geometries of fin type HEX, as shown in Fig. 3. The left figure shows a part of the perforated plate HEX. Here the current carrying part is the central copper bar and the helium flows through the perforations which are randomly arranged in the consecutive plates located around the copper bar. The right figure shows the fin type HEX which also consists of a central copper bar and circular plates located around it. The plates have no perforations, but the He flow is guided by

[1] Paschen tightness is a special property in high voltage insulation systems. The breakthrough voltage, *e.g.*, in vacuum depends strongly on the pressure of the surrounding medium. It means that an electrical component has to withstand the high voltage independent on the pressure of the surrounded medium. If the component is operated in vacuum it has to operate reliably even in the case of a vacuum failure.

missing circle segments cut away at the alternating outer sides of the plates (schematically presented in the blow up of the right figure which shows the He flow around the central Cu bar). This enforces the meandering flow of the helium mainly oriented perpendicular to the current flow direction, in contrast to the flow in the perforated plate HEX. Based on the analysis of the experimental results, both heat exchanger types can be operated in normal as well as in upside-down orientation without changing their performance for heater powers up to 400 W in the temperature range between 20 and 100 K. No change in performance is expected for higher temperatures. The free convection does not play a measurable role [7]. For lesser complexity and cost, the plate heat exchanger has been chosen as the HEX for the W7-X current leads.

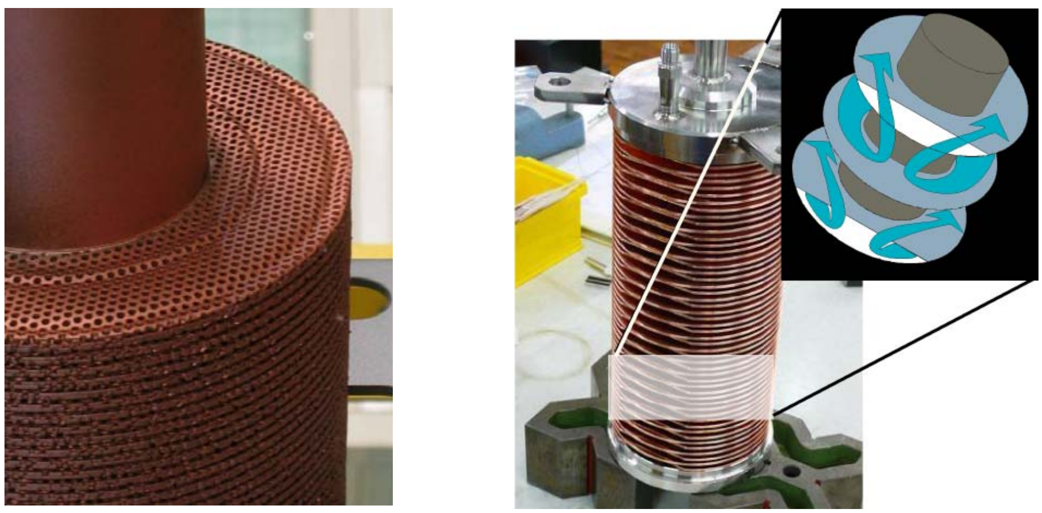

Fig. 3. Heat exchanger mock ups for testing the upside-down orientation. Left: perforated plate heat exchanger, right: fin type heat exchanger. The blow up in the right part shows the meandering helium flow (indicated by arrows), which is oriented mainly perpendicular to the current flow axis.

The high-voltage requirements of W7-X called for a special design of the electrical insulation system. The earlier designs (*e.g.*, for the ITER demo current lead) used a concentric electrical insulation tube around the pressure vessel of the current lead together with the use of stagnant helium as insulating gas. However, such a solution causes high thermal losses: stagnant helium available along and around the current lead causes thermal acoustic oscillations driven by the heat flow in the room temperature region of the lead. So a different approach has been chosen for all current leads currently under design and construction at FZK: the electrical insulation will be directly performed on the outer surface of the current lead pressure vessel and a G10 flange will be integrated to serve as a connection part to the vacuum vessel of the facility. First tests have shown encouraging high-voltage insulation performance and satisfactory mechanical strength.

Presently, the design of the W7-X current lead is in its final phase. The HTS material is on order and should be delivered by approximately the end of 2008. We plan to build two prototype current leads in the Forschungszentrum Karlsruhe and test them in a Paschen tight environment in the Current Lead Test Facility Karlsruhe (CuLTKa) which has to be newly built and commissioned. Afterwards, 14 series current leads will be built in industry whereas the final acceptance test of all leads will be done in CuLTKa.

IV. CURRENT LEAD DEVELOPMENT FOR JT60-SA

In the frame of the Broader Approach Agreement between Japan and the EU and concomitantly to the ITER project, a satellite tokamak project called JT60-SA has been agreed upon in 2006. The magnet system of JT60-SA consists of 18 toroidal field coils (25.3 kA), 4 central solenoid modules (20 kA) and 7 poloidal field coils (20 kA). Following the commitment of the German Government to the EU, FZK shall design, construct and test the current leads. In total 6 leads for a maximum current of 26 kA and 20 leads with a maximum current of 20 kA, mounted in vertical, upright position are required.

Again the current leads will be of the binary type, the HTS part covering the range between 4.5 K and 60 K while the heat exchanger should cover the range between 60 K and room temperature and be cooled by 50 K He [8]. Part of the results of the qualification programme of the current leads for W7-X can also be used for the leads of JT60-SA. This is especially valid for the HTS material and the electrical insulation.

Two prototype leads will be tested in CuLTKa using JT60-SA-relevant conditions. Afterwards 26 current leads will be built in industry whereas the final acceptance test of all leads will be done in CuLTKa.

V. SUMMARY

In the frame of the European Fusion Technology Programme and together with the CRPP in Switzerland, the Institute for Technical Physics of FZK has developed, constructed and tested a 70 kA HTS current lead demonstrator for ITER. The big success of this program has convinced ITER to change its design from conventional to HTS current leads. In total about ¼ of the 4.5 K cooling power consumption can be saved, which gives considerable cost savings.

In the future, FZK shall deliver current leads for two major fusion experimental devices presently under construction, the stellarator W7-X and the satellite tokamak JT60-SA. After the development and qualification phase ending with prototype construction and testing, the series current leads will be manufactured in industry and finally tested in a new test facility CuLTKa in Karlsruhe. The whole project will last until 2012/2013.

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