Conceptual design of a High Temperature Superconductor current feeder system for ITER

V.L. Tanna¹, W. H. Fietz¹, R. Heller¹, A. Vostner², R. Wesche³, and G.R. Zahn¹
¹Forschungszentrum Karlsruhe, Karlsruhe, Germany
²European Fusion Development Agreement, Close Support Unit, Garching, Germany
³Centre de Recherches en Physique des Plasmas, Villigen, Switzerland
E-mail: vipul.tanna@itp.fzk.de

Abstract. The International Thermonuclear Experimental Reactor (ITER) project envisages a techno-economically feasible solution of its current feeder system in order to reduce the overall cryogenic requirements and operational costs. Since the ITER magnet system has a long stand-by time with respect to its operation duty cycle, it is essential to optimize the operational costs of the current feeder system taking into consideration both, the full current and stand-by modes. The present HTS technology has reached the maturity that HTS conductors are applicable for the current feeder system of ITER. The replacement of the actually planned conventional current leads by HTS current leads would provide considerable savings in the refrigeration investment and operational costs. Another option is the substitution of the water cooled high current aluminium feeders by HTS feeders, so called HTS bus bars. In this paper, the different design options of Bi-2223/Ag HTS based bus bars as prototype unit modules for ITER are discussed. The performance of different cooling schemes for HTS bus bars is studied and the design related critical issues e.g. metallic transition (65 K -300 K) and bending of bus bar, AC loss, thermal loss and reliability of the cooling system are investigated.

1. Introduction
High temperature superconductors have successfully demonstrated their considerable advantages over conventional materials. Therefore, a R&D program was launched in Japan and EU in order to design and construct high temperature superconducting (HTS) technology based current leads for ITER. Within the EU program a 70 kA HTS current lead demonstrator for ITER was successfully tested in 2004 [1-4]. Recently in the frame of a collaborative work between the Centre de Recherches en Physique des Plasmas, Villigen, Switzerland, and the Forschungszentrum Karlsruhe, Germany, the possibility of using HTS bus bars in ITER has been reported [5]. There, the possibility of replacing a part of the water cooled Aluminium bus bars by HTS feeders has been discussed. Figure 1 shows the layout of a HTS bus bar scheme for ITER. The substitution of a part of the aluminium bus bars would eliminate the electrical power losses with significantly reduced space requirements for their installation. In ITER, 68 kA DC bus bars are required for the TF system whereas AC bus bars are needed for the PF and CS systems, operating at maximum currents of 52 kA and 45 kA respectively [6]. Here, we only concentrate on the modular design of a 68 kA DC HTS bus bar system for ITER with a unit length of 12m.

Figure 1. Schematic lay out of current feeder system of the TF coils including the HTS feeder
2. Conceptual design aspects of a HTS bus bar for ITER

2.1 Design considerations and main parameters
The designed HTS bus bars have to fulfill the following requirements:
1. Maximum allowable steady state heat load of about ~ 3-4 W/m at 77 K.
2. Use of the warm dielectric insulation scheme.
3. HTS tapes are actively cooled in the cable area.
4. A temperature margin of at least 15 K should be maintained at an operating current of 68 kA.
5. The bus bar and its metallic transition to room temperature should be Paschen tight with minimum heat load.
6. Smooth bending and flexibility.
The main parameters of the 68 kA HTS bus bar are summarized below in Table 1.

| Parameter                        | Value                                           |
|----------------------------------|-------------------------------------------------|
| Rated current                    | 68 kA                                           |
| Critical current                 | 85 kA                                           |
| Unit length                      | 12 m                                            |
| HTS cable design                 | Power transmission type                         |
| HTS materials                    | Bi-2223/Ag/AgMg                                 |
| Typical tape dimensions          | 4.0 mm width x 0.22 mm thick                    |
| Ic of tape at 77 K and self field| 115 A                                           |
| Steel flex pipe dimensions       | 53 mm OD, 50 mm ID.                            |
| Super insulation                 | 25 layers/cm                                    |
| Cryostat                         | Steel flexible pipes                            |
| Max. discharge voltage / test voltage | 17.5 kV / 36 kV          |
| Coolant                          | 50 K He/ 70 K sub-cooled LN$_2$                 |
| Final outer diameter of bus bar  | < 140 mm                                        |

2.2 HTS bus bar design concept
Many design and development activities for HTS power transmission cables are reported [7]. In this paper, we mainly concentrated on the warm dielectric design to make the design simpler. The superconducting Bi-2223/Ag/AgMg tapes are arranged in multilayers and wound onto a flexible stainless steel pipe. This sub-assembly is housed in a flexible steel cryostat with vacuum and super insulation in order to minimize the steady state thermal loads. The forced flow active cooling of the HTS tapes bundle and alternative flow in the central flexible pipe is considered. The cooling aspects are discussed in section 3. The warm dielectric insulation (e.g. Teflon) will be wrapped around the steel cryostat for protection against the high voltage. Finally, a steel sleeve will be wrapped around the warm dielectric for mechanical protection.

2.3 Bus bar transition: metallic heat exchanger (65 K -300 K)
The function of the bus bar transition is to connect the HTS bus bar at cryogenic temperature to a metallic conductor and the bus bar at room temperature to the power supply. The Paschen tight design of such transition is essential. This transition design requires attention for material selection i.e. optimization between conduction and resistive losses e.g. copper of a RRR of 50 is envisaged to be used for high current termination design. The series cooling of the transition along with the HTS bus bar has been envisaged to remove the thermal loss efficiently.

2.4 Design optimization
The standard Bi-2223/Ag/AgMg tapes from European Advanced Superconductors (EAS) are used in the design study. The critical current of the single tape is a function of the temperature
and, particularly in power transmission cable design; it is determined by the magnetic field orientated parallel to the broad face of the tape. We have carried out the optimization study for a fixed outer diameter of the flexible steel pipe of 53 mm at different operating temperatures e.g. Helium at 50 K with $\Delta T = (T_{\text{bus}} - T_{\text{op}}) = 15$ K and sub-cooled LN$_2$ at 70 K with $\Delta T = 5$ K, respectively. The number of HTS tapes required for the design current is optimized with respect to the self field of the HTS-bus bar using the critical current scaling laws for a single tape as reported in [4]. As an illustration, Figure 2(a) shows the relation between the magnetic self field, the number of layers and critical current of the single tape and figure 2(b) shows the relation between the number of layers and critical current of the bus bar, respectively. The effective critical current decreases and in that case more number of layers are required e.g. 24 layers at 65 K and 42 layers at 75 K for a 68 kA HTS bus bar with critical current of 85 kA. Each layer carries equal number of tapes i.e. 35 tapes per layer. The smooth and large bending radius of ~ 1200 mm has been envisaged in order to avoid enhanced field effects at bend locations.

3. Cooling aspects
The forced flow cooling of 1-3 kA class HTS bus bars with sub-cooled liquid nitrogen (LN$_2$) at 70-72 K has been discussed in the literature [9]. Particularly for ITER, we have investigated a possibility to cool the HTS bus bar either with 50 K Helium or forced flow sub-cooled LN$_2$ at 70-72 K. Figure 3(a) represents the 50 K He cooling scheme [8] and figure 3(b) shows the scheme for sub-cooled LN$_2$ cooling for the HTS bus bar and its metallic transition (65 K – 300 K) in series cooling mode. It is also not desirable to cool the HTS bus bar with 80 K He because it requires a huge amount of HTS material and large installation space requirements and nevertheless a lower temperature margin compared to other mentioned cooling options [4].
4. Thermo-hydraulics

Different sources of steady state heat loads acting on the HTS bus bar including radiation, conduction and Joule heating in the joints are estimated to be about 45 W at 50 K. In case of the TF bus bars, there is no AC operation (besides the charge and discharge of the coils) but AC losses due to current ripple of the power supply will be generated. Estimations show that in case of ITER, the TF system contributes with only a few mW of ripple loss at 600 Hz with 30 V reactive load voltage. A 1-D thermo-hydraulic model of the HTS bus bar has been developed for optimization of coolant requirement, pressure drop, and coolant inlet/outlet conditions. The analysis has been carried out for both the cooling options i.e. 50 K Helium and sub-cooled LN\textsubscript{2} at 70 K and the results are summarized in Table 2.

| Parameters                          | 50 K Helium cooling | 70 K (LN\textsubscript{2} sub-cooling) |
|------------------------------------|---------------------|----------------------------------------|
| Inlet pressure                     | 6 bar               | 2.5 bar                                |
| Inlet temperature                  | 50 K                | 70 K                                   |
| Flow length                        | 12 m                | 12 m                                   |
| Total mass flow rate               | 5 g/s               | 12 g/s + 2.2 g/s for sub-cooler        |
| Void fraction within the bundle region | ~ 50%               | ~ 40%                                  |
| Pressure drop within bus bar       | 0.3 bar             | ~ 0.7 bar                              |
| Available heat transfer coeff.     | 414 W/m\textsuperscript{2}K | 300 W/m\textsuperscript{2}K           |
| \(\Delta T = T_{\text{out}} - T_{\text{in}}\) in the bus bar | 1.75 K               | ~ 2.0 K                                |
| Refrigeration plant efficiency     | 0.284               | 0.30                                   |
| Power consumption                  | ~26 kW              | ~27 kW + 5 kW LN\textsubscript{2} for sub-cooler |

5. Conclusion and Outlook

The design concept, optimization and main parameters of a TF HTS bus bar model for ITER have been studied. The operating temperature is one main parameter for the HTS bus bar design. The optimization between the amount of superconductors and operating cost of the cryogenic system is essential. 50 K He and 70 K sub-cooled LN\textsubscript{2} options are possible options for an ITER HTS bus bar. The 50 K He option looks more economic because less superconductor is needed compared to 80 K He cooling. Sub-cooled LN\textsubscript{2} cooling consumes more power and gives less temperature margin compared to 50 K Helium cooling but the LN\textsubscript{2} cooling system is much simpler. In a further step, the detailed conceptual design of PF and CS HTS bus bars including its metallic transition (65 K – 300K) will be worked out.

6. References

[1] R. Heller et al, Forschungszentrum Karlsruhe Internal Report FE.5130.0061.0012/A, Oct 2004, unpublished
[2] R. Wesche, Deliverable 4.1, EU Contract FU06 – CT 2003 – 00024 (EFDA/02 1014), CRPP Report, October 2004, unpublished
[3] R. Heller et al, EFDA No. TW4-TMSF-HTSCOM-Deliverable-1”, Forschungszentrum Karlsruhe Internal Report, May 2005, unpublished
[4] R. Heller et al, IEEE Transactions on Applied Superconductivity, Vol. 15, No. 2, June 2005, pp. 1496-1499.
[5] R. Wesche et al., EFDA No. TW4-TMSF-HTSCOM-Deliverable-2”, CRPP Internal Report LRP 805/05, July 2005, unpublished.
[6] ITER DDD 4.1, Pulsed Power Supplies, Appendix-A, N 41 DDD 18 01-07-06 R 0.3, pp. 35-37.
[7] S. Mukoyama et al, IEEE Trans. on Applied Superconductivity, Vol.13, No.2, June 2003, pp. 1926
[8] ITER DDD 34 cryo plant and distribution, August 2004, section 2.1-2.6.
[9] Deukyong Koh et al, IEEE Trans. on Appl. Superconductivity, Vol. 14(2), June 2004, pp. 1746-1750.