Current Feeder System for the KSTAR Device

Y. S. Kim, Y. M. Park, K. Kim, Y. K. Oh, C. H. Choi, J. W. Sa, N. I. Her, and G. S. Lee

***Abstract*—The current feeder system consisting of superconducting (SC) bus-lines, SC bus-line interface terminal, and current leads is used as the current transmission system for the KSTAR SC coils. The current lead system consists of 11 pairs of vapor-cooled leads for the PF coils and a pair of leads for the TF coils. The PF coils are operated at full currents only during a portion of the entire time. The heat loads of current leads in idle mode, when it carries no current, depend quite strongly on the using material. We have measured the heat load and temperature profile when the overload current was charged in 200 A optimum brass lead. Also, the current feeder system requires a long bus-line that must supply a large amount of current from a current lead to SC coils. We have designed a SC bus-line with NbTi Cable-In-Conduit Conductor (CICC) to reduce Joule heating loss. The CICC is cooled with forced-flow supercritical helium (SHe). The bus-line requires higher reliability and safety than those of the SC coils of the KSTAR. The KSTAR bus-line has been designed to have an independent vacuum space and consist of SHe return and 60 K thermal shield line for shielding. To connect the bus-line with a cryostat of the KSTAR and current lead box, we have developed a prototype SC bus-line interface terminal.**

***Index Terms*—Current feeder, current lead, interface terminal, KSTAR, superconducting bus.**

I. Introduction

The SUPERCONDUCTING coils of the Korea Superconducting Tokamak Advanced Research (KSTAR) device have 16 sets of Toroidal Field (TF) coils and 7 pairs of Poroidal Field (PF) coils which include 4 pairs of Central Solenoid (CS) coils (PF1, PF2, PF3, PF4) [1]. The TF coils, CS coils, and PF5 coils are made of Nb_3Sn Cable-In-Conduit Conductor (CICC). Two pairs of PF coils (PF6, PF7) are made of NbTi CICC. The TF coils are connected in series and carry 35.2 kA. The PF coils have an up-down symmetry and the operating current is about 20∼25 kA [2].

In large fusion devices using superconducting (SC) coils, the function of the current feeder system is to transfer a large amount of current from power supply to the coils without energy consumption. The current feeder system needs much more excellent stability and safety than the coils themselves. When the emergencies such as, a coil quench or a suddenly power failure, occur, the large magnetic energy stored in the coils must be extracted through the current feeder system [3].

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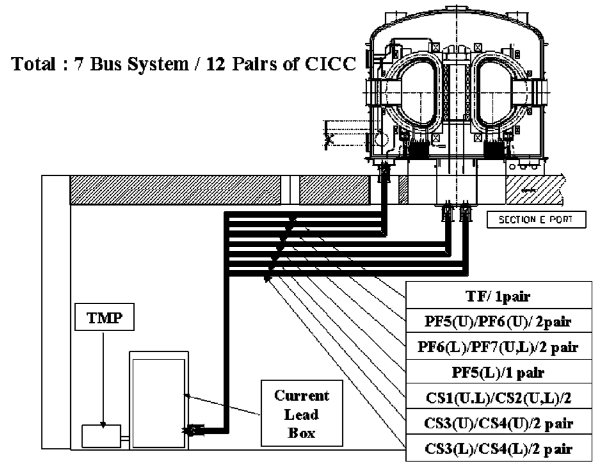

Fig. 1. Configuration of the SC bus-lines for the KSTAR device.

TABLE I
SPECIFICATIONS OF THE SC BUS-LINE FOR THE KSTAR DEVICE

Items	Specifications
Num. of Ducts	7
TF Coils	1
PF Coils	6
Num. of Conductors	12 pairs
Type of Conductor	NbTi CICC
Coolant	forced-flow SHe
Rated Current	
TF Coils	35.2 kA
PF Coils	20 ~ 25 kA
Total Length of Duct	200 m

In this paper, we report the conceptual design of the current feeder system for the KSTAR device. The KSTAR current feeder system consists of SC bus-line, interface terminal, and current lead system.

II. Design of Current Feeder System for the KSTAR

A. SC Bus-Line

We have conceptually designed the SC bus-lines to reduce the Joule heating loss from current lead to SC coils. Fig. 1 shows the configuration of the KSTAR SC bus-lines. The bus-lines have 7 ducts and 12 pairs of CICCs. Because the 16 TF coils are connected in series, only one pair of CICC is necessary to transmit current for the 16 TF coils. The other ducts for the PF coils include two pairs of CICCs. Table I shows the specification of the bus-lines.

Fig. 2 shows the cross-sectional view of the bus-line for PF coils. The bus-lines consist of NbTi CICCs, thermal shields,

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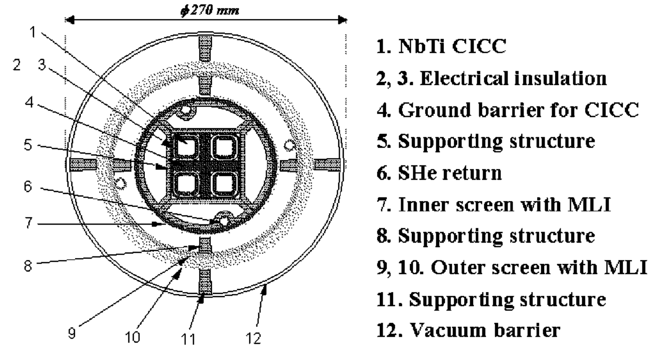

Fig. 2. Structure of the SC bus-lines for the KSTAR PF coils.

electrical insulations, and support structures. The jacket material of the CICCs is stainless steel 316LN. The average length of the bus-line duct is about 30 m and the total length is 200 m. For the higher thermal stability than that of the coils, the bus-lines are designed to have a double thermal shield system that consists of an inner and outer cover with multi-layer insulation (MLI). The inner screen is connected to the supercritical helium return (6 K) through a bus-line CICC, and the outer screen of thermal shield serves as 60 K shield by using a gas helium (GHe). The support structure and spacer are made of GFRP (G-10). They include a grounded separator between the four CICCs.

The static heat loads, conduction from warm surface to the cold region through the support, and radiation from 60 K shields are estimated. The conduction heat load is calculated with the equation.

$$Q = k_a A \frac{dT}{dx}$$

where k_a is the mean thermal conductivity given by

$$k_a = (T_1 - T_2)^{-1} \int_{T_1}^{T_2} k(T)\, dT.$$

A is the area of cross section of solid, dx is the length of the solid, and dT is the temperature difference. On the other hand, the radiation heat load is given by

$$Q = \sigma F_e A (T_h^4 - T_c^4)$$

where σ is the Stefan Boltzman constant ($\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4), F_e is the emissivity factor which includes the emissivity of the inner and outer surface, A is the surface area, T_h and T_c are the effective temperatures of hot and cold surface, respectively. The heat load into the thermal shield channel (60 K) of the bus-lines is about 1200 W (6.0 W/m). The heat load from the thermal shield channel to the supercritical channel (4.5 K) is 150 W (0.75 W/m).

B. SC Bus-Line Interface Terminal

We have developed a prototype SC bus-line interface terminal that is to connect the bus-line with the cryostat of the KSTAR and current lead box. It was designed to satisfy following requirements.

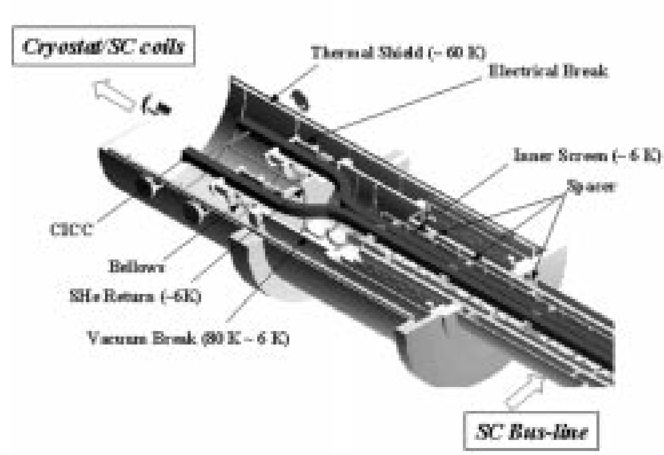

Fig. 3. Three-dimensional view of the SC bus-line interface terminal.

1) The vacuum space should be separated from the KSTAR cryostat in order to operate the bus-line safely when the cryostat vacuum is broken.
2) Two electrical insulations should be required to break the induced eddy current at the cryostat due to the pulse mode operation and to cut the current flow to the vacuum break which is connected to the CICC.
3) The flexible structure should be able to compensate the thermal contraction stress due to the cool-down from 300 K to 4.5 K.
4) Convenient maintenance should be required for the long operation of the device.

Fig. 3 shows a 3-dimensional structure of the prototype interface terminal. The electrical break at CICC part in the interface terminal is designed to resist over a 15 kV breakdown voltage, which is the requirement of the KSTAR SC coils. The eddy current due to the pulse operation of the coils is cut off at another electrical break, GFRP. The thickness and the inner diameter of GFRP are 30 mm and 504 mm, respectively. And then, there is a bellows to prevent the stress due to the thermal shrinkage of the long bus-lines. The bellows thickness is 0.4 mm.

We performed the thermal and structural analysis for the prototype interface terminal. Fig. 4(a) shows temperature profiles for the vacuum break part of the interface terminal when CICC was cool down to 4.5 K by the SHe. The conduction heat load from the warm part (300 K) to the CICC cold part (4.5 K) through the thermal anchor and GFRP support is estimated as about 3.3 W. For the stress analysis it is assumed that the KSTAR cryostat vacuum is broken. The maximum stress of 87 MPa appears at the bellows. The maximum transverse and longitudinal displacements are 1.03 mm and 2.23 mm, respectively. More detailed performance test for the prototype interface terminal is now going on. We will report the test results in future.

C. Current Leads

The power transmission system for the KSTAR device requires a current lead to link the bus-line at 4.5 K to the normal bus bar at 300 K. The current lead system consists of 11 pairs of vapor-cooled leads for the PF coils and a pair of leads for the TF coils. The current capacity of the TF and PF leads are 40 kA and 25 kA, respectively. The refrigeration load of current lead

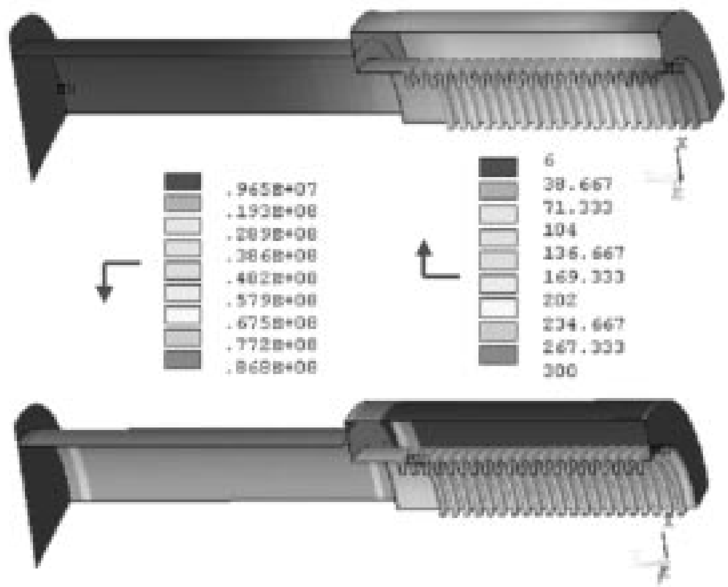

Fig. 4. ANSYS analysis for the SC bus-line interface thermal (upper figure) and stress (lower figure).

system is about 20% of the KSTAR total refrigeration load. The main design approach for the KSTAR current lead system is to reduce the huge refrigeration loads due to the conduction and Joule heating in the large vapor cooled current leads.

On the other hand, the KSTAR PF coils are charged only during a short time, 70 s/20 min (350 s/60 min), in baseline (upgrade) operation mode. As a result, the current charging time of PF coil is about 0.46 hr/day (0.78 hr/day) in baseline (upgrade).

The evaporation rate of an optimum current lead at zero current is strongly depends on the lead material [4], [5]. Estimated ratio of the heat loads for the various vapor-cooled leads are

$$Q_0/Q_{opt} \sim 0.68 \quad \text{for copper}$$

$$Q_0/Q_{opt} \sim 0.56 \quad \text{for brass (Zn 30\%)}$$

where Q_0 and Q_{opt} are the heat load at zero current and at optimum current, respectively. Also, in case the superconducting magnets operate at the full current only during part time, it is worthwhile to consider an overloaded current lead. At an optimum current, the overloaded leads evaporate somewhat more helium. But at zero current, the evaporation due to overloaded leads is considerably less than that in optimum leads. The maximum overloading factor depend on the lead material and maximum acceptable temperature [6].

We have measured the temperature profile and transient effect when the overload current is charged in 200 A commercial vapor-cooled brass (Zn 10%) lead (AMI: America Magnetic Industry). The evaporation rate was estimated from zero to maximum of 400 A at every 50 A step. The current charging rate at each current was maintained at a constant of 0.5 A/s.

The temperature profile versus time and at each position on the lead is shown in Fig. 5 when the 400 A overload current was charged. When the current is constant, we observed that the helium evaporation rate and the voltage drop in both of the terminals are maintained at constant. The evaporation rate in this lead is estimated with $Q_0/Q_{opt} \sim 0.64$. The voltage drop is

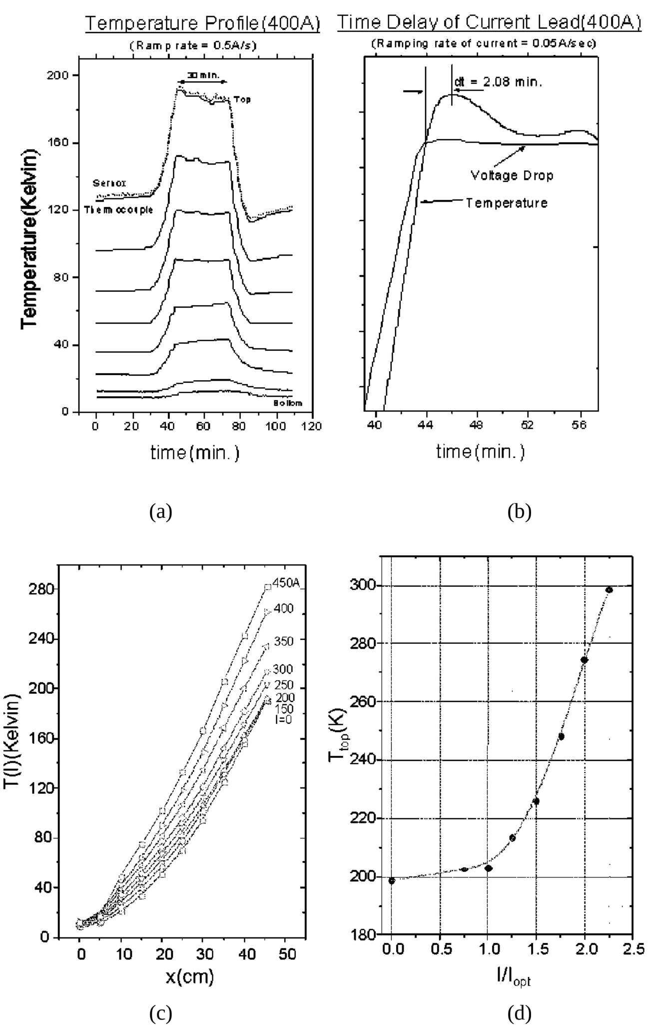

Fig. 5. Test results of the 200 A brass vapor-cooled lead. (a) temperature profile versus current charging time. (b) Transient time. (c) Temperature versus lead position. (d) Temperature at lead top versus I/Iop.

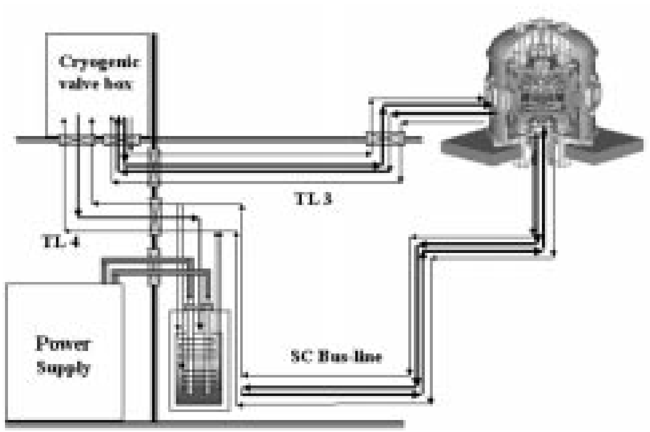

Fig. 6. Schematic diagram for the cooling scheme of current feeder system.

TABLE II
REQUIREMENTS TO COOL THE CURRENT LEAD AND SC BUS-LINE

Item	Current lead		SC bus-lines	
	cooling	shield	cooling	shield
Coolant	LHe	GHe	SHe	GHe
Cooling channel	1	18	24	7
Inlet	1	1	4	1
Outlet	1	1	1	1
T_{in}(K)	4.2	60	4.5	60
T_{out}(K)	~300	80	5.5	80
P_{in}(bar)	~1.3	-	-	-
P_{out}(bar)	~1.0	19.5	3.0	19.5
ΔP(bar)	0.3	0.02	0.05	0.02
Mass flow(g/s)	25/40	20	28	10

about 100 mV at both terminals. Fig. 5(a) and (b) shows an overheating on the lead after the current was stabilized. The transient time is observed about 2 min. In Fig. 5(d), in case of $I/I_{op} < 1$, the temperature at the top end of the lead is at about 200 K. But, when $I/I_{op} > 1$, we can see that the temperature significantly increased due to the higher Joule heating effect. The temperature rise of the lead seems to be proportional to I^2. The more detailed analysis for the brass vapor-cooled lead will be performed in future.

III. Cooling Scheme for the Current Feeder System

Fig. 6 shows the schematic diagram of the cooling scheme for the current feeder system. The 60 K GHe lines for shielding the bus-line and current lead box consist of 21 lines in parallel and are supplied through transfer line (TL) 3 and returned by TL4. The inner diameter of the GHe line is 10 mm, and the length is about 174 m. The 4.5 K SHe is required to cool the CICC of the bus-lines. The SHe lines for the bus-line are supplied through TL3 together with other SHe lines for the coils. Table II shows the cooling parameters for the KSTAR current feeder system.

IV. Summary

The current feeder system is conceptually designed for the KSTAR device. The SC bus-line has NbTi CICC as a conductor. The heat loads for the designed SC bus-lines are estimated. The thermal stability is higher than that of the SC coils because of the double thermal shields design. The developed prototype interface terminal has vacuum and electrical break from the cryostat of the KSTAR, and flexible structure to compensate the thermal shrinkage due to the cool down. We will estimate the quality for the prototype interface terminal. To reduce the huge helium refrigeration load of the KSTAR cryogenic facility, we consider the overload current leads for 11 pairs of the PF leads.

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