Fabrication of Cables for the Background-Field Magnet System of SSTF

S. Lee, B. Lim, S. Baang, M. Kim, H. Park, J. Kim, I. Han, B. Lee, and K. Kim

***Abstract*—The Korea Superconducting Tokamak Advanced Research (KSTAR) device has a fully superconducting magnet system consisting of 16 Toroidal Field (TF)and 14 Poloidal Field (PF) coils. For the test of the KSTAR cable-in-conduit conductor (CICC), an ambient magnetic field of ±8 T with a maximum change rate of 20 T/s is required and a background-field magnet system is being developed for the Samsung Superconductor Test Facility (SSTF). The CICC for PF1-5 is used as the conductor for background-field coils to check the validity of the PF CICC design. Two pieces of cables have been fabricated and the cable has the length of 870 m and the diameter of 20.3 mm. Pitches are 40, 80, 145, and 237 mm at each cabling stage. The void fraction of the CICC is expected to be more than 36%.**

***Index Terms*—Background-field coils, CICC, KSTAR, PF coils, SSTF, superconducting cable.**

I. INTRODUCTION

THE KSTAR device is an advanced quasi-steady-state tokamak. The magnets of the device, consisting of 16 TF coils and 7 pairs (upper and lower) of PF coils, are all superconducting to achieve long pulse operation (>20 s). According to the reference scenario, the maximum B and dB/dt exposed to PF coils are about 8 T and 12 T/s, respectively [1].

The SSTF should be able to test the KSTAR PF CICC under the conditions mentioned above. The SSTF background magnet system is to provide 8 T magnetic flux density and 20 T/s ramp rate to the testing objects. The background magnet system is composed of the following components:

— Main Coil (MC) to ramp up the field to 8 T with 3 T/s ramp rate;
— Blip Coil (BC) to add 1 T subsequently and ramp down back to 8 T with 20 T/s ramp rate; and
— Compensation Coil (CC) to protect MC against the fast field variation of magnetic flux.

Two halves of split solenoids form the MC with a nominal gap of 250 mm [2].

With regard to the CICC for the MC, we adopted the same as those of PF1-5 coils to check the validity of the PF CICC design. The conduit material is Incoloy 908 and superconducting (sc) strands are Nb3Sn. The cabling pattern is $3 \times 4 \times 5 \times 6$. Two sc and one copper strands are cabled together to become a triplet in the first cabling stage. At the last stage, voltage-tap sensors (VTS) are inserted.

In this work, we describe the establishment of processes to fabricate the cable for MC. It includes the development of roll dies to control the size of the final cable and a particle blower to remove the particle on the cable surface coming from the friction between the cable and die. The optimal arrangement of two kinds of strands with different characteristics to make the cable as homogeneous as possible is described.

Manuscript received September 24, 2001. This work was supported by Korea Ministry of Science and Technology.

S. Lee, B. Lim, S. Baang, M. Kim, H. Park, J. Kim, and K. Kim are with the Samsung Advanced Institute of Technology, Taejon 305-380, Korea (e-mail: silee@venus.sait.samsung.co.kr).

I. Han is with Nexans Korea, Chungbuk 363-812, Korea (e-mail: iyhan@nexanskorea.com).

B. Lee is with Shinki Wire Inc., Kyungki 487-801, Korea (e-mail: skwire@yahoo.cc).

Publisher Item Identifier S 1051-8223(02)03612-6.

TABLE I
ELECTRICAL PROPERTIES OF Nb3Sn STRAND FOR KSTAR

Strand Type	Jc (A/mm2)	Qh (mJ/cc)	RRR
MELCO Type A	995	164	169
MELCO Type B	1024	216	200
IGC	874	252	206

II. MATERIALS

A. Nb3Sn Strands

Regarding Nb3Sn strands for fusion devices, ITER (International Thermonuclear Experimental Reactor) designated the HP (High Performance) I and II specifications [3]. For the KSTAR magnet system, KSTAR HP-III specification is defined as the critical current density (Jc) more than 750 A/mm2 @ 12 T and hysteresis loss (Qh) less than 250 mJ/cc per ±3 T cycle.

Nb3Sn strands are made by drawing the 8-mm rods supplied by MELCO (Mitsubishi Electric Corporation) and IGC (Intermagnetics General Corporation) to 0.778 mm diameter. The final diameter of the strands is 0.78 mm after chrome plating.

MELCO has developed 3 types of rods (type A, B, and most recently C) for KSTAR magnets. IGC provides one type of the rod. The MELCO type A, type B, and IGC wires have the electrical properties as shown in Table I [4].

Among three types of strands, MELCO type A (Type A) shows a good ac characteristic. Both of MELCO and IGC wires fall within the KSTAR specification.

Mechanical properties including a yield stress and a tensile strength were measured and compared for both a MELCO and an IGC wire. Both wires showed almost the same yield stresses, around 380 MPa. With regard to the tensile strength, however, the MELCO wire's was 526 MPa and exceeded the IGCs by 22 MPa. The strands start to deform above yield stress limit and the yield stress is a more important factor than tensile strength in cabling. From that point of view, the both wires mentioned above are safe in a same degree.

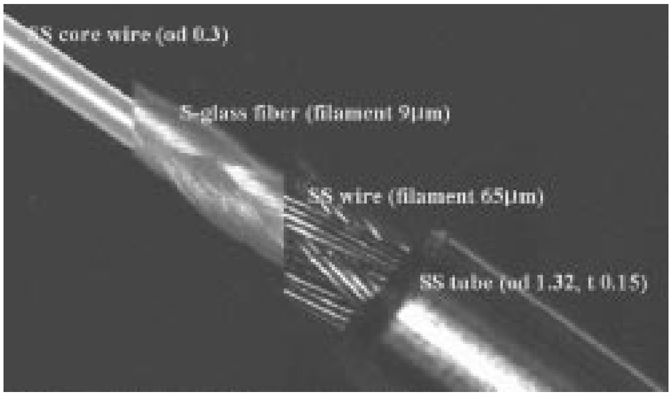

Fig. 1. Composition of internal voltage-tap sensors.

B. Internal Voltage-Tap Sensor

Internal voltage-tap sensors (VTS) are installed in KSTAR magnets for the quench detection. We developed a VTS for the KSTAR CICC. The VTS has the structure of a stainless-steel core wire (0.3 m dia.) at the center, S-2 glass braid, stainless-steel filament (65 μm dia.) braid, and a stainless-steel capillary tube (1.32 mm dia.) outermost. The material for both the filament and the tube is stainless-steel 316L. The resistance per unit length and the breakdown voltage are about 12 Ω/m and 800 $\pm$ 50 V in the air, respectively. A picture of the VTS magnified by 50 is shown in Fig. 1.

1) Insertion: There are four candidate positions of VTS insertion inside the CICC: center of the final cable ($3 \times 4 \times 5 \times 6$), valley of the final cable, center of the final subcable ($3 \times 4 \times 5$), and center of the triplet. The valley of the final cable is the most vulnerable to noises and the triplet is the least. The maximum noise voltages are 1333.5 mV at the final cable valley, 281.6 mV at the center of the final cable, and 1.61 mV at the triplet [5]. The triplet is the best position but not desirable because the VTS will deform too much and fail to survive the cabling work.

2) Termination: The VTS picks up the voltage occurring between the two termination points during quench. Six VTSs are inserted at the center of the final cable as mentioned and the distances between the two adjacent termination points are equal.

The termination of VTS is made by brazing the core wire to the capillary tube surface. We tested two methods: both-side brazing after full cut and one-spot brazing after half cut.

Procedures for the former method are as follows:

— Cut the sensor at a desired position.
— Remove the capillary tube, SS filament braid, and S-2 glass braid at both terminal sides.
— Bend the core wire until it touches the capillary tube surface at both terminal sides.
— Braze the core wire to attach to the tube surface at both terminal sides.

Procedures for the latter method are as follows:

— Remove the half of the encapsulating tube using a small pneumatic grinder until the core wire appears.
— Clear the braids in the brazing area carefully not to disturb the brazing work.
— Braze the core wire until the brazing wire fills up the cut empty space by brazing.

TABLE II
ARRANGEMENT OF THE MC-2 SUBCABLES

Stage No.	Num of Sub-Cable	Num of selection		Num of strand*			Num
		Type-up	Type-lo	M	I	C	
1	120			2	0	1	69
				0	2	1	51
2	30	2	2	4	4	4	21
		3	1	6	2	4	9

* M: Mitsubishi, I: IGC, C: OFHC

C. Particle Blower

A cabling die was made of monomer-cast nylon, diameter 21.5 mm. We found some particles appeared from the surface of the die because the cable scrubbed the die surface. We devised a particle blower to remove the particles on the cable surface. We made a cylindrical tube, which had a larger diameter than that of the cable die, for the cable to pass through the hole freely. It consists of two halves of the cylinder. We made a channel with a semicircle cross section on the inner surface in azimuthal direction and a port to blow the instrument air in tangentially to the channel. The air flowed through the channel and out through another port near the air input. The particles are expected to drag toward outside of the cable and to the surface of the channel by the pressure difference.

D. Roll Die

Roll dies are used to control the size and surface quality of the final cable. The four sets of roll dies, two vertical rolls and two horizontal rolls, are used. The vertical and horizontal rolls are installed alternately with die diameters changing gradually 21.4→20.7→20.4→19.9 mm.

E. Final Wrapping

At the final stage of cable fabrication, the cable is wrapped with the thin stainless-steel strip, 30-mm wide and 0.05 mm thick, with 20% overlap at each side. When a strip from a roll ran out, we made it overlap with another strip about 1 cm and fixed them with a spot welder.

III. METHODS AND RESULTS

A. Cable Arrangement

Three types of Nb3Sn strands were used for this work; Type A and B, and IGC. We intended to make triplets required for one of the MC halves, MC-1, with the Type-A strands. Triplets for the MC-2 were made by mixing the Type-A, the Type-B, and IGC strands.

For the MC-1, triplets and 3×4 subcables were fabricated without any difficulty because there was no mixing problem. The 3×4 subcables were composed of 4 MELCO triplets (4-MT) and the number was 30.

The MC-2 cabling methods up to the second stage are shown in Table II. We used same kind of strands to make a triplet for convenience. At the second stage, we mixed MELCO triplets and IGC triplets to produce two kinds of subcables. One was to mix 2 MELCO and 2 IGC triplets (2-MT/2- IT). The other was to mix 3 MELCO triplets and 1 IGC triplet (3-MT/1-IT). Mixing was made in such a way that the difference between the number

TABLE III
OPTIMUM ARRANGEMENT OF SUB-CABLES FOR MC

Stage No.	Num of Sub-Cable	Num of selection			Num of strand*			Num
		Type-up	Type-mid	Type-lo	M	I	C	
2	60				8	0	4	30
					4	4	4	21
					6	2	4	9
3	12	3	2	0	32	8	20	5
		3	1	1	34	6	20	5
		0	3	2	24	16	20	2
4	2	2	3	1	190	50	120	1
		3	2	1	188	52	120	1

* M: Mitsubishi, I: IGC, C: OFHC

of the MELCO strands and the number of IGC strands could be minimized. Note that we did not classify the triplets in more detail by which type of MELCO strands they were containing. The number of the MELCO triplets was 69 and the IGC triplets, 51. The number of 2-MT/2-IT was 21 and 3-MT/1-IT was 9, making 30 of 3 × 4 subcables.

Other than the original intention, we changed our mind to cross-mix the 3 × 4 subcables for the MC-1 and those of the MC-2 when the second cabling stage was to finish. This was because we might have several advantages if we made the two coils as equally between them and homogeneous inside the respective cable as possible. One of the advantages is the MC is expected to sustain the KSTAR simulating environment better than in the first intended case because the MC-1 and the MC-2 will have the averaged characteristics in Jc, and AC loss. If the MC as a test object survives such environment it can ensure the reliable operation of PF1-5 coils.

The optimal arrangement needed to handle too many 3 × 3-matrix manipulations and was solved by a computer programming. The result is shown in Table III. The target was to minimize the difference between the number of the MELCO strands and the number of IGC strands in each and every subcable as in the 3 × 4 cabling stage of the MC-2.

B. Sensor Insertion and Twist Pitches

We fabricated three dummy cables to check the possibilities of the sensor insertion candidates and to choose the better twist pitches related with cable losses such as coupling, eddy current, and hysteresis losses. Two sets of pitches were tested; 40 × 80 × 165 × 275 and 40 × 80 × 145 × 237 mm.

Regarding the three candidates for sensor insertion mentioned above, the resistance of each sensor, which was used to check the position of termination, was measured at each stage. We found that the center of the final cable was the only place where the sensor could survive the CICC jacketing work. Other places were not the case, the reason being supposed such that the cable would be slightly damaged when the jacket is deformed to a square shape at the squaring stage of the tube-mill process [6].

For the pitches, we monitored the final cable diameter and found the two testing sets of pitches mentioned above satisfied the requirement, 20.7 ± 0.3 mm though the second resulted in a little smaller diameter. The rate of reduction in void fraction was calculated to be 0.64%, negligibly small. Therefore, we selected the scheme with the smaller final pitch.

TABLE IV
RESISTANCE OF SENSORS FOR MC-1 AND MC-2

Coil	Sensor No.	Plan Dist. (m)	Resistance (kΩ)	Resist. Per unit L (Ω/m)	Calc. Dist. (m)
MC-1	1	26.8	0.32	11.9	26.5
	2	193.9	2.29	11.9	192.8
	3	361.0	4.28	12.3	348.5
	4	528.1	6.28	11.9	526.1
	5	695.2	7.34	10.7	684.5
	6	862.3	9.09	10.6	857.9
MC-2	1	22.5	0.24	11.1	21.4
	2	189.6	2.00	10.8	185.0
	3	356.7	4.23	12.4	340.0
	4	523.8	6.24	12.5	500.4
	5	690.9	8.19	12.4	661.6
	6	858.0	10.18	12.4	820.3

C. Sensor Resistance and Void Fraction

From the dummy cable work, all sensors in the center of the final cable proved to survive after the cable jacketing. Following the method, two real cables were fabricated with about 870 m length and 20.3 mm diameter. We measured the resistance of all sensors for the MC, recalculated the termination locations, and compared them with the plan values as listed in the Table IV. We found the resistance per unit length was different and the difference was 6.2% for MC-1 and 6.4% for MC-2.

To improve the void fraction, many efforts were made in jacketing as well. The dimensions including thickness and corner radius of the jacketed conduit were inspected in detail [6]. The void fraction was calculated to be above 36%.

IV. CONCLUSION

We fabricated two sets of cables, 870 m long and 20.3 ± 0.1 mm diameter, one for each half of the MC. Two sets of cabling pitches were tested with various dummy cables fabricated and 40 × 80 × 145 × 237 mm was selected finally. MELCO superconducting wires were mainly used and IGC wires were also used. The optimal arrangement of IGC wires was investigated to make the cable as homogeneous as possible. We investigated the location for VTS insertion, where VTS could be inserted without any damage, and found the center of the final cable was the safest place. The void fraction of the fabricated CICC is expected to be above 36%.

REFERENCES

[1] J. H. Schultz, "KSTAR design description doc.," *KSTAR Magn. Syst. Rev. T13/14*, 1999.
[2] S. Baang *et al.*, "The background magnets of the Samsung superconductor test facility (SSTF)," *IEEE Trans. Appl. Superconduct.*, vol. 11, pp. 2082–2085, 2001.
[3] S. Kim, "Development of the central solenoid (CS) model coil with Nb3Sn cable-in-conduit (CIC) superconductor for the uperconducting tokamak fusion device," Ph.D. dissertation, Seoul National University, Feb. 1999.
[4] M. Kim *et al.*, "The results of performance tests of superconducting wires for KSTAR magnets," Physica C, submitted for publication.
[5] J. H. Schultz, "Signal/noise voltages in KSTAR internal voltage sensor candidates,", KSTAR Doc. No: KSTAR-USMIT-JHSchultz-102600-01, Oct. 26, 2000.
[6] B. Lim, S. Lee, and K. Kim, "Fabrication of the KSTAR superconducting CICC," IEEE Trans. Appl. Superconduct., submitted for publication.