The Background Magnets of the Samsung Superconductor Test Facility (SSTF)

[a] Sungkeun Baang, Keeman Kim, Yongjin Kim, Hyunki Park, Sangbo Kim, Qiuliang Wang,
[b] Mikhail P. Alexeev, Oleg P. Anashkin,Denis P. Ivanov, Victor E. Keilin,Ivan A. Kovalev, Sergei L. Kruglov, Valery V. Lysenko,Sergei M. Miklyaev,Igor O. Shchegolev, Vladmir I. Shcherbakov,Sergei Shevchenko, Igor O. Shugaev,Mikhail I. Surin

***Abstract*—The background magnet system of SSTF (Samsung Superconductor Test Facility) for KSTAR (Korea Superconducting Tokamak Advanced Research) is now under design. The main coil (MC) is split solenoids and the gap can be changed from 0 to 750 mm. The ID of MC is 750 mm. It will be wound using a CICC (cable-in-conduit conductor) designed for the central solenoid of KSTAR. The central field is 8 T at 22.5 kA when the gap is 250 mm. The ramp rate of MC is 3 T/s. A pair of blip coils will simulate (during the discharge) 1 T amplitude and 20 T/s rate electromagnetic disturbances expected from the KSTAR operation. To compensate the inductive interaction between MC and blip coils during the discharge of the blip coils, a pair of cancellation coils is foreseen. Both blip and cancellation coils (BCC) are fed in series and generate 1 T central field @ 7 kA and 250 mm gap. The BCC are wound with CICC and cooled internally and externally.**

***Index Terms*—Blip Coil, Cancellation Coil, KSTAR, SSTF, Superconductor.**

I. Introduction

SSTF (Samsung Superconductor Test Facility) is being constructed at SAIT (Samsung Advanced Institute of Technology) Daduck campus in Taejon, Korea [1]. The main purpose of this facility is the test of superconducting CICC (cable-in-conduit conductor) to be used for the KSTAR (Korea Superconducting Tokamak Advanced Research) magnets [2]. All three kinds of CICC (one for toroidal field (TF) coils and two – Nb3Sn and NbTi – for poloidal field (PF) coils) will be tested as short samples and full-scale coils. It is also planned to test some types of CICC joints in SSTF.

All these tests have to be performed at conditions which should be nearly similar to those in KSTAR during its plasma operation.

II. Background Magnet System for SSTF

The following equipment for SSTF is now under design:
1. Two halves of the split main coil (MC) producing a background magnetic field up to 8 T at the center of magnet. The nominal gap size between these two coils is 250 mm (can be increased up to 750 mm). The MC should withstand charging (or discharging) at a ramp rate up to 3 T/s.
2. Two halves of blip coils (BC) producing an additional field up to 1 T in the same gap, in the same or in opposite direction to the MC field. These coils should be able to produce dB/dt up to 20 T/s being discharged exponentially with time constant of 50 ms.
3. Two halves of the cancellation coils (CC) reducing the electromagnetic influence of BC on the MC.
4. Superconducting transformer (ST) supplying the sample under test with the current up to 50 kA in 1 s.

III. Main Coil (MC)

To simulate the operating conditions of the conductors and/or coils, the MC should meet the following main requirements:
-Central magnetic field B_0 up to ± 8 T.
-Central field ramp rate dB_0/dt up to ± 3 T/s.
-Nominal gap between the turns 250 mm.
-Field inhomogeneity along the sample (± 140 mm length) both in radial and axial directions should not exceed 10%.
-The inner diameter (ID) of MC should not be too large (to make the MC easier in operation and to reduce the cost of conductor).
-The gap between the halves of MC can be varied in the range from the minimum gap to 750 mm.
-The main axis of the MC is horizontal. However, the possibility to change the spatial orientation of the MC axis to vertical should be accommodated in the design.
-For the MC winding, the CICC for the KSTAR central solenoids (CS) will be used.
-The MC will be continuously wound pancakes, making maximum usage of the existing equipment and the experience obtained in manufacturing and testing of the KSTAR CS model coil [3].

A. MC Conductor

The MC will be wound of the Nb3Sn CICC manufactured for the KSTAR central solenoids. The main parameters of the CICC are given in TableI.

B. Optimization of the MC Dimensions

The dual goal of the dimension optimization process is to meet the specification and to minimize the total conductor length needed to wind the MC. The MC dimensions were chosen as a compromise between the cost of material

Manuscript received September 18, 2000. This work was supported in part by the Ministry of Science and Technology of Korea.
[a] The authors are with Samsung Advanced Institute of Technology, Taejon, 305-380, Korea (telephone: 84-42-865-4078, e-mail: baang15 @samsung.co.kr).
[b] The authors are with Kurchatov Institute, 1 Kurchatov's Sq., 123182, Moscow, Russia (telephone7-095-196-9911, e-mail: kev@isssph. kiae.ru).

TABLE I
MC CONDUCTOR MAIN PARAMETERS

PARAMETER	UNITS	VALUE
Outer dimensions:	mm^2	
without insulation		22.3×22.3
with insulation		23.9×23.9
Conduit thickness	mm	2.4
Conduit material		Incoloy 908
Strands number		360
Twisting scheme		3×4×5×6
Wires in the first triplet		2SC+1Cu
Cu/NonCu in SC strand		1.5/1.0
Strand diameter	mm	0.78
Copper cross-section	mm^2	126
He cross-section	mm^2	100
RRR		>100
Strands coating		Cr, 1 μm
Strand AC loss (per ± 3 T cycle)	mJ/cc	<250
n value		>20
CS operating current @ 7.8 T	kA	26.5

and the following considerations.

1. The length of test sample inside the region of homogeneous (±10%) BC field should be of order of the last twisting pitch in the cable. It means that the BC diameter should be about 500mm. And, the BC has to be placed inside the MC. To restrict the coupling between these two coils the MC should be larger than 700 mm.
2. The ID of the MC should be considerably larger than the gap width. From the consideration of field homogeneity, it is preferable to have a coil configuration close to the Helmholtz coil.
3. In KSTAR, the smallest bending radius of the CS conductor is 422 mm. As for the MC, it should not be considerably smaller.

Based on these considerations and field distribution calculations, the MC ID of 740 mm was chosen.

C. MC Configuration Choice

After some preliminary calculations, three configurations of MC were computationally compared in detail (Fig. 1). They have 14, 16 and 18 pancakes in each half, respectively. The calculation results are given in Table II. Though all versions have rather close parameters, the version B was chosen for further design based on the following reasons:

-Although the length needed in the version C is slightly less than those in A and B, its operating current at the central field of 8 T is larger.

-The final choice has been done in favor of B due to (a) somewhat less conductor length and (b) hydraulic considerations (16 pancakes are suitable to divide each half of MC in 4 or 8 parallel hydraulic paths).

In addition to the computation of the central gap size (d_g) of 250 mm between the sections, the data for other d_g values (25 mm and 500 mm) were obtained. The results are given in Table III.

D. MC Fabrication

The MC will be made from the CICC by wind-react-insulate method. Each half of MC will be wound by the continuous pancake winding method with a single piece of cable approximately 846 m long without joints inside the winding pack.

The similar winding machine and technology used for winding of the KSTAR CS Model Coils will be applied for MC manufacturing [3].

E. MC Preliminary Hydraulic Layout

Fig. 2 shows the schematic diagram of MC hydraulics (sensors are not shown here). The total cryogenic capacities available for SSTF is equivalent to ~ 20 g/s of helium mass flow rate. It is reasonable to distribute the available capacity (in g/s) in the following preliminary manner:

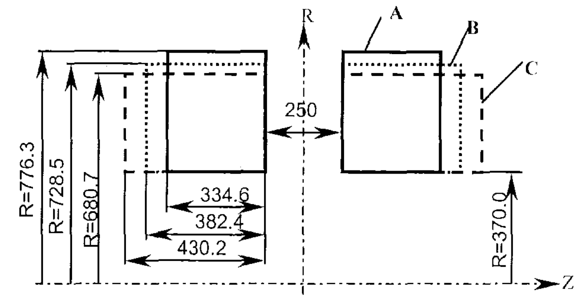

Fig. 1. The comparison of geometry of MC for optimization (unit: mm).

TABLE II
RESULTS OF MC PARAMETER CALCULATION

PARAMETER	UNITS	VERSION A	VERSION B	VERSION C
Inner diameter	mm	740	740	740
Outer diameter	mm	1552.6	1457.0	1361.4
Height	mm	334.6	382.4	430.2
Number of turn in each half		238	240	234
Number of pancakes		14	16	18
Number of layers		17	15	13
Operating current	kA	21.81	22.38	22.85
Fraction of critical current		0.42	0.44	0.46
Length of wire	m	2×857	2×828	2×772
Central magnetic field	T	8.0	8.0	8.0
Max. magnetic field on inner radius	T	9.66	9.71	9.82
Inductance	H	0.14	0.13	0.11
Stored energy	MJ	34.00	32.55	31.30

TABLE III
MC PARAMETERS AT OPERATING CURRENT 22.38 KA

PARAMETER	UNITS	CENTRAL GAP (MM) 25	CENTRAL GAP (MM) 500
Field in the center	T	9.8	5.9
Peak field in windings	T	11.0	9.1
Inductance	H	0.152	0.122
Stored energy	MJ	38.1	30.6
Axial forces between sections	MN	−32	−8.1

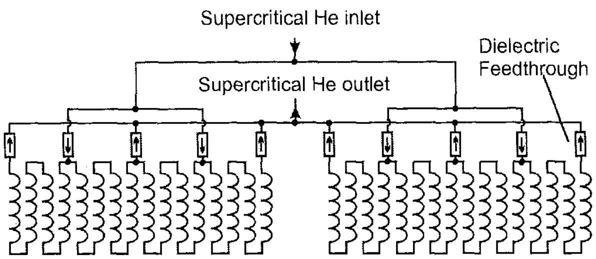

Fig. 2. Hydraulic layout of MC.

MC mass flow rate	12
MC current leads	2.5
BCC (including cryostat losses, current leads and pressurized He circulation)	2.5
ST (including current leads)	1
SS circulation	2
Total:	20 g/s

Therefore, approximately 6 g/s is available for each half of the MC.

IV. Blip and Cancellation Coils (BCC)

The mutual inductance between the BCC system and MC should be close to zero. The BCC should add to (or extract from) the central field 1 T in 50 ms discharge (i.e. dB/dt = 20 T/s) with maximum possible repetition rate. The BCC gap should be adjustable. The BCC geometry should not disturb the 90% field homogeneity along ±140 mm length both in radial and axial directions. BCC are placed co-axially inside MC.

The requirements to the radial gap between the MC and the BCC are inherently contradictory. From the homogeneity considerations the gap should be minimal. The gap should be as large as possible to reduce the electromagnetic influence of the BCC on the MC.

This contradiction leads to two following conclusions:
-The radial buildup of the BCC should be small, and

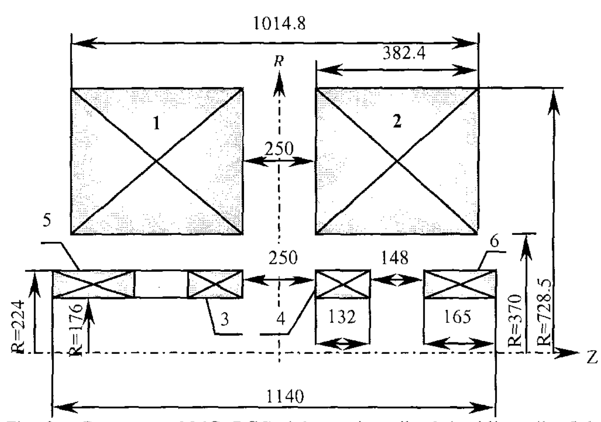

Fig. 3. Geometry of MC+BCC: 1,2 - main coils, 3,4 - blip coils, 5,6 - cancellation coils (unit: mm).

TABLE IV
Main Parameters of BCC

Parameter	Units	Blip coils (3,4 in Fig. 3)	Cancellation coils (5,6 in Fig. 3)
Inner diameter	mm	352	352
Outer diameter	mm	448	448
Height	mm	132	165
Number of turns in each coil		72 (6 layers)	90 (6 layers)
Number of turns in each layer		12	15
Operating current	kA	+7.0	-7.0

the current density should be relatively large.
-The dimensions of the BCC conductor should be relatively small to allow its winding on a relatively small diameter.

The latter restriction makes it difficult to use a mechanically self-supported CICC with a relatively thick conduit wall. The main results of the solution search are as follows:
-Relatively small size CICC tightly packed with Nb3Sn strands will be used. To compensate for its high hydraulic resistance (and hence relatively small mass flow rate) it will be placed in a LHe vessel to add some external pool-boiling cooling. Therefore, a combination of CICC and pool-boiling cooling will be used.
-The high mechanical stresses in the BCC windings will be accommodated by the radial reinforcement structure cooled by pool-boiling LHe.

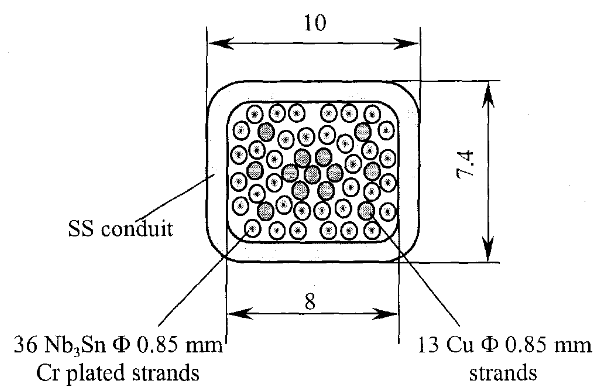

Fig. 4. BCC conductor cross-section (unit: mm).

TABLE V
BCC Conductor Strand Data

Parameter	Units	Value
Strand diameter	mm	0.85 ± 0.01
Amount of copper	%	25 ± 2
RRR		> 100
Number of filaments		25531
Critical current @ 10 T	A	> 400
Hysteresis losses @ ± 3T	mJ/cm^3	< 600
Twist pitch	mm	10 ± 1
Cr plating thickness	μm	1

TABLE VI
BCC CONDUCTOR MAIN PARAMETERS

PARAMETER	UNITS	VALUE
Dimensions	mm^2	10 × 7.4
Conduit thickness	mm	1
Conduit material		SS316LN
Conduit cross-section	mm^2	28.3
Number of sc strands		36
Number of Cu strands		13
Strands cross-section	mm^2	27.8
He cross-section	mm^2	14.5
Copper cross-section	mm^2	12.5
Void fraction	%	34

A. Optimization of the BCC Dimensions

The optimization of the BCC dimensions was performed using the following inputs:
-To simplify the design, assembly, and operation both blip and cancellation coils have the same ID = 352 mm.
-The BCC are layer wound and have even number of layers.

The geometrical characteristics of BCC are presented in Fig. 3 and Table IV.

B. BCC Conductor

The design of the BCC conductor is shown in Fig. 4. The BCC conductors are composed of Nb3Sn strands developed and manufactured by the Bochvar Institute. The strand parameters are given in Table V.

The cabling scheme is as follows. At first, six superconducting strands are cabled around the central copper strand of the same diameter. The cabling pitch is 60 mm. Then, six such subcables are cabled around the central subcable made of 7 copper strands. The second stage cabling pitch is 180 mm. The cable is wrapped with stainless steel tape and is pulled into 10 mm diameter × 1 mm thick stainless steel tube. The joints among tube pieces are made by TIG welding. After the cable is pulled inside the conduit, they are flattened by turks-head machine to its final rectangular shape. The Russian Cable Institute will do the cabling and jacketing. The main parameters of the CICC for the BCC are given in Table VI.

C. Cryogenic Design and Hydraulic Layout of BCC

The cryogenic and hydraulic layouts of the BCC are shown in Fig. 5. The BCC are enclosed in two liquid helium vessels, containing one BC and one CC each. The vessels are fastened to each other using a structure capable of withstanding mechanical forces up to 106 N (attractive or repulsive). The directions of the forces are determined by the relative direction of the currents in the MC and the BCC. The structure allows for the superconducting sample to be installed in the center of the MC as well. Both halves of the BCC cryostat are connected by tubes to an auxiliary helium container placed above the MC. The tubes connected to the BCC cryostat are used to fill with liquid helium, to evaporate helium gas out, and also to accommodate the BCC bus bars. There are two independent superconducting electrical links made in the auxiliary helium container: one between two halves of BC and the other between two halvesof CC.

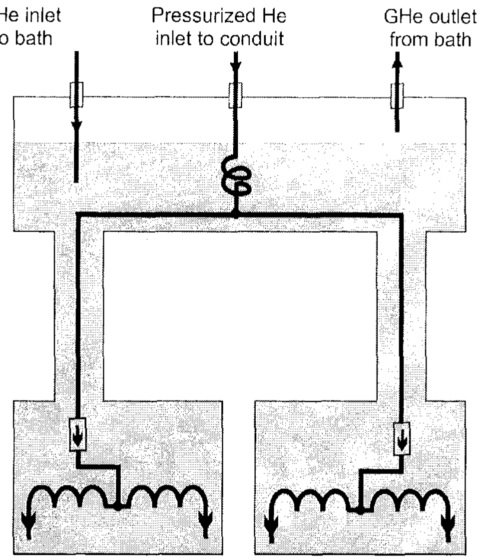

Fig. 5. Hydraulic layout of BCC.

There are two independent current leads and bars for the BC and the CC. Therefore, depending upon the method of connection of the BC and CC current leads, three different modes of operation are possible. One is that the BC and the CC are connected in a way that their total field in the gap is a difference of the BC and CC generated fields. Two, the two halves of the CC are disconnected. Three, the BC and the CC are connected in a way that their total field in the gap is a sum of the BC and CC generated fields.

Pressurized helium passing through the precooler in the auxiliary helium container flows to the BCC cryostats by two parallel streams and then to the central parts of the BC and CC windings. During the flow along the BCC channels, the pressure drops to the value of the BCC cryostat. And, two-phase helium flows out of the coils to the BCC cryostat.

V. CONCLUSION

A set of split magnets to test short samples and joints of the KSTAR CICC is designed. The MC will produce 8 T central field in 250 mm gap distance in 3 T/s charging/discharging process. The BCC will impose 20 T/s ramp rate and 1 T amplitude field on the object under test.

Provisions are made to increase the gap between the halves of the coils up to 750 mm in order to provide capability of testing full size coils for KSTAR project as well as for other superconducting projects to be implemented in Republic of Korea.

REFERENCE

[1] S. Baang, S.H. Baek, H.J. Choi, E.J. Chung, Y.B.Chang et al., "The test facility for the KSTAR superconducting Magnets at SAIT," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp 645-648, 2000.

[2] J.H. Schultz et al., "The KSTAR Superconducting Magnet System," *Proc. of MT-15*, Beijing, China, 1997.

[3] S.H. Kim, Y.H. Kim, Y.H. Kim, H.S. Kim, and K.H. Chung, "Fabrication of the KSTAR Central Solenoid model coil (II)," *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, pp. 232-235, 1999.