Conceptual Design Study for a 16 Tesla Conductor Test Facility, SUCCEX

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***Abstract*—As a part of a conceptual design study for a steady-state demonstration reactor (K-DEMO) of which the major and minor radii are around 6.5 and 2.0 m, respectively, toroidal field magnets which can generate around 8 T at plasma center with a peak magnetic field of ∼16 T are being studied. For conductor tests under such a high magnetic field, a new conductor test facility is required and a conceptual design activity is going on, in parallel. The conductor test facility, named SUCCEX (SUperConducting Conductor EXperiment), will feed the sample with a current up to 100 kA and the sample temperature will be varied from 4.5 K to ∼20 K. Moreover, Sultan-like conductor tests, U-shaped joint-less sample tests will be conducted. The 16-T Nb_3Sn magnet, with a bore of ∼1-m diameter, is divided into three concentric split pairs, inner coil (IC, peak field of 16.4 T), middle coil (MC, 13.6 T), and outer coil (OC, 7.9 T), connected in a series, with a nominal operating current of ∼18 kA. Each split pair coil is made of its own distinctive rectangular shaped cable-in-conduit conductor (CICC). The overall design concept and preliminary results of electro-magnetic, structural, and thermo-hydraulic analysis are presented.**

***Index Terms*—Cable-in-conduit conductor, fusion magnet, high field magnet, test facility.**

I. Introduction

IN ORDER TO accelerate the realization of fusion energy, a variety of efforts are being actively carried out worldwide. For example, Korea also adopted the so called fast track approach [1] and has initiated a conceptual design study for the next generation fusion demonstration power plant (K-DEMO) [2]. One of the key current design philosophies is engineering feasibility. The size of the K-DEMO will be quite close to that of ITER in order to directly utilize the development of tokamak plasma physics during the ITER operation phase [2]. The major radius of the K-DEMO is only slightly increased compared to that of the ITER, to about 6.5 m and the target toroidal field (TF) at the plasma center is ∼8 T, at the moment. More details on the current K-DEMO TF magnet conceptual design can be found elsewhere [3].

The maximum toroidal field of the K-DEMO is expected to be about 16 T. Moreover, the size of the TF magnets need to be substantially enlarged compared to that of the ITER magnets as a vertical maintenance scheme is adopted [3]. This is a quite challenging task and a test facility will be definitely needed. We have already reported on a conceptual design study for such a test facility, so called PUMA (PUlsed MAgnet) [4], for the test of superconducting cable-in-conduit conductors (CICCs), which is basically an upgrade of the KSTAR central solenoid model coil (CSMC). But the maximum field of the PUMA is only 12 T. Here we report on our new plan, SUCCEX (SUperConducting Conductor EXperiment) magnet conceptual design. The overall concept is quite similar to the recently reported ENFASI (ENea FAcility for Superconducting Insert) [5], but the design of SUCCEX is more concentrated on the test of CICCs, especially for the K-DEMO magnets.

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II. Overall Design Concept

The cross-sectional view of the SUCCEX magnet is shown in Fig. 1(a). It is basically a split pair solenoid magnet system which is capable of a long length semi-circle type U-shaped conductor sample test and a SULTAN-like sample [6] test as well. In Fig. 1(a), only the upper part of the magnet is presented. Currently, the cross sections of the K-DEMO TF CICCs are rectangular and it is expected that a bending radius below 0.5 m will be possible. The inner bore size of the SUCCEX magnet was set to 1 m to accommodate possible design changes of the K-DEMO magnets. The semi-circle type conductor sample test is beneficial as there is no joint in the sample so that we don't need to worry about a voltage generation at the joint. The distance between the sample terminal and voltage tap will be good enough for voltage relaxation. But for the K-DEMO central solenoid (CS) CICC, it may not be easy to make a U-shaped sample and furthermore, the facility can support the joint technology development, so that a SULTAN-like sample test mode should be possible. The gap between the upper and lower coils of the SUCCEX magnets is designed to be 140 mm.

The SUCCEX magnet consists of three separate pairs of coils, which were named by their geometric locations: the inner coil (IC), middle coil (MC) and outer coil (OC). The cross-sectional dimensions for each CICC are shown in Fig. 1(b). As there is no central cooling channel in the CICCs, we are planning to limit the maximum liquid helium flow channel length to be less than 100 m, so that every double pancake of each coil will have a helium inlet and outlet. At the moment, the designated helium channel length for each of the coils, IC, MC and OC are 41, 39 and 85 m, respectively. Depending on the fabrication capability, the length of each CICC and the total number of inter coil joints as well, will be decided. Some space is allocated in between the IC, MC and OC for the helium

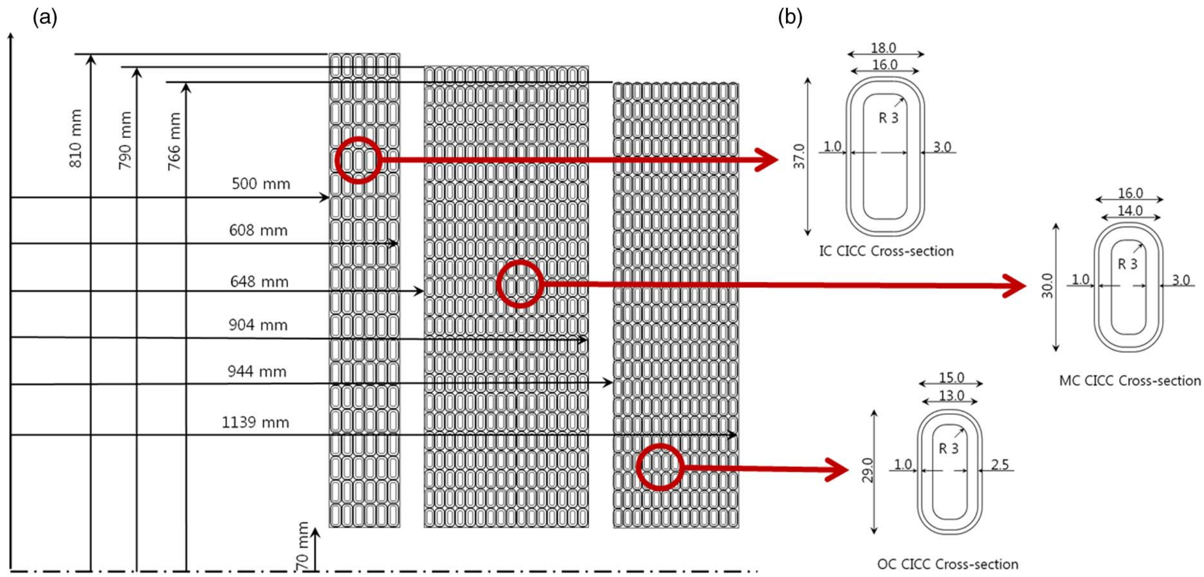

Fig. 1. (a) Cross-sectional view of the SUCCEX magnet (Upper part). (b) Physical dimensions of the CICCs in mm unit. (From top to bottom, inner coil, middle and outer coil CICCs, respectively).

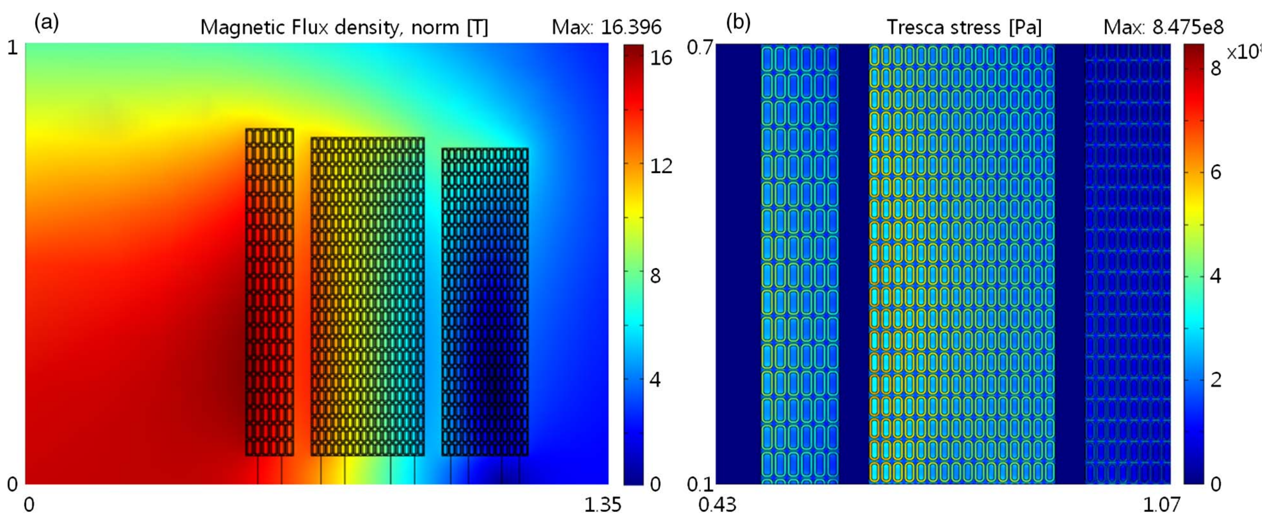

Fig. 2. (a) Magnetic flux density distribution of the SUCCEX magnet. The maximum field is about 16.4 T. (b) Tresca stress distribution of the most loaded region. The numbers on the left and bottom side correspond to the geometric location in m unit.

inlet, outlet and the inter coil joints, and for an easier overall structural assembly.

The nominal operating current is 18 kA. The magnetic field magnitude distribution around the magnet is shown in Fig. 2(a). The peak fields in each coil, IC, MC and OC are 16.4, 13.6 and 7.9 T, respectively. The magnetic field at the center is about 15.33 T. Together with the self field generated by sample current, 16 T test will be possible. The stored magnetic energy is estimated to be ∼370 MJ and the total inductance is about 2.28 H. The temperature margins for all the CICCs are above 1 K and the estimated hot spot temperatures are below 100 K. A preliminary stress analysis also has been carried out. Structural fixtures are not considered. Only the effects of thermal contraction during the cool-down process and the Lorentz force are simulated by using commercial finite element method (FEM) software. However, to prevent a collapse between the upper and lower magnets, stainless steel blocks are inserted for the simulation as depicted in Fig. 2(a). The CICC jacket will be made of AISI 316LN stainless steel and the insulation material is just assumed as G10. The material properties listed in the work of A. della Corte and his coworkers [5] are used for the calculation. The stress analysis results are shown in Fig. 2(b). The Tresca stress is presented to compare with a recently reported result [7]. The maximum Tresca stress is about 850 MPa, which is far less than the static yield stress criteria of ∼1 GPa adopted in ITER [7].

III. CICCs Design Parameters

Preliminary CICCs design parameters are listed in Table I. As shown in Fig. 1(b), rectangular shape CICCs are adopted for all coils and the void fractions are less than 30% in order to reduce mechanical degradation [8]. The jacket thickness is 3 mm for the IC CICC and 3, 2.5 mm for the MC and OC CICCs, respectively. It seems to be good enough to endure the mechanical stress as shown in Fig. 2(b) but further study on the

TABLE I
PRELIMINARY CICC'S DESIGN PARAMETERS

parameters	IC	MC	OC
■ Cable pattern	(3SC)x4x5x6	(2SC+1Cu)x3 x4x6	(1SC+2Cu)x3 x4x6
No. of SC strands	360	144	72
No. of CU strands	-	72	144
■ Void fraction (%)	27.62	26.96	26.96
■ Strand		High Jc (> 2600 A/mm^2) Nb_3Sn Strand 0.82 mm diameter	
Cu/non-Cu		1.0	
RRR		100	
■ Insulation		0.1 mm Kapton (400%, 0.4 mm) + 0.15 mm S-glass fiber tape (400%, 0.6 mm, including voltage tap)	
■ Jacket Thickness (mm)	3	3	2.5
■ Twist Pitch (mm)			
1st stage		50	
2nd stage		110	
3rd stage		170	
4th stage		290	

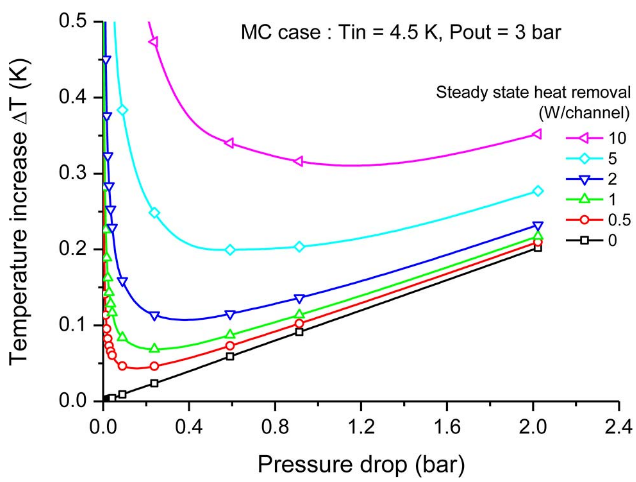

Fig. 3. Steady-state outlet helium temperature variation as a function of pressure drop for various heat loads for the MC CICC.

maximum quench pressure effect needs to be carried out. All CICCs will be insulated by 4 layers of 0.1 mm thick Kapton and 0.15 mm thick S-glass fiber tapes, sequentially. Then they will be impregnated by the standard vacuum pressure impregnation (VPI) process [5]. High critical current density, ~2600 A/mm^2 at 4.2 K and 12 T, rod restack processed (RRP) Nb_3Sn strands will be used for all the CICCs. The diameter of 0.82 mm, including about 2 μm thick Cr plating, and residual resistivity ratio (RRR) of 100 is the candidate superconducting strand. The required superconducting strand will be about 5.6 ton.

In a steady-state operation condition, assuming an inlet temperature of 4.5 K and an outlet pressure of 3 bar, about 10 W per channel cooling power can be achieved within an acceptable temperature increase at the outlet. Fig. 3 shows the outlet temperature variation under various heat loads and pressure drops for the MC section. The corresponding helium mass flow rate is about 10 g/s. The minimum quench energy

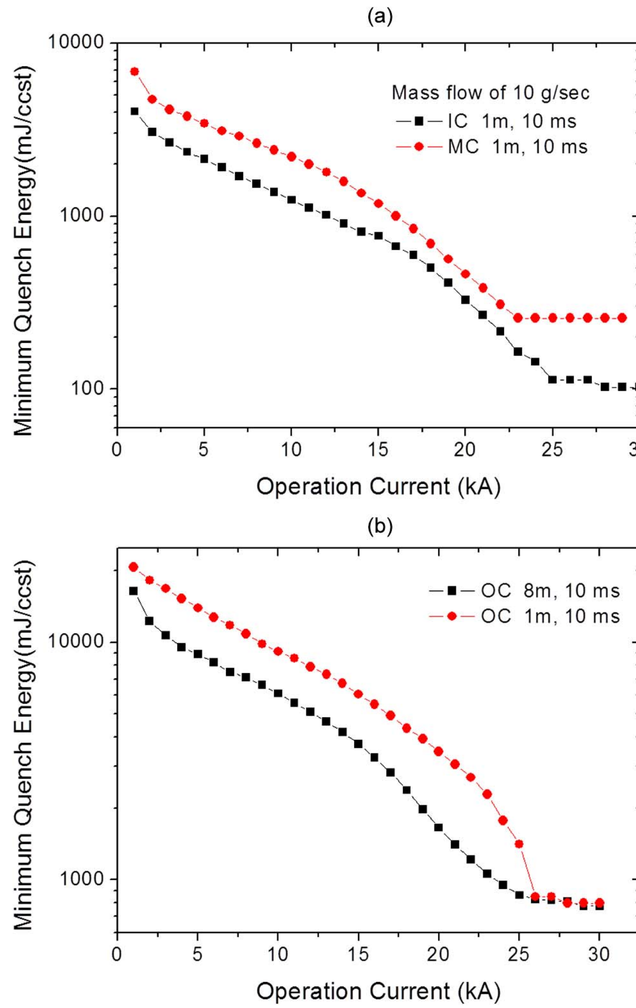

Fig. 4. Minimum quench energy calculated by the code GANDALF. Gaussian dc heat pulse is applied at the center of the CICC's. (a) For the IC and MC CICCs under the mass flow of 10 g/s. (b) For the OC CICC, a stagnant case with different heating zone width.

in this circumstance is well above 500 mJ/ccst for both the IC and MC conductors, as shown in Fig. 4(a). The 1-dimensional simulation code GANDALF [9] was used for the estimation. The applied field is assumed as uniform, the peak field value is used, and a 10 msec heat pulse is applied at the center, 1 m wide. The dc heat pulse is Gaussian shaped and as the current increases, the minimum quench energy is searched [4]. The critical current density is calculated by using the scaling law based on strong-coupling theory [10]. The applied strain on the strands during the operation is assumed to be −0.5%, since the current stress analysis shown in Fig. 2(b) does not separately treat each strand within the CICC. For the OC conductor, where the lowest field is applied compared to the others, the stability margin is quite good enough even for a stagnant case or even if the heating zone is increased to 8 m wide, as shown in Fig. 4(b).

Further works are still going on. For example, further optimization study is required, ac loss estimation will be initiated and overall structural fixtures need to be considered. The winding pack design is almost finished. Currently, a continuous winding scheme is being considered as shown in Fig. 5, which was already discussed for the PUMA upgrade [4]. In each layer, a 90 degree sector shall be allocated for a turn transition

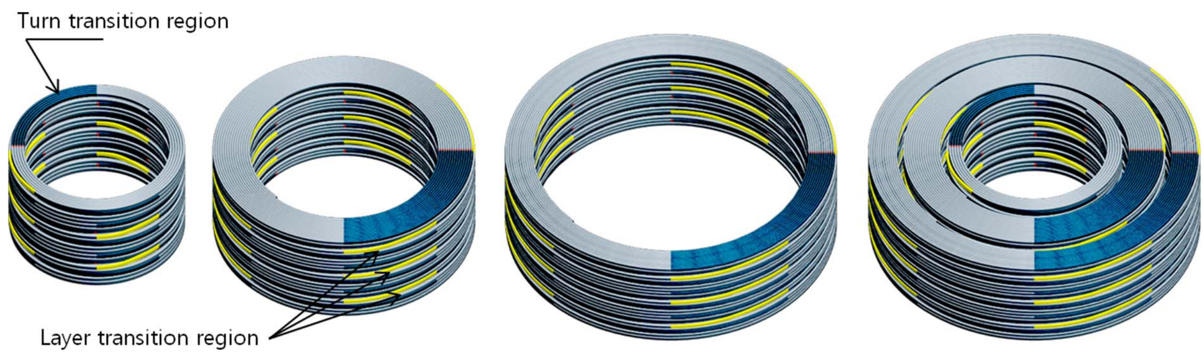

Fig. 5. Continuous winding scheme for the SUCCEX magnet (From left to right, IC, MC, OC, and assembled upper part). Turn transion and layer transion regions are colored blue and yellow, respectively.

(colored blue in Fig. 5) and an additional 45 degree sector, for a layer transition (yellow colored region).

IV. Summary

In parallel with the 16 T K-DEMO TF superconducting magnet, a conceptual design study for the relevant test facility is being carried on. The overall design concept for the SUCCEX magnet has been decided. It consists of three concentric split pairs of coil, which will generate a field of ∼16 T. Both the U-shaped joint-less sample and SULTAN like sample tests shall be carried out. The designed magnet bore size is 1 m diameter, at the moment. Preliminary rectangular shaped CICCs design parameters are presented together with some electro-magnetic, stress and stability analysis results. A possible winding scheme is also discussed, however, a more detailed design study, such as quench analysis, ac loss estimation, is needed and is going on.

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