Manufacture and Test of Bi-2212 Cable-in-Conduit Conductor

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***Abstract*—The CFETR, "China Fusion Engineering Test Reactor," is a new tokamak device. Its magnet system includes the toroidal field (TF), central solenoid (CS), and poloidal field coils. The main goal of this study is to build a fusion engineering tokamak reactor with fusion power of 50–200 MW and self-sufficiency by blanket. The maximum field of CS and TF will get around 15 T, which is much higher than that of other reactors. New materials could be used to develop the magnet technology for the next generation of fusion reactors. Bi2Sr2CaCu2Ox is considered as a potential material for the superconducting magnets. An R&D activity is running at ASIPP for the feasibility demonstration of cable-in-conduit conductor based on the Bi2212 wire. One subsize conductor cabled with 42 wires was designed and manufactured. In this paper, the manufacturing procedures and first test results of Bi-2212 conductor samples are described in details, including wire specifications, cabling and compaction process, conductor heat treatment, as well as test results on ac loss and critical current.**

***Index Terms*—Bi2212, conductor, critical current.**

I. Introduction

CHINESE Fusion Engineering Test Reactor (CFETR) is a new tokamak device in China. The geometry and target parameters of plasma are given according to physics design [1], [2]. The preliminary basic parameters of CFETR are shown in Table I [3], which includes two phases. The magnet system for CFETR consists of sixteen Toroidal Field coils (TF), a Central Solenoid (which consists of 6 coils) (CS) and six Polo-dial Field coils (PF) [4], as shown in Fig. 1. Magnet is the core of CFETR, whose technology is a challenge, especially for CS and TF coils. The maximum field of CS and TF will be much higher than present devices, which could reach to 16 T in Phase II. New materials have been considered to apply for the next generation magnet system.

TABLE I
Preliminary Basic Parameters of CFETR

Item	Parameters	
	Preliminary	Upgrade
B_t	4.5–5 T	∼7.5 T
I_p	8–10 MA	∼14 MA
R	5.7 m	6 m
a	1.6 m	2 m

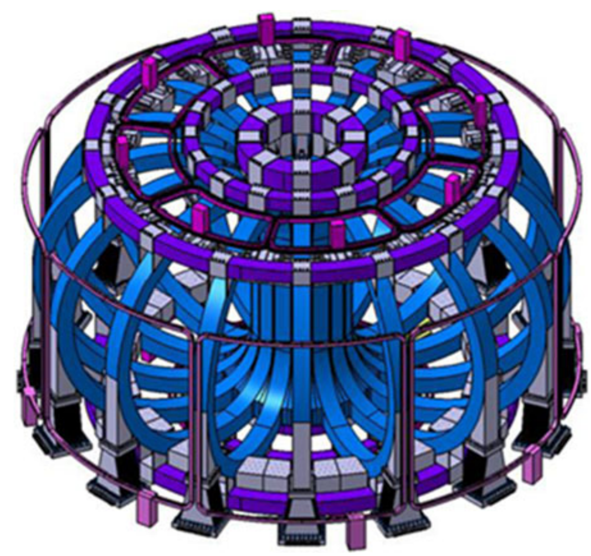

Fig. 1. Demonstration of magnet system for CFETR.

New opportunities at magnetic fields above 20 T are beyond the reach of present Nb-based superconducting materials. Bi2212 is a promising material for the development of superconducting magnets in the 25–30 T range [5], [6]. Compared to Nb_3Sn, Bi2212 has a bigger temperature margin during operation under peak magnetic field in the range of 12–15 T of the magnet system for fusion reactor. It is economical for next generation of fusion reactor to use Bi2212 conductor, considering the possibility of high operational temperature (10–30 K) to get rid of cooling with liquid Helium, even though the cost of Bi2212 is higher than Nb_3Sn at present. Bi2212 is also the only cuprate superconductor that can be made into round wire

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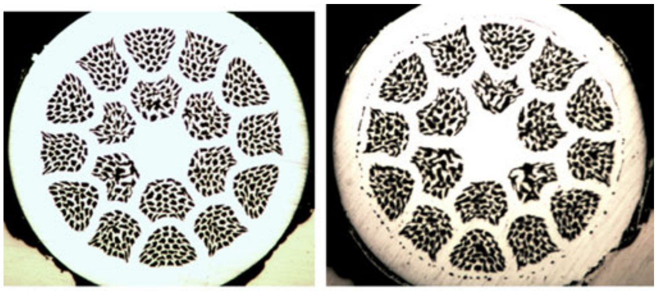

Fig. 2. The cross-sectional micrographs of unreacted (left) and reacted (right) Bi2212 RW.

TABLE II
PARAMETERS OF THE TESTED BI2212 WIRE

Material	Ag–0.2wt% Mg sheathed Bi-2212
Diameter	1.0 mm
Filament configuration	19 × 18
Ag/Mg:Ag:Bi2212	1.8:1:0.9
I_c at 0 T, 4.2 K	about 400 A
I_c at 12 T, 4.2 K	about 146 A

(RW), which makes it possible to develop a CICC with Bi2212 RW [7], [8]. At present, cable-in-conduit conductor (CICC) is mainly made of Nb_3Sn and NbTi strands, such as ITER conductors [9], [10]. In 2003, JAEA develop one Bi2212 cable with 800 wires. Its I_c achieved 10 kA at 12 T @ 20 K [11]. One characteristic of Bi2212 is that it needs to be aged with O_2. It's difficult to be performed for the conductor because it has the jacket [12]. But it needs to develop the CICC for fusion application in the future.

In order to develop the technology of Bi2212 CICC, one small conductor with 42 wires was manufactured. Because there is no detailed design for CFETR conductors, the small conductor layout was designed with 3 stages and short twist pitch, which referred to ITER conductors [9]. It is the first R&D step for CFETR conductor, which is to verify the feasibility of Bi2212 CICC. In this paper, the manufacturing procedures were introduced, including wire, cable, heat treatment and conductor. The conductor was tested at 4.2 K with self back field. The results show a good performance of the conductor, which will provide solid basis for further development of full size conductor.

II. BI2212 WIRE AND CABLE

Bi2212 RW samples were manufactured using the powder in tube (PIT) method by Northwest Institute for Non-ferrous Metal Research (NIN). The cross-sectional micrographs are shown in Fig. 2 for the wires before and after heat treatment. The parameters of wires are listed in Table II and Fig. 2.

The Bi2212 conductor will be mainly used for high magnet, e.g. CFETR TF or CS. The performance degradation is the main issue. The layout design of cable is important. The short twist pitch (STP) design was used for ITER CS conductor, which solved the problem of performance degradation due to strain. The layout of Bi2212 cable referred to the ITER CS [9]. The parameters of Bi2212 cable is shown in Table III.

The cable is with a 3-stage layout, and no central spiral, and thinner wraps like those used in ITER cable. The total number

TABLE III
PARAMETERS OF CABLE

Item	Parameter
Layout	$2 \times 3 \times (6+1)$
Twist pitch	
Stage 1	20 mm
Stage 2	50 mm
Stage 3	87 mm
Diameter (no compaction)	10 mm
Diameter (after compaction)	9.0 mm

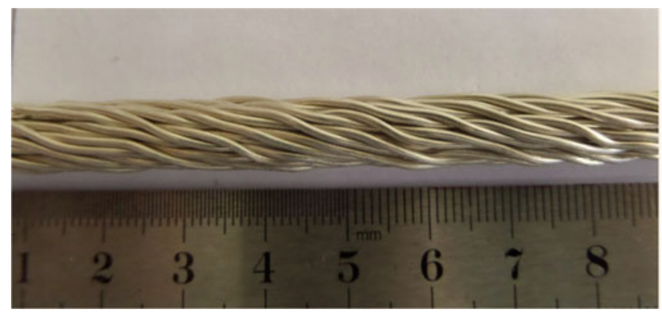

Fig. 3. The final Bi2212 cable (the 3rd stage).

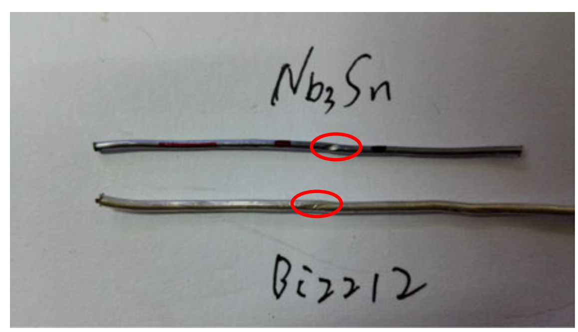

Fig. 4. Indentation on Nb_3Sn and Bi2212 wire in STP cable.

of wires is 42. The cable was manufactured in Changtong Company. During the first cabling experiment, it was found that the wire was easily broken during bending. So the wire was pre-heat treated at low temperature to reduce the hardness. Because of the low mechanical properties of Bi2212 wire [13], the cabling tension was fixed less than 10N. The final cable was compacted by rollers with special shape in order to reduce the damage on the cable surface. The final cable is shown in Fig. 3.

The STP layout causes the big stiffness. The wire inside cable is easy to be damaged during cabling, e.g. STP cable with Nb_3Sn, as shown in Fig. 4. The maximum depth of indentation in Nb_3Sn STP cable is about 0.2 mm [14]. In order to avoid the serious damage on wire, the diameter of Bi2212 cable was compacted to $8.5 \sim 9$ mm. the destructive examination was made on compacted cable, and no serious damage was found, shown in Fig. 4. The depth of indentation is less than 0.05 mm. From the former research, there is no obvious degradation for these kinds of wire [15].

During conductor compaction, the cable inside tube was also kept the same diameter. There is no further compaction for the cable.

Fig. 5. Photo of manufactured Bi2212 conductor with SS jacket outside and Ag tube in between.

TABLE IV
DIMENSIONS OF CABLE AND TUBES

Item	Dimension before compaction	Dimension after compaction
Outer dimension of cable	10 mm	9.0
Ag tube	15 × 1.75 mm	12.6 × 1.8 mm
SS tube (316L)*	25.5 × 4.5 mm	22.2 × 4.7 mm

*Note: the dimension of SS tube is mainly to meet the requirement of compaction machine.

There is no serious damage for the wire in the whole process of conductor manufacturing by visual inspection. The present indentation on wire could not have impact on the performance. But it needs to be pointed that the damaged state of wire should be kept as less as possible.

III. CONDUCTOR

Like other CICCs, the Bi2212 cable needs to be inserted into jacket. But the Bi2212 needs heat treatment in an Oxygen free environment. In the process, the wire cannot contact with general stainless steel, e.g. 316L or 316LN, since it could reduce the performance of Bi2212 during heat treatment. In order to avoid the problem, one Ag tube was used as isolated layer between cable and jacket for the sake of heat treatment, shown in Fig. 5.

The dimensions of cable, Ag and SS tube are shown in Table IV.

The cross section of Bi2212 conductor is shown in Fig. 6.

After manufacturing, the conductor was heat treated at $T_{\max} = 890\,^\circ\mathrm{C}$ for 30 minutes. The temperature reduced to 830 °C with the speed of $5\,^\circ\mathrm{C/h}$, and then heat treated at $T_{\max} = 830\,^\circ\mathrm{C}$ for 48 hours in a standard oxygen environment.

Before conductor heat treatment, five wire samples were heat treated to verify the furnace, and as a witness wire for I_c performance.

IV. TESTING RESULTS AND DISCUSSIONS

In this section, the test results were given. As the testing capacity limitation of our test facility, only critical current with self field was measured.

The total length of tested sample was 500 mm, and 200 mm long conductor was in testing zone. The sample was fully soldered together with one bent ITER CC conductor, as shown in Fig. 7. The current was provided by superconducting transformer (up to 20 kA), as shown in Fig. 8.

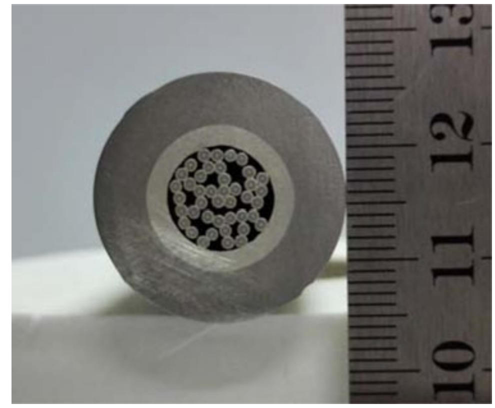

Fig. 6. Cross section of Bi2212 conductor.

Fig. 7. The soldered joint.

The testing was performed in liquid Helium. The test result is shown in Fig. 9. The criterion is selected to $1\ \mu\mathrm{V/cm}$. From the results, the critical current of Bi2212 conductor is 13.1 kA at self-field and 4.2 K.

The distribution of self field was computed, shown in Fig. 10. The maximum self field is 0.41 T.

The conductor was subjected to cabling and compaction. The wires inside conductor endure some mechanical force, whose performance could decrease possibly. Five wire samples were prepared to evaluate the performance conductor. The wire samples were tested without back-ground field. The lowest critical currents at 0 T are about 540 A.

After computation, the evaluated critical current of conductor is about 15.4 kA, as shown in Fig. 10. There is around 15% degradation on I_c for the wire inside conductor after cabling and compaction. This could be partly caused by wire deformation during manufacture. But the heat treatment could be the mainly issue. Firstly, the witness samples were not heat treated together with conductor because of special aging method for conductor. Secondly, the five witness samples showed

Fig. 8. Assemble conductor sample for I_c test at self-field and Liquid He.

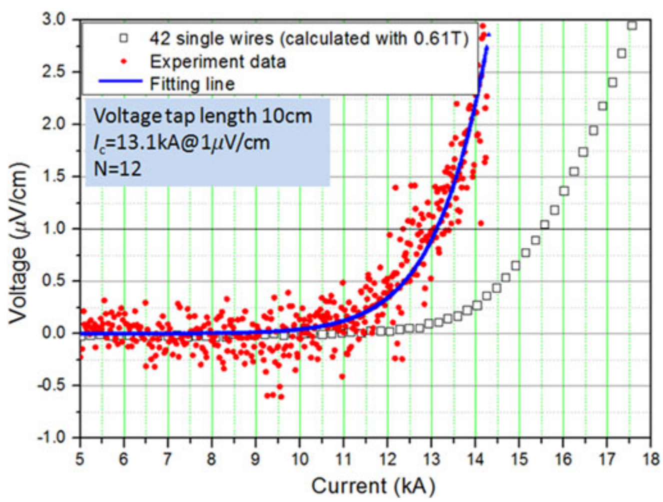

Fig. 9. Testing results of I_c for Bi2212 conductor with 42 strands.

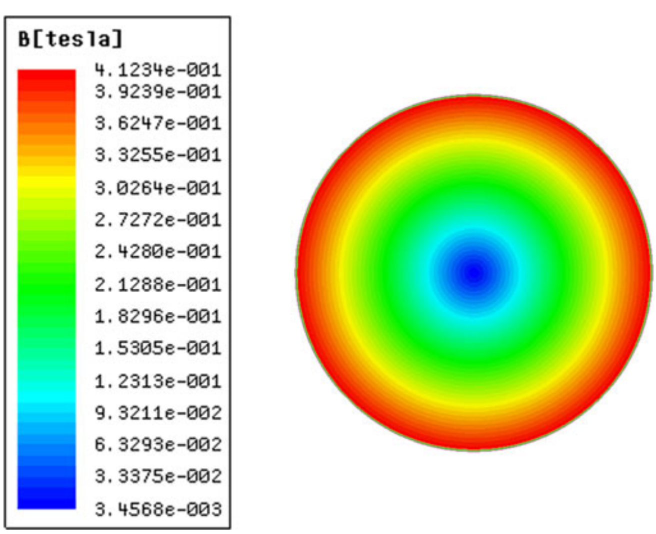

Fig. 10. Analysis on self field with FEM.

different performance. The maximum difference is about 100 A at 0 T. For the comparison, the lowest wire performance was chosen. Further investigations on conductor heat treatment will be conducted to achieve better results.

One issue on conductor heat treatment is the jacket. For the Bi2212 conductor, it is impossible put the whole conductor in O_2 during heat treatment, because the jacket could block the penetration of O_2 in Bi2212 cable, especially for long length. So the O_2 was considered to go through the inner conductor, which could make the O_2 contact with Bi2212 cable easily. But this method needs to consider the isolation between Bi2212 and 316L/316LN jacket. The conductor needs compaction to achieve the required dimension. So the material of isolation should have good mechanical properties. Ag has good mechanical properties and is soft enough. Ag tube is one good choice, and the thickness had better more than 1.5 mm, because thinner Ag tube could be folded during compaction. In future, we will find and try other materials.

At present, the performance of conductor made of Bi2212 wire remains in low level. In future, the high pressure (e.g. 50 atm) heat treatment with O_2 will be considered for Bi2212 conductor. But it is the main challenge for development of conductor. According to our preliminary research, the conductor with jacket outside was heat treated with O_2 going through the inner jacket. The method could be considered as the development of future conductor. In the next step, we will develop the new Bi2212 conductor with high pressure heat treatment.

V. Conclusion

One sub-size Bi2212 conductor was developed. The conductor was manufactured with 42 twisted Bi2212 wires with 3 cable stages. The cable was inserted into one Ag tube with aim of well performed heat treatment, and then inserted on SS tube. The conductor was heat treated in O_2 with normal pressure (1 atm). The critical current was measured at 4.2 K and self field, which reached to 13.1 kA. The evaluated critical current is 15.4 kA with witness wire, indicating around 15% conductor degradation on I_c after the whole process of conductor manufacture. Further investigations on conductor manufacture will be conducted to achieve better conductor performance, especially for heat treatment. Moreover, the conductor with high pressure heat treatment will be manufactured and tested to compare to the normal one.

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