Advanced Fusion Technologies Developed for JT-60 Superconducting Tokamak

A. Sakasai, S. Ishida, M. Matsukawa, N. Akino, T. Ando, T. Arai, K. Ezato, K. Hamada, H. Ichige, T. Isono, A. Kaminaga, T. Kato, K. Kawano, M. Kikuchi, K. Kizu, N. Koizumi, Y. Kudo, G. Kurita, K. Masaki, K. Matsui, Y. M. Miura, N. Miya, Y. Miyo, A. Morioka, H. Nakajima, Y. Nunoya, A. Oikawa, K. Okuno, S. Sakurai, T. Sasajima, K. Satoh, K. Shimizu, S. Takeji, K. Takenaga, H. Tamai, M. Taniguchi, K. Tobita, K. Tsuchiya, K. Urata, J. Yagyu

Japan Atomic Energy Research Institute, Naka Fusion Research Establishment
Naka-machi, Naka-gun, Ibaraki-ken, 311-0193 JAPAN

E-mail: sakasai@naka.jaeri.go.jp

Abstract. The modification of JT-60 is planned as a full superconducting tokamak (JT-60SC). The objectives of the JT-60SC program are to establish scientific and technological bases for the steady-state operation of high performance plasmas and utilization of reduced-activation materials in economically and environmentally attractive DEMO reactor. Advanced fusion technologies relevant to DEMO reactor have been developed in the superconducting magnet technology and plasma facing components for the design of JT-60SC. To achieve a high current density in a superconducting strand, Nb_3Al strands with a high copper ratio of 4 have been newly developed for the toroidal field coils (TFC) of JT-60SC. The R&D to demonstrate applicability of Nb_3Al conductor to the TFC by a react-and-wind technique have been carried out using a full-size Nb_3Al conductor. A full-size NbTi conductor with low AC loss using Ni-coated strands has been successfully developed. A forced cooling divertor component with high heat transfer using screw tubes has been developed for the first time. The heat removal performance of the CFC target was successfully demonstrated on the electron beam irradiation stand.

1. Introduction

The modification of JT-60 is planned as a full superconducting tokamak (JT-60SC) [1, 2]. The objectives of the JT-60SC program are to establish scientific and technological bases for the steady-state operation of high performance plasmas and utilization of reduced-activation materials in economically and environmentally attractive DEMO reactor [3]. The plasma current of JT-60SC is I_p = 4 MA, the toroidal field is B_t = 3.8 T, the major radius is R_p = 2.8 m and the minor radius is a_p = 0.85 m (the elongation κ_{95} ~ 1.8, the triangularity δ_{95} ~ 0.35). Comparison of the cross-sectional views between present JT-60U and designed JT-60SC is shown in Fig. 1 along with the present perpendicular NBI. In JT-60SC, primary heating and current drive are conducted using NBI system consisting of 2 N-NBI units, 8 perpendicular and 4 tangential P-NBI units and ECRF system. The superconducting coil system is composed of toroidal field (TF) coils, central solenoid (CS) and equilibrium field (EF) coils. A magnet stored energy of the TF coils for JT-60SC is estimated to be 1.7 GJ, which is the largest value in comparison with main coils constructed so far and in construction now.

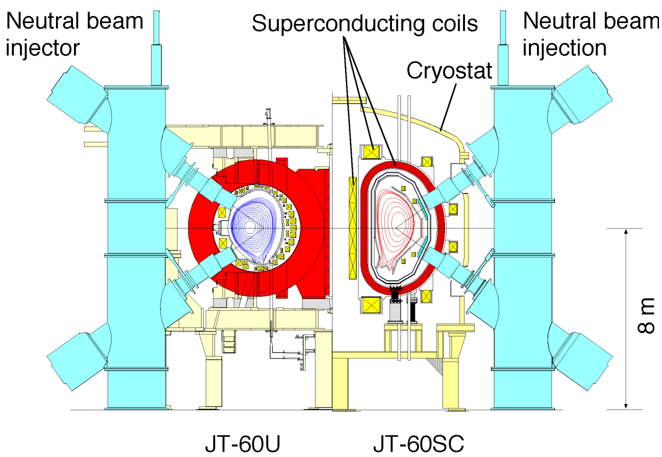

Fig. 1. Cross-sectional views of the present JT-60U and the designed JT-60SC.

Advanced fusion technologies relevant to DEMO reactor have been developed in the superconducting magnet technology and plasma facing components for the design of JT-

60SC. A Nb_3Al strand of an 11 km length with a high copper ratio of 4.1 has been newly manufactured for the TFC of JT-60SC. The R&D to demonstrate applicability of Nb_3Al conductor to the TFC by a react-and-wind technique have been carried. A full-size NbTi conductor with low AC loss and reduced cost required for the EF coils has been successfully developed. A forced cooling divertor component with high heat transfer using screw tubes has been developed and tested by the electron beam irradiation.

2. Development of Nb_3Al Superconducting Magnet

2.1 Design of Toroidal Field Coils for JT-60SC

The TF coil system of the JT-60SC has been designed to consist of 18 “D” shape coils, which have a height of 6.0 m and a width of 3.9 m. The maximum magnetic field (B_{max}) in the windings is 7.4 T at an operational current (I_{op}) of 19.4 kA. Table I shows the main parameters of the TF coils [4].

TABLE I: MAIN PARAMETERS OF THE TF COILS.

Overall Height / Width	6.0 m / 3.9 m
Number of Coils	18
Nominal Operating Current	19.4 kA
Max. Magnetic Field at	7.4 T
Total Coil Current	54 MAT
Total Stored Energy	1.7 GJ
Max. Volt to Ground	13.5 kV
Weight per Coil	23.5 ton

The Nb_3Al conductor is a promising superconductor for the magnets of JT-60SC, because of its low strain sensitivity on superconducting performances. A stainless steel (SS316LN) conduit is adopted for JT-60SC, because Incoloy 908 requires careful control of the oxygen concentration during heat treatment. The superconducting strand of Nb_3Al or Nb_3Sn with relatively high critical current density (Jc) is required for JT-60SC. The current density of the cable-in-conduit (CIC) conductor for the TFC of JT-60SC (B_{max} = 7.4 T) is relatively higher than that for the TFC of ITER (B_{max} = 11.8 T). Therefore, a superconducting strand with high Cu/non-Cu ratio is required to attain a highly stable coil. The allowable Cu/non-Cu ratio of the strand for the TFC of JT-60SC was estimated to be around 4. The Cu/non-Cu ratio for a Nb_3Al Insert Coil under the framework ITER-EDA was 1.5. Nb_3Al strands with a copper ratio of > 2 have not been developed yet. The development of the Nb_3Al strand with a high J_c gives a compact magnet design and substantial cost saving because of the reduced amount of the superconducting materials.

In addition, the Nb_3Al conductor allows us to fabricate the TFC by a react-and-wind technique. The TFC of JT-60SC was designed to make it possible to be fabricated by the react-and-wind technique for superconducting magnet technology of the large-scale magnet fabrication such as the TFC of SSTR [5].

The maximum bending strain of the TFC conductor for JT-60SC becomes 0.4%, which does not make large decrease of Jc. The bending strain ε is defined as follows,

$$\varepsilon = \frac{D}{2R}, \qquad (1)$$

where D is the diameter of the cable, R is the curvature radius of bending. The TF coil has consists of 7 double pancakes with 154 turns. The conductor is designed to be a squired CIC conductor installed a cable, which consists of 216 Nb_3Al strands and 108 pure copper wires into a squired stainless steel conduit [6].

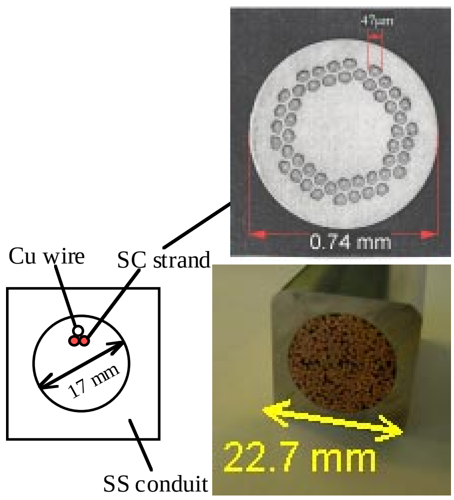

Fig. 2. Views of Nb_3Al strand and full-size conductor developed for the TFC of JT-60SC.

2.2 Development of 30 m length Nb_3Al Full-size Superconductor

The development of a Nb_3Al strand with a high copper ratio of 4.1, which was the optimizing value to the magnetic field of 7.4 T for the TF coil, was carried out. A Nb_3Al strand of an 11 km length in total was successfully drew down to 0.74 mm diameter (filament diameter of 47 μm) without breakage by increasing the quality of jelly roll structure (Fig. 2). A procedure for finishing a long piece of long Nb_3Al strand with a high copper ratio of 4.1 has been established [7].

This strand was coated with 2 μm Cr and cabled together with a pure copper wire. The superconducting cable inserted into a 30 m length conduit with two butt-welded joints, which was composed of three unit conduits of a 10 m length. The CIC conductor has the same configuration as the designed full-size TFC conductor. Figure 3 shows a view of the 30 m length Nb_3Al full-size conductor in process of the cable insertion. The non-Cu J_c of developed Nb_3Al strands was 1914 A/mm^2 at 7.4 T, 4.2K from the J_c measurement. Because of the thermal contraction effect from the SS conduit, the measured critical current (I_c) of the conductor was decreased to 98% of I_c estimated from the product of the I_c in strands by the number of strands. In the case of the Nb_3Sn CIC conductor, the decrease of I_c was estimated to be 79% [6]. This result indicated the low strain sensitivity of Nb_3Al conductor in comparison with the Nb_3Sn conductor.

Fig. 3. A view of the 30 m length Nb_3Al full-size conductor in trial manufacture.

2.3 R&D for Demonstration of a React-and-wind Technique

In the design of JT-60SC, the react-and-wind technique with the Nb_3Al CIC conductor using stainless steel was studied for the TFC. As an advanced superconducting magnet technology relevant to the large-scale magnets of DEMO reactor, Nb_3Al superconductor is an advantageous candidate because of the low degradation of the critical current density by the thermal and bending strain [8]. From viewpoints of fabrication reliability and cost, a react-and-wind technique is essential for the fabrication of large TFC (ex. the size of 11 m × 16 m in SSTR). The large TFC can be easily fabricated with high reliability and reduced cost by the technique. Furthermore, the heat treatment time of Nb_3Al is around one third that of Nb_3Sn. Heat treatment of Nb_3Al conductor can be completed in short time (50 hr at 750°C). By the technique without a huge size furnace, an effective cost reduction for the fabrication of the large magnet is expected as compared with a wind-and-react transfer technique.

A half of the 30 m length Nb_3Al full-size conductor was used to fabricate a D-shaped double layer coil with the same bending strain of 0.4% as the fabrication of the TFC of JT-60SC (Fig. 4). In this fabrication by the react-and-wind technique, spring back of the conductor in the winding process should be taken into consideration. Due to existing spring back, an overbending is required to form the

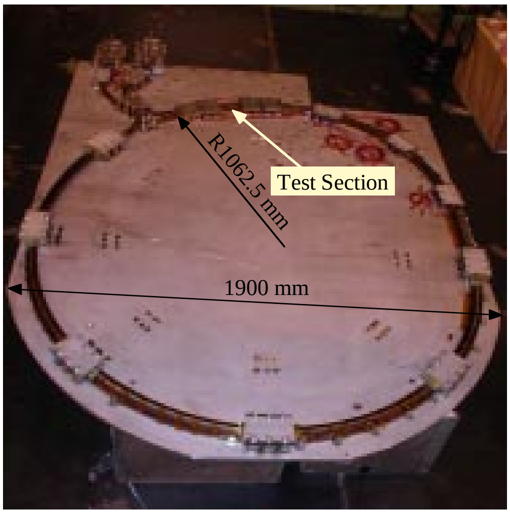

Fig. 4. A Nb_3Al D-shaped double layer coil for the demonstration of a react-and-wind technique.

CIC conductor into a designed curvature in the bending process.

The fabrication process of the D-shaped double layer coil by the react-and-wind technique is as follows. 1) Bending the Nb_3Al conductor into a radius of 2125 mm by a roller bender. 2) Bending two terminal parts to a radius of 300 mm, which is the same curvature as the terminal joint of the designed TFC, and S-shape with a radius of 150 mm by a bender with three points. 3) Heat treatment (flat top of 50 hr at 750± 5°C) with a ring-shaped muffle case in a furnace to precisely control heating temperature. 4) Bending the conductor into a designed shape (test section: R1062.5 mm) by a roller bender and a bender with three points. 5) Shaping into the D-shaped double layer. 6) Fabrication of terminal joints.

After the heat treatment, a compression stress of about 2 tons applied the cable with thermal contraction effect from the SS conduit. However, the cable in the terminal part moved only 1.6 mm. This result indicated that a locking of the cable in the conduit with the curvature of R300 mm was confirmed. Although the bending strain of the conductor at the test section (position of magnetic field application) became 0.40%, the bending strain in the load condition with the overbending became 0.57%. In the other small curvature positions, the maximum bending strain in the load condition was limited to 0.8%. The spring back was estimated to be 197 mm (load condition: R880 mm, free condition: R1077 mm) in the final bending process. The D-shaped double layer coil will be tested to verify the react-and-wind technique with I_c measurement in December 2002. The effect of the overbending in the fabrication process on superconducting performances can be investigated.

3. Development of Reduced Cost NbTi Conductor

A NbTi conductor is applied for equilibrium field (EF) coils in JT-60SC because of relatively low magnetic field (< 5 T) in the windings. For the EF coils, the conductor with low AC loss is required. The NbTi strands coated with Cr can realize low AC loss [9]. However, the Cr coating is rather expensive. Development of NbTi conductor with low cost coating instead of Cr coating is an important issue. A full size NbTi conductor composed of 2 μm Ni-coated strands was newly fabricated. From the AC loss measurement of the conductor, a coupling time constant was measured to be 140 ms (Fig. 5). The Ni-coated NbTi conductor can be adopted for JT-60SC. The Ni coating is the reference candidate for the poloidal field coils of ITER. Therefore, this conductor can be also applied to ITER. The fabrication of reduced cost NbTi conductor has been established.

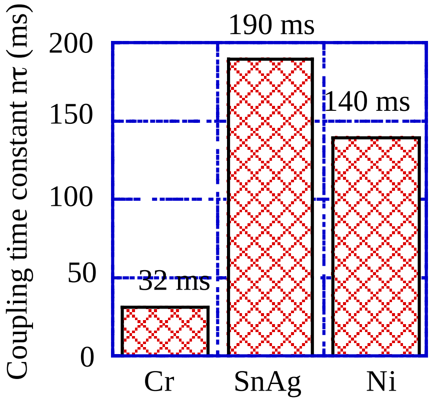

Fig. 5. The coupling time constant for Cr, SnAg and Ni-coated NbTi conductors.

4. Development of Forced Cooling Divertor Component with High Heat Transfer

Realization of the forced cooling divertor under a high heat load in the range of 10 - 15 MW/m^2 is one of the most important issues for JT-60SC [10]. In the activity of the ITER divertor R&D, various types of the divertor targets have been developed using swirl tubes. The critical heat flux of the screw tube (M10, fin pitch of 1.5 mm) near the boiling region was evaluated so far [11]. It was found that the screw tube had a higher heat transfer than the swirl tube. However, the heat transfer coefficient of the screw tube has not been evaluated yet.

A more simplified structure can be applied for the JT-60SC divertor. A prototype flat CFC (carbon fiber composite) target with screw tubes, which had helical fins like a nut, was manufactured aiming at cost-effectively manufactured divertor target with a sufficient heat removal performance for JT-60SC (Fig. 6). The CFC (CX-2002U) tiles were brazed onto a

Cu-alloy heat sink with a 1-mm thick Cu-interlayer at one step of heat treatment (870˚C in a vacuum furnace). Prior to the brazing step, four screw tubes were made directly in the Cu-alloy heat sink [12].

The heat removal performance of the CFC target was successfully demonstrated on the JAERI Electron Beam Irradiation Stand. The evaluated heat transfer coefficient of the screw tube (M10, fin pitch of 1.5 mm) at the non-boiling region was roughly 3 times higher than that of the smooth tube of 10 mm inside diameter. This corresponds to 1.5 times that of the swirl tube of 10 mm inside diameter with a tape twist ratio of 3. A heat cycle test of 10 MW/m^2 showed that the CFC target with the screw tubes could withstand for 1400 cycles. These results indicate that the divertor target plate with the flat CFC tiles and the screw tubes is a promising candidate for the JT-60SC.

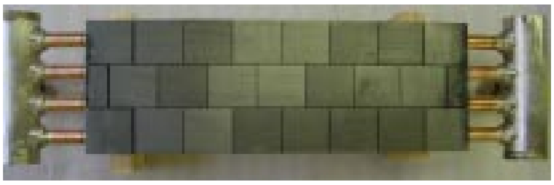

Fig. 6. A prototype flat CFC target with heat removal of 10 MW/m^2.

5. Conclusions

The modification of JT-60 is planned as a full superconducting tokamak (JT-60SC). Advanced fusion technologies relevant to DEMO reactor have been developed in the superconducting magnet technology and plasma facing components for the design of JT-60SC. To achieve a high current density in a superconducting strand, Nb_3Al strands with a high copper ratio of 4 have been newly developed for the TFC of JT-60SC. The R&D to demonstrate applicability of Nb_3Al conductor to the TFC by a react-and-wind technique have been carried out using a full-size Nb_3Al conductor. The D-shaped double layer coil fabricated by the react-and-wind technique in consideration of spring back will be tested to verify the fabrication technique in December 2002. A full-size NbTi conductor with low AC loss using Ni-coated strands has been successfully developed. A forced cooling divertor component with high heat transfer using screw tubes has been developed for the first time. The heat removal performance of the CFC target was successfully demonstrated on the electron beam irradiation stand.

Acknowledgments

The authors would like to thank the members of the Japan Atomic Energy Research Institute who have contributed to the JT-60 project, and appreciate contributions from Superconducting Magnet Laboratory and NBI Heating Laboratory.

References

[1] S. Ishida et al., Proc. of 19th IEEE/NPSS Symposium on Fusion Engineering, Atlantic City 2002, p. 276.
[2] A. Sakasai et al., Proc. of 19th IEEE/NPSS Symposium on Fusion Engineering, Atlantic City 2002, p. 221.
[3] S. Ishida et al., IAEA-CN-94/FT/2-5, in this conference.
[4] T. Ando et al., IEEE Transactions on Applied Superconductivity, 12 (2002) 500.
[5] M. Kikuchi, Nucl. Fusion 30 (1990) 265.
[6] K. Kizu et al., IEEE Transactions on Applied Superconductivity, 12 (2002) 575.
[7] F. Hosono et al., IEEE Transactions on Applied Superconductivity, 12 (2002) 1037.
[8] T. Ando et al., IEEE Transactions on Applied Superconductivity, 32 (1996) 2324.
[9] Y. M. Miura et al., IEEE Transactions on Applied Superconductivity, 12 (2002) 611.
[10] S. Sakurai et al., Plasma Phys. Control. Fusion 44 (2002) 749.
[11] J. Boscary, M. Araki et al., Fusion Technology 35 (1999) 289.
[12] K. Masaki et al., Proc. of ISFNT-6, San Diego, 2002, to be published in Fusion Engineering and Design.