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Advances in the manufacturing activities for the supply of 9 TF coils of JT-60SA Tokamak and associated validation program

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ADVANCES IN THE MANUFACTURING ACTIVITIES FOR THE SUPPLY OF 9 TF COILS OF JT-60SA TOKAMAK AND ASSOCIATED VALIDATION PROGRAM

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Summary

The status of the manufacturing of 9 of the 18 Toroidal Field (TF) coils of the JT-60SA tokamak under ENEA responsibility is presented. The activity, carried out in the framework of the Broader Approach Agreement between Europe and Japan for the construction of the JT-60SA tokamak, has officially started on October 2011 after the kick-off meeting between ENEA and ASG superconductors in Genoa. The 9 coils are being manufactured under the supervision of ENEA in collaboration with the JT-60SA European home team by ASG superconductors. The remaining coils will be constructed by ENEA's French counterpart CEA. Once completed, the coils will be delivered to CEA at Saclay to perform the cold tests before final shipping to Naka. The manufacturing consists of several steps and phases. The first phase regards the completion of the manufacturing drawing and components needed for the production. Therefore the first year of activity has been devoted to the issuing of the manufacturing drawings and procurement of the tools. Also, prior to the start of the manufacturing, a preparatory activity has been planned aimed at setting-up the most critical manufacturing process. At this aim, several qualification activities have been performed. In this report an overview of the principal milestones reached during the preparatory phase and a description of the qualification activities with relevant test results are presented. Also the activities implemented for the next year are described.

Introduction

On October 2011 the kick-off meeting for the contract between ENEA and ASG Superconductors signed the official start of the activity for the construction of 9 of the 18 Toroidal Field superconducting coils of the JT-60SA magnet. The manufacturing includes the integration of the coil winding pack, insulated by means of glass fiber epoxy impregnation, into the steel casing equipped with instrumentation. This activity is carried out within the Broader Approach Agreement between EU and Japan institutions. The first year of the contract aimed at preparing all the manufacturing drawings and designing of the related tools and components needed to carry out the activity. Also several special processes have been qualified by means of dedicated mock-ups according to the technical specifications issued by ENEA and the JT-60SA European home team. The conclusion of the contract is expected within the summer of 2016 with the delivery of the last coil to the cold test facility to be tested in cryogenic conditions and then sent to Naka site in Japan for the assembly.

The construction of the 9 TF magnets by ASG Superconductors foresees the following main steps:

1. Receiving, inspection and acceptance testing of JT-60SA and ENEA Supplied Items and Procured Materials: conductor and casing components;
2. Winding of each conductor length to form a double pancake (DP);
3. Stacking of 6 DPs to form the complete winding pack (WP) of each magnet;
4. Impregnation of the coil WP;
5. Assembly of the internal electrical joints and terminations;
6. Insertion of the coil WP into steel casing;
7. Coil casing closure by welding;
8. In-case impregnation and curing;
9. Coil casing final machining;
10. Assembly of cooling pipes and instrumentation;
11. Package of TF coil for shipment;

The list reported is only representative of the main steps, but each of them is characterized by a number of sub-steps long to detail. For instance, step 2 includes at least the following sub-steps: i) preparation of conductor (straightening, cleaning, sandblasting); ii) wrapping of conductor turn insulation; iii) manufacture of helium inlet, including check of weld integrity and insulation of joint; iv) winding of conductor, with manufacture and installation of DP insulation. Associated to these manufacturing steps is the definition of specific procedure, drawings and testing, that must accompany the coil along its life. Also, since JT-60SA TF magnets are unique in dimensions, the relevant manufacturing tools could not be re-used from previous projects. In the following sections the main components developed and the results of the validation program carried so far are presented.

Description of the activities

Components and tooling

To carry out the construction process several tooling has been designed and procured. Also most of the materials needed have been already procured and are available at ASG, specifically:

- Glass tapes for electrical insulation of the conductor;
- G10 fillers for the pancake transition and electrical terminations;
- Epoxy resin for the impregnation of the coil and subsequent embedding in the casing;
- Solder, chemical products, explosion bonded plates and machining for the manufacturing of the inner electrical joints of each coil;
- Electrical breakers;

- Voltage taps;
- Temperature sensors.

The following subsections are devoted to a description of the main items needed to carry out the manufacture of the coils.

Vacuum chamber for acceptance testing

As already recalled in the list of steps foreseen during the manufacture of each coil, the manufacturer has to perform some tests on the conductor before winding. The tests foreseen include pressure tests at 30 bar and leak test up to 10^{-8}mbar*l/s. Both these tests must be performed within a vacuum chamber to guarantee a vacuum of 10^{-4} mbar. Figure 1 shows the vacuum chamber already installed at ASG premises and the associated pump system. The chamber has been already commissioned in September 2012 on a conductor unit length (UL) 240 m long intended to commission the winding line.

Figure 1 Vacuum chamber and pumping system for acceptance tests on spooled conductors.

Winding line

The main step in the coil manufacture is represented by the winding of the conductor to form the double pancake (DP). The DP is constituted by two layers that must assure tight tolerances. For instance the straight leg of the coil (approximately 7 m long) must have a geometric centerline included in a cylinder with 1 mm radius. The winding line consists of many parts. First the spooled conductor must be placed on a de-spooling machine, re-straightened and finally bent to form the D-shape of the coil. Figure 28 shows the straightening and bending tools during the final tests before installation in ASG premises.

Figure 2 Straightening and bending tools of the winding line during final test before installation in ASG premises.

The winding line is composed of many other parts not shown but already available at ASG. These parts are the cleaning and sandblasting device needed to reach a proper level of roughness on the surface on the conductor jacket to guarantee a proper level of adhesion to the insulation. Also a wrapping tool is present to wrap the glass tape around the jacket. Once bent the conductor is kept in contact with a D-shaped tool having exactly the nominal dimensions of the inner side of the coil to guarantee to respect of the tolerances fixed at the design level. It is worth noting that the winding line is controlled by an automatic system capable to give the defined shape by assigning the geometrical features.

Lifting tool

In order to handle DPs after winding a dedicated tool has been developed. Figure 3 shows an image of the lifting tool already available at ASG premises. The tool is capable to move not only the DP but also the winding pack (WP) after the proper stacking on the stacking bench. At this aim the tool is equipped with a proper extension to contain the additional weight of the inner joints and terminations that are mounted at the end of the stacking operation.

Figure 3 Lifting tool for DPs and WP

Benches for DP and WP preparation

In the manufacture process after winding two important steps are foreseen to wrap the insulating tape around the DP and the stacking and final insulation of the WP respectively. Figures 4 and 5 show the DP and WP benches already available at ASG premises. Note that both benches are equipped with special tooling for the adjustment of the dimensions before the final insertion of the winding in the casing structure.

Figure 4 DP manufacture bench

Figure 5 WP manufacture bench

Impregnation mould

After winding and stacking 6 DPs to form a complete WP, the coil will be inserted in an impregnation mould where, after verification of the correct geometry, it will be impregnated. The impregnation is a Vacuum Pressure Impregnated process (VPI) therefore the mould is capable to apply a pressure on the WP and is equipped with a heating system to apply the curing cycle needed to the epoxy resin to gelify. Figure 6 shows the mould undergoing to the final tests before installation in Genoa.

Figure 6 Impregnation mould during final tests before installation in Genoa.

Orbital welding machine

One of the last operation of the coil manufacture is the application of the He piping system. This process will be carried out by using an orbital welding machine completely automated for a perfect reproduction of each weld. Figure 7 shows the orbital welding already at ASG premises where it has been successfully tested.

Figure 7 Orbital welding machine for He piping welding.

Laser tracker

During the DP stacking and before the impregnation the winding dimensions will be measured by means of laser tracker systems. Figure 8 shows the laser tracker already procured by ASG to perform the geometrical survey.

Figure 8 Laser tracker for dimensional survey.

Vacuum chamber for final tests

Before the subsequent insertion of the coil within the casing structure and after the proper impregnation, the coil will be tested in a vacuum chamber to perform several tests. The main tests foreseen are leak tests and Paschen tests in vacuum. Figure 9 shows the vacuum chamber already installed in ASG equipped with the pumping system and the window needed to monitor the occurrence of a discharge during the Paschen tests.

Figure 9 Vacuum chamber to perform final test on coil.

Validation test program

A number of aspects of the design and manufacture for the JT-60SA TF coil require validation prior to their adoption.

The qualifications activities aim at verifying the compliance of the applied technological solutions with the design requirements of the magnet. This validation test program is almost concluded and is the base reference for the construction of the coils. The following sub-sections describe briefly some of the most critical qualifications.

Insulation shear strength test

The insulation made by fiber-glass vacuum impregnated with epoxy resin is one of the most critical process in the TF coil manufacturing. Therefore the evaluation of its performance in terms of ultimate shear strength and capability to survive to the cyclic loading are of extreme importance. In this regard, the following minimum requirements have been established:

- minimum fiber-glass content of 60 % by volume,
- minimum shear strength capacity after impregnation of 55 MPa at 4 K, corresponding to 40 MPa at 300 K,
- minimum shear strength capacity after 36000 cycles of 20 MPa at 300 K.
- must not degrade mechanical properties after 20 kGy.

ASG and ENEA adopted to this purpose a sample made by two plates of steel separated by 2 mm of fiber-glass epoxy resin, simulating inter-turn insulation. The sample has been prepared in accordance with the manufacturing procedure required during production. Figure XX shows the sample in the test facility during the execution of the strength test at room temperature. The tests have been concluded successfully, in fact the minimum shear strength at room temperature was larger than 50 MPa and than 65 MPa at cryogenic temperature.

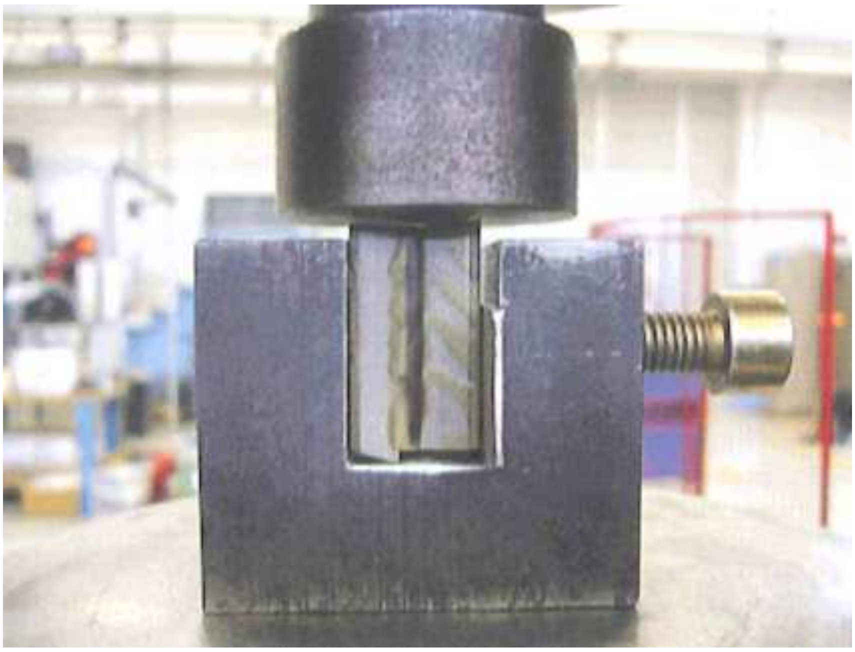

Figure 10 Shear stress sample during the static load at the test facility.

Impregnation beam

Insulation system represents an important aspect in the design of the coil both for withstanding high mechanical loads and to assure the electrical properties. The insulating layer must be able to withstand high voltage differences that could arise during a quench due to a sudden transition of superconductive material to a normal state. In order to insulate the winding pack against an electrical voltage of at least 3.8 kV a total of 3 mm layer of ground insulation must be installed around complete winding pack.

The quality of electrical insulation and the respect of geometrical tolerances required in the design have been validated on a 1 m long impregnated beam realised by ASG. Figure XX shows an image of the beam at the end of the impregnation cycle before the application of the conductive painting needed to perform the electrical tests. The beam has fulfilled completely the electrical requirements being capable to resist up to 5 kV between turns and up to 15 kV in the ground voltage.

The following electrical test have been performed:

- Ground insulation resistance at V=500V / 1min: 31.4 GΩ.
- Ground insulation HV at V=3.8 kV DC / 1 min: I<1µA.
- With conductive painting test repeated up to 15 kV with no electrical discharge.
- Ground insulation resistance at V=500V / 1min: 30.0 GΩ.
- Inter-turn electrical resistance at 75 V (R=79 G Ω), 100 V (R=102 G Ω) , 150 V (R=155 G Ω). Additional test with different supplies up to 10 kV with no electrical discharge.

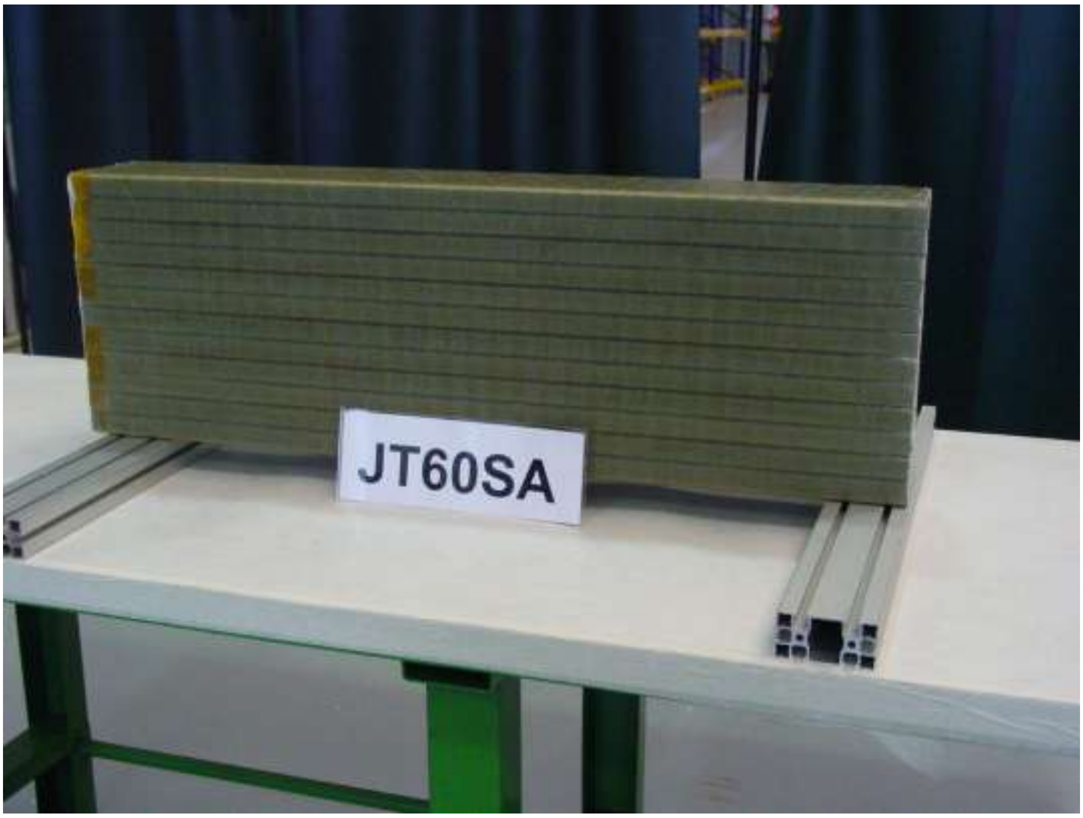

Figure 11 Impregnation beam before the application of the conductive painting and the execution of the associated electrical tests.

The beam will be successively employed also in the qualification of the embedding process into a casing mock-up that will be performed at the beginning of 2013.

He inlet

Another critical component in the manufacture of the TF coils is the He inlet insert. Through this element He cooled at 4.5 K will be fed into the DP. The insert is made of a piece of stainless steel welded on the conductor jacket and it is conceived in order to minimize the pressure losses. Since the inlet is located in the inner side of the coil it will experience high static and cyclic mechanical loads therefore it is mandatory to qualify the welding procedure.
To investigate the integrity of He-inlet welding the following test have been performed:

- n°3 thermal shock cycles in liquid nitrogen.
- Visual check, dye penetrant test, X-ray destructive test.
- Pressure at 25 bar/1h and He leak test result 4*10-10 mbar l/s.

Welding process is critical also for possible deterioration of superconducting properties of the underlying NbTi cable. At this aim the temperature of the conductor has been monitored during welding to control that it did not exceed 500 °C for more than 30 s.

Figure 12 shows the cable underlying the He inlet insert after the welding process and the successive removal of the jacket. It is apparent that the strands were not heavily damaged due to the heating. To quantify the possible degradation occurred to the strands closest to the welding path a dedicated measurement of the critical current density at different temperature and magnetic field of different strands will be carried out by ENEA.

Figure 12 NbTi and copper strands underlying the He inlet insert after the destructive examination of the sample to perform measurements of the strand degradation.

In particular, the degradation will be evaluated by comparing the electrical properties of pieces of the same strand in the virgin state with pieces extracted from the thermal affected zone and with pieces subjected to a controlled heating up to 500 °C for 30 s.

The He insert has been qualified for the electrical insulation properties. After the application of glass tape, the specimen has been impregnated with epoxy resin and subjected to voltage up to 5kV without any electrical discharge at room temperature.

Figure 13 He inlet insert covered by glass tape to perform the insulation and the related electrical tests.

Internal joints and terminations

Although superconducting, the TF coil will experience some electrical resistivity in the internal joint connecting the adjacent pancakes and between one coil and another (or the feeders) through the terminations.

Figure 14. Terminations and inner joint sample preparation.

On this regard, ASG chose to adopt the mono-block twin-box configuration [1] for the inner joints, whereas for the terminations the standard twin-box solution has been imposed at the design level [2,3]. In order to qualify the manufacturing process and to verify the respect of the electrical and hydraulic requirements a joint and terminations prototype has been conceived. The sample constituted by two terminations for the current feeding and one joint will be tested in ENEA Superconducting laboratory with different currents up to 20 kA in a bath of liquid He.

Conclusions

The manufacture of the 9 TF coils of JT-60SA magnet is proceeding according to the schedule. The validation program has been almost completed and after the installation and commissioning of some of the most critical components the winding of the first DP could start. In particular the experimental tests on the relevant mock-ups have shown that design requirements are well fitted either from the point of view of the mechanical and electrical performance.

References

1. Decool, P., et al., "JT-60SA TF magnet joints developments and prequalification", (2012) IEEE Transactions on Applied Superconductivity, 22 (3), art. no. 6069839, .
2. Zani, L., et al., "A new design for JT-60SA toroidal field coils conductor and joints", (2008) IEEE Transactions on Applied Superconductivity, 18 (2), art. no. 4520261, pp. 216-219.
3. PID, Plant Integration Document, 2012, edited by B. Spears.