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Progress in the manufacturing activities for the supply of 9 TF Coils of JT-60SA Tokamak

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PROGRESS IN THE MANUFACTURING ACTIVITIES FOR THE SUPPLY OF 9 TF COILS OF JT-60SA TOKAMAK

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Summary

Abstract

In the framework of the Broader Approach Agreement for the construction of the JT-60SA tokamak, ENEA is in charge to provide 9 of the 18 Toroidal Field (TF) coils of the JT-60SA magnet system. The remaining coils will be provided by ENEA's French counterpart CEA. The 9 Italian coils are being manufactured by ASG superconductors in Genoa under the supervision of ENEA. Coordination of the activities of the European voluntary contributors to the project is accomplished by the JT-60SA European home team in Garching, Germany. Since the contract between ENEA and ASG has been signed in 2011, all the engineering tasks associated to manufacturing have been completed. Also all the tooling needed in the different manufacturing stages have been procured, finally all the critical processes have been qualified. On late 2013 manufacturing activity has officially started with production of the first series double pancake (DP). The following five that constitute the first winding pack (WP) have been completed by the end of 2013. Afterward during 2014 the impregnation of the first WP has been completed, and in parallel the winding and stacking operations of the second, third and fourth WPs have progressed. At the time of writing the first two WPs have been impregnated, the third is starting the impregnation phase and, regarding the fourth, winding is progressing with the first four DPs already manufactured.

The second phase of the manufacturing activity that consists in the WP integration into casing and associated final coil preparation will start with the delivery of the first casing set to ASG by ENEA within the end of 2014. Nonetheless, preparatory activities have been accomplished with the design, purchase and commission of the relevant tooling and with the successful completion of the qualification activities associated to this phase.

1 Introduction

In questa sezione si inquadra il lavoro svolto all’interno dell’Accordo di Programma (o eventualmente nel quadro dell’Accordo di collaborazione) e si mettono in evidenza motivazioni e finalità del lavoro senza tuttavia anticiparne le conclusioni. (stile Normale testo)

The JT-60SA experiment is one of the three projects to be undertaken in Japan as part of the Broader Approach Agreement, conducted jointly by Europe and Japan. The mission of the JT-60SA project is to contribute to the early realization of fusion energy by addressing key physics issues for ITER and DEMO. The JT-60SA magnet is characterized by 18 toroidal field (TF), 4 central solenoid (CS) and 6 equilibrium field (EF) coils. All of these coils are superconducting, cooled by supercritical helium at 4.4 K and thermally protected in a cryostat.

In September 2011 ENEA signed with ASG Superconductors a contract for the procurement of 9 TF superconducting coils. TF coils are constituted by a winding pack (WP) inserted in the containment structure. Each WP is made of six double pancakes (DP) electrically connected by five internal joints located on the top of the coil. Each DP is wound from a 240 m cable in conduit conductor (CICC) constituted by a twisted multi-filamentary NbTi and copper strands inserted in a jacket of 316L material. Each pancake has six turns, and each turn is 18.8 m long in average. WPs have an overall height of about 8 m (including inner joints) and a width of 4.37 m. Nominal cross section are 150 mm x 347 mm. Total weight is about 6.3 tons.

In the course of the first two years of contract, all the manufacturing drawings and designing of the related tools and components have been accomplished. Also the qualification of several special processes and the commissioning of the tooling used in winding pack manufacturing have been completed. Recall, indeed, that JT-60SA TF coil are, with the exception of ITER, currently under construction, the largest TF superconducting coils ever built. As a consequence of the tight tolerances requested for its operation, all JT-60SA components, and especially TF coils, have been designed to the best current technological knowledge. This implied the definition of an intense validation program that has regarded not only the materials employed, but also the procedures and tooling foreseen. Apparently, in some cases, such as the set-up of the winding line and its subsystems, or the welding process, the qualifications undertaken lead to modifications or optimizations of the original prescriptions with unavoidable delays in some process. Nonetheless, the first DP has been manufactured in late 2013; this officially started winding production. At time of writing two WP have been wound and impregnated and a third is ready to be impregnated. Coil manufacturing proceeds with the integration of the WP into the steel casing structure and with the final coil preparation that includes the installation of the piping for the WP cooling, instrumentation and more important final casing machining defined on the base of the actual position of the WP inside the casing. This second phase of manufacturing will start officially with the delivery by ENEA of the first set of casing, foreseen within the beginning of 2015. Nevertheless, WP production may continue with the temporary storage of the produced WP in the ASG workshop. Concerning validation program carried out in 2014, it is worth mentioning the welding of the rectilinear casing mockup and subsequent embedding carried out in the workstation that will be utilized for the embedding of the actual coils. Also electrical breakers, that will be mounted on the He cooling piping to electrically interrupt the connection between WP and ground have been further qualified in 2014.

2 Description of activities and results

2.1 WP manufacturing

The winding pack of JT-60SA TF coils is made of six DPs electrically connected by five internal joints located on the top of the coil. Each DP is wound from a 240 m cable in conduit conductor (CICC) constituted by a twisted multifilamentary NbTi and copper strands inserted in a jacket of 316L material. Each pancake has six turns, and each turn is 18.8 m long in average. DPs are cooled by 4 g/s of He at 4.4 K. He inlet are located in the middle of the conductor length and the outlet at the joints so that the hydraulic length is

about 113 m. WPs have an overall height of about 8 m (including inner joints) and a width of 4.37 m. Nominal cross section are 150 mm x 347 mm. Total weight is about 6.3 tons.
Winding process and stacking operations are separated in the manufacturing process adopted. This choice, although at the cost of an increased number of process to be performed, has been dictated by the conviction that any possible shape correction could be more easily achieved on a dedicated stacking station than on the winding table. Also this approach allows an easier implementation of the electrical inner joints.
For what regard insulation properties, 1 mm of glass around conductor jacket, provided by two half-overlapped layers 0.25 mm x 25 mm glass tape, are applied during winding. After winding one half-overlapped layer 0.25 mm x 50 mm glass, corresponding to 0.5 mm thickness of DP ground insulation, is wrapped at the end of the DP winding; then additional 2.5 mm of ground insulation, by means of 5 half-overlapped 0.25 mm x 50 mm glass tape, is applied on the stacking bench to the WP. Note that in this process, the 0.5 mm of DP ground insulation plays also a mechanical role in keeping the shape of the DP after winding and before subsequent stacking.

2.1.1 Conductor winding

DP winding is performed on a dedicated winding line constituted by two rail mounted carriages that host the de-spooling and the moving/rotary winding form. The tooling for conductor handling are suspended on two portal structures. On the first portal the straightening unit is installed. On the second portal the bending and the conductor insulation machines are mounted. Conversely the conductor cleaning equipment are installed on a mobile support between the two portals and are formed by the washing machine equipped with ultrasonic, rinsing and drying modules. The winding line, envisages the use of a reserve: namely the conductor is subdivided in two sub-spools and the winding starts from the midpoint.

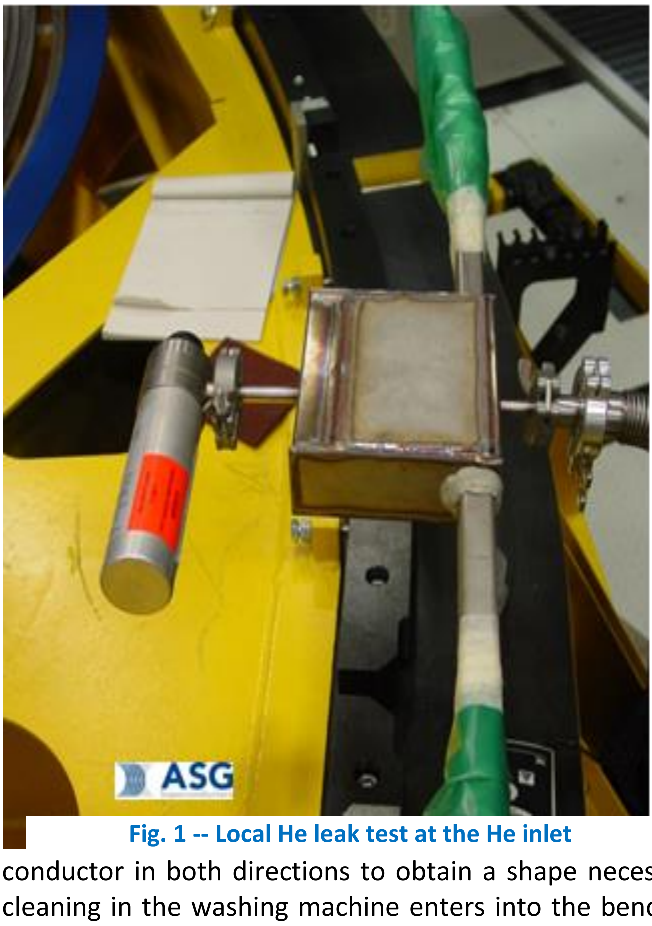

Fig. 1 -- Local He leak test at the He inlet

Once transferred the first half of the conductor on the reserve spool and made accessible the midpoint, the layer jump and the He-inlet welding are realized. Note that both He inlet machining and joggle tooling are removable tooling that are placed in position at the very beginning of each winding operation.
The first layer of DP is counter-clockwise wound using the half conductor on the de-spooling carriage. Completed the first layer, the reserve spool is positioned on the de-spooling carriage and the second layer of DP is wound in a clock-wise direction.
The straightening equipment, located close to the conductor de-spooler, straightens the conductor in both directions to obtain a shape necessary for the following bending. The conductor after cleaning in the washing machine enters into the bending unit and comes out with the proper shape. The process goes on in a cabinet with aluminum-oxide sandblasting equipped with suction guns.
Before starting the winding of the D shape, a local leak test of the He nozzle, welded onto the jacket, is performed. Figure [1] shows the local vacuum chamber mounted around the He inlet to carry out this test. Acceptable leaks are specified in 10^{-8} Pa*m^3/s, typically, values measured are two orders of magnitude below this limit.

Fig. 2 -- Straight leg of the first pancake during winding onto the winding table

To guarantee the adhesion between jacket and resin up to the high shear values specified at the design level, sand blasting is performed after bending to avoid the smoothing of the jacket surface caused by the bending rollers. This approach, that has been rarely applied before, implied a continuous optimization and improvement of the sand-blasting unit during the commissioning phase due to the limited space available and to the curved configuration of the conductor .

After sand-blasting, the conductor is insulated with glass tape and then laying down on the 20 tons moving/rotary Teflon coated winding table. The table movements are synchronized with the cable advancement, which is defined by the theoretical development of the length compared to the length measured

All movements of winding line mechanical components are synchronized at a maximum speed of 1 m per minute and software controlled. Figure [2] shows the straight leg of the first pancake of a DP during winding. The high accuracy of conductor positioning on the winding table can be easily recognized. The tooling for keeping the conductor against the winding table are not even used, so straight is the conductor in the process. In this regard, note that the winding table has an accuracy and planarity of 0.2 mm capable to meet the requirement that the DP centerline be contained in a cylinder 2 mm in diameter. Dimensional measurements of the DPs have been performed at the different production stages even on the winding table to commission the tooling.

Completed winding, the DP is transferred onto the bench for ground insulation and terminal exit shaping. This bench is equipped with a set of reference beams that identify the nominal shape of the DPs. Adjustable tools can however be installed to recover any possible deviation from the specified tolerances. Also G10 fillers in the layer jump and terminal exists areas are mounted at this stage to sustain the winding and provide the needed insulation. During WP-01 manufacturing an extensive dimensional campaign of each DP has been conducted in order to assess the validity of the process and to identify possible improvements. At this stage either inboard and outboard surfaces have been measured using laser tracking, also width, height, planarity and centerline of straight leg have been recorded with the aim at correct any possible deviations from the nominal values. In this regard, recall that the winding process guarantees tight tolerances on the inboard surface, since the conductor is wound from the middle and it pull close to the winding table with a tolerance of 0.2 mm. Figure [3] shows a typical measurement of the DP centerline performed at this stage.

On the DP bench the electrical tests aimed at identify electrical short-circuits are also performed prior to perform stacking. The check of inter-turn insulation is performed by capacitive discharge test (PJ) with max turn voltage of 80 V/turn. The PJ test allows a comparison between two impulsive electric responses of the coil. By comparing the obtained waveforms, any turn or coil layer short-circuit can be easily highlighted. Figure [4] shows the comparison of a standard response obtained during the PJ test with that produced by artificially short-circuiting the inter-turn insulation. It is apparent the different behavior in the two cases.

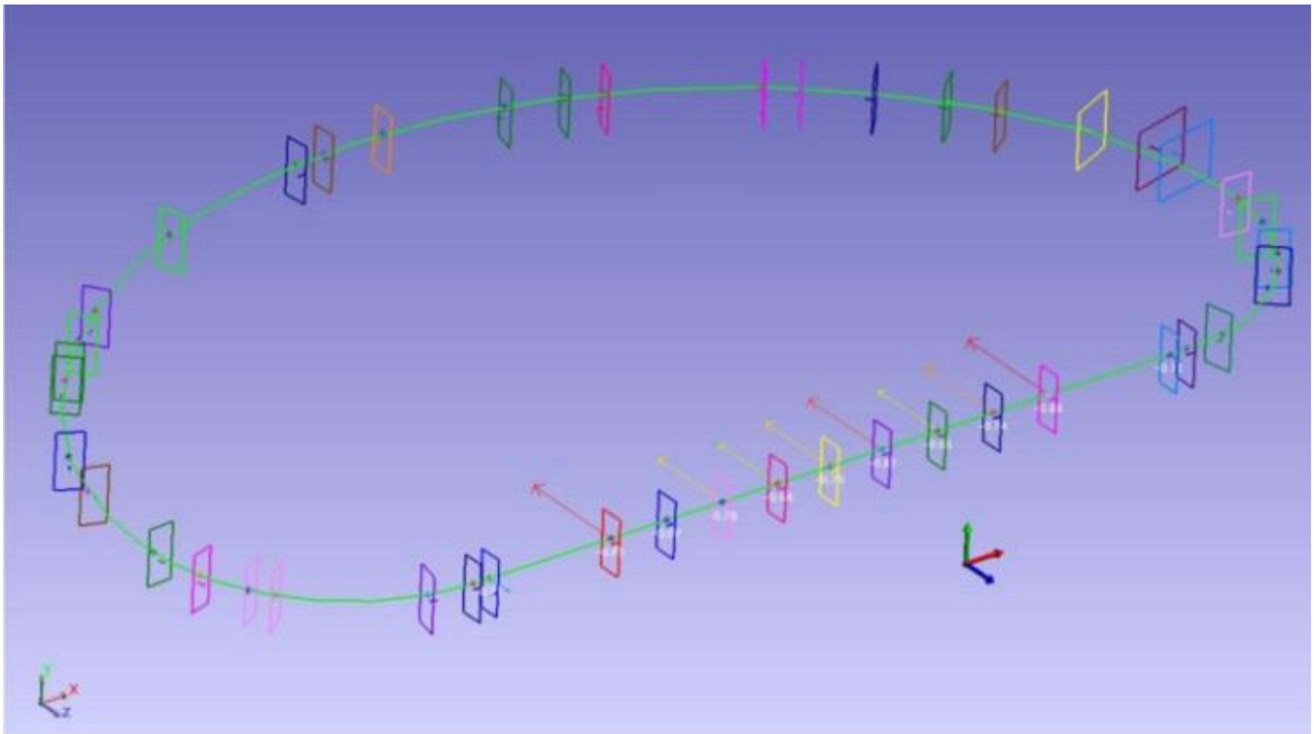

Fig. 3. DP centerline reconstructed form laser tracker measurements.

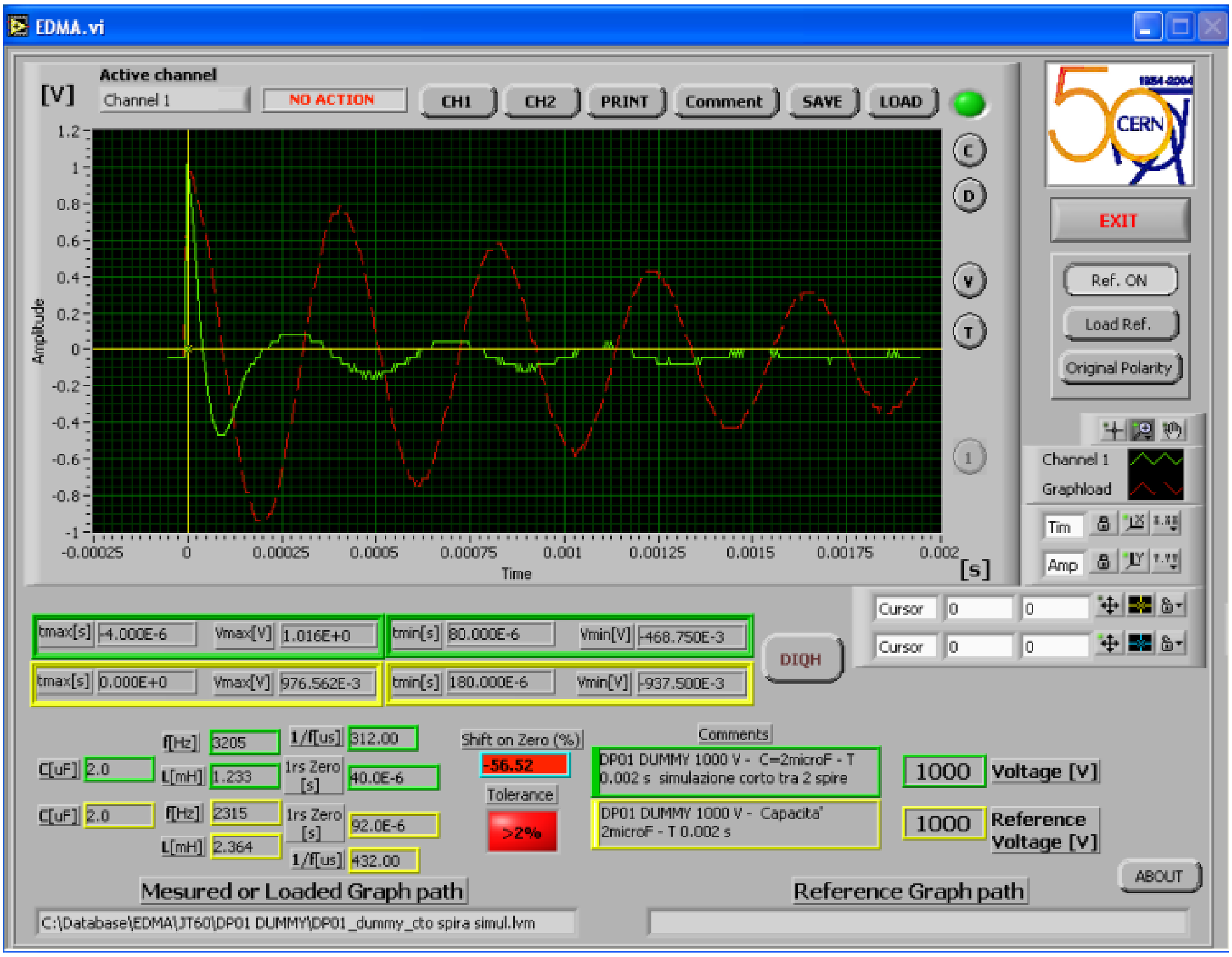

Fig. 4. Voltage decay during PJ test. The red curve represents a standard behavior, the green curve a discharge with a simulated inter-turn short-circuit..

Completed the dimensional and electrical tests, each DP is moved to the stacking bench, where up to 6 DPs are stacked for composition of the TF winding package. This bench is equipped with a set of reference beams that identify the nominal width of winding pack. Adjustable tools can however be installed to recover any possible deviation from the specified tolerances. Fine dimensional survey is again carried out using a laser tracker to identify the centerline.

Figures [5]-[7] show the stacking operations of the first DPs of the first WP and the WP at the end of the stacking. Note in Fig. [5] the presence of the vertical beams that are positioned according to the nominal layout of the DP and that, for this reason, constitute a sort of pass-no-pass gauge for DP winding. In Fig. [7], at the completion of the stacking operation, also the structures designed for correct any possible deviations with respect to the nominal position are mounted and easily recognizable. In this figure the laser tracker , used for dimensional survey is also distinguishable in the middle of the WP.

In this phase also the electrical inner joints and terminations are mounted and welded. The internal joints represent the series connection between the different DPs of the coil. Both inner joints and terminations are made using the twin box solution. The terminals of two different DPs are inserted inside a box obtained from explosion bonded stainless steel/copper/stainless steel sandwich, and then compacted by pressing and welding of the stainless steel covers. The requested length of the jacket is removed to allow the insertion of the cable inside the twin-box using dedicated tooling. The stainless steel wrapped around the unjacketed cable is removed. Silver plating is applied by electrolytic process on the strands facing the copper box bed inside the connecting box. The electrical connection between the prepared conductor and the terminal box is ensured by compacting the cable in the connecting box with the cover. The compaction of the terminal has been achieved applying a 130 tons load up to complete closure of the gap between connecting box and cover. Local leak test of the joints is performed similarly to what is done for the He inlet. Then WP ground insulation is applied and after a complete dimensional survey the WP is ready to be brought to the impregnation bench for the final operations.

Fig.5 DP01 placed on the stacking station.

Fig.6 DP02 is stacked on DP01.

Fig.7 WP01 at the completion of stacking process


Fig.8 Overhead view of the ASG workshop during WP02 manufacture

Fig.9 WP01 being transferred to impregnation area

To easily understand the flow of manufacturing operations Fig. 8 shows an overhead view of the ASG workshop during WP02 manufacturing. The stacking station, with already the first three DPs mounted, is recognizable at the bottom, in the middle the ground insulation for DP is visible and on the top the winding table at the portal for sand-blasting and bending can be observed.

Finally, Fig. 9 shows the movement of the first WP from the stacking station to the impregnation and curing workstation that concludes the first phase of the WP manufacturing. In particular, the dedicated tooling for handling the single DP and the completed WP can be observed. It consists of a rigid frame that grasps the winding and avoids any deformation during the movements. The frame is also equipped with a support for the internal joints and terminations that are visible in the picture.

2.1.2 WP impregnation

As for the preceding processes, also impregnation is carried out in a dedicated facility where all the driving parameters are controlled and recorded. It consists of a tilting table, to prevent void formation during resin injection, on which an impregnation mould is assembled. The mould consists of thin stainless steel casing assembled all around the WP. The lower casing part is placed on the impregnation table, with the outboard surface placed in the nominal position, before the WP transfer; the upper part is then assembled and welded to the lower one. After casing assembling, a series of clamps is installed on the mould modules in order to press WP ground insulation and guarantee the required tolerances. Dimensional survey based on Laser-Tracker drives the final adjustment of the coil before impregnation. Between clamps and casing, a series of pressing plates is placed, to spread the load. Insulating plates positioned between casing and mould modules, and between casing and pressing plates, allow to limit heat dispersion. Also inner joints, located at the top of the coil, are vacuum pressure impregnated (VPI) with rest of the WP with the exception of the terminals that will be insulated after connections with feeders in the final assembly phase in Naka.

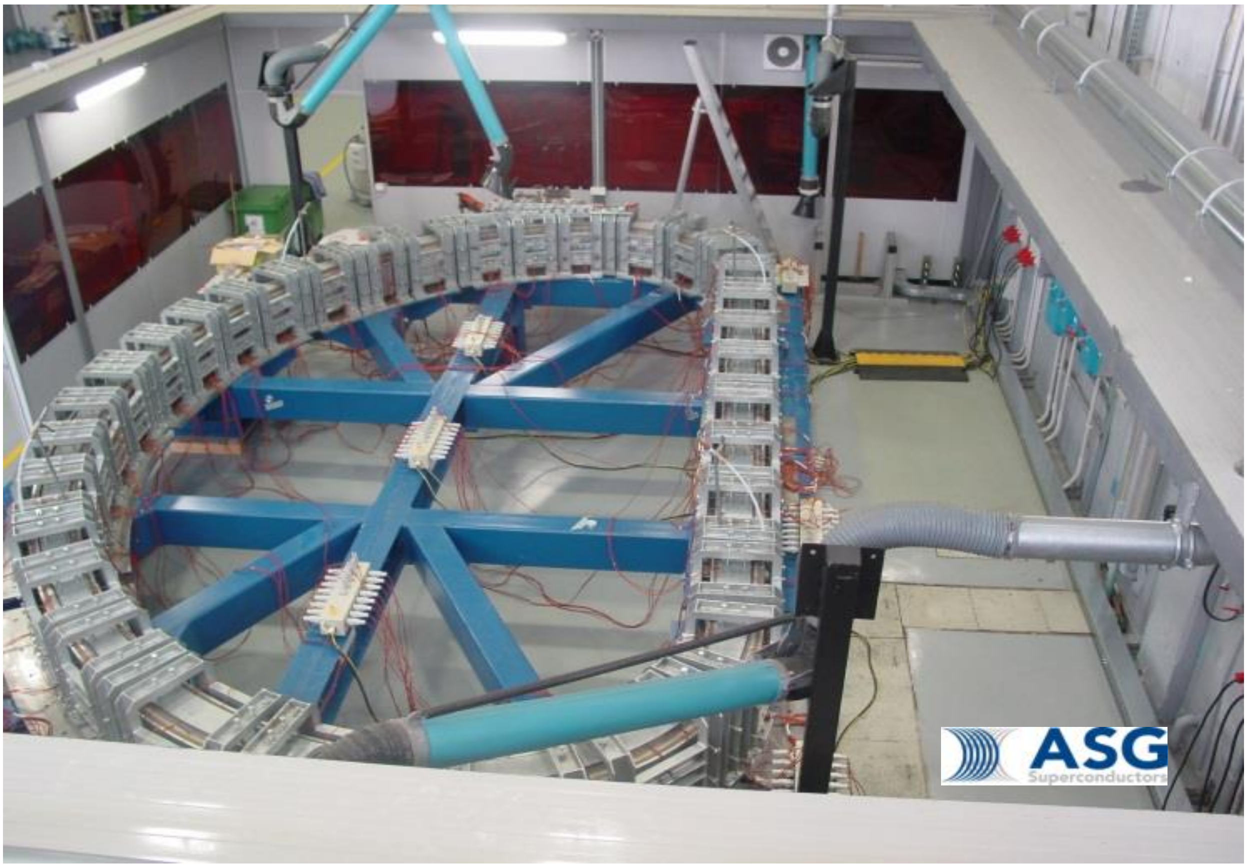

Fig. 10 WP01 at the beginning of the VPI process.

The VPI process starts with the evacuation of the casing to remove trapped air and moisture, so when the resin is injected into the mould, the penetration of the resin is complete, without voids or bubbles. Once filled, a positive pressure is applied to force the slightly viscous resin into the small spaces of the insulation matrix. The pressurization cycle is repeated several times. Then the resin is cured at the appropriate temperature. Figure 10 shows the WP01 at the beginning of the VPI process, connectors for heaters and clamping structure around the D shape of the WP are clearly visible.
Completed the resin curing cycle, the mould is cooled down to room temperature; then mould segments are removed and WP is transferred to inspection/cleaning station. Figure 11 shows the transferring of WP01 from impregnation to cleaning station. Worth noting is the casing structure that encloses the WP.

Fig. 11 – WP01 is transferred to cleaning station after VPI

On the cleaning station, see Fig.12, the casing is removed, and the WP surface is cleaned (see Fig.13). The qualified conductive paint is put on the WP surface and a complete dimensional survey is carried on. The measurements allows to position the twelve targets on the inboard surface that will be used for centering the WP inside the casing structure and the correct assembly in the tokamak hall. Concerning centerline, the barycenter of the straight leg, is calculated on 11 sections. Each points stays inside a cylinder Ø 0.76 mm instead of the acceptable Ø 2.00 mm.
On the base of this survey, it was also possible to estimate the change in cross section induced by the VPI process. Specifically, the 347±5 mm nominal height of the measured cross sections, see Fig. 3, although within tolerance, experienced a decrease in the range [-5.2;-1.9] mm, while the 150±3 mm nominal height changed in the range [-4.2;-2.0] mm. To conclude, the WP01 was successfully impregnated, with the inboard surface 2.7 mm maximum inward and 1.8 mm maximum outward with respect to the nominal, and the outboard surface well within the nominal surface. The subsequent insertion into the casing structure does not let anticipate at present any difficulties caused by the WP dimensions. Nonetheless, note that the

measurements taken will allow to simulate the insertion with respect to the nominal and actual casing as soon as finally machined.

Fig. 12 WP01 on cleaning station before conductive paint is applied

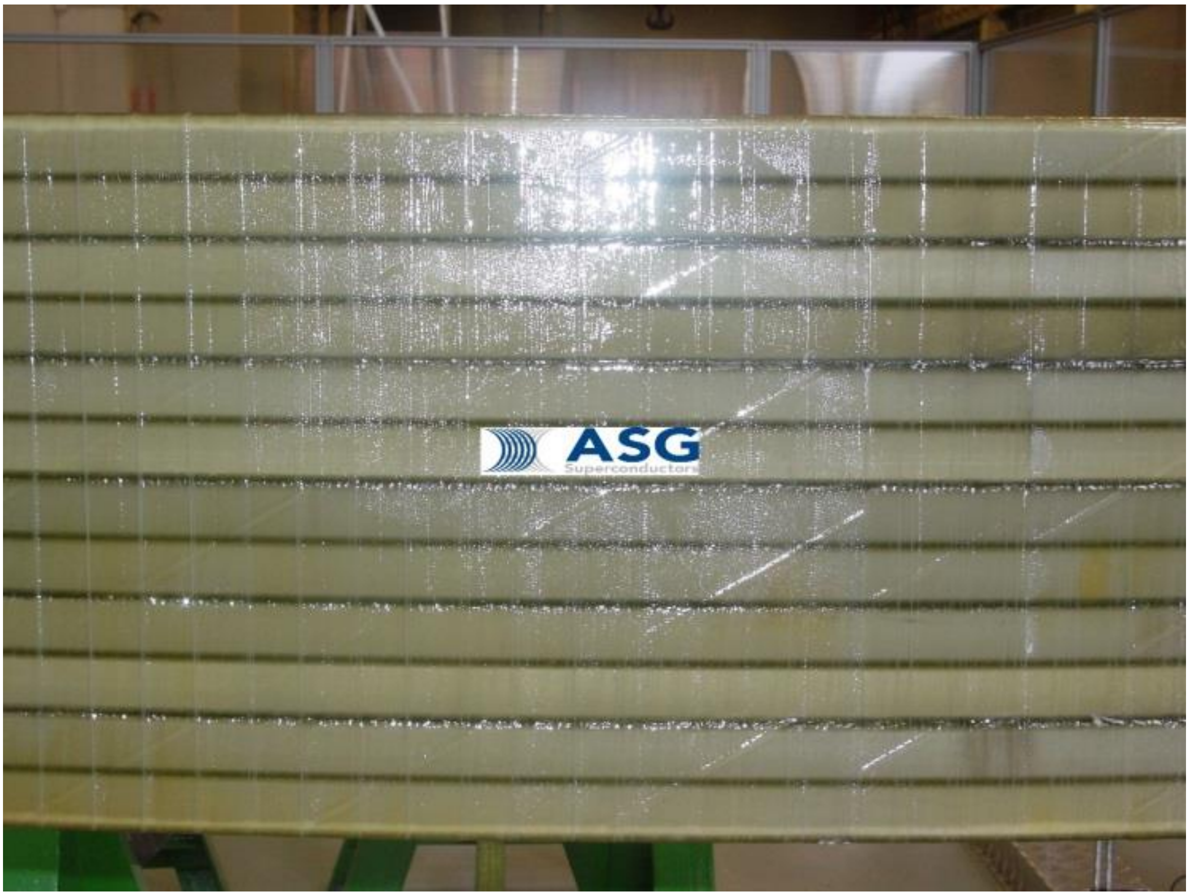

Fig. 13 – Visual inspection of WP01 impregnation

2.1.3 Acceptance tests

A part the dimensional survey described previously, each WP is also subjected to flow, leak and electrical tests. Flow test is been performed either before and after impregnation, flow rates measured before remained unchanged after.

The global leak rate has been measured after impregnation in the vacuum tank shown in Fig. 14 and in the casing mould before. The test was carried out by pressurizing the WP with He up to 2.5 MPa and creating vacuum in the dedicated annular chamber surrounding volume. The maximum leak found during one hour of test was 9.4 x 10-11 mbar*l/s well below than the acceptable limit of 10-7 mbar*l/s.

Fig.14 – WP01 inside D-shape vacuum tank at the completion of global leak test.

Fig.15 – Temporary insulation on terminations needed to carry out Paschen test.

The list of acceptance tests performed on the WP ends with the following electrical tests:

- Electrical resistance at room temperature
- Inductance measurements
- Ground insulation resistance
- Interturn insulation resistance

Finally a Paschen test in the vacuum tank is carried out using Nitrogen as surrounding medium at 10, 100, 10^3, 10^4 Pa. To proceed with the test a temporary insulation around the terminations (see Fig. 15) is applied. No discharge has been detected in the 3.8 kV voltage range applied at the coil terminals.

2.2 Tooling commissioning

The entirety of the tooling for TF coil manufacturing has been designed and purchased within 2013, nonetheless, during 2014, some of the tooling for the later operations have been installed and, where possible, commissioned using full scale mock-up.

In this regard, Figure 16 shows the workstation dedicated to the cleaning operations after WP impregnation and curing. It consists of ten adjustable pneumatic supports Teflon covered on which the WP is mounted to carry out the finishing. Apparently, this workstation was commissioned during the first WP manufacturing. In this phase, the thin casing structure that covers the WP inside the impregnation mould is removed, also the excess of resin is taken away and the conductive paint is applied.

Fig.16 – Cleaning workstation.

Fig.17 – Tooling for WP insertion into the casing.

Fig.18 – Embedding workstation.

Figure 17 shows the tooling for insertion of the Wp inside casing components. It consists of a central core on which the WP is grasped and of two lateral carriages that move the two outboard shells of casing structure onto the WP. Subsequently, the central core will be rotated and the WP with the two outboard structures will be placed in a vertical position in order to perform the welding of the two 47 mm thick transverse joints. Rotated again in a horizontal position the coil will be placed on a secondary workstation for the welding closure of the inboard covers. Then the coil will be ready for the embedding operation. This device was designed in 2012, ordered and delivered in 2013 and finally installed in ASG workshop at the beginning of 2014. Note that, due to the large mass of the component and of the tooling itself an evaluation of the floor resistance was performed, also in order to be qualified from the safety point of view, a full scale mock-up of the WP was built and used for tests in the supplier's workshop before delivery to ASG.
Figure 18 finally shows the embedding workstation created to perform the embedding process on the TF coils. It consists of an embedding station with adjustable supporting pillars to ease resin flow and prevent the formation of voids. A dedicated heating system is also placed around the coil to complete the curing cycle at the end of the process.

2.3 Qualification activity related to insertion

As mentioned in the introduction the TF production consist of two phases, one associated to winding and the second concerning insertion into casing. To test the process that will be carried out as soon as the casing structure will be available, ASG developed a few activities by using a WP mock-up and two mock-ups of the casing sets.

2.3.1 Insertion qualification

The 1m long WP, made of 72 steel bars that simulate the conductors, constructed during the qualification activity for WP impregnation, has been used to test the insertion phase into the casing. At this aim, ENEA provided ASG with two sets of 1 m long casing mock-ups: one geometrically similar to the straight leg area and one, although rectilinear, similar to the curved leg in the area of the transverse welding. Therefore, in view of the subsequent welding two different insertion tests were simulated in ASG. First, the impregnation beam (see Fig.19) has been inserted in the curved leg mock-up (see Fig. 20).

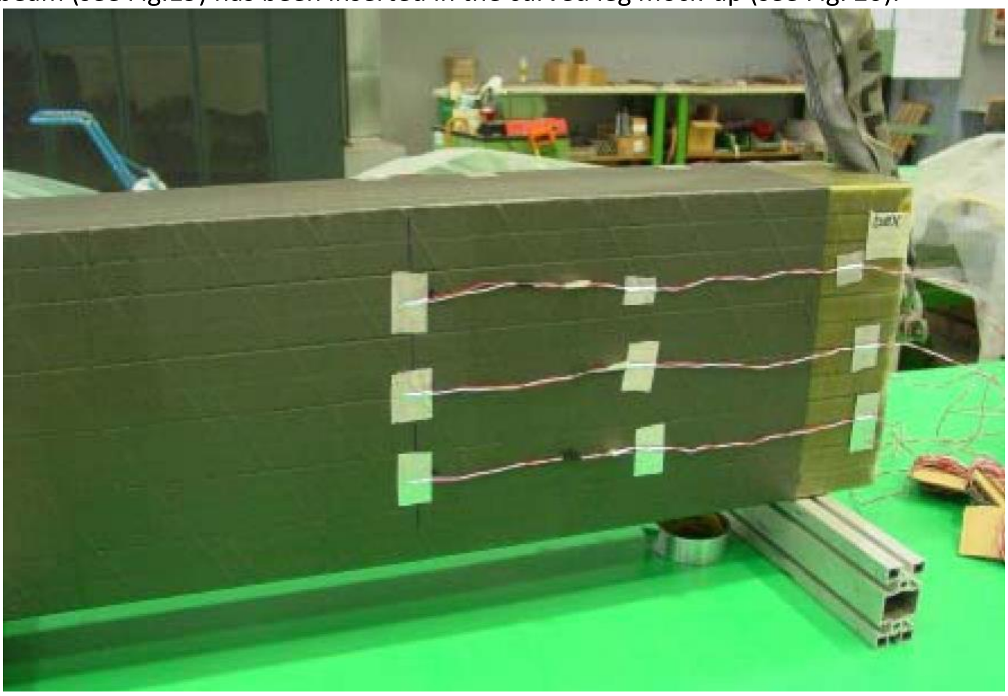

Fig. 19. Impregnation beam equipped with thermocouples before insertion in the curved leg mock-up.

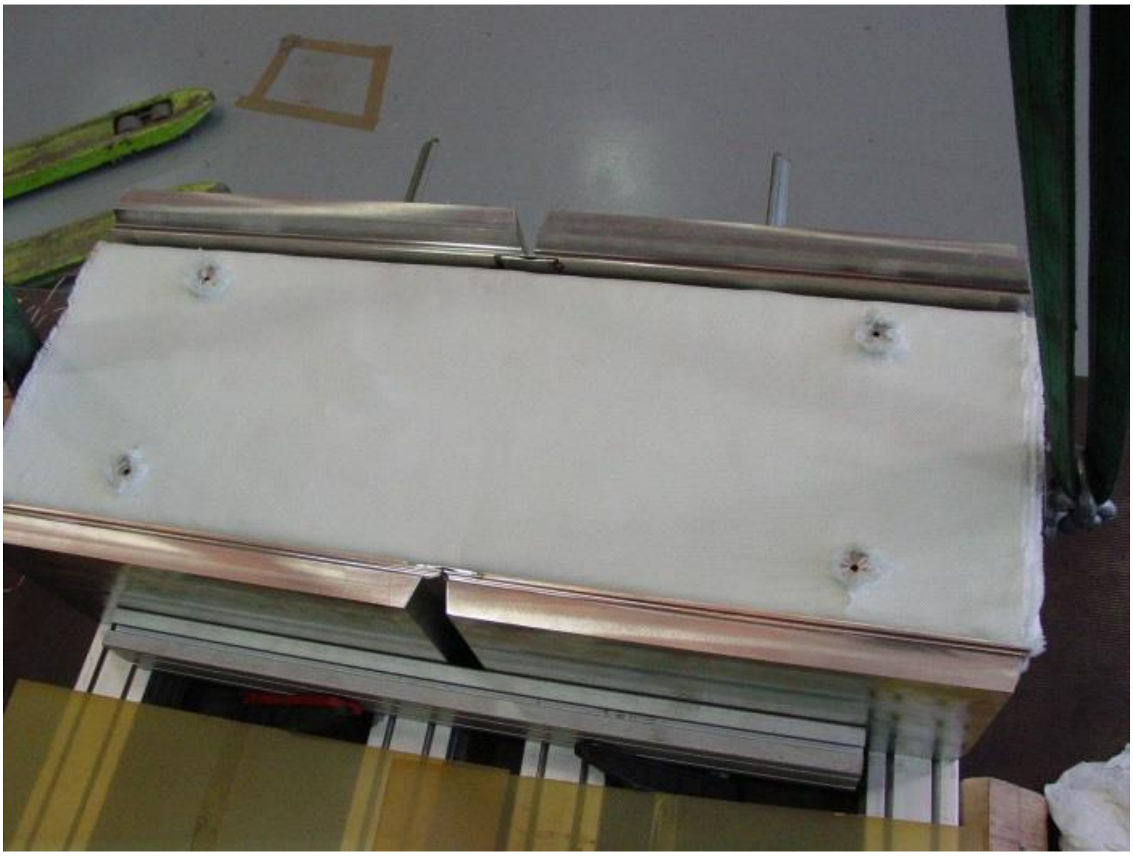
Fig. 20. Curved leg mock-up with beam inserted.

Fig. 21. Straight leg casing mock-up with wedge spacers before beam insertion.

Then, after the completion of the welding phase the impregnation beam has been re-used for insertion and embedding in the straight leg casing mock-up. (see Figs. 21 and 22). Worth noting in Fig. 19 is the presence of three thermocouples attached to the beam surface to monitor the temperature during welding of the transverse joint; indeed, temperature on the WP must be kept below 100°C to not damage the epoxy resin used for the impregnation. Figure 20 shows the beam inserted in the casing already covered with a 5 mm thick layer of glass clothes. The holes in the glass to make accessible the targets glued on the impregnation beam are also visible; these targets that in the actual TF coil will be six on the straight leg and six in the curved leg, will be used to identify the location of the WP inside the casing and to perform correspondingly the machining and assembly.

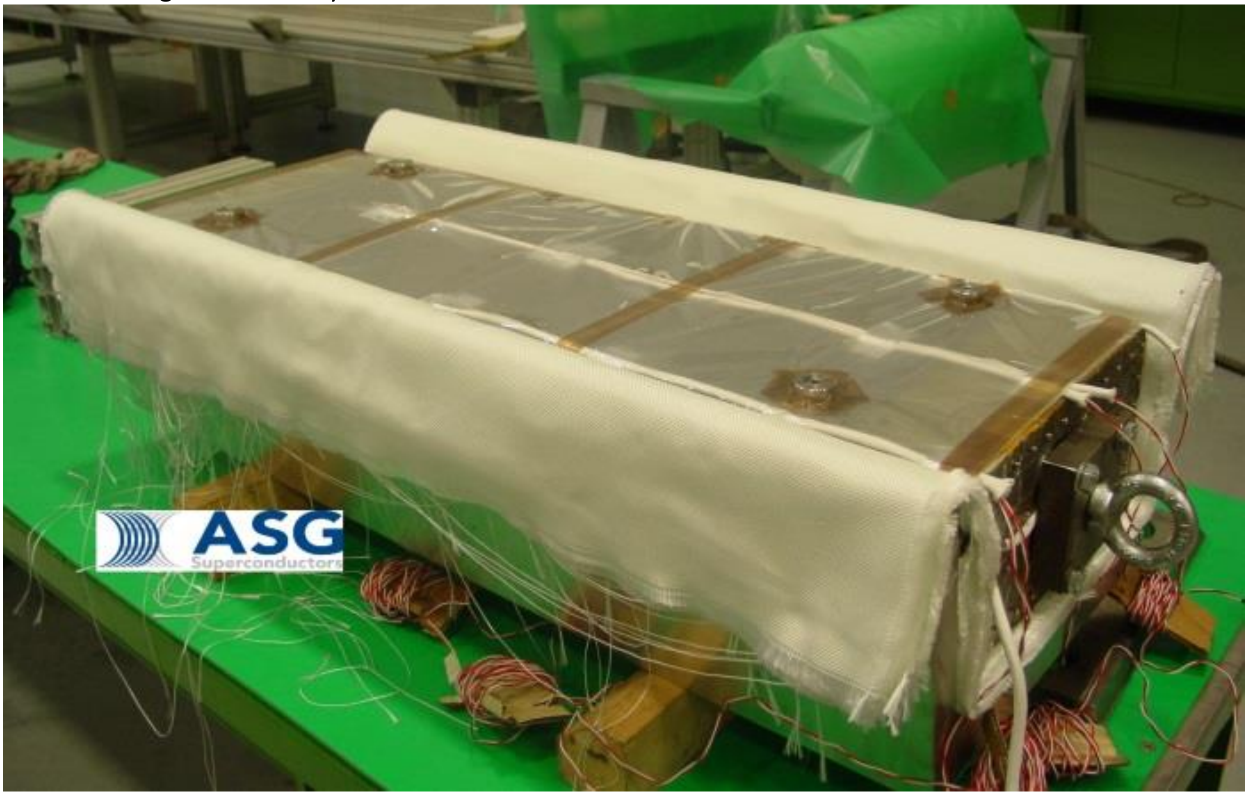

Fig. 22. WP mock-up inserted in straight leg mock-up.

Figure 21 shows the straight leg mock-up prepared and ready to accommodate the WP. The six G10 wedge spacers, equal to those employed in the actual coil, have been glued on the lateral sides below the casing cooling channels. Figure 22, finally, shows the WP mock-up inserted. In this case it is also apparent the presence of a layer of detaching tape that covers the WP all around its surface and is used to permit the sliding of the WP with respect to the embedding resin impregnation in operations. Note that the nominal 5 mm gap between WP and casing on the outboard and lateral surfaces is eventually closed by adding as much glass clothes as needed. This is apparent in the straight leg where the lateral sides have an inclination but it may also occur in case the WP after the impregnation would be smaller of the nominal dimensions.

2.3.2 Welding qualification

Welding for closing coil WP inside casing is performed in two steps: transverse welding to join straight and curved leg of casing and longitudinal welding of covers. Figure 23 shows the inside of the curved leg with the steel protection plate already placed in the 3 mm height recess machined on the casing internal surface. This recess, created to host the protection reduces the nominal height of the welding seam from the original 50 to 47 mm. Nonetheless its presence was considered necessary not only to assure adequate protection to the WP but also to properly flow the weld backing through a channel machined in its thickness not shown in Fig. 23.

Fig. 23. Curved leg mock-up prepared to host the WP beam before transverse welding.

Since transverse welding will be performed on the actual TF coil in a horizontal position the mock-up has been placed vertically and clamped in an external rigid structure to simulate the constraints that the assembly tool will generate on the coil as shown in Fig. 24. Simultaneous welding of the GTAW first pass was adopted on the 2 short sides of the case and along the case corners to limit distortions. After the completion of the first GTAW pass, visual and dye penetrant tests have been performed without evidencing any relevant indications. Welding also of the covers have been completed on both mock-ups (see Fig.25). These, according to the layout foreseen in operations has been performed with the mock-ups 90° rotated and with the longitudinal chamfer in frontal position. Particular attention has been dedicated to the transverse welding of the cover case. Also in this case the backing gas protection was performed by inserting a pipe inside the channels present behind each joint.

Fig. 24. Curved leg mock-up ready for transverse welding.

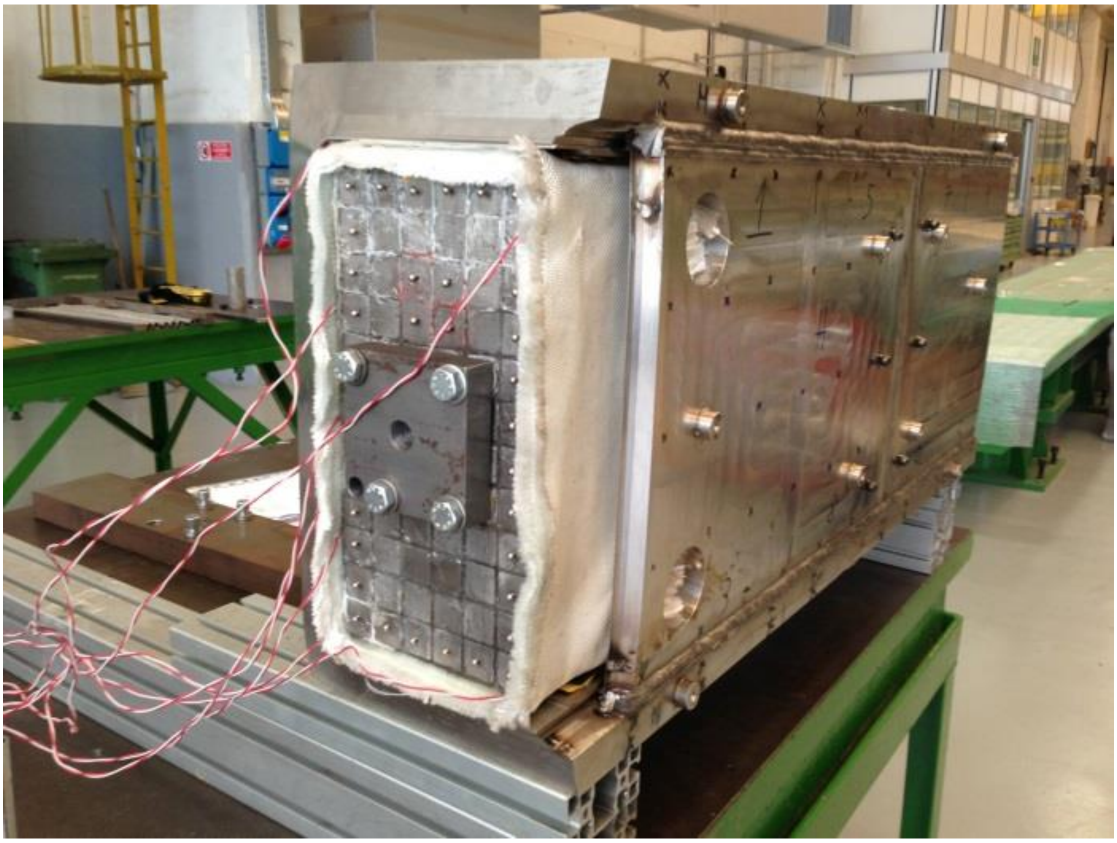

Fig. 25. Curved leg mock-up at the end of the cover welding.

The curved leg mock-up after extraction did not show any damage burning or coloring of the glass sheet, indeed the maximum temperature recorded was 130 °C behind the backing strip and 80 °C on the beam

surface. The mock-up has been cut in two parts. Full penetration and proper gas shielding have been detected.
A complete geometrical survey, in the different stages, of the transverse and longitudinal welds allowed to define 5 mm of extra-length as necessary on each transversal joint to avoid the interference between case and coil due to welding shrinkage of the single transverse joint.
As final outcome of the welding qualification, the procedure for UT measurements and weld repair has been defined.

2.3.3 Embedding qualification

On the straight leg mock-up the embedding procedure has also been tested. This has been performed after complete welding of the cover. To induce a proper pressure on the glass clothes the gap between cover and WP, 10 mm nominal, has been filled with additional layers of glass cloths and the force needed to accost the cover to the casing has been measured. To perform the embedding the mock-up has been placed, as shown in Fig.26, on the impregnation station that will be used for the impregnation and curing of the actual TF coils. Since it will not be possible to visually inspect the final embedding after it has been completed, it is important that the process is well understood and well controlled. At this aim after embedding the mock-up has been cut to inspect the impregnation.

Fig.26 -- Straight leg mock-up ready for the final embedding.

3 Concluding remarks

The successful completion of the first WP of the JT-60SA TF coils represents a fundamental milestone in view of the fabrication of the 9 TF coils by ASG Superconductors on behalf of ENEA in the framework of the

Broader Approach program. All the critical steps in the WP manufacturing have been set-up and, at the time of writing, already two WPs have been impregnated, and a third is ready to start impregnation. Although most of the critical operations were qualified in advance with the use of dedicated mock-up, only the first WP allowed to completely assess all processes. For this reason, for instance, an extensive use of laser tracker measurements at the end of each step was performed. Manufacturing can now proceed with the WP integration into casing. Again the vast majority of the critical steps have been already qualified, however a complete assessment of the process will be possible only in occasion of the manufacturing of the first TF coil whose completion is expected within mid-2015.

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5 Abbreviations and Acronyms

DP = Double Pancake
WP = Winding Pack
TF = Toroidal Field
PF = Poloidal Field
QCP = Quality Control Plane