JT-60SA TOROIDAL FIELD COILS (TFC) MANUFACTURE

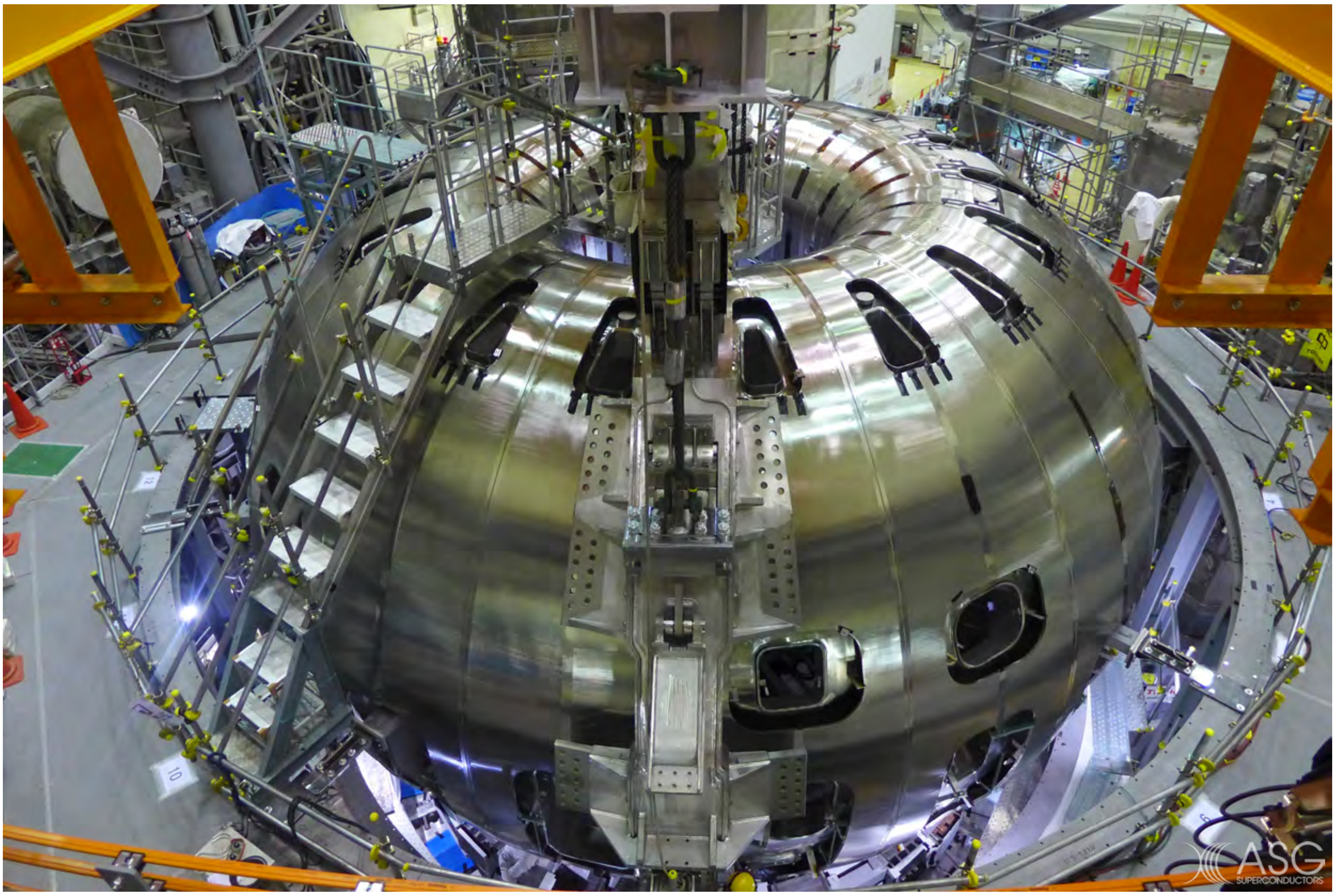
Giovanni Drago

The assembly of the tokamak was completed in 2020 and at the end of the same year also the cooldown was executed; on 02/03/2021 the complete toroidal system was fed up to the nominal current of 25.7 KA.

JT-60SA is a superconducting tokamak machine designed to contribute to the early realization of fusion energy by supporting the exploitation of ITER and research toward DEMO by addressing key physics issues, installed at Naka site in Japan.

The Italian Atomic Energy Agency ENEA awarded the contract for the manufacture of 10 Toroidal Field Coils (9+1 spare) for the JT-60SA project to ASG Superconductors.

Insertion of the last coils in the machine (Courtesy of JAEA)



Introduction

In 2011 under the framework of the Broader Approach Agreement between the European Atomic Energy Community and the Government of Japan, the Italian Atomic Energy Agency ENEA awarded the contract for the manufacture of 10 Toroidal Field Coils (9+1 spare) for the JT-60SA project to ASG Superconductors. The manufacture of the remaining 10 TF coils necessary for the project was managed by the French Atomic Energy Authority.
The superconducting tokamak machine at the Naka site in Japan is designed to contribute to the early realization of fusion energy by supporting the exploitation of ITER and research toward DEMO by addressing key physics issues.
To achieve this, JT-60SA is designed to be completely superconducting and thus able to produce 100 s long shots with a plasma current IP of about 5.5 MA.
The toroidal magnetic system is composed of eighteen D-shaped coils, wound using NbTi conductor, capable of generating a maximum field of 2.25 T on the central axis of the plasma and a maximum field of 5.65 T at the innermost equatorial plane of the coil straight leg. The modules are operated at a temperature of 4.4 K with a theoretical temperature margin of 1 K. They are energised by a current of 25.7 kA.

Coil description

Each coil is manufactured starting from a CIC (Cable in Conduit conductor consisting of a Cu-NbTi strands rope (strand diameter Ø=0.81 mm) wrapped with a thin stainless-steel band and inserted in an AISI 316L stainless steel jacket 2 mm thick. The overall conductor dimensions are 22.0 × 26.0 mm with a void fraction of 32%.

Figure 1, 2, 3 Details of the JT-60SA conductor

The conductor is wound in D-shaped Double Pancakes (DP) consisting of two layers of 6 turns each, insulated by means of two wrappings of half-overlapped fiberglass tape.
After winding, 6 DPs are stacked together to form the Winding Pack (WP) of each coil. The WP cross-section dimensions are 150 × 347 mm with overall width of ~5 m and length of ~8.2 m including the electrical joints between DPs and terminations.
Once the WP has been assembled and ground insulated using fiberglass tape, it is impregnated with epoxy resin inside a vacuum tight case assembled and welded all around the winding.
Then the WP is inserted into a thick stainless-steel casing able to contain all the magnetic forces acting on the conductor during operation. The total weight of the coil is ~16 tons.

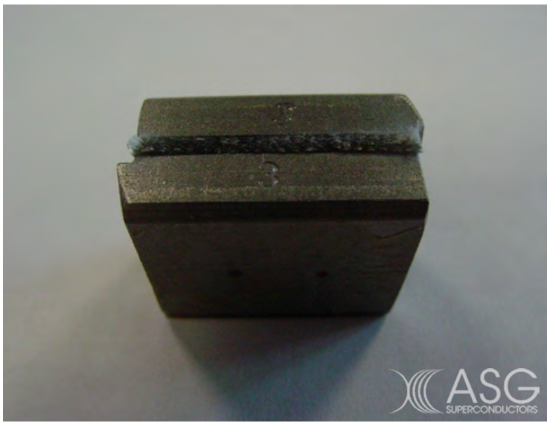
Process qualification and manufacturing tooling procurement
During the first year of the project activities were focused on the following three different tasks:

a) Definition of the detailed manufacturing plan and preparation of detail drawings of the relevant components.
b) Conceptual design and development of the tooling for the WP and TFC manufacturing.
c) Preparation of samples and mock-up for the validation of the design and process qualification to verify that the envisaged procedure meets the main design requirements.

<u>Design Validation</u>
The most important process to be qualified is the turns insulation, consisting of fiberglass tape impregnated with epoxy resin, required to meet stringent requirements in terms of shear strength derived from the calculated mechanical forces acting between the turns.
The performance of the insulation in terms of ultimate shear strength and capability to withstand the cyclic loading has been evaluated on standard samples, comprising two stainless-steel plates separated by fiberglass epoxy resin, simulating the inter-turn insulation. The sample were tested both at room temperature and at 4 K as well as under fatigue conditions and were shown to meet the following requirements:

— minimum shear strength capacity after impregnation of 55 MPa at 4 K, corresponding to 40 MPa at 300 K
— minimum shear strength capacity after 36,000 cycles of 20 MPa at 300 K

The following show the shear strength sample under test:



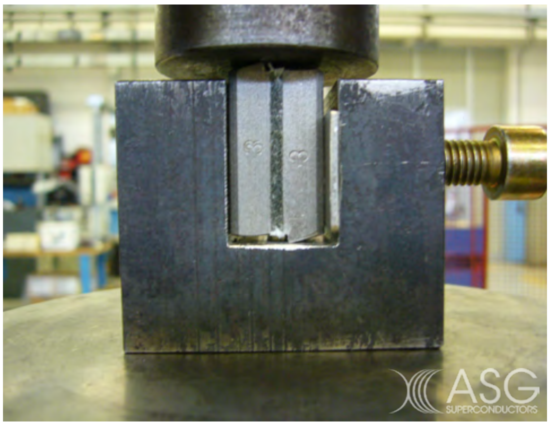
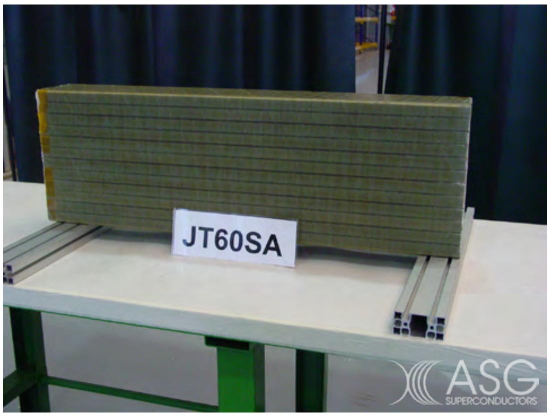


Figure 4, 5 Shear Test Sample / Shear test sample during testing

The insulation and impregnation processes were also validated by the manufacture of a 1 m impregnation beam, using straight stainless steel bars to represent the WP cross section. The beam was assembled, insulated and VPI impregnated and then submitted to electrical test to verify that all the requirements for the insulation were satisfied.
The ground insulation was successfully tested up to 15 kV, while the turns insulation reached 10 kV. In both cases, no faults were detected.
The following show the impregnation beam already painted with conductive varnish for grounding:



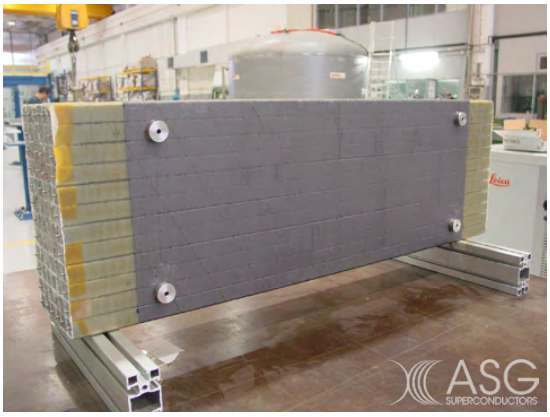


Figure 6, 7 Impregnation Beam / Impregnation Beam with grounding paint and reference markers

The impregnation beam was used also for the qualification of other processes: as a first step it was instrumented with thermocouples and inserted into the coil casing mock-up to verify that the temperature increase during the casing welding was not high enough to damage the resin of the impregnated WP.
Then, after welding, the mock-up was submitted to a second impregnation cycle in order to simulate the embedding impregnation.
The mock-up cut after the impregnation is shown in the following images:

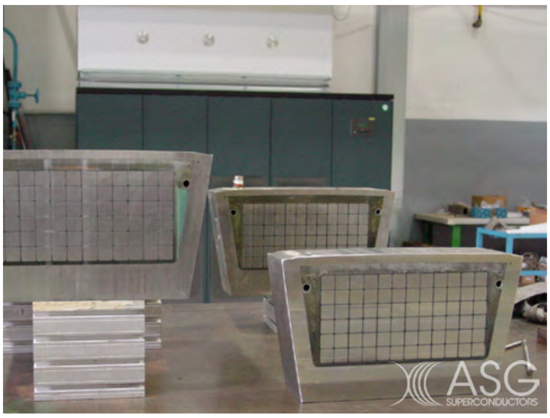



Figure 8, 9 Impregnation Beam inside casing mock-up / Casing mock-up cut after embedding impregnation

Another important process to be qualified was the manufacture of the internal joints which provide the electrical junction between different DPs of the coil. The joints are realized following the "praying hands" concept based on the configuration where the two conductors forming the joint are coming from the same side of the coil. The conductors are inserted into a pre-machined junction box made from a three-layer (stainless steel – copper – stainless steel) explosion bonded plate, pressed against the low resistance copper intermediate plate and compressed by the stainless-steel covers which are welded to the main body of the box.
The electrical resistance of the joint at 4 K had to be less than 5 nΩ.
To guarantee the low resistance of the joint, silvering of the inner surface of the box as well as the end portion of the conductor rope is necessary and several trials and mock-ups were required to define the silvering process parameters. The joint sample shown in the following figure was tested by ENEA with positive results:

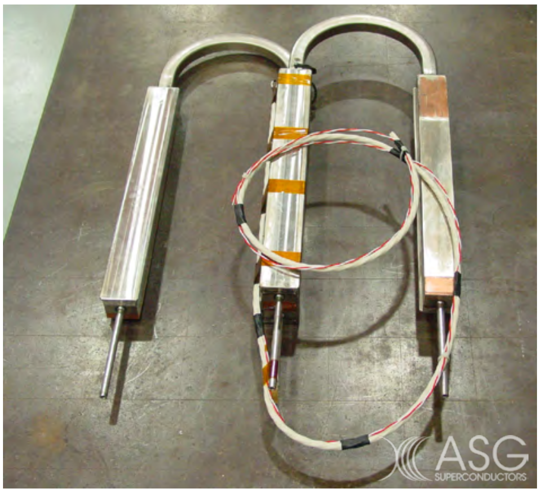


Figure 10 Full size joint sample tested by ENEA

<u>Manufacturing tooling</u>
In parallel with the mock-ups and process qualification work, the conceptual design of the main tooling was performed followed by the procurement and installation of the main tooling for the manufacture of the coils.
The most critical item was the winding line which is composed of different units assembled and synchronized to perform the DP winding. In detail the line is equipped with an unwinding spool which supplies the conductor necessary for the winding, a straightening unit to remove any residual bending present on the conductor, a cleaning unit, a calendaring unit to bend the conductor to the required radii, a sandblasting unit, a taping unit and finally a winding table which hosts the bent conductor.

The unwinding spool and the winding table are shown below:

Figure 11, 12 Winding Line-Unwinding spool / Winding Line-Winding Table

Another important tool necessary for manufacturing the WPs is the impregnation station which consists of a steel framework equipped with several modules able to allow the thermal expansion of the WP during the impregnation cycle. The framework can be tilted along the longitudinal side to ease the resin flow during impregnation. Each module is equipped with frames to transfer to the WP the force to compact the insulation and with heating elements to regulate the temperature of the coil during the process.

Figure 13 Impregnation station

The integration of the WP inside the casing required the design of a specific tool able to support the WP during the assembly of the casing parts and to tilt the final assembly to a vertical position in which to perform the casing welding to achieve annular containment of the whole surface of the WP. A challenging aspect of the design of this tool was the small gap between the WP and the casing, being only 5 mm, which strongly influenced the design of the WP supports. The dimensions and loads of the tilting toll required verification of the floor capacity.

Figure 14 Assembly and tilting tool

Manufacturing plan

The Toroidal Field Coil (TFC) manufacturing was divided into two steps – one for each of the main components supplied by ENEA: the conductor for the winding and the stainless-steel casing for the final assembly of the coil. At the end of each manufacturing step, a complete acceptance test was performed.

WP manufacturing

The first step is the WP manufacturing which starts with the conductor acceptance test to assess the conductor tightness. The conductor supplied as a single layer solenoid was inserted into the vacuum chamber to perform the pressure/leak test, evacuating the chamber and pressurizing the conductor. All the conductor lengths tested showed a leak rate lower than 2×10^{-9} mbar*l/s as required by the specification. After the test, the conductor is transferred to the winding line for the DP winding operations: the conductor is first straightened to remove the previous bending deformations, then it passes through the cleaning unit to clean the jacket surface by means of detergent and ultrasound bath.

The next equipment of the line is the bending unit which, by means of plastic deformation, gives to the conductor the required curvature radii for the DP. Once the conductor is bent, the sandblasting unit gives to the conductor surface the roughness necessary to ensure good adhesion of the insulation (fiberglass and resin). This unit represented the most challenging set up, due to the need to operate on a low curvature radius of the turns in the transition region from the straight part to the outer region of the coil. The next unit is the taping machine which applies to the sandblasted conductor the fiberglass tape to realize the turn insulation. Finally, the wound turns are transferred to the winding table.

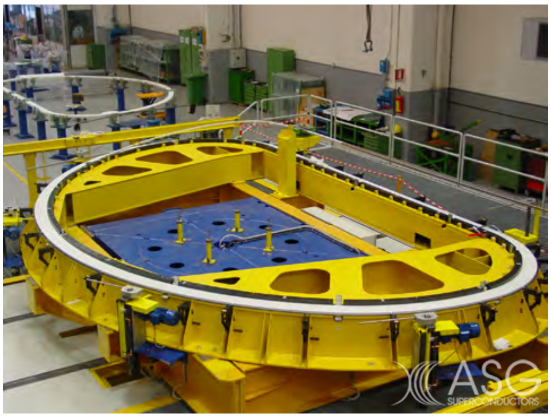


Figure 15, 16 DP winding completed / Winding of DP 2nd layer

Once the winding operations have been completed the DP is moved by means of the lifting tool to the DP insulation station where several operations are completed: bending the DP leads, removing the jacket and silvering the superconducting rope for the next joints, and applying the DP insulation.
The completed DP is then moved to the stacking station where six DPs forming the WP are stacked together; in this phase, checking and adjustment of the alignment is performed. After stacking, the ground insulation is manually applied by wrapping the WP with several tapings up to the final thickness of 3 mm. A further check on shape and dimensions is performed prior to moving the WP to the impregnation station. The requirements in terms of tolerances were quite demanding especially in terms of the overall dimensions of the WP: on the cross-section of the coil the tolerances are ±3 mm on the width and ±5 mm on the height and referred to the coil dimensions (4370 × 7330 mm) these represent 0.04 & 0.06 %. In addition, the most stringent requirement is set on the centerline of the WP straight part which has to stay inside a cylinder of Ø2 mm.

Figure 17 DP stacking

After application of the ground insulation the WP is moved to the impregnation station where it is inserted inside the impregnation mold which consists of a thin stainless-steel casing split into two halves which are welded all around the WP to realize the resin containment. During this operation the shape of the WP is checked by means of the Laser Tracker to control the alignment within the prescribed tolerances.
Moreover, after the welding and prior to starting the process cycle, the tightness of the casing is verified to ensure that the the maximum leak rate is not exceeded. The ground insulation of the WP is checked and the mold is used as a vacuum vessel to check the leak rate on the conductor and internal joints/terminations.
Once the mold has been checked, the VPI impregnation cycle can be executed performing all the different phases controlling the temperature vs. time as well as all the other parameters. The whole impregnation cycle, including the preliminary heating, the ramping up and down to the different temperatures and the final cool down to room temperature (RT) lasts about 12 days.
After the VPI cycle the WP impregnation casing is dismantled and the WP is cleaned before the application of the conductive varnish to realize the electrical grounding.

Figure 18, 19 WP VPI impregnated / WP after grounding varnish application

On the completed WP the intermediate acceptance tests are performed, executing a complete dimensional survey and referring the results, especially the centerline position, to the reference points (12 in total) glued on the inner surface of the WP. These reference points are used for the next assembly operation and for the final interface machining.
In addition, hydraulic tests on the conductor circuit are performed inside a dedicated vacuum chamber: pressure/leak test is performed by pressurizing the conductor up to 30 bar and measuring the leak rate with respect to the chamber, then a flow test is carried out to verify that during the impregnation no obstruction of the conductor circuit occurred.
While the WP is inside the vacuum chamber, Paschen tests comprising consisting of High Voltage tests in a gas atmosphere at different vacuum/pressure conditions are also performed. These are executed in N2 gas at different pressure steps from vacuum (10-3 mbar) to 100 mbar. At each step a voltage of 3.8 kV is applied to the conductor to test the electrical tightness of the insulation.
Finally, the standard electrical test (inter-turn and ground insulation) and measurements (Resistance and Inductance) are executed.
This test campaign releases the WP for the next manufacturing stages.

Figure 20 WP introduction into Vacuum chamber for testing

TFC manufacturing

The second step is the TFC manufacturing which starts with the insertion of the WP inside the stainless-steel casing which consists of two main "C" shaped parts 50 mm thick to be assembled and welded to provide containment around the outer surface of the WP. The inner closure is ensured by 20 mm covers that have later to be welded to the "C" shaped parts. For the insertion of the WP inside the casing, only a small clearance is provided: this small 5 mm gap requires that the dimensions and tolerances both of the WP and the casing are well respected to allow the assembly. Due to the precision achievable on the WP following resin impregnation being lower than the precision of the casing components obtained by mechanical machining, the gap is not constant all around the WP surface. For this reason a fiberglass cloth to be further impregnated has been chosen as the filling material, the thickness of which was determined by means of a full geometrical survey both of the coil and the casing. Firstly, the two parts of the casing are installed on the carriages while the WP is positioned on the inner core of the tilting tool. Secondly, the assembly of all the components is performed. Finally the assembly is tilted into a vertical position to allow the execution of the welding between the two parts of the casing. Once the transversal welding has been completed, the coil is tilted again into a horizontal position and moved onto supports for the installation and welding of the inner covers.

Figure 21, 22 WP and coil casing onto the assembly tooling / Assembly tilted in vertical position for welding execution

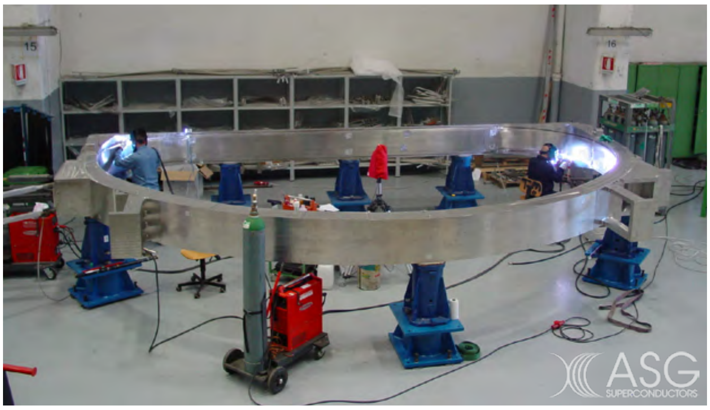


Figure 23 Cover welding

After the casing welding, the coil is ready for the embedding impregnation of the fiberglass in between the WP and the casing to secure the WP position with respect to the casing. For this VPI impregnation the casing acts as a mold ensuring the tightness for the resin injection and only the blanking of some openings, for example the reference point on the inner surface, is necessary.
A complete dimensional survey follows the embedding impregnation to define the reference planes to be used for the final interface machining. These reference planes are defined by the position of the centerline of the straight leg and are characterized with respect to the reference point of the WP. During the machining other references on the outer surface of the coil are added to allow the final installation. The final machining operations have been commissioned to an external company which performed the activity under ASG responsibility and supervision.

Figure 24 TFC interface machining (courtesy of Officine CLP)

After machining the coils were returned to the ASG premises for completion, comprising the routing, welding and insulation of the cooling circuit as well as the installation and routing of instrumentation. Once the coil has been completed all the acceptance tests were performed and attended by ENEA and the leak/pressure test was also attended by a certified third party.

Figure 25 TFC completed

Coil testing and installation

All the JT60-SA TF coils were successfully tested at the CEA site (near Paris). The test was carried out at cold condition feeding each coil up to the full current of 25.7 kA, including an induced quench obtained by reducing the LHe flow. After the testing, before the shipment to Japan, the OIS (Outer Interface Structure) which represents the mechanical interface between two adjacent coils inside the machine was assembled. Both the testing and OIS assembling activities were in charge to Fusion For Energy. Performed under responsibility and supervision of the European Agency for Fusion (F4E-Fusion for Energy)

The assembly of the tokamak was completed in 2020 and at the end of the same year also the cooldown was executed; on 02/03/2021 the complete toroidal system was fed up to the nominal current of 25.7 KA.

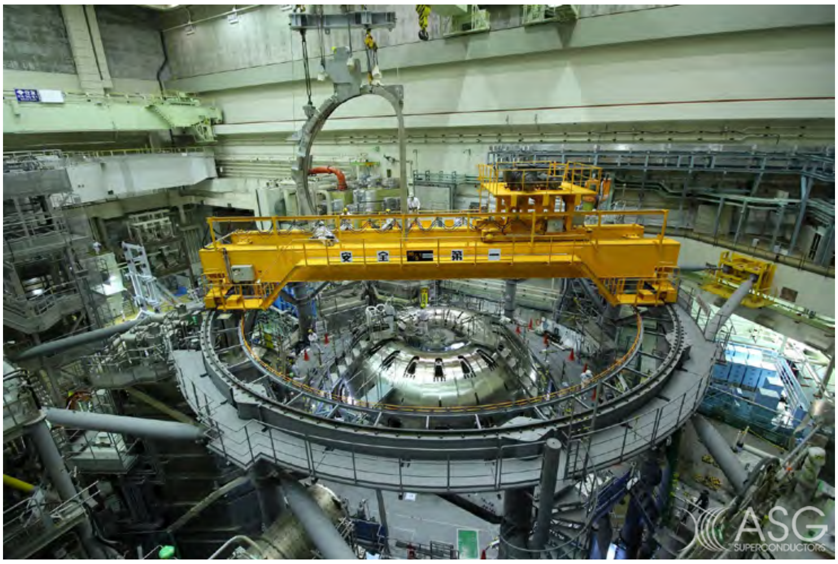


Figure 26 TFC assembling on the machine (Courtesy of JAEA)

Special thanks to ENEA, Fusion For Energy and all ASG Superconductors team who made it possible to complete this important project.