PROGRESS OF THE JT-60SA PROJECT

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Abstract

The JT-60SA project was initiated in June 2007 under the framework of the Broader Approach (BA) agreement and Japanese national fusion programme for an early realization of fusion energy by conducting supportive and complementary work for the ITER project towards supporting the basis for DEMO. With the project now in an advanced implementation stage, the early defined approach for its implementation has proven to be successful and hence continues to be employed. This is underpinned by the very close collaboration between QST in Japan, F4E in Europe, and all other European stakeholders: the EU Voluntary Contributors (EU-VCs) and EUROfusion. As of September 2018, the closure of the torus has been accomplished. All TF coils have been manufactured, tested at full current and cryogenic temperature demonstrating a consistent temperature margin, and assembled. All Equilibrium Field (EF) coils manufacturing was completed by the middle of August 2016. Three CS modules were completed by March 2017 while manufacturing of the last CS module has recently been completed. The manufacture and delivery of all 26 High Temperature Superconductor Current Leads (HTS CLs) was completed in November 2017. All large power systems, including the Switching Network Units and Super Conducting Magnet Power Supplies, have also been manufactured, delivered and with few residual commissioning activities still ongoing in Naka. With the cryostat base already in place since 2013, the Cryostat Vessel Body Cylindrical Section has been manufactured, preassembled, measured and delivered to Naka. The full scope of the Cryoplant, manufacturing and commissioning, is now successfully completed. The final assembly phase has therefore started together with the gradual execution of integrated commissioning leading to the completion of the assembly in March 2020 and a First Plasma in September 2020. The efficient start-up and scientific exploitation of JT-60SA by the large international team is a challenging enterprise, which will be similar to, and provide important input to, the ITER start-up phase. To optimize this phase, a broad set of coordinated activities have been carried out over recent years by a joint Japanese-EU JT-60SA Research Unit, fully integrated in the IPT and liaising with the broader Japanese and EU fusion physics community. The paper will overview the progress of the manufacturing and assembly of the JT-60SA machine towards First Plasma, and progress in preparing for the next phases of JT-60SA following this milestone.

1. INTRODUCTION

The JT-60SA [1-4] project was initiated in June 2007 under the framework of the Broader Approach (BA) agreement and Japanese National Fusion Programme for an early realization of fusion energy by conducting supportive and complementary work for the ITER project towards supporting the basis for DEMO. In 2009, after a complex start-up phase due to the necessity to carry out a re-baselining effort to fit in the original budget while aiming to retain the machine mission, performance, and experimental flexibility, the detailed design of the project could start immediately followed by the start of manufacturing of the long lead items.

Components and systems of JT-60SA are delivered by the implementing agencies (IAs): Fusion for Energy in EU and QST (previously JAEA) in Japan. With the project now in an advanced implementation stage, the early defined approach for its implementation has proven to be successful and hence continues to be employed. This is underpinned by the very close collaboration between QST in Japan, F4E in Europe, and all other European stakeholders: the EU Voluntary Contributors (EU-VCs) and EUROfusion. The employed management model follows the early establishment of a single Integrated Project Team (IPT) that operates in accordance to an agreed Common Quality Management System, defining resources and processes crossing the lines between organizations.

The same management model strategy is planned also for the period beyond 2020, that is when the facility will be jointly operated and enhanced by the EU and JA.

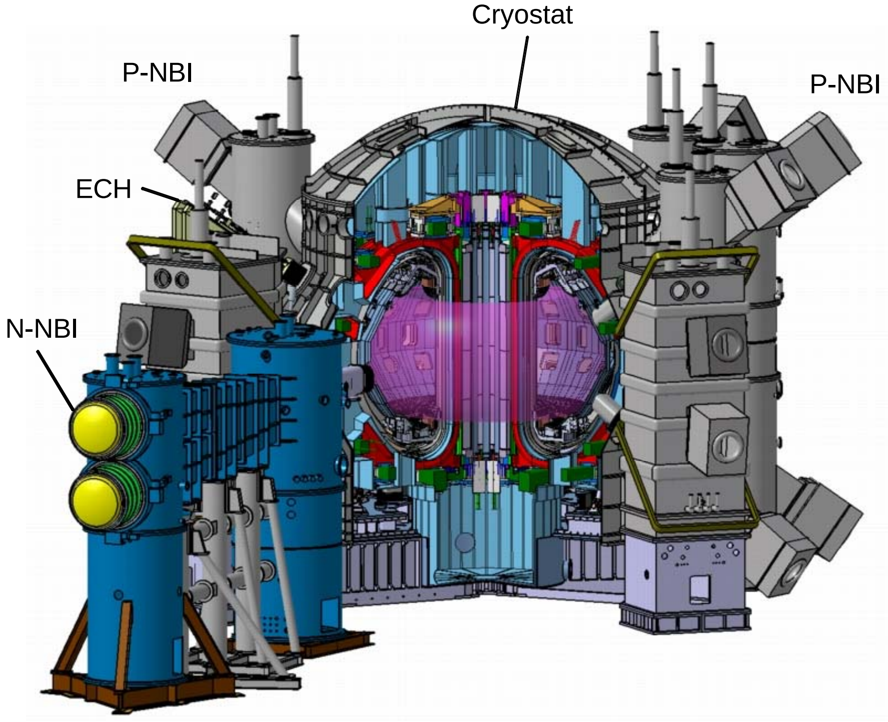

FIG.1 : View of JT-60SA

2. OVERALL DESIGN AND STATUS OF ASSEMBLY

JT-60SA is a fully superconducting tokamak capable of confining break-even equivalent deuterium plasmas with equilibria covering high plasma shaping with a low aspect ratio at a maximum plasma current of Ip=5.5 MA. Overall the machine view and the basic parameters of JT-60SA are shown in Figure 1 and Table 1 below. The machine has been designed with plasma shaping flexibility as first priority with a wide range of plasma equilibria in divertor configurations extending to high plasma shaping factors (S~7), low aspect ratio of A~2.5, and an inductive plasma current flattop of 100s with an additional heating up to 41 MW.

TABLE 1. JT-60SA MAIN PARAMETERS

Parameter		Value
Plasma Current		5.5 MA
Toroidal Field		2.25T
Major radius		2.96m
Minor radius		1.18
Aspect ratio		2.5
Elongation Kx		1.95
Triangularity		0.53
Flattop duration		100s
Heating & CD Power		41MW
	N-NBI	10MW
	P-NBI	24MW
	ECRF	7MW

The JT-60SA Project has three major objectives. The first objective is to provide supporting research for the ITER project to accomplish its technical targets. In order to realize a stable Q=10 operation in ITER, a number of key issues will need to be addressed. For example avoidance of disruptions and their mitigation, ELM mitigation and the development of ELM-free regimes, Divertor heat load reduction by radiative attached divertor regimes, etc.

JT-60SA can operate in the ITER-like configuration inductive mode under the break-even-equivalent condition. Hence the operation boundary of ITER high integrated performance plasmas without disruption or serious MHD instabilities will be investigated. The second, maybe even more significant, objective is to provide complementary research to ITER in order to develop a technically convincing and sound design basis for DEMO. Although ITER will aim to demonstrate stability of self-heated plasmas with 400-500 MW DT burning, an economically viable DEMO will need to operate with values of β_N significantly higher than those that ITER will aim to. Moreover DEMO, in light of the even higher fusion power conditions, will not be able to tolerate any ELM, will require careful control of the divertor detachment as well as mitigation tools in case of attached divertor regime, so to avoid damage to the divertor structures. In light of its high degree of flexibility and large volume, JT-60SA will provide a key research infrastructure to address such issues as well as investigate Steady State high β_N regimes. Finally, the third objective of JT-60SA will be to promote fusion researchers of the next generation, who are expected to play leading roles in ITER and DEMO.

JT-60SA will examine and optimize operation scenarios in some of the ITER and DEMO parameter regions [5]. For that purpose, JT-60SA has several distinct characteristics for flexible operation in a wide range of plasma parameters. In the limit of steady-state operation, high β_N plasmas are expected to be driven with, for example, Ip= 2.3 MA, B_T = 1.7 T, q_{95} = 5.6, f_{GW} = 0.85, f_{BS} =0.67, β_N = 4.1, HH_{98y2} = 1.3, P_{heat} = 37 MW (20 MW of N-NB, 10 MW of P-NB and 7 MW of ECRF). Profiles of the inductive, bootstrap, beam-driven, and ECRF-driven currents calculated using assumed ne, Te and Ti profiles. The resultant q profile would then have a reversed shear configuration with q_{min}~1.7 at r/a~0.5. For a reduced value of f_{GW} (0.6), a higher Ip of 2.9 MA could be non-inductively driven with the same HH_{98y2} of 1.3. In inductive regimes, the highest performance is expected at full current, the typical expected value of nτT will be ~5-7*10^{20} m^{-3}•s•keV, with Ip = 5.5 MA, f_{GW} = 0.8 and HH_{98y2}= 1.1-1.3. The expected threshold power for L to H transition (P_{LH}) is ~15 MW. Hence with the available heating systems a good confinement is expected.

With the above objectives in mind, and aiming to the optimisation of the overall system design within tight cost constraints and dimensional boundary conditions given by the need to re-use some of the previous infrastructure of JT-60U, the JT-60SA design was developed with an integrated system level view. The basic strategy adopted led to an optimised design with low plasma aspect ratio (R/a), and with a carefully optimised TF conductor design and TF coil cross section layout to minimize its dimensions. As a result of the initial design phase, the superconducting magnet system of JT-60SA consists of 18 Toroidal Field (TF) D-shaped coils, a Central Solenoid (CS) with four modules, six Equilibrium Field (EF) coils. Each TF coil is wound from a rectangular steel-jacketed NbTi cable-in conduit conductor wound in 12 pancakes each with 6 turns. The PF magnet is composed of the CS and EF coils using Nb3Sn and NbTi cable-in conduit conductors, respectively. The magnet, together with its shields and current leads, are cooled by means of a cryogenic system whose design was carefully optimised, in large part due to the pulsed nature of the Tokamak, in order to reduce costs. The vacuum vessel (VV) is a double wall structure constructed with low cobalt SS to reduce activation levels with a flow of boric acid water between inner and outer shells. The divertor consists of inner and outer vertical targets with a V-shaped corner for the outer one to enhance particle recycling and reduce target heat flux, a private flux region dome, inner and outer baffles capable of withstanding a medium heat flux, and a divertor cassette body. Cryopanels will be installed below the divertor cassette for particle control. Three sets of copper coils consisting of a pair of fast plasma position control coils, 18 error field correction coils and 18 RWM control coils will be installed inside the VV. Fast plasma position control coils are situated between the VV and the stabilizing plate for holding horizontal plasma position and suppressing vertical instability. The cryostat consists of a vessel body and a base used for the gravity and seismic support of the machine.

With the basic design of the facility completed in 2009 the procurement of long lead items, such as Conductor and Vacuum Vessel, could be immediately started while the detailed design and preparation of the technical specifications of all major systems could also be undertaken. The detailed design kept always as a key requirement the need to achieve tight tolerances during the assembly phase. In particular, the assembly design of the magnet was considered throughout the whole Tokamak system design process to ensure the required field accuracy and the necessary strength and stiffness of the joints, not to mention respect for the project budget during the critical assembly phase. This involved detailed consultations with the assembly contractor, optimization of tolerance assignments and process qualifications. As it can be visible in Figures 1and 2, the assembly is now in an advanced state. As of September 2018, the closure of the torus has been accomplished. All 20 (18+2 Spares) TF coils have been fully tested at full current and cryogenic temperature demonstrating a consistent temperature margin, and in line with the predictions. Following air shipment of the last 2 coils to cut delivery time, in March 2018, the TF magnet has been delivered and fully assembled in the torus and the closure of the VV could be finalised – see Figures 2, and 3.

With the target of a First Plasma in September 2020, the system construction process is now progressing with the installation of the upper EF coils, the CS, Cryostat Thermal Shield, internal cryolines, magnet feeders, etc. At the same time the commissioning of plant systems is now underway with a view to start the full integrated commissioning towards first plasma to be started in March 2020.

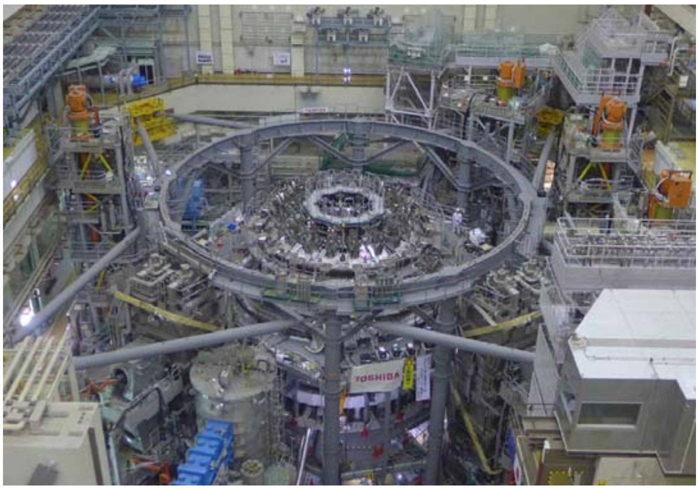

FIG.2 : Current view of the Torus Hall

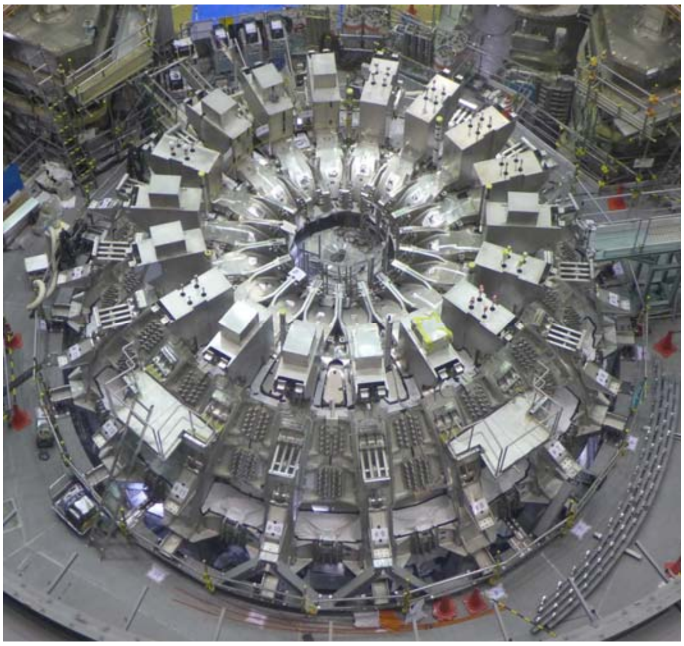

FIG.3 : Current top view of the Torus

3. MAGNET SYSTEM

The backbone of JT60SA is its Magnet system. Due to the requirement on long pulse duration it is entirely Superconducting, with 18 NbTi Toroidal Field (TF) coils, 6 NbTi Equilibrium Field Coils, and 4 Nb_3Sn Central Solenoid (CS) stacked modules.

The TF is provided by a set of 18 coils, each wound from 72 turns (12 pancakes each with 6 turns) of a 22x26 mm2 rectangularly shaped, steel-jacketed, NbTi, cable-in-conduit conductor (CICC) [6-8]. In each coil, the winding pack (WP) is housed in a stainless steel casing with two additional cooling channels to aid magnet cool-down. In selected regions a thermal insulation layer is provided between the WP and the steel casing in order to smooth the thermal loads from the casings (e.g. due to eddy currents) onto the conductor and hence on the cryoplant during dynamic operation of the device. In the upper and lower inboard curved regions the coils are supported by conical eccentric adjustable bushings inserted between the casings. This flange has been designed and assembled in a pre-compressed state achieved by means of toroidal fasteners inserted during the final machine assembly. In the outboard region the coils are toroidally supported by a self-standing Outer Intercoil Structures (OIS). The OIS also consists of 18 equal parts. Each part houses and radially guides each coil. It does support the coils against out-of-plane loads while allowing limited radial movement due to the in-plane expansion of the coil. An insulated bolted friction joint forms a complete structure to house the full magnet. The TF conductor has been designed so as to ensure a minimum temperature margin of 1.2 K in normal operating conditions and a minimum of 1 K after a full plasma disruption. The superconducting strands consist of NbTi filaments embedded in a copper stabilizing matrix surrounded by a resistive barrier needed to control the inter strand coupling currents while allowing current redistribution. The superconducting strands are cabled with a multi-stage arrangement. In the first stage 2 NbTi strands will be cabled with 1 Copper strand (needed to meet Hot Spot temperature criterion). Further details of the TF Magnet design are described in [3]-[5] while the manufacture of the coils is reported in [6]-[8].

After manufacturing [9-11], each coil has been delivered to the CEA-Saclay TFC Test Facility where it has been tested at cryogenic temperature and full current [12]. All of the 20 (18+2 Spares) TF coils have been fully tested demonstrating a consistent temperature margin, fully in line with the predictions, thus giving confidence that their performance will be as designed during Tokamak operation. Such cryogenic testing included analyses of hydraulic performance and ground resistance at cryogenic temperature and after a warm-up cycle. Once tested, each coil has been fitted with its corresponding OIS sector. This was done in a workshop immediately adjacent to the Cold Test Facility. In this facility, each coil (~15500kg) has been rotated 'on edge', i.e. with its straight leg along the ground and its curved leg up in the air, to allow the OIS (6 000kg) to be lowered vertically down around it. This intermediate step was instrumental in ensuring a good match and thus reducing the assembly time on Site.

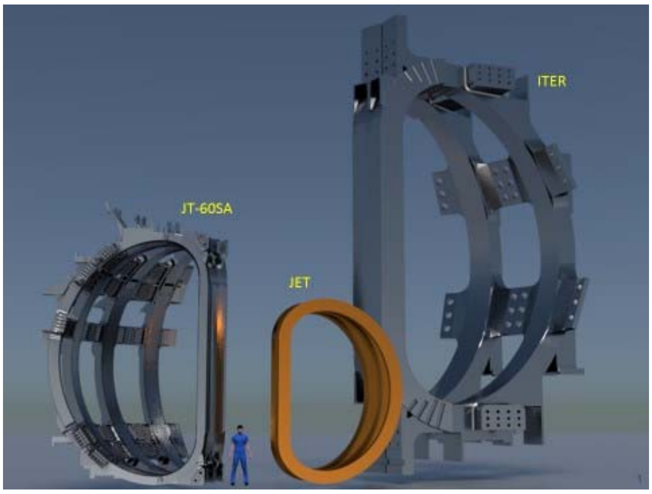

FIG. 4 : comparison of the TF coils of JT-60SA, JET, and ITER.

FIG. 5. Pre-assembly of an OIS sector onto a TF coil

After the pre-assembly process of TF Coil and its mating OIS, each assembly has then been carefully packed and inserted in a suitably designed transport frame for its long voyage to Naka in Japan. While this was normally carried out by sea, i.e. using a rool-on/roll-off transport vessel from Europe to the Tokai port of entry and lasting typically 6-7 weeks, the last two TF coils to be assembled in the torus have been air-transported by means of a large Antonov An-124 aircraft from Paris to Nagoya airport in Japan. This was deemed as cost effective as it allowed to recover a delay that was accumulated in the last period of fabrication of the TF coils resulting from some manufacturing issues which required an accelerated recovery in order to maintain the assembly schedule.

FIG. 6 and 7: Loading of the last 2 TF coils in Paris, and the Antonov An-124 landing at Nagoya Airport

FIG. 8 : one TF coil before assembly

Once delivered to Naka, the first step in installing each coil in the tokamak has been to fit its Straight Leg Insulation (SLI) – a 3mm layer of GRP plates on one side of its straight leg and a customized set of stainless steel shims on the other side, selected according to measurements made on the side of the preceding coil.

Each coil was then positioned vertically using a dedicated rotating frame in the tokamak Assembly Hall and lifted up over the assembly frame with the building crane. It was then lowered between the beams of the a dedicated rotary crane into the 20° gap in the torus left by the preceding assembly of 340° of the Vacuum Vessel (VV) and its Thermal Shield (TS). The coil was then rotated (Fig 9) around the VV & TS to its target position (Fig. 4), necessitating the temporary progressive disassembly of the VV supports. The first coil was positioned directly opposite the opening in the torus for the final sector. Subsequent coils were added to each side of it, generally but not always alternately. Vertical ports to the vacuum vessel, between the coils in odd-numbered sectors, were installed progressively to maintain maximum working space.

The achievement of an error field lower than 10^{-4} required a very careful alignment and installation of each coil. The design of the TF magnet, with a separate OIS and adjustable crown pre-compressed keys, allowed this adjustment to be carried out efficiently. The current centreline of each coil was could then be aligned with its nominal position. To achieve this, precise supports for the 2 vertical crown plate reference planes at the bottom of the straight leg have been positioned beforehand, and later adjusted to compensate for any error in the machined positon of those planes. Two laser trackers have been employed during final position adjustment of each coil: one located inboard, viewing the tracking points machined on the straight leg (top, middle and bottom), and one outside the torus viewing the tracking points machined on the curved leg (primarily at the midplane). Once positioned correctly, the first joints to be fastened have been the bolts and then the pins of the highly loaded and closely-packed Inner Intercoil Structure (IIS, Fig. 10) at the top and bottom of the straight leg. The M30 and M36 Inconel 718 nuts and studs were tightened with specially adapted hydraulic torque wrenches. An ultrasonic extensometer was used to confirm that the applied preload was within the required acceptable range.

FIG. 9: TF Coil Rotation around the torus

FIG.10: Inner Intercoil Structure

In the IIS, although an interference fit for the shear pins is needed to achieve the required strength and stiffness of this critical joint, a freeze fit was considered unacceptably irreversible. Therefore a conical pin and split bushings were developed for JT-60SA. The pin is equipped with a male thread used to pull it into place and an interior female thread that may be used to remove it. To avoid in-situ machining to align the pin holes of neighbouring coils, offsets were accommodated by machining the axis of the conical inner surface of each bushings offset from the axis of its cylindrical outer surface. The pair of bushings could then be rotated to bring their inner axes into alignment. After the installation of the IIS, the 5 pairs of splice plates used to bolt the shear panels of the OIS to each neighbouring coil were customized prior to installation to accommodate any misalignment. 22 M42 Inconel 718 studs were used to bolt each pair of splice plates. They were hydraulically tensioned simultaneously, with a 22-head tool, in order to maximize the preload remaining when the load is transferred from the tensioner to the nut.

The final, 18th TF coil had to be inserted into the tokamak together with the final sector of the vacuum vessel and its thermal shield. Such coil was pre-assembled together with the VV and the TS on a stand-up jig, fixing the relative position of the components. The whole pre-assembly was then stood up vertically and then lowered into the 20° opening in the VV/Torus slightly radially outboard of its final position in order to create a small toroidal clearance on each side. After lowering, the final sector was moved radially in to its final position, in part using the crane and in part using screws acting on sliding supports. The VV closure sector was then attached to its neighbours using internal jigs and then welded from the plasma side.

The high accuracy of the coil positioning achieved during assembly made a significant contribution to keeping the magnetic field errors within acceptable limits, in spite of variations already accumulated due to irreversible manufacturing processes. Besides thorough preparation this is primarily thanks to the adjustable nature of the processes designed.

In JT-60SA the 6 EF coils [7] and the 4 independently-controlled CS modules allow wide ranging and flexible control of the plasma shape. All EF coils manufacturing was completed by the middle of August 2016. Three CS modules were completed by March 2017 while manufacturing of the last CS module has also been completed in spring 2018. The stacking of all the CS modules will then start with the entire CS magnet delivered to Naka by December 2018. The EF coils vary in diameter from 4.4 m up to 12 m. Two different NbTi cable-in-conduit conductors are used with a central spiral coolant channel, one optimized for a peak field of 4.8 T for EF coils 1, 2, 5 & 6 and one optimized for a peak field of 6.2 T for the inboard EF coils 3 and 4. Both carry up to 20 kA. Two pick-up coils are co-wound in each coil for quench protection.

Manufacturing of the EF coils was completed in 2016. Since their large size (up to 12 m diameter for EF1) prohibits their transportation most were manufactured on site in Naka using modularized tooling. The coils were wound from single or double pancakes, depending on their size and hence how many turns could be made from a single conductor length. The pancakes were press-cured clamped in a mould before being stacked to form the winding pack. Then the ground insulation was wrapped and cured before clamps are fitted around the winding packs to keep them under compression during operation and provide support points.

Despite their large size excellent control of deviations from circularity was achieved during the winding and stacking of the EF coils. The preliminary assembly of the trapped EF coils was one of the first steps to be carried out in 2016 whereby the coils were rested on the lower cryostat base while the TF magnet assembly was carried out. Once this was completed the lower EF coils were raised and connected to the TF magnet. Thereafter the lowering and installation of the upper EF coils was initiated.

FIG.11: EF Coils 1-3 in the winding hall at Naka before assembly in the torus

FIG.12: CS Module 1 of 4

The CS is made of 4 modules, each with an outer diameter of 1.65 m and a height of 1.60 m. Each module is made from 6 octa-pancakes and 1 quad-pancake forming 549 turns. The conductor can carry 20 kA, giving a total of almost 11 MA-turns for each module.

The peak nominal field of ~9 T necessitated the development and fabrication of a Nb_3Sn cable-in-conduit conductor and hence the pancakes had to be wound before the 650°C heat treatment needed to produce the superconducting strand was performed. After heat treatment the turns were be separated carefully, without applying excessive strain, to allow the glass-kapton turn insulation to be wrapped around the conductor. Finally the pancakes were impregnated together to form each of the four modules. Currently all four solenoid modules have been completed. The completed four modules will now be stacked and compressed with tie rods. The finished solenoid will weigh almost 100 tonnes.

In order to limit heat loads onto the cryogenic system, JT-60SA employs a set of 26 High Temperature Superconductive Current Leads (HTS-CLs) [13]. These are specifically 6 for the TF Magnet, 12 for the EF Magnet, 8 for the CS. The manufacture and delivery of all HTS-CLs was completed in November 2017 at the Karlsruhe Institute of Technology (KIT) in Germany. Their performance was confirmed by testing each one of them at a dedicated test facility.

4. VACUUM VESSEL, THERMAL SHIELD, CRYOSTAT

The Vacuum Vessel (VV) of JT-60SA [14] is a double-walled structure fabricated with AISI 316L stainless steel with two shells each 18mm thick, an interspace of about 160mm, filled with borated water, which provides temperature control as well as shielding to reduce the neutron budget during Deuterium operation. Heated Nitrogen gas flow for baking at 200°C will also make use of the interspace between shells after draining the borated water. The double wall structure also provides enhanced stability to withstand the high loading conditions foreseen during plasma disruptive VDEs .

The VV (Fig. 13 below) was designed, fabricated, and assembled in 10 sectors: seven 40° sectors, two 30° sectors and one 20° sector. Each individual sector was fabricated in two parts at the factory in Japan, delivered to Naka and then welded together on site. Individual sectors were then gradually positioned onto the Cryostat Base and welded together after fitting and weld preparation activities. The near-torus of 340 degree was completed in late 2015 in order to allow the gradual installation of the thermal shield and the TF magnet. The final sector of 20° was only recently assembled, together with its mating TS and TF coil, after all other TF coils were in position. The prior construction of a mock up allowed careful prediction of weld distortions. Welding work and radiographic testing were carried out alternately to avoid formation of defects in the welded joint and finally resulting in the achievement of the required design tolerances. In parallel 55 ports and mating port bellows were fabricated for later installation once all EF magnets have been positioned.

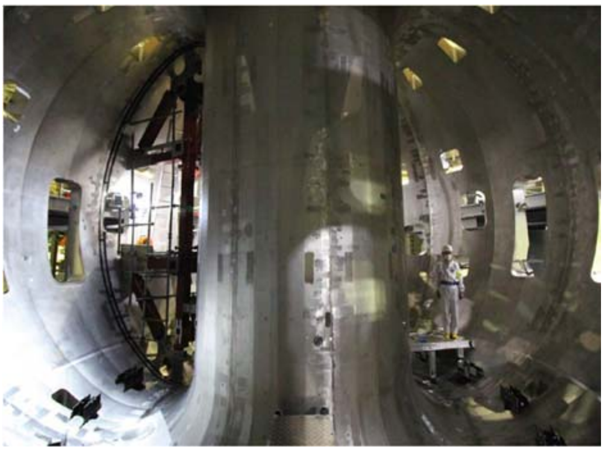

FIG.13: Internal view of the VV

FIG.14: External view of the VV and its TS

The Thermal Shield (TS) in in Superconducting Tokamak is a critical system required to limit the radiated heat load onto the magnet system at acceptable levels. In JT-60SA it is divided into a Vacuum Vessel Thermal Shield (VVTS), a Cryostat Thermal Shield (CTS) and a Port Thermal Shield. Thermal Shields are cooled at 80K by gaseous helium. All the VVTS and lower port TS were already fabricated in Japan and delivered to the Naka site in March 2016 in light of the required assembly delivery times. The VVTS, the most difficult to fabricate and critical to assemble, is a double wall structure which needs to be thin enough not to take excessive space but structurally stable by itself once formed in a torus. Its assembly was challenging in light of its flexibility when individual sectors were not yet fastened together and hence required several assembly trials and in-situ shape forming.

The Cryostat of JT-60SA [16,17] is composed of a Cryostat Base (CB), a Cryostat Vessel Body Cylindrical Section (CVBCS), both fabricated in the EU, as well as a cryostat top lid (CTL) procured in Japan. The entire cryostat assembly provides a vacuum boundary to insulate heat load from outside at room temperature to the Magnet operated at cryogenic temperature. The CB, with a diameter of 11.95m, and a weight of 260 tonnes was the first component installed in the torus hall as it provides the platform upon which the entire torus is supported. Conversely the CVBCS and CTL will be the last components to be installed after the assembly of the torus and its thermal shields will be completed.

The CVBCS, having a diameter of ~13.5 m and a weight of ~180 tonnes, is split in a number of vertical and toroidal segments to allow shipment. The whole assembly was fabricated in Spain and delivered in the middle of 2017 in Naka. Prior to shipment, the entire vessel was successfully pre-assembled (see Fig 15) at the factory in order to verify dimensional tolerances, matching surfaces at each mating interface, and hence make sure that the final installation phase, to be carried out in 2019, will run efficiently.

FIG.15: The Cryostat Vessel Body being tested for assembly at the factory prior to sea shipment to Japan

5. PLANT SYSTEMS

The Cryogenic System of JT-60SA [18], fabricated in Europe, supplies supercritical Helium to the magnet system (T=4.4K), Cryopumps (T=3.7K), HTS-CLs (T=50K) and the TSs (T=80K). It is built by six gaseous helium storage vessels, eight warm compressors, four helium compressors, a Refrigerator Cold Box (RCB) for producing helium at cryogenic temperature, an Auxiliary Cold Box (ACB) for distribution of the cryogenic media. With a total equivalent power at 4.5K of about 9kW, it is the largest refrigerator for a nuclear fusion facility after ITER. After a timely design optimisation, and factory fabrication, all subsystems were delivered to the Naka site in spring 2015, when final on-site assembly was carried out. The commissioning of the entire system, including all operating modes planned for the experimental phase of the facility (e.g. operation, baking, stand-by, etc.) were successfully completed in October 2016.

The Power Supply system of JT-60SA [19] was largely to be designed and procured anew in view of the completely different requirements deriving from the new SC magnet system of JT-60SA. Only a few limited components from the previous load assembly of JT-60U could be re-utilised, albeit with some refurbishments (i.e. the flywheel motor generators). The magnet power systems consist of a number of subsystems henceforth described.

The Super Conducting Magnet Power Supplies (SCMPS), a procurement carried out in Europe, are based on thyristor converters: one unit for TF coils (25.7 kA, 80 V, steady state) and ten units for the EF/CS coils (±20 kA, ±1 kV, 100s/1800s duty cycle). The entire set of SCMPS were gradually delivered to the Naka site by 2017, were installed and commissioned together with their respective suppliers and are now ready for their integration in the central control system and hence their integrated commissioning.

The Quench Protection Circuits (QPC) protects the SC coils (TF coils, EF coils and CS modules) in case of a quench by triggering a fast and secure switching network that rapidly (~10 seconds) dumps the magnet stored energy into a set of external resistors. The QPCs, developed and fabricated in Europe, is built by three units (25.7 kA, 2.8 kV) for TF coils, and ten units (±20 kA, ±3.8 kV) for EF/CS coils. Their switching system is based on a dc hybrid mechanical and static set of circuit breakers with the safety backing of pyro-breakers. The entire system was timely delivered to the Naka site in September 2014. The commissioning and final acceptance tests of the QPC were completed in June 2015.

The Switching Network Unit (SNU) for CS modules which produces high voltage for the plasma break down and current ramp-up were manufactured in Europe in 2015 and delivered to the Naka site in September 2016. Two SNUs for EF3 and EF4 procured by Japan were delivered to Naka in 2015. All the SNUs are rated for 20 kA and 5 kV and, similarly to the QPC, make use of an hybrid mechanical-static set of circuit breakers.

The PS for the upper/lower Fast Position Plasma Control Coils (FPPCC) have a rating of ±5 kA and ±1 kV), and are ac/dc thyristor converters which control the vertical and horizontal position of the plasma against instabilities. They are procured in Europe and were delivered to the Naka site in June 2016.

In addition to the above, the PSs for the Resistive Wall Mode Control Coils (RWMCC), Error Field Control Coils (EFCC) and ECRF gyrotrons are currently in an advanced state of their fabrication/delivery cycle.

Furthermore the Electric PS system of the Naka site has been also refurbished. For example JT-60SA will reuse two motor generators: H-MG with 400MVA/2.6GJ and T-MG with 215MVA/4.0GJ, as well as electric power directly from 275kV power grid. All of them will in total cover 100 sec operation with 41 MW heating and current drive.

6. IN-VESSEL COMPONENTS

JT-60SA will eventually be equipped with a full set of in-vessel components compatible with high power and long pulse operation.

A cassette type configuration has been chosen for the Divertor [20,21] . With a total of 36 cassettes, all remotely removable through the large radial RH ports, according to the device current exploitation plan a configuration with a lower single null (LSN) divertor is planned in the initial research phase. While all 36 lower cassettes have been already fabricated, Double Null (DN) operations will be deferred, largely for budgetary reasons, to the extended research phase. Partial mono-block targets for the lower divertor are planned to be adopted in the initial phase. Regarding the In-Vessel Plasma Facing Components (PFC), in consideration of the need to operate for 100s pulses, all must be designed to be actively cooled. Carbon tiles bolted on water-cooled copper alloy heat-sinks are employed for much of the FW: capable to exhaust ~0.5 MW/m2 for the full pulse duration and 10 MW/m2 for few seconds long transients. The divertor will employ brazed CFC mono-block targets, capable to exhaust 10-15 MW/m2 of steady heat load. This will be partially installed as a part of the outer Vertical Target (VT) at the start of the “initial research phase”. Inner and outer VTs with bolted CFC tiles will be replaced with mono-block targets by the end of this phase. Cryopanels for divertor pumping will also installed under the divertor cassettes with a pumping slot is opened in the cassette frame.

JT60-SA will also have a number of in-vessel coils available. These consist of fast plasma position control coils, error field correction coils and Resistive Wall Mode (RWM) control coils. All coils employ water cooled copper conductors.

While many of the in-vessel components are at a completed or advanced fabrication state, most of them such as cryopanels, divertor cassettes, the stabilizing baffle plate, in-vessel coils, with outboard first wall will only be installed inside the vacuum vessel after first plasma will be achieved in Sept 2019, when mainly an upper target plate will be installed. Such an approach will allow to execute the integrated commissioning towards the planned MA-Class plasmas to be achieved in the early commissioning phase, while minimising risks and allowing more time for the critical testing of individual in-vessel components.

FIG.16: lower divertor cassettes

7. HEATING SYSTEMS

A full set of plasma heating systems, compatible with the planned long pulse plasma operation has been developed for JT60-SA often refurbishing/upgrading the previously available system in JT-60U. Performance of a gyrotron enabling operation at two frequencies (110 and 138 GHz) was enhanced up to 1 MW for 100 sec in 2014 [22]. In 2015 an additional frequency of this gyrotron at 82 GHz was demonstrated for 1 sec at 1 MW, which is applicable for plasma start-up assist and wall cleaning. Modification of the magnetic structure of the negative ion source to extract a uniform beam and control of the plasma grid temperature for stable negative ion generation allowed a 15A beam for 100 sec [23]. The production of 22A, 100 s D- beam is still to be achieved, i.e. to fulfil the design requirement. As for the positive-ion-based NBI, 2MW (80 keV, 25A) D0 beam for 100 sec was already demonstrated for one unit in 2015 by the careful control of arc power and gas injection rate.

8. RESEARCH PLAN

The recent update of the JT-60SA Research Plan (SARP) involved more than 400 co-authors from both EU and Japan and led to an outline matching the new ITER Research Plan and the plans for DEMO. The principal objectives of the initial phases of JT-60SA (2020-2025) are along scenario developments and risk mitigations for ITER and DEMO. The longer term includes a strategy of transition from carbon wall to tungsten wall, that is however once the main mission of high-beta full non-inductive steady-state operations will be achieved (~2030). The collaborative work in preparation of the plasma experiments is taking gradually more weight, including numerous physics modelling activities covering transport, stability, energetic particle and integrated scenario development, neoclassical toroidal viscosity on plasma rotation, pedestal stability, the neoclassical tearing mode stabilization by ECCD, effects of energetic ions on MHD stability, and so on. The results obtained so far have consolidated the EU-JA joint capability in the prediction of the JT-60SA plasmas and operation.

9. SUMMARY AND OUTLOOK

The efficient start-up and scientific exploitation of JT-60SA by the large international team is a challenging enterprise, which will be similar to, and provide important input to, the ITER start-up phase. To optimize this phase, a broad set of coordinated activities have been carried out over recent years by a joint Japanese-EU JT-60SA Research Unit, fully integrated in the IPT and liaising with the broader Japanese and EU fusion physics community.

Indeed the implementation framework of the JT-60SA project came with opportunities but also with many challenges. Opportunities deriving from the broad set of expertise available in the collaboration set out in EU and JA, challenges deriving from the technically complex system, the tight budgetary constraints, as well as the well-known complexity associated with in-kind procurement, and a geographically distributed team.

The final assembly phase is now well underway together with the gradual execution of integrated commissioning leading to the completion of the assembly in March 2020 and a First Plasma in September 2020 closely followed by the demonstration of MA-Class divertor plasmas in the ensuing integrated commissioning phase to Feb 2021. As shown in Figure 16, the current scope of the JT-60SA project has reached 90% completion and will be ready for the forthcoming challenge of integrated commissioning. At this time, plans amongst the EU and JA Parties are being developed for the furtherance of the successful EU-JA collaboration in the frame of the Broader Approach Agreement. The next phase will include the joint operation of the device as well as a set of enhancements that should eventually broaden the capability of this research instrument.

Overall the progress so far has been successful thanks to an initial design which has so far proven to be proper and largely absent of requirements for changes, the early establishment of an integrated management model and, even more important, the wholehearted recognition and acceptance by the EU-JA joint team of a shared "*JT-60SA culture*". This was probably the main long-lasting achievement, essentially also attained in the other BA activities, of the JT-60SA project.

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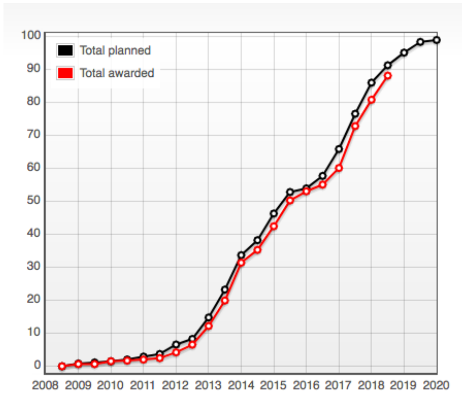

Fig. 16. Planned Value (black) and Earned Value (red) in the JT-60SA Project

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