Status of JT-60SA Project

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Abstract

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, detailed design of the project was begun. In 2012, with the majority of time-critical industrial contracts in place, it was possible to establish a credible time plan, and now the project is progressing towards the first plasma in March 2019. After focussed R&D and qualification tests, the procurement of the major components and plant are now well underway. In the meantime the disassembly of the JT-60U machine has been completed in 2012. The assembly of JT-60SA started in January 2013 with the installation of the cryostat base, the first item delivered from Europe, and continued in February 2014 with the installation of the three lower superconducting equilibrium field coils. Winding of the TF coils winding packs started in July 2013 in EU. A cold test facility for the TF coils has been installed at the CEA Centre in Saclay. The first TF coil will start tests in 2015. The manufacture of the EF4, EF5 and EF6 coils has been completed. All Vacuum Vessel sectors will be completed by April 2014 and their assembly will soon commence. The manufacturing of the cryostat vessel body has now begun, with final delivery planned in 2017. Contracts for all Magnet Power Supplies are placed, fabrication ongoing with the one for the Quench Protection System completed and their installation to commence in 2014. On-site installation of the cryogenic system will be completed in 2015, and it will be operational late in 2016. The dual frequency 110 and 138 GHz gyrotron has made significant progress towards allowing EC heating (ECH) and current drive (ECCD) under a wide range of plasma parameters. Oscillations of 1 MW for 10 s were successful at both frequencies in a world first for a dual-frequency gyrotron by optimizing electron pitch factor using a triode electron gun. On the N-NB system, the pulse duration and the current density of the negative ion source have been successfully improved from 30 s at 80 A/m² in the previous operation to 100 s at 120-130 A/m². The paper will give an overview of the present status of the engineering design, manufacturing and assembly of the JT-60SA machine.

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 in parallel to procurement of the project was begun. In 2012, with the majority of time-critical industrial contracts in place, it was possible to establish a credible time plan, and now the project is progressing on schedule towards the first plasma in March 2019.

After focussed R&D and qualification tests, the development of the major components and plant are now well advanced in manufacturing design and/or fabrication. In the meantime the disassembly of the JT-60U machine has been completed in 2012 and the engineering of the JT-60SA assembly process has been developed. The actual assembly of JT-60SA started in January 2013 with the installation of the cryostat base and continued in February 2014 with the installation of the three lower superconducting equilibrium field coils.
Fig 1: View of the torus hall, with the cryostat base and the EF coils already positioned.

The machine cryostat base, the first major item of EU hardware, fabricated by IDESA/Asturfieto, was delivered to Naka in January 2013, and installed in the torus hall. The material for the cylindrical shell, purchased by Japan and supplied by Outokumpu, has been already delivered to Spain. The manufacturing of the vessel body, by Asturfieto, has now begun, with final delivery planned in 2017.

In JT60SA 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). 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 with off center adjustable bushings inserted between the casings. This flange will be pre-compressed by toroidal bolts 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 will house and guide a coil. It will 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 will form a complete structure to house the full magnet. This OIS assembly, together with the inner curved section dowels, is provided mainly to resist the toroidal forces induced by interaction of the TF coil current with the transverse poloidal field from the plasma and poloidal field coils.

The conductor is designed so as to ensure a minimum temperature margin of 1.2 K in normal operating conditions and 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). The shape of the conductor was chosen as (slightly) rectangular to minimize the size of the entire winding pack. The cable and jacket are manufactured separately and then assembled using a pull-through, roll down and forming technique. The qualification of the JT-60SA TF coil reference conductor design has been carried out firstly by qualifying the candidate strands and thereafter by carrying out several conductor prototype tests which were then concluded with a full scale test of the reference conductor in the SULTAN facility. The results of the tests confirmed all previous extrapolations and at the reference operating point, corresponding to the magnetic peak field in the TF coil during operation (5.65 T) and the operating sample current (25.7 kA), exhibited a current sharing Temperature Tcs > 6.1 K. Conductor stability was also experimentally characterized indicating a proper margin during a plasma disruption event. The winding of a TF coil is achieved by stacking 6 double pancakes, electrically connected in series by electrical joints between their terminals. The He inlets are connected to the midpoint of each double pancake in order to feed fresh helium in the high field region of the pancakes.

CEA through Alstom, and ENEA through ASG, are presently manufacturing the 18 TF coils and one spare coil. All the strand has been fabricated by Furukawa Electric and the conductor cabling and jacketing has already passed half-production stage at ICAS in Italy. Winding of the double pancakes started in July 2013. At this point in time three winding packs have been completed by ASG and one by Alstom. Encasing and embedding with subsequent machining will start later in 2014 upon completion of the first two casings which will be delivered by Walter Tosto to the two winding companies. As soon as the coil will be full machined and hence completed they will be transported to the TF test facility in Saclay where they will be tested at full current. After that the TF coils will be assembled with the Intercoil structure, now being fabricated in France and thereafter shipped to Naka. The cold test facility for the TF coils has been installed at the CEA Centre in Saclay. The first TF coil will start tests in 2015. Testing will continue with the 19th coil planned to be tested in late 2016.

Fig 2 : The first TF Winding Pack completed, impregnated and covered with conductive paint.
The Poloidal Field magnet in JT60SA is constituted by a Central Solenoid (CS), and 6 additional Equilibrium Field (EF) coils. The CS assembly consists of a vertical stack of four independent winding pack modules, which is supported at the bottom of the TF coils through its pre-load structure. This pre-compression structure provides axial pressure on the stack to keep the segments in contact in all conditions. It consists of a set of tie-plates located at inner and outer diameters of the coil stack. The number of CS modules is selected to satisfy the plasma shaping requirements and minimize the number of current leads. The modules can be energized independently. The busbars, joints and cooling pipes are placed outside the coils. Each winding is formed from six octa-pancakes and one quadra-pancake with helium inlets at all joints/helium outlets on the outer surface. The six EF coils (EF1 to EF6) are attached to the TF coil cases through flexible plates supports allowing radial displacements. The EF coil positions and sizes have been optimized for the plasma requirements, within the constraints imposed by the access and ports around the vacuum vessel. Each winding pack consist of a stack of pancakes enclosed in a common ground insulation wrap. Handshake type joints are adopted in order to meet assembly requirements. The largest diameter EF coils (EF1, EF2, EF5 and EF6) are being directly manufactured on-site in Naka, because of the difficulties associated with their ground transportation. As the CS operates at high field it uses Nb3Sn superconductor. This conductor consists of a circular multistage cable around a small central cooling spiral. The number of superconducting strands is designed to ensure a minimum temperature margin of 1.0 K in normal pulse operating conditions. A Cr plating provides a contact resistance barrier to reduce the large coupling currents while still allowing current redistribution. The material of the CS jacket is a modified SS316 to service through Nb3Sn heat treatment (650°C - 100h). The operating current is 20 kA. The EF coils use two different dimensions of multistage NbTi CICC. Like the TF conductor, the jackets are also compacted and formed from circular tubes.

Manufacture of all the EF/CS coil conductor is taking place on the Naka site, in a purpose-built 600 m long jacketing line and building (based on the design of the ITER conductor facility), and using strand manufactured by Furukawa Electric. So far, by March 2013, seven CS conductor and 40 EF conductor lengths have been manufactured. The manufacture of the EF4, EF5 and EF6 coils has been completed by Mitsubishi Electric and the three coils have been already temporarily installed on the cryostat base ready for the assembly of the plasma vacuum vessel.
JT-60SA will use high temperature superconducting current leads, made by KIT. The first delivery of the current leads (for the TF coils) will take place in early 2015, with those for the PF coils will be delivered in 2015 and in early 2017.

The vacuum vessel of JT-60SA is composed of 18 toroidal sectors constructed out of SS316L with low cobalt weight content (< 0.05%), to reduce activation levels. The vacuum vessel is torus-shaped and double-walled with a shell thickness of 18mm. The double-wall cavity is filled with borated water to enhance the neutron shielding capability of the vacuum vessel. Every 40 degree, the vessel is attached at the bottom to a gravity support with a pack of spring plates. The vacuum vessel sectors are being manufactured by Toshiba Corporation as separate inboard and outboard segments to ease transportation. All sectors have been completed by April 2014 and assembly is now underway.

![Fig 4: View of the torus hall, with the VV being welded.](image)

The JT-60SA magnet power supplies are almost entirely made up of new components. The quench protection circuits are being manufactured for Consorzio RFX by Nidec-Ansaldo Sistemi Industriali. Manufacturing began on the 13 units in February 2013, installation will begin later this year at Naka. The switching network units are being manufactured for ENEA by OCEM Energy Technology. The contract was signed in October 2012, detailed design is underway, with delivery of final components due by September 2017. Magnet power supply units manufacture is being undertaken by JEMA for CEA, and by Poseico-JEMA for ENEA, with delivery due between mid-2015 and the end of 2017.

The cryogenic system of JT-60SA is designed to provide refrigeration capacity for the thermal shields of the cryostat, the High Temperature Superconducting (HTS) current leads, the superconducting magnet system and the divertor cryo-pumps. Different thermal shields around the vacuum vessel, the ports, the cryostat, and the distribution boxes as well as the Chevron baffles of the cryopumps are cooled at ~80 K. A flow of supercritical helium at 4.4 K and 0.5 MPa is circulated through the superconducting coils, feeders and the cold structures. In addition, refrigeration capacity at 3.7 K is provided for the panels of the divertor cryo-
The HTS current leads require helium cooling to between 50 K and 300 K. The refrigeration system comprises a cycle compressor station; a refrigerator cold box, with cryogenic expansion turbines, heat exchangers; an auxiliary coldbox with integrated subcooler, cryogenic compressors and cryogenic circulators; and means to store gaseous helium and liquid nitrogen. The Cryoplant fabrication is also well underway at ALAT in France. Its installation is due to commence at Naka in 2015.

![Cryogenic system being fabricated at the ALAT factory.](image)

The plasma Heating Systems in JT60SA are NBIs as well as ECRF. The NBI system is required to inject D0 beams of 20 MW and 30 MW for 100 s and 60 s respectively in the integrated research phases. The injection power finally will be increased up to 34 MW for 100 s in the extended research phase. The upgraded NBI system for JT-60SA consists of twelve positive-ion-based NBI (P-NBI) units and one negative-ion-based NBI (N-NBI) unit. In order to reduce costs, the location of the P-NBI system is the same as that of JT-60U. The P-NBI units control the power deposition profile and plasma rotation. The injection power of the P-NBI unit has been chosen to use the present ion source without modification. High power N-NBI is also required to provide sufficient NB current drive capability for high beta steady-state (full non-inductively driven) plasma development. It also contributes to the heating of a central region in high density plasma with a dominant electron heating fraction, which is relevant to DEMO plasmas heated by alpha particles.

Therefore a complete re-development of heating systems has been conducted on electron cyclotron (EC) and negative-ion-based neutral beam (N-NB) systems for JT-60SA. The dual frequency 110 and 138 GHz gyrotron has made significant progress towards allowing EC heating (ECH) and current drive (ECCD) under a wide range of plasma parameters. Oscillations of 1 MW for 10 s were successful at both frequencies in a world first for a dual-frequency gyrotron by optimizing electron pitch factor using a triode electron gun. On the N-NB system, the pulse duration and the current density of the negative ion source have been successfully improved from 30 s at 80 A/m² in the previous operation to 100 s at 120-130 A/m², which satisfy the rated operating values for JT-60SA. This progress has been achieved by controlling the negative ion production via the surface temperature of the plasma grid.
The requirements of the divertor cassettes are to remove ~40 MW of heating power during long pulse operation of 100 sec and to be compatible with remote handling (RH) maintenance within the radioactive environment of the vacuum vessel. The vertical divertor with CFC monoblock targets, plasma facing components with active cooling and compact divertor cassettes of 800 kg in weight for the RH system were developed to satisfy such requirements. The manufacturing of all 36 divertor cassettes with a heatsink of CuCrZr were completed in 2013 (Fig. 7). The tolerance of the heatsink surface is ±0.8 mm. As for the all divertor cassettes, the dimensional errors of the heatsink surfaces at the inner divertor and the outer divertor were within ±0.3 mm and ±0.5 mm, respectively. Consequently, high dimensional accuracy of the heatsink surface was achieved in the divertor cassette manufacturing after the heat treatment of stress relieving and the machining.

Fig 6: progress of beam current in JT-60SA negative Ion NB system after its refurbishment.

Fig 7: Divertor cassettes with heatsink of CuCrZr.