JT-60SA Construction Status

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Abstract—**The construction of the JT-60SA tokamak is one of the three projects of the Broader Approach activities being undertaken jointly by Japan and Europe. The construction of the new load assembly and the refurbishment of some reutilized equipment from JT-60U is now well underway, and is on track to produce its first plasma in March 2019. As a satellite tokamak of ITER, and being superconducting, JT-60SA has the objective of supporting ITER in its operation as well as complementing ITER in the definition of the design basis of DEMO, particularly to identify the best ways to extend plasma pulse lengths toward steady state.**

Index Terms—**Experiment, nuclear fusion, overview.**

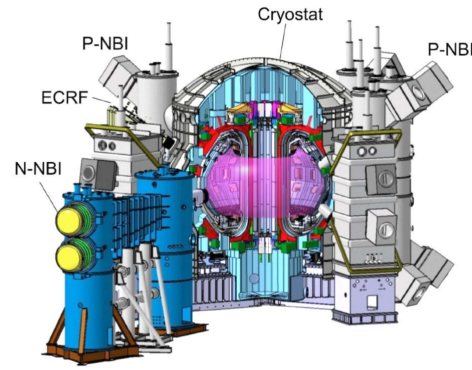

Fig. 1. JT-60SA cutaway.

I. Main Features and Performance

JT-60SA's MISSION is to contribute to the early realization of fusion energy by addressing key physics issues relevant for ITER and DEMO. JT-60SA has the objective of helping ITER quickly find how to optimize plasma performance, in particular to identify and explore how to operate fusion power reactor plasmas in DEMO. The emphasis of JT-60SA's design is thus on ways to extend plasma pulse lengths toward steady state.

JT-60SA is a fully superconducting tokamak able to confine 100-MK plasmas in power-breakeven-equivalent conditions—deuterium will be used as it is closest to ITER/DEMO plasma conditions, but its much lower radioactivation allows rapid exploration of operating conditions while staying within overall operating license constraints. JT-60SA uses, where possible, equipment from JT-60U, in particular its neutral beam (NB) heating system.

Plasma-facing components will initially be faced with carbon, but in later operational phases may be replaced with tungsten, depending on ongoing experiments worldwide.

JT-60SA's usefulness is therefore based on its ability to provide JET/JT-60U-level plasmas, but with long pulse capability, to give the most relevant level of support when ITER enters operation.

A general cutaway view of the JT-60SA tokamak is shown in Fig. 1. The plasma has a major radius of 2.96 m, minor radius of 1.18 m, and elongation and triangularity are typically in the range of 1.9 and 0.5 for the design basis scenarios. Inductive current will be up to 5.5 MA, and the device will focus on pushing pulse length toward steady state. One of the main advantages of JT-60SA is its rather capable heating system with 34 MW of NB and 7 MW of electron cyclotron (EC) installations.

The overall operating range of JT-60SA places it squarely in the realm of breakeven JET-like discharges with extensions to even higher density and confinement time. Its operating program [1], starting before ITER, will allow ITER to accelerate up to $Q = 10$ operation, and support the early narrowing of DEMO specifications. Using DD fuel, the operating conditions with DT can relatively easily be inferred, and by keeping strictly to limited neutron yield during the early operating years the need to rely on the planned remote maintenance of JT-60SA can be deferred until sufficient experience has been accumulated.

II. Organization and Schedule

The Broader Approach activities are carried out by two implementing agencies (IAs): the Japan Atomic Energy Agency (JAEA) for Japan, and Fusion for Energy (F4E) for Europe. Whereas JAEA places all contracts for Japanese procurements and services, 90% of Europe's contribution is covered by commitments undertaken at national government level. These "Voluntary Contributors" (VC - France, Italy, Spain, Belgium, and Germany) have nominated "Designated Institutions" (DI - for JT-60SA these are CEA, ENEA, CNR/RFX, CIEMAT, SCK-CEN and KIT) who actually place the contracts for European procurements and services. The coordination of the European procurement, and the remaining 10%, is provided by F4E. (Within JT-60SA alone, Fig. 2, the voluntary contributors provide 84% of the total European contribution, and F4E 16%).

For each Broader Approach project, an integrated project team has been constituted, consisting of Japanese (JAEA) and

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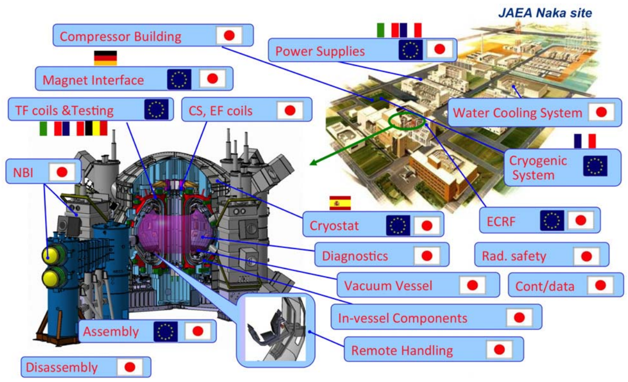

Fig. 2. Sharing of procurements.

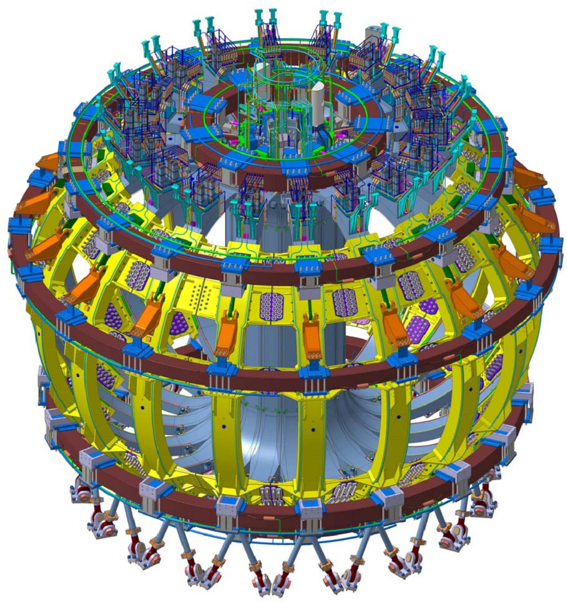

Fig. 3. JT-60SA magnet system.

European (F4E + VCDI) Home Teams with a small managing Project Team, and distributed technical coordination functions. Procurement arrangements signed between the IAs define the technical and schedule scope. Agreements of Collaboration are signed between F4E and VCDIs to cover F4E's commitments.

This produces a mix of organizations with long term commitments and budgets, and organizations whose participation is voluntary and whose budget constraints are shorter term. Nevertheless this system works well and, with ~90% of contracts now placed, the overall schedule, with first plasma in March 2019, is being maintained.

III. Procurement Progress

A. TF (Toroidal Field) Magnet

In the overall magnet configuration (Fig. 3), each D-shaped coil has a rectangular steel jacketed NbTi cable-in-conduit conductor force-flow cooled by supercritical helium. The 18 coil casings are wedged together over their (insulated) straight length to support in-plane centralizing forces with friction. Overturning moments are resisted by intercasing keys in the upper and lower inboard curved regions, precompressed by toroidal bolts during assembly, and by curved outer intercoil bolted shear plates. The coil gravity supports, which incorporate a cryogenically cooled thermal barrier and their own thermal shields, are bolted to the cryostat base.

The coil strand is being made for Europe by Furukawa Electric in Japan, has been tested at various facilities in Europe, and is being cabled and conduited by ICAS near Rome. Alsthom in Belfort and ASG in Genoa are manufacturing the coils, including one spare coil. The casing for both coils is being made by Walter Tosto in Chieti and shipped to the coil manufacturers. Once encased and impregnated, the coils will be sent for a complete full current cold test at Saclay (Paris), before shipment to Japan. Meanwhile, the outer intercoil structure is being manufactured by SDMS in Saint-Romans, and the gravity support by Alsyom in Tarbes. Currently, the strand contract is almost complete, about 1/2 of the conductor is manufactured, and winding of the coil double pancakes are just about to begin (a little late).

Casing, gravity support and intercoil structure manufacturing are all underway, and the test facility in Saclay already has its cryostat and cryogenic system, and is being equipped for testing, with a view to being ready to test the first TF coil in May 2014. Testing will continue with the 19th coil planned to be tested in October 2016. This gives a reassurance that 18 TF coils can be on site by the end of 2016, as required for the machine assembly schedule.

B. PF (Poloidal Field) Magnet

JT-60SA uses six equilibrium field (EF) coils numbered anticlockwise from above the outer midplane, and a central solenoid (CS) split into four modules, each with separate power supplies. The EF coils use NbTi cable-in-conduit conductor, force-flow-cooled by supercritical helium. The CS uses a Nb_3Sn conductor likewise force-flow-cooled by supercritical helium. This strand is identical to that used for ITER, and the conductor is very similar. The EF coils are bolted to the TF coil casing and to the outer intercoil structure. The CS is supported from the lower inboard TF coil casing, from an extended structure around EF coil 4.

Manufacture of all the coil conductor is taking place on the Naka site, in a purpose-built 600 m long cabling and jacketing line and building, and using strand manufactured by Furukawa Electric. Currently, ~60% of the EF conductor has been completed, and 25% of the CS conductor. The latter is currently being tested in a model coil at the National Institute for Fusion Science in Toki. The two smallest EF coils can be manufactured in the factory and shipped to the site. EF4 was already delivered by Mitsubishi Electric to Naka in April 2012, and has since been fitted out with attachment clamps and terminals. The planarity of the coil is much better than the specification, with the deviation of the current center less than 0.6 mm. A building and winding line has been purpose-built at the Naka site for the larger coils (as well as for the wind-and-react process of the CS module manufacture). Manufacture of double pancakes for EF coils 5 and 6 began in 2012 and will be completed in mid-2013, and the finalized coils will be ready in November 2013 and installed on the cryostat base in

Fig. 4. Vacuum vessel sector being assembled in Naka.

a retracted position at the beginning of 2014. The manufacture of their upper relatives, however, only need to be ready once the vessel and TF coil assembly installation is completed, in 2017.

C. Magnet Shared Components

JT-60SA will use high temperature superconductor (bismuth strontium calcium copper oxide) current leads, made by Karlsruhe institute of technology (KIT), and similar to those used on Wendelstein 7X [2], to connect the coils to the coil power supplies in five cryogenically cooled coil terminal boxes (1 TF, 4 PF) mounted outside the upper cryostat vessel body. The layout of these electrical connections in the cryostat, and that of valve boxes for the various cryolines to the coils and structures inside the cryostat, features high level connections to the terminal and valve boxes, forced by the preexisting layout of the NB boxes around the machine base. Procurement on these systems will begin in 2014. The first delivery of the current leads (for the TF coils) will take place in 2014, with those for the PF coils being delivered in 2015 and in early 2017.

D. Vacuum Vessel

The JT-60SA vacuum vessel is made up of mostly 40° sectors. This double-walled structure will be filled with borated water during operation to enhance its neutron shielding function, and will be filled with nitrogen gas at 200 °C during backout. The vessel is equipped with gas puffing and pellet injection systems, and will reuse the JT-60U vacuum pumping system of turbomolecular pumps, mechanical pumps, and dry pumps. Due to their position near the machine, the turbomolecular pumps need magnetic shielding.

The vacuum vessel sectors are being manufactured by Toshiba Corporation as separate 40° (mostly) inboard and outboard segments to ease transportation. These are then brought together in the purpose-built Vacuum Vessel Sector Assembly Building at Naka.

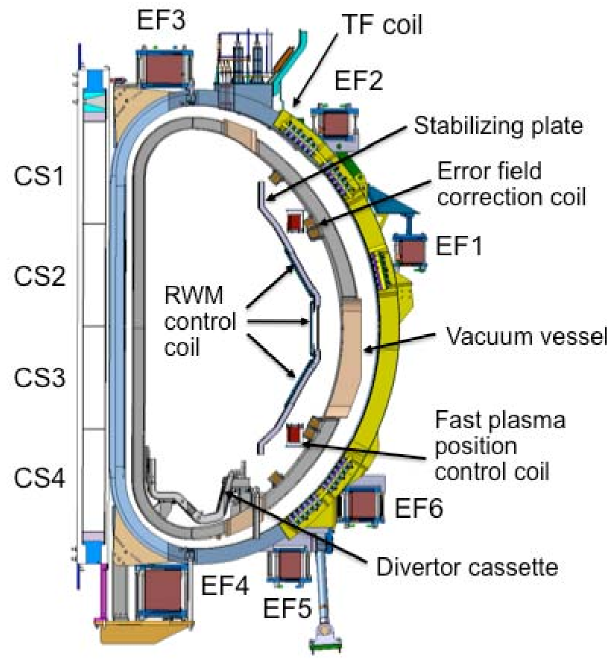

Fig. 5. In-vessel components.

Assembly building at Naka (Fig. 4). The dimensional tolerances of this process are well within the ±5 mm allowed. Currently, six 40° sectors have been completed, and all remaining sectors (1 40°, 2 30°, and 1 20°) will be ready by February 2014.

E. In-Vessel Components

The in-vessel components (Fig. 5) consist mainly of control coils, divertor cassettes, first wall, and cryopanels for vacuum pumping.

There are three sets of control coils, as well as the stainless steel stabilizing plate, which help control vertical displacement events and resistive wall modes:

1) error field correction coils - three poloidal coil loops in six-fold toroidal symmetry operating at 30 kA and a frequency of 10 Hz for the control of the effect of resonant magnetic perturbations on edge localized modes;
2) fast plasma position control coils - upper and lower toroidal coils operating at 120 kAT and with time response of 10 ms, to control vertical displacement events;
3) resistive wall mode coils - three coils round the port entrances at six symmetric toroidal locations, operating at 2 kAT with < 0.1-ms response time.

These systems are in the final stages of design, ready to start procurement in 2014.

Regarding the divertor to be used at the start of operation, all 36 cassette bodies have now been completed by Kinzoku Giken Co Ltd. (Fig. 6). These are now being fitted with plasma-facing components (Fig. 7), namely CFC monoblock on the target plates, and carbon and CFC tiles on the dome and baffles. All these components were completed by Kawasaki Plant Systems Ltd, and delivered to Naka by April 2013.

Fig. 6. Divertor cassettes delivery.

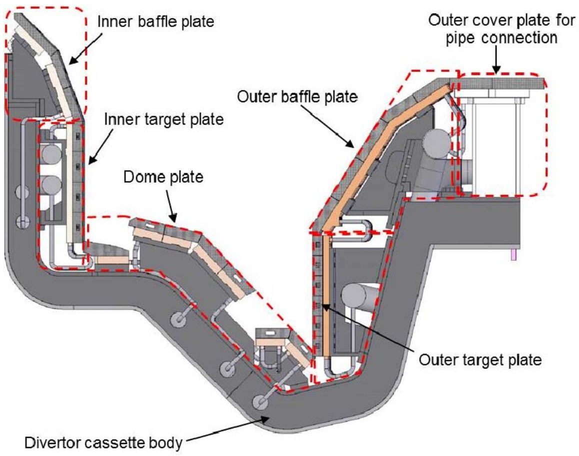

Fig. 7. Divertor main components.

Initial testing of the highest heat flux resistant monoblock components in the JEBIS (JAEA Electron Beam Irradiation System) facility in Naka indicated that the speed of testing would be rather slow (partly due to competition with ITER divertor testing) and that the performance was in fact well represented by infrared nondestructive testing (thermography), switching the temperature quickly from 95 °C to 5 °C, and measuring the cooling speed (after decay of the transient) and comparing it to a reference.

F. Cryostat

The JT-60SA cryostat consists of a heavy cryostat base, which will bear the structural and operational loads of the magnets and main vessel with contents, and a 34-mm thick single-walled stainless steel (304) cylindrical vessel body, with truncated conical sections in the inclined port regions, and a torospherical top lid, sized to support the weight of the ports and port plugs, as well as withstanding atmospheric pressure and a 20% overpressure in case of internal helium leak.

The cryostat base, the first major item of EU hardware, fabricated by IDESA and machined by Asturfieto, of Spain, was delivered to Naka at the end of January 2013, and installed in the torus hall by March 2013. The material for the cylindrical shell, purchased by Japan and supplied by Outokumpu in Finland, has been already delivered to Spain, who will commence manufacture of the vessel body during 2014, with a view to delivery in 2017. The lid manufacture (by Japan) will also commence in 2014. Both these components are first needed toward the end of the machine assembly.

G. Thermal Shield

The thermal shield, which will start procurement in 2013, consists of a cryostat thermal shield (CTS), between cryostat and magnets, a vacuum vessel thermal shield (VVTS), situated between the TF coils and vacuum vessel, and port thermal shields (PTSs). Together these provide complete screening of warm surfaces from those at cryogenic temperatures. This necessarily thin set of stainless steel structures consists of a single shell with multilayer insulation outside, for the CTS, and double-walled panels with edge frames for the VVTS and PTS. The PTSs are mechanically connected to the CTS, the VVTS, and the gravity supports, and the whole is supported by attachment to the TF coils at the bottom between coils EF5 and EF6, and at the top to the nine even-numbered coil casings.

The VVTS has to be divided electrically into 18 toroidal segments and 2 poloidal ones to avoid excessive eddy current heating. All shields are cooled by gaseous helium at 80 K.

H. Heating Systems

The 34 MW of NB power is provided by 12 2 MW positive ion beam injectors and 2 off-axis 5 MW negative ion beam injectors. The latter can drive significant toroidal current comparable with the inductive current density, at between 20% and 50% of the plasma radius. The former, by a mixture of co and counter-injection, strongly influences the plasma rotation velocity. The 7 MW of EC RF heating, provided by 4 launchers and 9 gyrotrons, at 110 and 138 GHz, is sufficient to flatten and even reverse the plasma safety factor profile in regions around the plasma mid-radius.

In 2012, JAEA began developing a 22 A 100 s 500 keV negative ion beam for JT-60SA. This development is taking place in three stages up to 2016, upgrading the power supplies and source power density, while improving beam uniformity and control, and suppressing arcing. Up to now the first phase has been completed successfully, reaching 100 A/m^2 100 s operation. This has to be raised to 170 A/m^2 100 s operation.

Regarding EC developments, a 110 GHz gyrotron has been operated at 1 MW for 70 s, and 1.4 MW at 9 s, close to the target of 1 MW for 100 s, and a good beam profile has been confirmed. A mockup of the poloidal and toroidal steering mechanism for the antennae has been made and the favorable characteristics are now determined. Furthermore, a dual frequency gyrotron has been successfully manufactured and its oscillation characteristics determined. It will be tested under long pulse operation in 2014. A second gyrotron will be procured in 2016, in time for first operation.

I. Diagnostics

JT-60U diagnostic systems are being reused as much as possible. Development is needed to take account of long pulses, to cover new areas of exploitation, and to improve information on plasma–wall interactions. For example, Langmuir probe arrays, able to withstand 10 MW/m^2 for 5 s, have been developed for the initial divertor. Similarly, an endoscope for the visible/infrared TV camera system has been developed for viewing the main chamber and divertor.

J. Magnet Power Supplies

The JT-60SA magnet power supplies are almost entirely made up of new components, based on existing motor-generator sets and main transformers. The TF coil system consists of three circuits in series, six coils in each, powered by a single unit at 26 kA/80 V dc. Such a system can charge or discharge the system over 25 min, allowing energization/deenergization every workday. There is also one nominal 2.8 kV fast discharge quench protection circuit (QPC) per six coils.

Each PF coil has its own 20 kA/∼1 kV dc power unit augmented with pre-existing booster units (EF) or new switching network units (SNUs) for the CS, and including a 5-kV QPC. Each in-vessel control coil system has its own dedicated power supply.

The QPCs are being manufactured for Consorzio RFX by Nidec-Ansaldo Sistemi Industriali. Type-testing was completed in 2012, and manufacturing began on the 13 units in February 2013, with delivery planned by March 2015. The SNUs are being manufactured for ENEA by OCEM Energy Technology. The contract was signed in October 2012, and detailed design is underway, with delivery of final components due by September 2017. Main magnet power supply units manufacture is being undertaken (for TF/EF) by JEMA of Spain for France (CEA), and (for CS/EF/FPCC) by Poseico-JEMA for Italy (ENEA), with delivery due between mid-2015 and end 2017.

K. Cryoplant

This feeds the in-vessel cryopanels (3.7 K), magnets (4.4 K), current leads (50 K), and thermal shield (80 K), as well as intermediate temperatures during cooldown. It consists of a helium refrigerator (warm compressors, oil/water removal, refrigerator cold box, heat exchangers, low temperature adsorbers, and expansion turbines), and an auxiliary cold box (heat exchangers, helium baths, cryogenic circulators, and cold compressor). It is essentially the same size as the K-Star cryoplant (7 kW) [3] but has the special feature of a long delay between the profile of heat input and that of heat arrival at the cryoplant. Thus, a long buffering time is needed to provide reserve for peak loads.

The contract was placed with Air Liquide Advanced Technologies at the end of 2012. Onsite installation will be complete in 2015, and it will be operational late in 2016.

IV. Reassembly

In 2010, the JT-60U disassembly process began. This was the first time a large radioactive fusion device had been taken apart in Japan, so the procedures and disposal processes were recorded carefully to add to the future knowledge base. The diagnostic bridge and upper truss were removed, a single TF coil/EF coil/vacuum vessel sector (1/18th) was removed, the remaining TF coil/EF coil sectors were cut and subsequently removed sleeve-like over the vessel, and then the vessel was cut in two and removed to the JT-60 storage building, with radiation-controlled environment. Only, the heating systems remain in the torus hall. The disassembly was completed at the end of 2012.

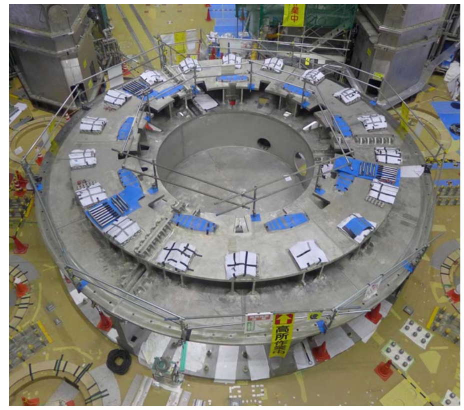

Fig. 8. Cryostat base assembled in place in March 2013.

The assembly process began in January 2013, with the arrival of the cryostat base from Europe. This was assembled by March 2013 (Fig. 8), with excellent dimensional tolerances (flatness < 0.3 mm, $xy < 0.2$ mm) across its 12-m diameter. The plan going forward is to add the lower EF coils (4, 5, and 6) in a retracted position, assemble 340° of the vacuum vessel, insert the then tested TF coils sleeve-wise over the vessel, at the same time adding the VVTS and coil structure. Once the torus is closed by mounting the final TF coil with the final vessel sector, the lower EF coils can be raised into their final position, and the upper ones added, and final ports, thermal shield, and cryostat vessel body and lid added. The assembly will then be completed by the connection of all peripheral equipment, notably the heating systems.

V. Further Information

Up-to-date information about JT-60SA can be found at http://www.jt60sa.org, and on the BA activities at http://www.ba-fusion.org. JT-60SA also has an interactive iBook in the iBookstore.

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William R. Spears, photograph and biography not available at the time of publication.