Installation and pre-commissioning of the cryogenic system of JT-60SA tokamak

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Abstract. The cryogenic system for the superconducting tokamak JT-60SA is currently being commissioned in Naka, Japan and shall be ready for operation in summer 2016. This contribution is part of the Broader Approach agreement between Japan and Europe. With an equivalent refrigeration capacity of about 9.5 kW at 4.5 K the cryogenic system will supply cryo-pump panels at 3.7 K, superconducting magnets and their structures at 4.4 K, high temperature superconducting current leads at 50 K and thermal shields between 80 K and 100 K. The system has been specifically designed to handle large pulse loads at 4.4 K during plasma operation. The mechanical and electrical assembly of the cryogenic system has been achieved within six months by October 2015. The main contractor Air Liquide Advanced Technology (AL-aT) have supplied eight parallel working screw compressors with a common oil removal and dryer system, a Refrigeration Cold Box and an Auxiliary Cold box with cold rotating machines. F4E has provided six GHe storage vessels and QST has provided the complete infrastructure and the facilities for the utilities. The paper gives an overview of the main design features, the infrastructure and the status of installation and pre-commissioning.

1. Introduction
Within the Broader Approach agreement between Europe (F4E, Fusion for Energy) and Japan (QST, Quantum and Radiological Science and Technology), CEA (Commissariat à l’énergie atomique et aux energies alternatives) is providing the cryogenic system of the Japanese JT-60SA (Japanese 60 Super Advanced tokamak, currently under construction in Naka in Japan.

JT-60SA is a complete superconducting tokamak which aims at generating up to 5.5 MA plasma during 100 s, so contributing to the early realization of fusion energy by addressing key physics issues for ITER and DEMO [1].
CEA has contracted the cryogenic system to Air Liquide Advanced Technology (AL-aT) in November 2012. After one year of conceptual and detailed design activities [2,3], followed by one year of manufacturing in Europe, the main components have been shipped within two months to Japan (Hitachi port) and arrived in Naka during April 2015. QST provided the buildings, the foundations for the storage area, and the facilities for the utilities. On site installation lasted for six months and the mechanical completion was released in October 2015. The following pre-commissioning activities were finished in February 2016 again on schedule.

After recalling the main relevant features of the system, the paper presents a status of the installation and pre-commissioning activities.

2. Main design features

2.1. Cryogenic users

The equivalent refrigeration capacity of the cryogenic system is about 9.5 kW at 4.5K which is supplied at four temperature levels. The average loads are summarized in Table 1 for the different cryogenic users and for three operation modes: the plasma mode (reference scenario 100s plasma repeated every 1800s), the stand-by mode and the baking mode.

The cryogenic system supplies helium at 80 K to the thermal shield (TS) of JT-60A vacuum vessel and the cryopump baffles, at 50 K to the High Temperature Superconducting (HTS) current leads, supercritical helium at 4.4 K to the toroidal field (TF), central solenoid (CS) and equilibrium field (EF) coils and their structures and also helium at 3.7 K to the cryopump panels.

| Cryogenic User                  | Temperature | Plasma operation mode | Standby (STS) mode | Baking mode |
|--------------------------------|-------------|-----------------------|--------------------|-------------|
| Thermal shields, cryopump baffles | 80-100/120K | 42000 W               | 41300W             | 135000 W    |
| HTS current leads              | 50-300K     | 25g/s                 | 13g/s              | 0 g/s       |
| TF coils and structures       | 4.4K        | 1794W                 | 1270               | 2260        |
| CS and EF coils               | 4.4K        | 1850W                 | 600                | 1130        |
| Cryopump panels               | 3.7 K       | 84W                   | Regeneration       | 0           |

2.2. Process design

The helium cycle is shown in Figure 1. The warm compression station (WCS) is composed of 8 screw compressors (housed in 4 units) running in parallel. They compress a nominal flow of 672 g/s from 0.105 MPa (LP) to 1.6 MPa (HP).

The refrigeration cold box (RCB) uses liquid nitrogen pre-cooling from 300K to 80 K. The main flow of 425 g/s is delivered to the thermal shields, while the remaining flow is expanded through two turbines in series from the HP to 0.13 MPa at about 10 K. The returning flow from the thermal shield is then re-cooled by the LN2 stage. A fraction of 25 g/s is mixed to achieve 50 K for the HTS current leads, and counter balanced with 25 g/s additional flow from T1. Finally, about 425 g/s is delivered to the cold end of the RCB at 30K. Part of the flow (400 g/s) is expanded in turbine T3 from 1.3 MPa to 0.5 MPa, to supply the Auxiliary Cold Box (ACB) with supercritical helium at 5 K. The remaining small flow (25 g/s) is supplying the supercritical loops 1 and 2.

In the ACB, helium liquid is collected in the 4.3 K and 3.6 K bathes while supercritical helium is delivered to the cryopump loop, the TF and structures cooling loop, and the EF and CS cooling loop. These two latter loops are driven by two identical cold circulators with capacities of 876 g/s and 960 g/s at 4.4 K and pressure heads around 0.1 MPa. The 3.6 K bath is pumped by very low pressure compressors at room temperature with a flow of 24 g/s. The return flow from the cryopump loop is expanded into the 4.3 K bath. The cold compressor compresses the vapor from the 4.3 K bath to the LP of the WCS.
During the commissioning, the performance of the system will be demonstrated by simulating the heat loads from the cryogenic users with dedicated test heaters installed in the ACB: 5.5 kW for the TF loop and for CS and EF loop, 300 W for cryopumps, and 150 kW for the thermal shields. The load from the current leads is simulated by an atmospheric heater.

![Figure 2. View of the cryogenic system during installation](image2)

**Figure 1.** JT-60SA cryogenic system simplified process scheme

**Figure 3.** JT-60SAC cryogenic system layout

### 2.3. Pulse load operation

During plasma operation, the coils and their structures are subjected to high cyclic heat loads from the nuclear heating, the eddy currents and the AC losses as shown in Figure 5. The cryogenic system is maintaining a stable and efficient refrigeration during the large dynamic heat loads by a load management through the compressors and a liquid thermal buffer. The varying load is managed by coupling the pressure controllers of the warm compression station and the liquid bath pressure in the ACB (Figure 4).

As four of the warm compressors are equipped with frequency drives, the plant can smoothly adjust its capacity to the dynamic loads. When the compressor flow reaches its maximum, a 7 m³ liquid helium buffer in the ACB temporarily absorbs the pulsed load. After a plasma pulse the heat is progressively released and the gas is returned to the WCS. After a pulse (DWELL period) the inlet temperature of the superconducting magnets can increase up to 4.8 K. While the thermal buffer temperature increases to 4.7 K, as shown by a dynamic modelling in Figure 5 [8] on an 1800 s reference plasma scenario. In this case, the cold compressor reduces its speed, and the LP return flow is throttled through the downstream valve of the cold compressor (Figure 4).
The management of dynamic heat loads has been experimentally validated at CEA Grenoble in the HELIOS facility [3] [5]. Dynamic modelling has also been performed to investigate the different controls to optimize the pulse load operation [7] [8].

![Figure 4. Pulse load management](image)

![Figure 5. Pulsed loads during the reference scenario.](image)

3. Cryogenic system installation

The cryogenic system has been installed at QST site in Naka jointly by AL-aT, Air Liquide Engineering Japan and local Japanese subcontractors. As the cryogenic system is working in a closed loop, design had to follow the Japanese Refrigeration Safety Ordinance standards in addition to the High Pressure Gas Safety Act. For components manufactured in Europe ASME standards have been agreed. QST received the installation permission from the local authority (Ibaraki Prefecture) after a submission of the manufacturing documents.

After the arrival of the components on site, the precise positioning of the main components at their final destination required special trailers and tools: The RCB has a diameter of 3.2 m, a length of 12 m and a total weight of 65 tons. The ACB has the same diameter of 3.2 m, but a bit shorter (11 m) and a total weight of 50 tons and the vacuum jacketed multi-line connecting the two cold boxes has a length of about 8 m and a diameter of 0.9 m, with 9 internal transfer pipes. The Oil Removal System and the four compressors skids were installed in the new WCS building. The six gaseous helium storage tanks, 250 m$^3$ and 70 tons each, were positioned on the foundations in the storage area. One storage tank is used as a quench tank and is equipped with a long diffuser to avoid local cooling of the carbon steel vessel in case of a quench or a fast discharge of the TF coil system, releasing about 250 kg of cold helium gas through the quench line [6].

The WCS is connected with the RCB and the storage vessels by a number of interconnecting pipes manufactured in Japan and inspected according to JIS (Japanese Industrial Standards). The pipes between the WCS and the RCB and also the quench line to the quench tank are routed on a common supports, along a pipe rack. The design of this pipe rack had to consider seismic events, including static analysis with 0.3g as horizontal acceleration and 0.15g as vertical acceleration.

During installation, more than 1300 welds have been performed on site to connect about 1000 m of piping between the different components of the cryogenic system. Non-destructive X-ray tests were performed on 10% of the welds made on site and all pipes were pressure tested with nitrogen gas up to 1.25 times the design pressure. No failure have been detected during all the X-ray tests, assessing the good quality of the welding on site. Tests with pressurized helium were performed to check the helium leak tightness at a level of $10^{-5}$ Pa.m$^3$.s$^{-1}$. 

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4. Facilities for utilities

After the mechanical completion and the electrical connection validation, the cryogenic system could be connected to the utilities, which are necessary for the pre-commissioning and commissioning activities (Table 2).

Table 2. Utilities consumption for commissioning

| Utilities       | Commissioning estimations |
|-----------------|---------------------------|
| Helium          | 2 tons, 13700 m³         |
| Liquid nitrogen | 3700 m³                  |
| Water           | 212 m³/h                 |
| Electricity     | max 2.4 MW, 9500 MWh     |

The total helium inventory of the overall cryogenic system including users is 3.6 tons and can be stored in the six helium storages. During pre-commissioning activities (conditioning) and commissioning only 2 tons are required as the ACB is not connected to the tokamak.

For liquid nitrogen, a 65 m³ tank is connected to the RCB with a vacuum jacketed line on the pipe rack. A nitrogen vaporizer provides gaseous nitrogen up to 0.5 MPa to the WCS and RCB.

QST provided cooling towers for an open cooling loop for the compressor skids with a capacity of 200 m³/h and a closed loop with 12 m³/h for to the various vacuum pumps, the turbines and the VLP compressors in the cryogenic hall.

Two small air screw compressors work intermittently for 12 hours, to supply 72 Nm³/h of compressed air to the pneumatic actuators of the cryogenic system and the JT-60SA and keep two buffers of 2 and 4 m³ at a pressure of 0.7 MPa.

4 Pre-commissioning

4.1 Cleaning and helium leak test

The pre-commissioning activities consist of cleaning and conditioning the helium circuits to remove impurities (nitrogen, water, air...) and to avoid heat exchanger and filter plugging. All interfaces pipes were blown with nitrogen in order to remove all solid particles due to installation activities or others. Main pipes were also blown with pressurized helium at 1.6 MPa to remove any remaining metallic particles and residuals inside the pipes. Filter at the inlet of the RCB and turbines bearings were inspected and cleaned before they were re-installed. The system is then completely closed and final helium leak tests are performed at all previously open interfaces.
4.2 Conditioning and gas analyses
One dry gaseous nitrogen pressurization and one purging followed by several cycles of helium pressurization and purging to vacuum are performed to dilute the impurities in the main vessels (helium storage tanks, charcoal adsorber, dryer, ACB bathes) and in all the circuits (HP, LP, VLP).

Nitrogen gas analysis have been checked and carefully calibrated with zero ppm and 10 ppm nitrogen in calibrated helium cylinders. The dew point sensors have also been calibrated with a 12.5 ppm water in calibrated helium cylinders. The gas analyses circuits were improved to optimize the calibration and measurement time response. For the nitrogen instrument, it appears to be very sensitive to temperature variation of the instrument.

The measurements of helium in five storage tanks gave values <3 ppm nitrogen impurity after the delivery of pure gas helium N60 (<1 ppm) and conditioning of the GHe storage tanks. One storage tank has been polluted due to air leakage in the ORS and will be purified during the commissioning at 80 K with the RCB adsorbers.

5.3 Drying
In order to remove any moisture in vessels containing adsorbents, drying is performed independently with hot gaseous nitrogen until a temperature of 100°C is reached in the whole vessels. Automatic drying sequences were tested thereby optimising the control loop parameters. The charcoal adsorber and the dryer from ORS have both been dried by passing 120 °C hot nitrogen, until the dew point reached a value below -60 °C and capacities warmed at 100°C. Similar procedures were applied to dry the two 80K adsorbers and the 20K adsorber from RCB.

4.3 Cryomachine installation
The Air Liquide turbines use static gas bearings on the shaft to allow speeds up to 150 000 rpm. A buffer volume is installed to ensure safe shut-down of the turbines in case of a stop of the plant or any abnormal situations. Before installation of the delicate turbines, the fast closing characteristic of the inlet valves to the turbines had to be carefully checked and complete cleanliness of pipes have been checked.

Cold circulators and cold compressor use magnetic bearings and are driven by a water-cooled electrical motor. Installation of this heavy components required a crane and guiding blocks for adjustment (Figure 8).

4.4 Control system implementation
The control system is composed of three SIEMENS (SIMATIC S7-400) Programmable Logic Controllers: one for the WCS, one for the RCB and one for the ACB. The 3 units manage about 350 input/output digital signals and about 350 input/output analogic signals. Two operating stations with eight control screens and one programming station are located in the control room whereas one portable remote operating station can be connected through a Wifi network (Figure 9).

5 WCS commissioning
5.1 Compressor skid preparation
The compressors have been conditioned by repeated evacuation and helium purging, leak tested and filled with special treated BREOX B35 oil. They were operated independently and in groups for several hours to check their capacities and to test the robustness and stability of the LP and HP pressure controls (Figure 11). The compressed helium downstream of the ORS was by-passed to the LP side. The HP set point is regulated by the unloading and loading valves from/to a GHe storage vessel. The LP pressure is regulated by the by-pass valves.
5.2 Functional and capacity tests

The smooth interaction of all eight screw compressors for extended period has been demonstrated during a 48 hour capacity test in a closed loop without intervention. After starting the compressors one after the other, the suction and discharge pressures stabilized as well as the total mass flow remained well within ±2/+5% as requested by the technical specification.

At full capacity, the measured flow rate of 731.5 g/s at 18.1°C was corrected as 707 g/s at 29 °C, higher than the specified flow of 680 g/s. The dissipated electrical power for the compressors of about 2.4 MW was absorbed predominantly by the water cooling system providing very good temperature stability. Part of the heat is dissipated through air convection in the WCS building. The vibration at different locations inside the skids have been measured and found to be within the specifications. The operating parameters for the aggregates A with frequency drive and the direct driven aggregates B are listed in the Table 3.

Table 3. WCS Capacity tests

| Parameters                  | Target values | Capacity test result (average values) |
|-----------------------------|---------------|---------------------------------------|
| Power Aggregate A/B         | 321/269 kW +/- 5% | 312/265 kW                           |
| Current Aggregate A/B       | <570/440 A    | 523/452 A                             |
| Mass flow                   | SPEC: 680 g/s -2%/+5% at 29°C | 731.5 g/s at 18.1°C                   |
| Inlet temperature           | 3°C to 45°C   | 18.1°C                               |
| Inlet pressure              | 0.105 MPa     | 0.105 MPa                             |
| Outlet temperature          | <35°C         | 21.2°C                                |
| Outlet pressure             | 1.6 MPa       | 1.6 MPa                               |
| Oil content outlet ORS      | <10 ppb       | Not yet measured                      |
| Water inlet temperature     | 10°C to 30°C  | 20.4°C                                |
| Water inlet pressure        | >0.3 MPa      | 0.33 MPa                              |
| Oil outlet temperature      | 40°C to 75°C  | 40°C                                  |
6 Perspectives and conclusion

The pre-commissioning activities have been finished end of February and the “Pre-Start-up Safety Meeting” is planned for mid-March to allow the start of the cool down. Before the performance test, protocol has been agreed between AL-aT, CEA, F4E and QST defining the detailed tests to be performed for acceptance, the criteria on temperatures, pressures, mass flows and heat loads, while taking into account the uncertainty of measurements and defining the required stability. Cool down aims first at 80K to demonstrate proper operation of the cryogenic purification system. Next, the cool down will be continued to 4.4 K using the turbines. At cryogenic temperatures the functional and capacity test will be demonstrated by injecting 6.5 kW into the 4.3 K helium bath. Finally the ACB with the cold compressor and cold circulators will be commissioned. The acceptance tests of the different cooling loops using the test heaters are expected to be finalized during summer 2016 and shall validate the overall operation of the cryogenic system, including the pulsed load operation.

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