Vacuum operation of first divertor campaign on EAST

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Abstract. Experimental Advanced Superconducting Tokamak is the first whole superconducting tokamak with divertor configuration commissioned in the world. Vacuum system is one of the most important sub-systems of EAST device. Wall conditioning also plays a very important role for the plasma operation. Because Ion Cyclotron Resonance Frequency discharge cleaning could be carried out with a high toroidal magnetic field, it is used often for wall conditioning, especially for boronization, which was done successfully on EAST. This paper describes the vacuum operation of this new device. The first part describes the vacuum system, consisting of pumping, fuelling and wall conditioning related sub-systems. Then the operation of the vacuum system is introduced including leak detecting, pumping, boronization, etc. At last, the plan for the coming campaign is discussed.

1. Introduction

Experimental Advanced Superconducting Tokamak (EAST) is the first whole superconducting divertor tokamak commissioned in the world [1]. Like ITER, it is designed to have the capacity of operating in limiter, single or double null divertor configurations. Also similar to ITER, during the plasma experimental operation, all the toroidal and poloidal field coils (totally 13 pairs) are in the superconducting state. The scientific and engineering missions of the EAST project are to establish technology basis of full superconducting coils tokamak for future reactors and to study physics issues of the advanced steady-state operation modes. The main design parameters of the device could be found in reference [1]. This paper will introduce the pumping, fueling and wall conditioning related work in the first divertor campaign.

2. Vacuum system

2.1. Chambers

The EAST vacuum system is comprised of 3 independent chambers, Plasma Vacuum Vessel (PVV), Cryostat Vacuum Vessel (CVV) and Cryogenic Valve Box vacuum chamber (CVB). The PVV consists of 16 completely welded stainless steel sections, with the capacity of resisting more than 1 atm pressure difference between PVV and CVV. The volume of PVV is about 40 m³ excluding 48 ports. CVV has two parts, main body and current lead part. The former contains all the superconducting coils and inner and outer thermal shields with the volume of about 160 m³. The later is comprised of two current lead tanks and current lead transfer lines, and the volume is about 22 m³. There are vacuum isolation blocks between these two parts for easier leak localization. However, the blocks are not strong enough to sustain a pressure difference as big as 1 atm, and there is a bypass tube.
connecting two parts. CVB contains the valves controlling the flow of the cryogenic circuits inside CVV, and it is an independent chamber. The volume is about 16 m$^3$.

The vacuum requirements are different for the 3 chambers. For PVV, it’s important to provide a good ultimate pressure for plasma discharge. The design value is $1.3 \times 10^{-5}$ Pa. For CVV, it’s required that the pressure should be low for a good thermal isolation, while it’s crucial for a superconducting device to have higher vacuum for better electrical isolation after the coils are charged [2]. The design specifications are <$1 \times 10^{-1}$ Pa at room temperature and <$5 \times 10^{-4}$ Pa at working state. For CVB, design requirements are not as high as those for CVV, because there is no electrode inside.

2.2. Pumping station
These 3 chambers have independent pumping systems. Figure 1 shows the scheme of EAST pumping system. For the PVV, there are 4 sets of Turbo-Molecular Pumps (TMP), each with the nominal pumping speed of 3.5 m$^3$/s. All of them are installed on a pumping duct (0.8 m in diameter and 6 m in length) connecting with one horizontal port of PVV. There are also 4 Cryo-Pumps (CP) on the duct, each with the nominal pumping speed of 5.8 m$^3$/s for N$_2$). Two more CPs are installed at the bottom ports connecting with the divertor region through tubes (2.5 m in length, and cross section area of 0.07 m$^2$). There are 3 sets of Roots (nominal speed of 0.6 m$^3$/s) plus rotary pumping stations (0.07 m$^3$/s) acting as the fore pumps of the TMPs. Between the TMPs and the Roots there is a liquid nitrogen trap of 0.07 m$^3$ for removing water from the pumped air and suppressing oil diffusion to the TMP stage.

The pumping system of CVV main body is similar to that for PVV. There are 4 sets of TMPs with lower pumping speed (each with the nominal speed of 1.5 m$^3$/s), and the fore pumps are the same. After cooling down of the cryostat, the magnet structure and its thermal shields act as a huge CP with superconducting coils at one temperature stage of about 5 K and thermal shields at about 80K. There are 3 more TMPs (each with nominal speed of 1.2 m$^3$/s) located at 2 Current Lead Tanks (CLT) and the transfer line. For CVB, there is one TMP station with the pumping speed of 0.6 m$^3$/s.

**Figure 1.** Scheme of EAST pumping system in 2007. D.C., HTc and LTc correspond to differential chamber, high critical temperature and low critical temperature respectively.

2.3. Gas injection system
There are two important functions of the gas injection system. One is for plasma density control and another for wall conditioning. The working gas for plasma fueling is hydrogen at the present stage. Two kinds of piezo-valves (maximum throughput being 60 and 4200 sccm respectively) are used. Helium and hydrogen are working gases of wall conditioning. One electrical magnetic valve is utilized with the flow rate adjusted between $5 \times 10^{-7}$ and $125 \text{ Pa} \cdot \text{m}^3/\text{s}$ depending on discharge cleaning methods, Glow Discharge Cleaning (GDC) or Ion Cyclotron Resonance Discharge Cleaning (ICR-DC).

2.4. Wall conditioning

To get plasma with low impurity level, it’s very important to have a clean first wall. In the present campaign, the first wall of EAST is metal. Except for 2 movable limiters made of Molybdenum, all the plasma facing area is stainless steel, including the divertor area. Baking and GDC are two routine wall conditioning techniques. There are 3 sets of baking sub-systems for EAST, Plasma Facing Component board (PFC) and port tube heating, double shell hot air heating and PVV pumping duct heating. Heaters are installed behind the PFC boards, its power supplier could be switched for the heaters installed on the port tube wall. Hot air (nitrogen) circulating inside the double shell of the PVV wall bakes the PVV. Armored heaters are distributed uniformly on the surface of the pumping duct for PVV. Armored thermal couplers are installed poloidally and toroidally on the PFC, port tubes and pumping duct.

Besides conventional GDC, ICR-DC is also an important conditioning technique. The primary advantage is that it could be applied with the existing of the toroidal magnetic field. The technique was successfully used on HT-7 [3], and becomes one of the routine conditioning methods, especially for boronization and between discharges.

In the HT-7 superconducting tokamak campaigns, it’s observed that boronization could suppress efficiently the high and low Z impurities in the plasma[3]. Same material, carborane ($\text{C}_2\text{B}_{10}\text{H}_{12}$) is used for EAST. This kind of white powder has lower level of toxicity and higher stability than other boron compounds. It is heated during boronization, and the sublimation is led into the GDC or ICR plasma through a high temperature tube. Residual gas analysis in the differential chamber and film thickness monitor are used for in-time monitoring of the process.

2.5. Control and safeguard

Basically all the vacuum related operation, including pumping, fueling and pressure and temperature data acquisition, could be conducted on industrial PCs. They’re at the top level of a vacuum control system with a three level structure. The bottom level control is performed on the local instruments manually, and the medium level control is based on PLC. The communication is based on profi_bus network. Besides that, a remote control server is setup for remote handling and monitoring through the LAN [4].

Safeguard is crucial for the operation of a superconducting tokamak. The running risks are categorized into 3 levels. The primary one would potentially cause damage to the device. The medium one could potentially cause damage to the vacuum system. The mildest one would influence the experimental operation. The judgment is based on the monitoring of the whole and partial pressure, and the states of the vacuum system units. The alarms are shown on the vacuum control station, and two levels of alerts are sent to the central control station. The high risk alert requires the central controller to stop experiment and discharge current in all the coils, while the low risk alert requires that the experiment be terminated but toroidal field current be kept.

3. Vacuum system operation

3.1. Pumping down

It takes the rotary pumps about 4 hours to pump down the PVV from atmosphere to $1\text{E}3 \text{ Pa}$, when the Roots could be put into use. After another 1-2 hours, TMP could be started. For CVV main body, it takes a little longer period (e.g. about 5 hour) before starting the Roots, and 1-2 hours before the TMPs
(efficient pumping speed of about 5 Pa m\(^3\)/s) were started. The pumping for the current lead section and CVB takes much shorter time. After cooling down to the working temperature, the ultimate pressure of CVV and CVB could easily reach \(1 \times 10^{-5}\) Pa.

3.2. Leak detecting

Leak detecting is essential for the success of the engineering commissioning, especially for such a whole superconducting device. The sealing for the CVV is mainly rubber, and for the PVV is mainly aluminum for big flanges and OFHC copper for smaller ones. The most crucial leak is that of the coolant circuit inside CVV. Taking the toroidal field coil as an example, it’s required that the total leakage should be lower than \(1 \times 10^{-6}\) Pa m\(^3\)/s. It consists of 16 cages, therefore, during the construction, it’s designed that leakage for each cage should not exceed \(3 \times 10^{-8}\) Pa m\(^3\)/s, considering welding is needed to form a whole unit. An important part of the vacuum operation is to ensure that each cooling circuit meets the leak control requirements. It’s found that the biggest leak in the CVV is the outer thermal shield circuit with a leakage of \(10^{-5}\) Pa m\(^3\)/s, barely meeting the requirement.

3.3. Wall conditioning

Shortly after leak detecting, baking is applied continuously, and CPs are put into use and show high efficiency on water removing. Most of the time, the temperature of PVV chamber is kept at 110-130 °C by hot air heating. The temperature of PFC and port tubes is lower than 100 °C. For the pumping duct, the maximum temperature is kept lower than 110 °C, otherwise the cryogenic heads of the CPs on the duct would be higher than 20 K, leading to outgassing to the PVV. The baking system is applied all the time. Besides that, GDC is carried out for about 170 hours and ICR-DC for about 40 hours. With the help of these routine conditioning, the ultimate pressure of PVV reached \(10^{-6}\) Pa with the help of TMPs (efficient pumping speed of about 10 m\(^3\)/s) and CPs.

Boronization with GDC plasma and that with ICR-DC plasma are successfully carried out to extend operational region and enhance the flexibility on plasma control during ramp-up phase [5].

4. Summary

The EAST vacuum system is commissioned. During the divertor campaign, it’s checked that present leakage met the working requirements. With the help of wall conditioning, the TMP and CP combination provided a good condition for plasma discharge. The ultimate pressure of CVV and CVB are also below the design values. EAST will have a graphite first wall for the next campaign. Correspondingly, pumping capability during wall conditioning will be upgraded. Besides, pumping system of CVV and the vacuum control will be enhanced.

Acknowledgements

The work is partially supported by National Nature Science Foundation of China. The presenter is grateful to JSPS-CAS Core-University Program in the field of “Plasma and Nuclear Fusion” for sample analysis. The author would like to thank Mr. A. Nagy of General Atomic for the helpful discussion on gas injection Valves, and Prof. J. Gerhold on cryogenic insulation.

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