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Vacuum System for HL-2A Tokamak

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Abstract The vacuum system for HL-2A was built in 2003. The test results indicated that this system is feasible. It consists of three main parts: a pumping system, a pumping divertor and a glow discharge cleaning (GDC) system. For the pumping system, there are three main functions: (1) evacuating the vacuum vessel thus to produce an ultra high vacuum, (2) removal of impurities released during baking and (3) pumping during GDC. The pumping divertor controls the particles at the plasma edge and the GDC system provides a clean wall conditioning. During the first campaign of physical trial experiment on HL-2A, the ultimate pressure reached 4.6×10^{-6} Pa, and the total leakage and outgassing rate in 12 hours was 1.8×10^{-5} Pa·m^3/s, which is close to that of ASDEX.

Keywords: pumping system, pumping divertor, glow discharge cleaning system, leakage & outgassing rate

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1 Introduction

The vacuum system of today's tokamak devices has been designed to meet the operational requirements of the experiments. The operation can be divided into five modes, (1) pumping-down and leakage detection of the vacuum vessel, (2) baking, (3)plasma-facing component (PFC) conditioning, (4) evacuation and control of the particles at plasma edge, (5) plasma operation. It is well known that the plasma discharge should be carried out in an environment of ultra-high vacuum, in addition to the other required experimental conditions. The vacuum system of a tokamak should pump out the impure gases, (mainly H_2O and hydrocarbon produced during the glow discharge cleaning), quickly pump out the working gas after the pulsed discharges, and control the particle flow present with plasmas. To meet these requirements, a remote-controlled turbo molecular pump with a high compression ratio, and a high rotation speed has been widely used on tokamaks such as TEXTOR[1], ASDEX[2], JT-60[3], in a stable operation with a weak magnetic field and a pumping capability under a heavy load, as well as a relatively high speed when pumping the plasma compound following a pulsed discharge. In most of the vacuum systems on a medium-sized machine a two-stage pumping is used, and on a large-sized machine a three-stage pumping is used with a front stage. Furthermore, the pumping limiter or pumping divertor is used for pumping and controlling of the edge neutral particles. Table 1 shows the configuration and technical characteristics of the vacuum systems on several tokamaks.

2 Pumping system

To meet the technical requirement of a nuclear fusion experimental device and the structural features of HL-2A, eight turbo-molecular pumps of 3500 l/s are used as main pumping devices. The whole system is composed of three pumping stages with a converged front-stage similar to that on ASDEX. The schematic structure is shown in Fig. 1 and 2, where the main pumping pipe consists of three sections: one section with a ϕ 350 mm diameter, another with a ϕ 350 mm diameter for rectification, and the last with a right angle. It is connected to the vacuum chamber through eight uniformly distributed ports on both the upper and lower tilted windows of the vacuum vessel. Its equivalent conductance is 2.4 m^3/s for the upper tilted ports and 2.6 m^3/s for the lower tilted port. Eight ultra high vacuum gate valves with a ϕ 400 mm diameter are installed between the vacuum chamber and the pump. The effective pumping rates of the pumps are 1.4 m^3/s for the upper ports and 1.6 m^3/s for the lower ports.

The front stages of the molecular pumps are jointed each other on the horizontal front stage pipe via bellows and pneumatically isolating valves. The front stage-pumping system consists of three parallel sets of pumping devices. One of them is a set of Roots pumps together with two sets of 2X-70 rotary pumps in series.

Table 1 Configuration & technical characteristic of tokamak vacuum systems

Item	HL-1M	TEXTOR	ASDEX	JT-60	EAST*	HL-2A
Total leak rate ($Pa\cdot m^3/s$)	3×10^{-8}	7×10^{-7}	1×10^{-5}	5×10^{-8}	1×10^{-8}	1×10^{-5}
Ultimate pressure (Pa)	5.6×10^{-6}	1×10^{-6}	3×10^{-6}	1.3×10^{-6}	1.3×10^{-5}	4.6×10^{-6}
Outgassing rate($Pa\cdot m^3/s$)	8×10^{-6}	3×10^{-6}	3.6×10^{-5}	5×10^{-6}	4×10^{-5}	1.8×10^{-5}
Main pump turbo molecular pump	3 × 1500	4 × 3500	8 × 3500	16 × 3500	4 × 3500 2 × 20 k (cryopump)	8 × 3500
Effective speed (m^3/s)	1.5	6.5	12	54.4	8.2	12
Fore pump	3 × 30 Rotary pump	4 × 70 Roots pump 4 × 16 Rotary pump	2 × 300 Roots pump 4 × 20 Rotary pum	8 × 450 Roots pump 8 × 70 Rotary pump	4 × 550 Roots pump 4 × 70 Rotary pump	1 × 600 Roots pump 1 × 70 Rotary pump 2 × 450 Turbo molecular pump, 2 × 30 Rotary pump
Ratio of pumping speed rate	50:1	218 : 4.4 : 1	400 : 7.5 : 1	100 : 5.2 : 1	50 : 6.3 : 1	200 : 8.6 : 1, 240 : 15 : 1
Control of the particles at plasma edge	Pump limit turbo molecular pump	Pump limit turbo molecular pump	Divertor titanium sublimation pump	Divertor in-vessel cryopump	divertor cryopump	Divertor titanium sublimation pump
Wall conditioning	GDC siliconized Li deposition	RG-GDC carbonization boronization	GDC carbonization boronization	ECR-DC boronization	ICRF-DC boronization	GDC siliconization boronization

*The vacuum system of EAST is under construction

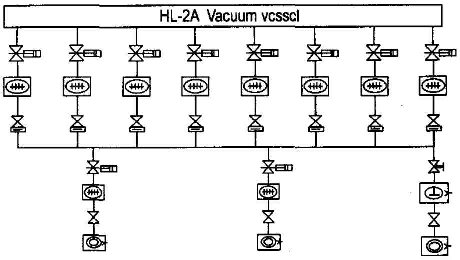
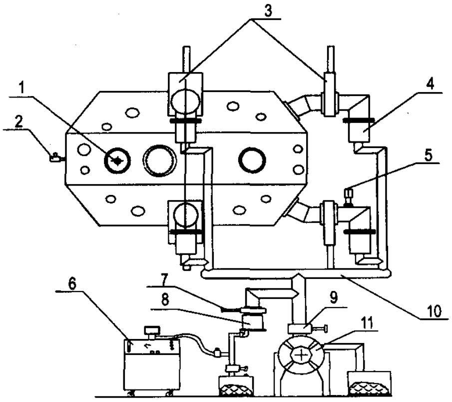


Fig.1 The schematic diagram of vacuum system in HL-2A



1 ionization vacuum gauge; 2 calibrated leakage; 3 ϕ400 mm gate valve; 4 3500 l/s molecular pump; 5 quadrupole mass spectrometer; 6 He leakage detector; 7 ϕ150 mm gate valve; 8 450 l/s molecular pump; 9 2X-30 rotary pump; 10 common foreline; 11 Roots pump

Fig.2 The main pumping system (1/4)

The other two sets have one F-150 turbo molecular pump and one 2X-70 rotary pump in series. The pumping rate in the main pumping device of HL-2A is 200 : 8.6 : 1 for the front stage with a set of Roots pump and a set of rotary pump, and 240 : 15 : 1 for the front stage with two sets of 450 l/s molecular pump and a set of 30 l/s rotary pump. As the pumping rates of the molecular pumps, Roots and rotary pumps were not fast enough on ASDEX [2], so the four molecular pumps had to keep pumping under GDC with a gas pressure of 10^{-1} Pa due to the high pressure in the front-stage pipe. The pumping abilities of the front stage sets are well matched in the main pumping system of HL-2A so as to be able to avoid the above defect.

Vacuum detectors, such as the quadrupole mass spectrometer, B-A gauge, wide-range ZJ-27 gauge, and thermocouple vacuum meter, are installed on the vacuum chamber, the pipes before and behind the $\phi\,400\,\mathrm{mm}$ gate valve, and the front stage pipes, respectively. The vacuum parameters and performance can be monitored throughout the process of a physical operation for HL-2A.

3 Pumping divertor

For a long-pulse operation of fusion experiments or a future fusion reactor, the pumping of neutral gas is an essential requirement for achieving a steady-state plasma, especially in a divertor configuration. However, pumping is not only a technical issue to provide a fast enough pumping speed at a proper location, but also closely linked to particle transport in the scrape-off layer (SOL) and divertor plasma. Many things have to be considered in current experiments when the details of the neutral particle exhaust are designed. The required evacuation and control of the particles at the plasma edge on the divertor device are realized by forwardly exhausting from the molecular pump ASDEX-U Divertor I[4] and from the toroidally continuous cryopump (ASDEX-U Divertor II[5], DIII-D advanced Divertor & JET[6]), as well as by adsorbing the surface of the vacuum vessel(PDX, ASDEX[7]). The processes of the advanced divertor i.e., the pumping divertor, radiation divertor and detached divertor can all be demonstrated through pumping and controlling the local particles under a divertor configuration. This target can be achieved with a pumping divertor of HL-2A consisting of 14 sets of titanium-sublimating pumps, and a proper gas puffing system.

The divertor system of HL-2A consists of 4 sets of neutralizing plates, water-cooling multi-shaped curved copper pieces, and multipole coils. There are 128 water connectors on the neutralizing plates to feed water in and out of the system. To cool the system, salt-free water at room temperature is used during the discharges. The throat pipeline for cooling the divertor is conformed to the curved surface of the plasma. The throat pipeline is 3 cm wide and 40 cm long with a conductance of $7.6 \times 10^4\ \mathrm{l/s}$. The pumping function of the system largely depends on the absorption of the gases by the titanium film deposited from the sublimation of 14 titanium balls.

The flow order of titanium sublimation is performed as follows:

Preheating titanium balls ($10\,\mathrm{A} \sim 20\,\mathrm{A}$, 5 min)-> sublimation of titanium balls ($40\,\mathrm{A} \sim 50\,\mathrm{A}$, 20 min)-> Interval (5 min ~10 min)->Shots of experimental discharge.

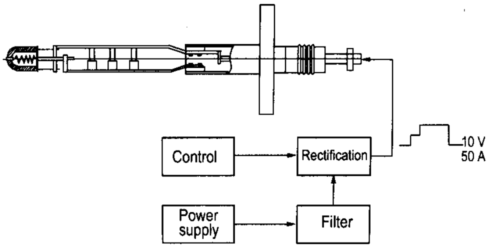


Fig.3 Titanium sublimation

The pumping divertor of the titanium sublimation is shown in Fig. 3. The titanium balls are made up of titanium iodide half-ellipsoids with a $\phi\,21.5\,\mathrm{mm}$ diameter and a 5 mm thickness. The approximate amount of titanium available is about 15 g. There is a tungsten whorl with a $\phi\,1.2\,\mathrm{mm}$ diameter taken as a heater on the sphere shell. One tip on the whorl is welded to the surface of the sphere shell by means of argon arc welding. Another tip is connected to the electrical feeder on the flange with a molybdenum shell. Three uniformly-distributed molybdenum sticks hold the sphere shell of the titanium balls. The heating current flows through the circuits consisting of a center molyb denum shell, tungsten wires, titanium shell and 3 molybdenum sticks. The sputtering speed is always kept constant when the power is fixed.

The titanium sublimation is powered by a power supply system, the voltage of which is primarily transformed from a single-phase civil electrical supply, and then rectified and filtered to get the proper power to heat the titanium balls ($100\,\mathrm{W} \sim 500\,\mathrm{W}$). The titanium sublimation procedure includes two stages, i.e. preheating and heating. The time and current for each stage are continuously adjusted. The working state of the titanium balls can be automatically changed to the heating state from the preheating state. In order to avoid effects of the floating potential of the vacuum vessel on the plasma discharge, the switching on and off of each power supply system for the titanium sublimation is controlled.

4 GDC system

Taylor discharge cleaning, glow discharge cleaning and ECR discharge cleaning have been widely used for wall conditionings and for tokamaks currently in use[8]. These technologies are important to reduce the impurities, such as C and O, and to control their recycling. They can also be used to condition the first wall in-situ based on the CVD theory, such as siliconization, and boronization, and then to optimize the plasma-first wall interactions, finally to improve the plasma discharge performance.

Table 2 Total and partial pressure during the first physical experiment of HL-2A

T	P_t	P_{18}	P_{28}	P_{32}	P_2	Remark
25 °C	2.4×10^{-4}	2×10^{-4}	2.9×10^{-5}	6.9×10^{-6}	1×10^{-6}	Unit: Pa
85 °C	3.1×10^{-3}	2.8×10^{-3}	1.9×10^{-4}	6.4×10^{-6}	4×10^{-5}	Constant temperature keeping for 48 hours*
119 °C	1.4×10^{-3}	1.2×10^{-3}	1.6×10^{-4}	5.1×10^{-6}	2.1×10^{-5}	
100 °C	6.4×10^{-4}	4.9×10^{-4}	1.3×10^{-4}	2.4×10^{-6}	1.6×10^{-5}	
50 °C	4×10^{-5}	2.6×10^{-5}	1.2×10^{-5}	7.6×10^{-7}	9×10^{-6}	Heat preserving for 120 hours
25 °C	1.6×10^{-5}	8.9×10^{-6}	5.1×10^{-6}	3.8×10^{-7}	2×10^{-6}	

* As the neutralizing plates of the divertor in the vacuum chamber is required to be baked at temperature of 85 °C, so the temperature of the vacuum chamber has to be kept to 85 °C for 48 hours to pump out the gases from the plates.

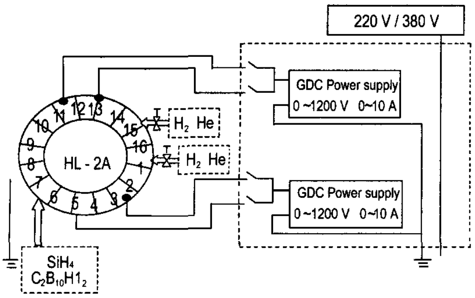


Fig.4 Glow discharge cleaning (GDC) system

GDC is selected for the conditioning and in-situ treatment of the first wall on HL-2A. The system is shown in Fig. 4, where four stainless steel anodes, each in a size of $\Phi 25\,mm \times 450$ mm, are installed in the limiter shadow region outside the bulk plasma in the vacuum chamber. Each anode consists of a stainless steel pole and a shield, which looks like a lamp mantle. Each anode pole is connected via a ceramic insulator to its anode mantle, which in turn is directly connected to the vacuum chamber. By way of combining the anode, working gas, and the vessel of the vacuum chamber via electrodes on the window flange, an electrical circuit is set up through the GDC power supply system. As shown in Fig. 4, two GDC power supply systems, whose output voltage and current are 0 ~ 1200 V and 0 ~ 8 A, respectively, are shared with four anodes, i.e. each with two anodes. The whole system can be used for different wall conditioning (H_2, He) and different in-situ coatings(siliconization, boronization) according to the requirements of physical experiments.

Uniform glow plasmas can be achieved when some of the gate valves in the main pumping system are shut, and the amount of the feeding gas and output of the power supply systems are properly adjusted. The typical parameters are as follows: gas pressure of the vacuum chamber 3×10^{-2} Pa~ 8×10^{-2} Pa, anode voltage 420 V ~ 730 V and current 2.4 A ~ 5.6 A.

5 Experimental results

Rough pumping was carried out with a 600 l/s Roots pump and a 70 l/s rotary pump for the front stage pumping set in a serial 2-stage mode after leakage detection. The pressure reached 800 Pa in 56 min after the startup of rotary pumping. Then the Roots pump was turned on and the pressure reached 10 Pa in 18 min. With this vacuum degree the molecular pump can start up. The results of the rough pumping indicated that the two-stage combination of a Roots pump and a rotary pump could meet the technical requirements of the experiments.

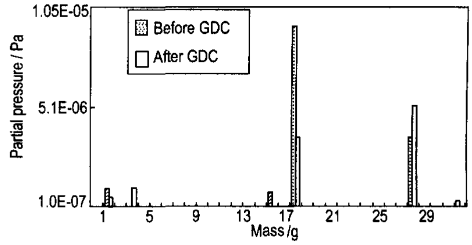


Fig.5 Partial pressure in the vacuum chamber before and after He GDC

HL-2A has a complicated structure with a high outgassing rate. After the leakage detection at room temperature, the vacuum reached 2.4×10^{-4} Pa in several days. The mass spectrum measurement showed that the main component of the residual gas is H_2O(86%). After wall-baking with 120 °C water for about two weeks, it reached 2×10^{-5} Pa at room temperature, and the percentage of H_2O decreased to 56%. The total gas pressure and the components of the residual gas during baking in the first physical operation of HL-2A are shown in Table 2.

The mass spectra of the residual gases in the vacuum chamber before and after GDC are shown in Fig. 5. After 50 hours of GDC, the total gas pressure of the vacuum chamber and the partial pressure of H_2O decreased to 1.4×10^{-5} Pa and 6.9×10^{-6} Pa, respectively. The percentage of H_2O decreased from 86% to 49.5%. These experimental results assured a good conditioning of vacuum and first-wall for HL-2A experiments.

A lower single-null divertor has been successfully established in the first physical campaign on HL-2A in 2003. With this kind of divertor, although it is difficult to measure the effective pumping rate of titanium sublimation due to the complexity of the compact structure

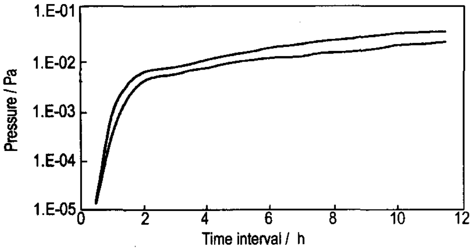


Fig.6 The vacuum recovery curves in HL-2A vessel

of the vacuum vessel of HL-2A, it can be indirectly calculated by using the parameters of the total leakage and outgassing rate together with the ultimate pressure.

By measuring the pressure rise when isolating the vessel with all the vacuum valves, closed, the total leakage and outgassing rate of the vacuum chamber can be attained from the following equation:

$$Q = V \times \frac{\Delta P}{\Delta T}, \tag{1}$$

where $Q, \Delta P, \Delta T$ and V are total leakage and outgassing rate, pressure change in the vacuum chamber, time interval and volume of the vacuum chamber, respectively.

Fig. 6 shows the pressure recovery curves in HL-2A vacuum chamber. The total leakage and outgassing rate for 12 hours is 2.98×10^{-5} Pa·m^3/s, which is a 56% decrease from that (4.7×10^{-5} Pa·m^3/s) in 2002. Also, the total leakage and outgassing rate after the titanium sublimation operation is 1.8×10^{-5} Pa·m^3/s, and the equivalent pumping amount of the sublimation is 0.5 Pa·m^3. The ultimate vacuum parameter approaches the same value (3.6×10^{-6} Pa) as those on ASDEX[2].

6 Conclusions

In the experimental campaign 2003 on HL-2A a lower single-null divertor plasma discharge with a plasma current of 168 kA and a plasma duration of 920 ms was successfully obtained. After a continuous operation for 112 days, the pumping system was demonstrated to have met the requirements of baking and GDC. The pumping and control of the edge neutral particles was conducted via the pumping divertor. The GDC system provided a good first-wall conditioning for the experiment. The vacuum parameters on HL-2A achieved are as follows: the ultimate vacuum is 4.6×10^{-6} Pa and the total leakage and outgassing rate is 1.8×10^{-5} Pa·m^3/s for 12 hours. They have approached those levels obtained by ASDEX at the beginning of its development. Corresponding engineering and technical conditions have been used in the high-parameter discharge and advanced divertor configuration experiments on HL-2A.

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