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Preparation of Vacuum Chamber of the KTM Tokamak for Experiments

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Abstract—This article describes the vacuum system of the KTM tokamak and also presents an algorithm for the technological mode of conditioning of the tokamak vacuum chamber (VC) performed before and during the experiment and its influence on production of glow discharges. The applied procedure of the vacuum chamber preparation, despite the atmospheric leakage in 2021, provided the possibility to develop conditions for conducting experiments at the KTM tokamak and to obtain discharges with the highest currents and discharge durations for this facility achievable at the time of writing of this article. As a result of the analysis of experimental data, the conditions have been established under which plasma discharges are not formed.

Keywords: vacuum technique, glow discharge, ohmic heating, mass spectra of residual gases, atmospheric leakage, desorption

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INTRODUCTION

One of the main goals of physical research on the KTM tokamak is to study the behavior of materials of the first wall and divertor plates under the influence of powerful thermal and corpuscular flows from the plasma. A distinctive feature of the KTM vacuum chamber is the divertor design, which allows for prompt replacement of divertor plates without disturbing high vacuum [1]. The vacuum chamber (VC) is made of 08Cr18Ni12Ti stainless steel. The thickness of the inner cylindrical part of the VC wall is 3 mm; the thickness of the outer wall is 5 mm. Prior to the 2020 pilot campaign, practically the entire surface of the vacuum chamber was lined with FP-479 graphite produced by Schunk Kohlenstoffechnik GmbH (Germany) in accordance with the project; graphite tiles were installed directly into the vacuum chamber after opening the hermetic factory package without additional preparation procedures [2].

The volume of the KTM vacuum chamber is 13.5 m^3; the total internal surface area of the chamber is about 33 m^2. The nominal heating temperature of the chamber is 200 ± 10°C. The entire surface of the VC, except for the inner cylinder, is heated using ohmic heaters. The inner cylinder is heated by induction by applying an electric current to the central solenoid.

VACUUM PUMPING, MEASURING, AND RECORDING EQUIPMENT

For preliminary low-vacuum pumping of the VC, three 2NVR-250D fore vacuum rotary vane pumps of AO Vacuummash with operating speed $S_0 = 63$ L/s are used. For high vacuum pumping of the vacuum chamber, three Agilent Technologies Varian Turbo-V 3K-T turbomolecular pumps with speeds $S_0 = 2050$ L/s as per N_2 and $S_0 = 2300$ L/s as per H_2 each are used. The effective pumping rate of the VC by the three pumps is about $S_{\text{eff}} = 2000$ L/s. Nitrogen traps and filter elements made of Petryanov cloth installed at the inlet of each pump are used to prevent oil from entering the chamber volume of the unit from the rotary vane pumps. Vacuum pressure is measured using Agilent ConvecTorr analog sensors with a measurement range

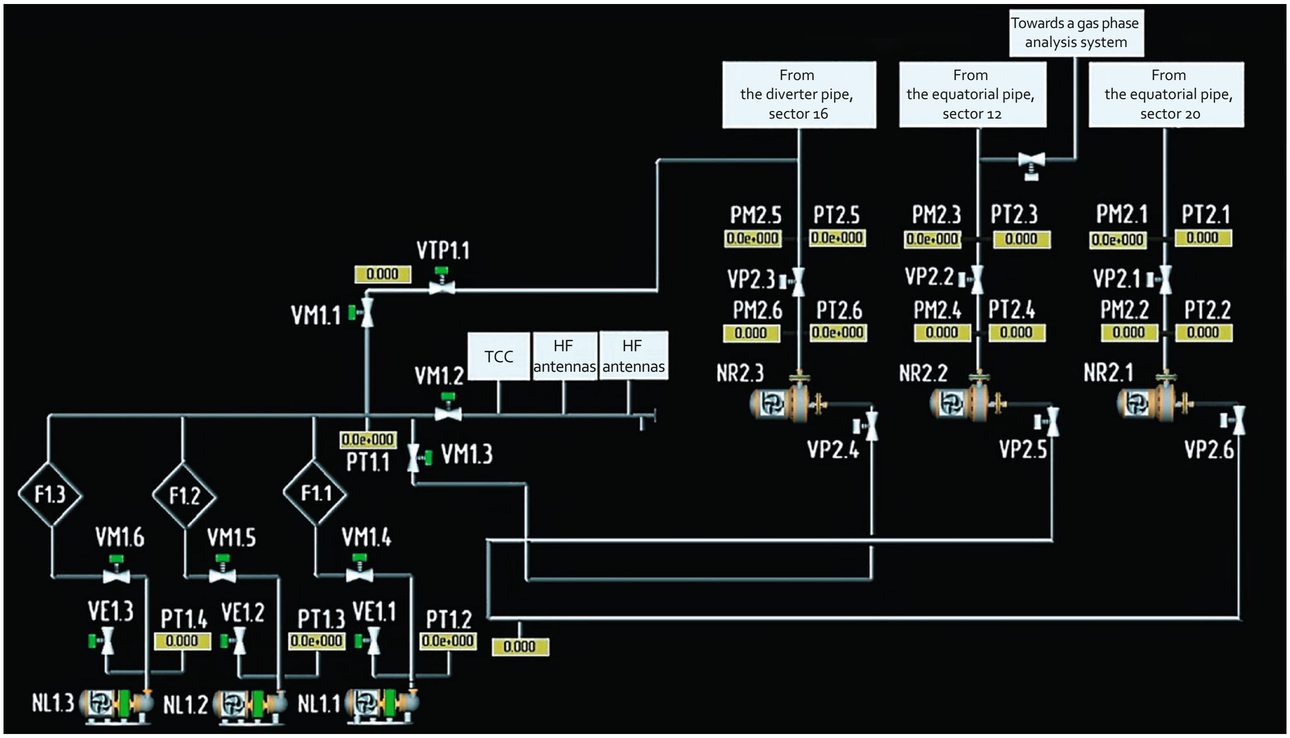

Fig. 1. Display of vacuum pumping system.

of 1 × 10^{-4}–750 Torr and Agilent IMG-100 analog sensors with a measurement range of 5 × 10^{-9}–1 × 10^{-3} Torr. Pressure recording is performed by an Agilent XGS 600 vacuum controller with a response time of <20 ms. The vacuum pumping control system is based on Advantech ADAM 6000 distributed analog and discrete I/O modules; the information from the modules is fed to an Advantix process controller under the control of a Trace Mode real time monitor. Data on the state of vacuum equipment and recorded pressures are displayed on the screens in the control room of the KTM installation (Fig. 1). An Extorr XT-200M quadrupole mass spectrometer with independent pumping is used to monitor the impurity content in residual gas. An MS-4 helium leak detector manufactured by NPF Progress is used to search for and eliminate leaks in the vacuum chamber.

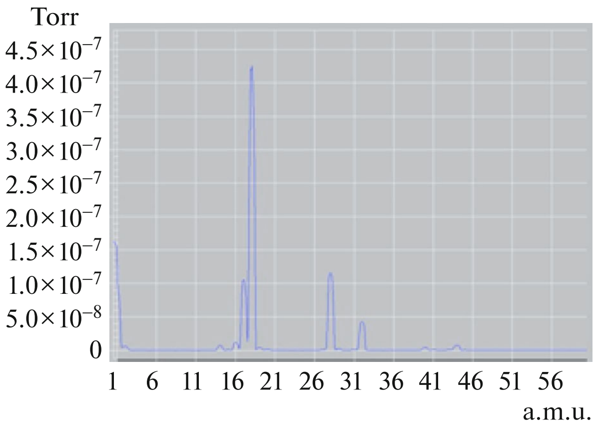

Fig. 2. Mass spectrum before VC heating.

CHAMBER CONDITIONING DURING PREPARATION FOR EXPERIMENTS

The algorithm for preparing a vacuum chamber for plasma discharges implemented in the autumn experimental campaign of 2021 consists of the following steps: initial vacuum pumping with the search for leaks, high-vacuum pumping and ohmic heating of the VC for 72 h at a temperature of 190 ± 10°C in order to remove water vapor from the inner surface of the vacuum chamber, and then glow discharges (GD) in various gases: Ar, H_2, and He with the GD duration in each gas of approximately 2, 36, and 23 h, respectively. Before the start of ohmic heating after the elimination of leaks, the limiting pressure in the vacuum chamber of the KTM is (2–4) × 10^{-6} Torr. In the mass spectrum illustrated in Fig. 2, one can see the presence of peaks of amu 17, 18, 28, 32, 40, and 44, indicating the presence of water and indicating the presence of atmospheric leakage.

After ohmic heating for 72 h and a glow discharge in a medium of various gases (Ar (2 h), H_2 (36 h), He (23 h)), water and molecular oxygen were eliminated. The residual pressure after cooling the vacuum cham-

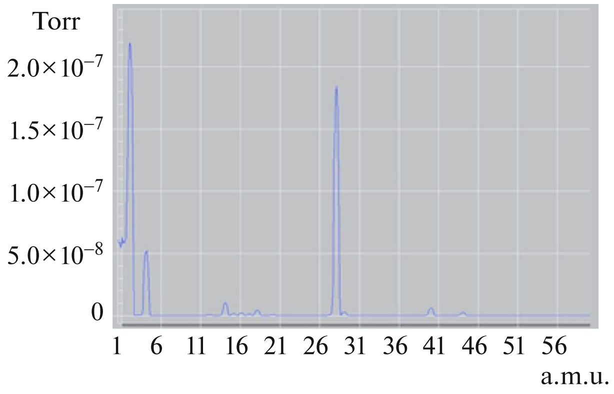

Fig. 3. Mass spectrum before plasma discharge.

ber and all cleanings was $P_{res} = (6–7) \times 10^{-7}$ Torr. The mass spectrum of the residual gas before the plasma discharges in the vacuum chamber is shown in Fig. 3.

Figure 4 shows the mass spectrum 2 h after termination of the plasma experiments at the end of the working day (mass spectra were recorded using additional pumping of the mass spectrometer).

From the comparison of Figs. 3 and 4, one can see an increase in the peak of amu 32; i.e., after plasma experiments, the content of O_2 increased, which is a consequence of the presence of a significant leakage of the atmosphere into the chamber.

At night, during the breaks between plasma discharges, the vacuum chamber was conditioned by a helium glow discharge for 8–10 h, followed by pumping out for 4–5 h. After overnight cleaning, the mass spectrum is identical to the mass spectrum shown in Fig. 3. Analysis of the mass spectrum showed the absence of amu 32.

RESULTS AND DISCUSSION

In order to estimate the gas flow emission from the graphite wall Q_{gas} and the atmospheric leakage into vacuum chamber Q_{leak}, the cumulative flow to chamber Q was calculated as follows:

$$Q = Q_{gas} + Q_{leak} = \frac{V\Delta P}{\Delta t}, \tag{1}$$

where $V = 13.5$ is the volume of the tokamak vacuum chamber, m^3; $\Delta P = 9.2 \times 10^{-5}$ is the pressure change in the chamber in time Δt, Torr; and $\Delta t = 30$ is the measuring time of pressure after closing the gates separating the vacuum chamber from the high-vacuum pumping chamber, min.

The gas flow into the chamber was measured before the beginning of the autumn experimental campaign after a 10-day heating of the VC at $T \approx 200°C$ and cooling to room temperature. The obtained value of flow into the vacuum chamber was $Q \approx Q_{leak} = 6.5 \times 10^{-4}$ L Torr/s.

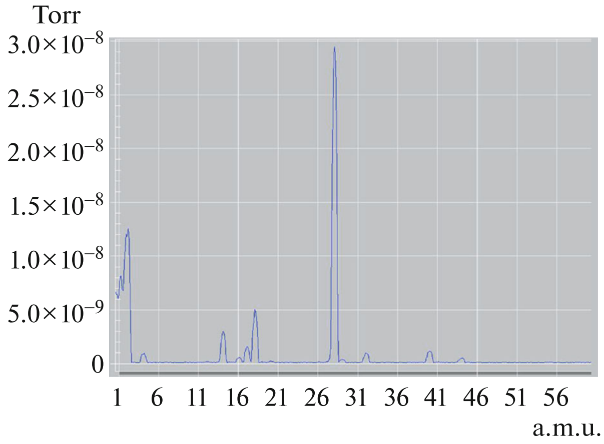

Fig. 4. Mass spectrum 2 h after plasma discharges.

The total gas flow into the vacuum chamber can also be estimated by the following equation using the values of limiting residual pressure P_{res} in the chamber and the effective pumping velocity, which is S_{eff} = 2000 L/s:

$$\begin{aligned} Q = Q_{gas} + Q_{leak} &= P_{res}S_{eff} = 6\times10^{-7}\times2000 \\ &= 1.2\times10^{-3} \text{ L Torr/s.} \end{aligned} \tag{2}$$

Comparing the calculated gas flow from Eq. (2) and the determined flow from Eq. (1), we can conclude that the level of flow from the atmosphere and gas emission from the chamber walls is comparable and is about $(6–7) \times 10^{-4}$ L Torr/s.

Desorption of surface contaminants from the chamber walls, including oxygen entering the chamber by flowing in from the atmosphere, in interaction with the plasma is the main mechanism of impurities entering the plasma discharge. It is known that desorption of one monolayer of oxygen in a chamber with a small radius $a = 1$ m would make it possible to fill it with a gas with a density higher than the usual density of hydrogen plasma, namely, 3×10^{19} m^{-3} [3]. Therefore, it is critically important to remove oxygen from the surface of the walls of the vacuum chamber facing the plasma. In preparing the KTM vacuum chamber for the experiment, together with ohmic heating of the chamber, the reduction of oxides to water in a hydrogen glow discharge was used, followed by removal of the accumulated water by a helium glow discharge. The key parameter for estimating the periodicity of tokamak first wall cleaning is the time of oxygen monolayer buildup. The estimated oxygen monolayer buildup time for the existing KTM is about 18 h, which in turn obliges technicians to clean the chamber every night before experiments. The following assumptions were made when calculating the oxygen monolayer buildup time: oxygen concentration in the ambient air is 20%; all oxygen from external leaks is adsorbed on the first wall.

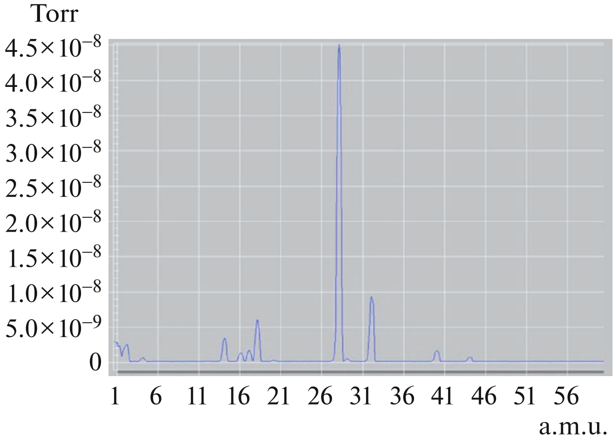

Fig. 5. Mass spectrum of residual gases after two days without cleaning.

The following example can be given in support of the above. At the end of the autumn–winter campaign, the drive of the glow discharge electrode failed, which made it impossible to carry out night cleaning in the future. An experiment was conducted on the effect on discharges of not cleaning nightly with a glow discharge. As a result, it was found that after the second night without cleaning, it was not possible to obtain plasma discharges with a current higher than 20 kA. Figure 5 shows the mass spectrum of residual gases in the KTM VC after the second night without cleaning. At the same time, the absolute pressure in the chamber increased to 8×10^{-7} Torr.

To improve the cleanliness of the chamber and obtain a higher residual vacuum, it is necessary to continue further search for leaks, as well as to develop additional methods for cleaning the first wall, such as cleaning the chamber with a Taylor discharge and a series of training discharges on hydrogen.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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