Modern Diagnostics for Investigation of Lithium Element Behavior in Tokamaks

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Abstract—The introduction of lithium as a material for production of in-vessel plasma-facing elements of the tokamak necessitates the development of the corresponding diagnostic instruments. A series of diagnostic devices have been developed and fabricated for tokamaks T-10 and T-11M which make it possible to investigate the processes of lithium transport in the tokamak plasma scrape-off layer (SOL), real-time dynamics of lithium deposition at various temperatures of a collecting surface by means of the microbalance technique, adsorption/desorption process of hydrogen isotopes on the lithium surface, and influence of an electric field on lithium trapping. Scanning of plasma parameters is provided by Langmuir probes. Such devices can be used to extract the lithium deposited on the inner walls of the tokamak vacuum chamber without opening it. For these purposes, a lock chamber and bellows-free vacuum input allowing movement and rotation is provided. It is planned to perform the study of the tokamak plasma interaction with in-vessel lithium-based elements by means of infrared (IR) thermometry. It is planned to try out this technique on the T-11M tokamak using a special device based on an IR camera.

Keywords: lithium, diagnostics, transport, deposition, sorption/desorption, IR thermometry

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INTRODUCTION

It was convincingly shown in some experimental studies that the use of lithium as a material of the plasma-facing elements of a tokamak and a stellarator leads, on one hand, to a considerable improvement of plasma discharge parameters and, on the other hand, to the possibility creating long-lived in-vessel elements [1–4]. Therefore, both the plasma physics and technological problems of the developed stationary thermonuclear fusion reactor may be solved. Taking into account a high sorption activity of lithium with respect to hydrogen and its isotopes, it is necessary to exclude its uncontrolled deposition on the reactor chamber walls and, thus, reduce the tritium accumulation. The design of closed circulation of lithium in the chamber with the use of lithium emitters and collectors [1, 5] based on capillary-pore systems makes it possible to solve this problem in general; however, a part of the flux of lithium atoms may reach the chamber walls and should be eliminated. To solve this problem, a procedure of lithium extraction from the inner surfaces of the vacuum chamber in the T-11M tokamak with the help of a cryogenic target under the conditions of glow discharge in the inert gas (helium, argon) and hydrogen (Fig. 1) was developed in [6].

An important aspect of studying the interaction between the lithium-based materials and tokamak plasma is the development of IR thermometry, which would make it possible to investigate the dynamics of this process and determine the level of arriving heat fluxes. The problem consists in the change in such a parameter important for optical measurements as the radiating capacity of the lithium surface under real tokamak conditions; the radiating capacity may vary considerably owing to the interaction between lithium and residual gases in the vacuum chamber with production of reaction products and the process of sprayed substance transport, as well as the change in the surface exposed to the tokamak plasma.

DIAGNOSTIC DEVICES FOR TOKAMAK T-11M

The designed cryogenic diagnostic target (Figs. 2a and 2b) includes a collecting element in the shape of a smooth hollow cylinder with a diameter of 58 mm and a length of 200 mm. The cryogenic temperature of the
collecting surface is provided by pouring liquid nitrogen into the inner cavity through the filler tube. The evaporated nitrogen is extracted from the cavity directly to the atmosphere. The construction contains a lock chamber to extract and install the target without opening the tokamak vacuum chamber. The transport nodal point is designed on the basis of disk bellows providing a longitudinal target motion up to 600 mm to install it in the working position. The cryogenic target is electrically isolated from the chamber, which extends the experimental capacities of this device, making it possible to change its electrical potential with respect to the plasma. The temperature control of the target collecting surface is executed by means of a thermocouple embedded into the inner cavity.

The further development of construction of the device consisted in increasing the efficiency of lithium trapping by the collecting element owing to enlargement of the collecting surface by means of its ribbing (see Fig. 2c) or establishment of the capillary-pore structure.

The use of such a construction allowed us to study the mechanisms of lithium transport in the chamber and estimate the efficiency of lithium extraction and the influence on different factors on it (Fig. 3). It was shown that the maximum lithium extraction rate in the T-11M tokamak reaches 3.5 μg/h. This provides the extraction of such amount of lithium for one procedure that is collected on the chamber walls after 200 operating discharges of the T-11M tokamak, which is equivalent to its two-week operation. In addition, being arranged in the shadow of the lithium limiter, the target was used to study the lithium transport directly in the operating discharge of the tokamak.

The installation of a heating element into the cavity of the collecting element of the target (Fig. 4) made it possible to investigate the dependence of the lithium transport process and hydrogen trapping and release by the target on the temperature of its surface in the temperature range from −200 to +400°C.

In the next modification of the device, the replacement of the disk bellows with the vacuum input based on a liquid-metal coupler provided large (almost unlimited) linear displacements and an unlimited rotation of the target around its axis. The elimination of the bellows allowed us to increase considerably the reliability and resource of the vacuum input and make this construction more compact (its longitudinal size does not exceed 200 mm) and cheaper. The modification of the lithium-extraction device on the basis of the liquid-metal vacuum input for the T-11M tokamak is shown in Figs. 5 and 6. The device includes an outer Wilson-type gland seal made of fluoroelastomer and an inner capillary-pore metal seal saturated with Ga–In eutectic alloy with a melting temperature of 16°C. The space between the seals is evacuated to a pressure of 300 Pa. The vacuum input operates at a temperature above 20°C. The realization of such a construction of the vacuum input in the diagnostic Langmuir probe of the T-11M has demonstrated its high service properties.
DIAGNOSTIC DEVICES FOR TOKAMAK T-10

The experience in designing and operating the described devices on the T-11M tokamak made it possible to design an experimental device for studying the lithium flux distribution and its collection in the vacuum chamber of the T-10 tokamak, on which the experiments with a lithium diaphragm started to be performed in 2016. The collecting surface of this device is designed in two variants (Fig. 7): in the shape of a smooth cylindrical surface (collection and extraction) and a probe that makes it possible to carry out a real-time control of the thickness of the deposited lithium layer. Such a possibility is provided by a quartz piezoelectric sensor imbedded in the target (the quartz crystal microbalance (QCM) method). The transport nodal point of this device based on the liquid-metal input and supplemented with a device for the axis angular displacement allows us to scan the density distribution of lithium atom and ion fluxes and their direction. Two variants of such a device fabricated for the T-10 tokamak that differ from each other in the design of their head part are shown in Fig. 8. The molybdenic shield and molybdenic protective case provide the protection of the smooth collecting surface and the piezoelectric sensor from the impact of the plasma. By the moment when this paper was written, the experiments with the first variant of this device (lithium collection and extraction) had been performed and proven its efficiency. At a temperature of the collecting surface of up to 350ºC, the lithium collection rate was 2.1 μg/h.

IR THERMOMETRY OF THE LITHIUM SURFACE

To study the interaction between the lithium-based materials and the tokamak plasma, it is necessary to develop an IR thermometry method which would make it possible to investigate the dynamics of this process and determine the level of incoming heat fluxes. In addition to the correct choice of technical parameters of instruments and the equipment connected with them, a crucial point in the IR diagnostic development is the calibration process. It is known that the reliability of temperature measurements by an IR camera depends on a correct consideration of the radiation capacity of the investigated surface ε. In the case of studying the in-vessel elements based on the capillary-pore system with liquid lithium, this problem requires an additional consideration. The total radiation capacity of the pure surface of lithium is 0.05 [7]. Since lithium is an extremely active metal with respect to the residual gases (O₂, H₂, CO₂, N₂, and H₂O) in the tokamak chamber, we should expect that surface films consisting of the products of reactions of lithium with these gases would be formed over time and their thickness would be different. A surface layer that is formed on lithium is a complex mixture of products of elementary reactions whose composition depends on that of the atmosphere in the chamber and the water vapor content. In addition, it will change over time. Therefore, it is difficult to determine and predict the change in the surface radiation capacity. In addition, it is impossible to exclude the influence of the process of erosion product transport from the surface of other in-vessel elements. When the lithium
limiter surface undergoes the impact of the technological and working plasma discharges, we can expect that its properties would change owing to its purification from the products of erosion and chemical reactions. In this connection, it is of significant importance to work out the IR diagnostics of lithium in-vessel elements (limiters) under the real tokamak conditions, when it is possible to model in full measure the influence of the residual gas atmosphere and the plasma impact on the surface radiation capacity.

The diagnostics for the T-11M tokamak is achieved with the help of a device (Fig. 9) based on an IR camera with a spectral range from 7 to 14 μm, which is arranged at the flange of the diagnostic port and observes the lithium limiter surface through the window of barium fluoride.

The IR camera is fixed and pointed at the investigated object by means of a suspension. To preclude the window from becoming dusty in the process of technological operations of purification of the inner sur-

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**Fig. 6.** Fabricated device for lithium collection on the T-11M tokamak with a vacuum input based on the liquid-metal coupler.

**Fig. 7.** Device for lithium collection for the T-10 tokamak: in the shape of a smooth cylinder (a); in the shape of a diagnostic probe (b, c).

**Fig. 8.** Fabricated device for lithium collection for tokamak T-10: in the shape of a smooth cylinder (a); in the shape of a diagnostic probe (b).
face of the vacuum chamber and the limiter (the glow and induction discharge), a movable shutter is used.

It is possible to estimate the quality of IR thermometry from the point of view of its information capability by comparing the observation data for the surface of the longitudinal lithium limiter of tokamak T-11M obtained by using high-speed cameras of the optical (Fig. 10a) and infrared (Fig. 10b) ranges during regular plasma discharges (Fig. 10).

CONCLUSIONS

The complex of diagnostic and technological devices was designed for tokamaks T-10 and T-11M to study the processes of lithium particle transport in the SOL of the tokamak, the dynamics of lithium deposition at various temperatures of the collecting surface, adsorption and desorption of plasma-forming gases by lithium, and the influence of different factors on the lithium trapping process. The complex includes IR thermometry of the investigated in-vessel elements. The operability and effectiveness of these devices was proven in experiments.

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