ABSTRACT

thesis for the degree of Doctor of Philosophy (PhD) in specialty 6D072300 – "Technical Physics"
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Development of Diagnostic Methods for Processes in Plasma and on the First Wall Surface of a Tokamak Facility

The thesis presents the results of diagnostic systems development designed to monitor plasma, measure temperature on the surface of studied materials, measure configuration of zero magnetic field on the KTM Tokamak, as well as the results of experimental studies with their use.

Relevance. The Republic of Kazakhstan is completing the creation of the KTM Tokamak - a toroidal type facility for studying the interaction between high-temperature plasma and first-wall materials for future experimental and industrial fusion plants. The KTM facility is one of the significant links in cooperation of advanced countries of the World on the creation of environmentally friendly and safe thermonuclear energy of the future. Plasma with current I_p = 750 kA and aspect ratio A = 2 should be obtained at the KTM facility. Facilities with a similar aspect ratio have not been created so far (for traditional Tokamaks A> 3, for spherical A <2), therefore, a study of plasma physics in such facility is also quite interesting. Thus, improvement and use of diagnostic methods designed to measure parameters of the KTM Tokamak plasma cord and the interaction between plasma and studied first-wall materials of future fusion reactors (FR) is an urgent task. Despite the fact that all Tokamak-type facilities share a common principle of operation, each of them is unique and has its own structural and physical features. This leads, at least, to the need to adapt physical diagnostics to a specific installation, and often to the development of new devices.

The first experimental work at the KTM Tokamak revealed a number of design features of the facility. These features are associated with asymmetric design of the vacuum chamber and presence of massive conductive elements (such as a divertor table, flanges of vacuum chamber, etc.). At the initial stage of a plasma discharge, significant currents of up to 100 kA are induced in the KTM vacuum chamber. As experiments have shown, the presence of massive unevenly distributed conductive elements leads to complexity and inaccuracy of simulation induced in the vacuum chamber of eddy currents and, accordingly, to the inaccuracy of calculating the field zero configuration in the KTM vacuum chamber. In addition, in the KTM Tokamak, due to design restrictions on the electromagnetic system and power supplies, it is possible to obtain only a relatively small value of electric field strength at the bypass, which does not exceed 1.6 V/m.

This fact, along with a relatively low value of the toroidal magnetic field equal to 1 T, imposes restrictions on the magnitude of scattered poloidal magnetic fields and the size of region with so-called zero field necessary to achieve avalanche ohmic breakdown. Therefore, this place is the most sensitive to inaccurate modeling. In addition, reliable modeling of magnetic fields in this region is of great importance for predicting one of the necessary conditions for a plasma discharge initiation at its initial phase, which affects the entire plasma discharge. Thus, direct measurement of field distribution near zero value inside the KTM vacuum chamber and verification of settlement codes was an urgent task.

Video surveillance systems for plasma are an integral part of the diagnostic complex of Tokamak-type facilities. These systems are one of the first in introduction phase and the main ones, both at the Tokamak commissioning stage and in the subsequent operation of the facility.

However, due to structural and technological features – long diagnostic pipes (limiting the viewing angle), electromagnetic and neutron effects, and direct installation of video cameras at pipes with viewing windows are difficult or impossible. In this regard, it is necessary to develop special optical paths (endoscopic systems) for transmitting images from input lens to the camera’s matrix. Thus, video surveillance systems for plasma are becoming a complex set of technical means, incorporating a large set of various optical elements. The design of the KTM Tokamak vacuum chamber has long equatorial pipes that significantly limit the visual observation of the plasma cord. In this regard, the use of a technical solution was required to overcome the problem of long pipes.

One of the important controlled parameters when studying the plasma-wall interaction is heating temperature of surface of the plasma facing materials and value of the affecting plasma heat fluxes. On the KTM Tokamak, maximum heat fluxes of plasma (up to 20 MW/m^2) per divertor will correspond to those expected in ITER. In this regard, use of measuring and monitoring the temperature of heating surface of studied materials under the effect of heat plasma flows is relevant.

Optical thermometry methods do not require the sensor contact with the body, temperature of which is measured, and therefore can be applied where the use of contact methods is difficult. IR thermometry methods measure very high temperatures. When using a thermal infrared camera, it is possible to determine the temperature distribution pattern on material surface with high spatial resolution. In this case, measurement can be performed with high speed. The optical thermometry methods are well applicable when measuring surface temperature of bodies with an emissivity close to that of a absolutely black body, as well as with its previously known value (e.g. at Tokamaks when measuring temperature of graphite mounted as first-wall material, since its emissivity close to 1).

The use of the metal first wall leads to the problem of accuracy in determining the temperature of its surface when measured by optical IR thermometry. This is due to the fact that metals are not "black" bodies, have low emissivity, and often it is temperature dependent. In addition, emissivity depends on the state of material surface and can change over time due to both surface modification because of plasma radiation and reprecipitation of atoms and dust particles from other parts of discharge chamber, for example, beryllium on divertor plates made of tungsten. Moreover, measurement error can reach tens of percent, especially in the region of high temperatures.

To solve the problem of changing the emissivity of body during surface heating and changing its state, a special two-color pyrometer is developed for ITER using the principle of pyroreflectometry. The development of this method is at the R&D stage.

One of the disadvantages of the developed diagnostics is temperature measurement at only one spatial point. However, there are strong temperature gradients on the surface of the metal first wall and divertor due to the uneven distribution of plasma flows; therefore, development of a measurement method that allows measuring the spatial temperature distribution on the surface of studied materials, in particular metals, with high accuracy is extremely urgent.

Thus, creation and use of special measuring instruments that allow obtaining experimental data that provide research on the KTM Tokamak is of great importance for implementation of the entire research program in this unique facility.

The goal of the thesis is development and improvement of measuring instruments and methods for plasma diagnostics for research on the KTM Tokamak.

To achieve this goal, the following tasks were solved:

– development of a method for direct accurate measurement of zero configuration of the magnetic field in the KTM vacuum chamber;

– measurement of zero field configuration at the KTM Tokamak;

– verification based on obtained experimental data of numerical codes for calculating the distribution of poloidal magnetic fields inside the KTM vacuum chamber;

– development of a KTM plasma video surveillance system;

– study of a plasma cord formation using the KTM Tokamak plasma video surveillance system;

– development of infrared imaging diagnostics for monitoring the temperature distribution over studied material surface at the KTM Tokamak;

– development of a method to improve the accuracy of thermographic measurements at the KTM Tokamak's materials made of metal.

Scientific novelty:

– A device and method for direct measurement of zero field configurations at the KTM Tokamak were developed for the first time.

– Verification of settlement codes for modeling and reconstructing the distribution of poloidal magnetic fields for the KTM Tokamak was carried out for the first time.

– An endoscopic plasma observation system in visible range has been developed for the KTM Tokamak

– A system of IR visualization of the KTM Tokamak was developed to monitor the distribution of temperature fields on studied material surface under the effect of heat plasma flows.

– For the first time, a method has been developed for correcting thermographic measurements of metal temperature over a wide temperature range under conditions of rapid heating under the effect of high-temperature plasma flows.

Key points for defense:

– Method for direct measurement of the magnetic field zero configuration inside the KTM Tokamak vacuum chamber using a matrix of three-component Hall sensors;

– KTM Tokamak plasma cord visualization system;

– The measuring method of temperature distribution on surface of studied samples of candidate materials in the KTM Tokamak, based on the use of a thermal imaging camera, as well as external infrared illumination to control emissivity factor.

Practical significance:

– The developed method for direct measurement of zero field configuration made it possible to verify the settlement codes. The obtained measurement results were used to refine the model of the KTM electromagnetic system, which in turn increased accuracy of the calculations. The method is applicable to other facilities of controlled thermonuclear fusion (CTF).

– The developed KTM Tokamak plasma visualization system made it possible to implement video surveillance of plasma cord, solving the problem of long equatorial pipes, and significantly expanded possibilities of experimental studies at KTM. A similar system can also be used at other CTF facilities.

– A method is proposed for significantly improving the accuracy of thermographic measurements of surface temperature of studied materials, in particular metals, under the effect of plasma flows in conditions of KTM Tokamak.

The results of the thesis, introduced on the KTM Tokamak, are presented in the Appendix to the thesis.

The main results of the work enabled to implement timely preparation and physical start-up (first and second stages) of the KTM Tokamak, as well as to demonstrate the operation of the facility at EXPO 2017.

The association of the thesis' topic with the research program plans.

The thesis was supported by grants from the State Institution “Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan” within the framework of Agreement No2064/GF4 dated February 12, 2015 on the topic “Development of a numerical model of the magnetic field dynamics o in a Tokamak vacuum chamber taking into account induced eddy currents and its verification on zero configurations of the KTM Tokamak field ” for 2015-2016, and also of Agreement

No.305 of March 30, 2018 on the topic AP05133148 “Development of a method for thermographic measurements of the candidate material surface per the FR’s walls and its implementation at the material testing KTM Tokamak for 2018-2020, as well as within the framework of republican budget program entitled “Applied scientific research of a technological nature” for the event of “Scientific and technical support for creation and operation of the Kazakhstani thermonuclear material testing Tokamak” of the Ministry of Energy of the Republic of Kazakhstan of the topic “Preparation of a complex of physical diagnostics and techniques for determining the plasma parameters of the KTM Tokamak” 2015-2017.

Personal contribution of the author. The main results and provisions of the thesis were obtained and developed personally by the author or under his guidance, as well as with participation of experts from the IAE NNC RK. Analysis of obtained results and formulation of the main conclusions were carried out jointly with scientific consultants.

Testing the results of the thesis research.

The main research results were reported and discussed at 8 international scientific conferences:

1. The 25-th IAEA Fusion Energy Conference (St. Petersburg, 2014);
2. The IX international Conference “Modern Plasma Diagnostics Methods and Their Application” (Moscow, NRNU MEPhI, 2014)
3. The X international Conference “Modern Plasma Diagnostics Methods and Their Application” (Moscow, NRNU MEPhI, 2016);
4. World Congress of Engineers and Scientists (WSEC-2017, Astana);
5. The VIII International Conference “Semipalatinsk Test Site: Heritage and Prospects for the Development of Scientific and Technical Potential (Kurchatov, Kazakhstan, 2018);
6. The 27-th IAEA Fusion Energy Conference (Ahmedabad, India, 2018);
7. The 46th Zvenigorod Conference on Plasma Physics and CTF (Zvenigorod, Russia, 2019);
8. The 3-rd Quantitative Infrared Thermography Asian Conference (Tokyo, Japan, 2019);

as well as at 4 competition conferences, schools and meetings:

1. The XIII R&D Conference-Competition for Young Scientists and Specialists of the NNC RK (Kurchatov, Kazakhstan, 2014);
2. The XIV Kurchatov Interdisciplinary Youth Scientific School (Moscow, Russia, 2016);
3. The 9-th IAEA Technical Meeting on Steady State Operation of Magnetic Fusion Devices (IAEA Headquarters, Vienna, Austria, 2017).
4. Poster competition among doctoral students of the Shakarim State University (Semey, 2018).

The provisions of the thesis were reported at a meeting of the Plasma Physics Department of NRNU MEPhI, as well as at the STC of NNC RK.

Moreover, main results of the thesis were reported and discussed at scientific seminars of the Technical Physics and Heat Power Engineering Department, at joint scientific seminars of the Faculty of Engineering and Technology of the Shakarim State University and the STC of the Shakarim SU, Semey.

Publications. In total, based on results of the studies described in the thesis, 9 articles have been published in refereed scientific journals, 3 of which – in peer-reviewed scientific journals of the Republic of Kazakhstan recommended by Education and Science Monitoring Committee, 2 – in journals indexed in Scopus and Web of Science, and 1 – in the IAEA technical document.

The structure and scope of the thesis. The thesis consists of the introduction, four chapters, conclusion and the list of references, there are 129 pages in total, 86 figures, 37 tables, a bibliography consisting of 95 titles, and 3 appendices.