KTM Tokamak Project. Present and Future Activity

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Abstract. Specialized experimental complex on the basis of spherical Kazakhstani Tokamak for Material testing (KTM) is created by Kazakhstani and Russian Federation organizations in National Nuclear Center of Kazakhstan. Tokamak KTM is intended for studies in the field of fusion material science and plasma-surface interactions. In 2007 the construction of tokamak KTM was completed and the facility was delivered to Kurchatov. The following activities were carried out: test assemblage of the facility at the manufacturing plant (Efremov Institute), production tests of the KTM facility in accordance with the programs and techniques for testing the vacuum chamber, electro-magnetic system, transport slice device and movable divertor device. 2008-2009 activities were aimed at completion of the tokamak construction, mounting of the KTM systems at the site, off-line tests and preparations for physical start-up. Start-up of the complex is scheduled for 2010. The paper describes main parameters of spherical tokamak KTM, physical start-up program, goals of plasma-physics and material studies, main of which are study of plasma interaction with materials' surfaces, study of physics of tokamaks with aspect ratio A-2 under ohmic and RF-heating, study of physics of divertor area and divertor, study of first wall materials and divertor armor under stationary mode and plasma disruption mode.

1. Introduction

Creation of ITER reactor is first step to practical utilization of controlled fusion energy. Next step – development and creation of demonstration reactor DEMO – will require great scope of studies and tests carried out at both the reactor ITER and the existing and being constructed facilities and test-benches. At the same time ITER will not be able to answer the material science issues and the problems of stability of the materials of first wall and divertor, which are extremely important for designing and operation of future fusion reactors. So the realization of the material studies at the specialized Tokamak KTM is the task of current importance which solution is necessary for development of controlled fusion technologies.

Tokamak KTM is specially created for carrying out the activities in the field of materials science, improvement of new integrated research methods and innovation technologies, development of high-end and nuclear technologies, as well as scientific potential in the Republic of Kazakhstan. Main parameters of the facility and its features are described in [1-5].

2. KTM General Description

Tokamak KTM was designed for systematical material test studies in the field of fusion. Tokamak KTM consists of the following main sections: vacuum chamber, movable divertor device (MDD) and transport-sluice device (TSD), electromagnetic system (toroidal and poloidal field coils and central solenoid), system of plasma additional RF-heating, and experimental data acquisition and processing system. The structure of tokamak KTM is given in *FIG. 1*, and basic parameters are described in Table I.

TABLE I. MAIN PARAMETERS OF KTM TOKAMAK

Major radius R	0.90 m
Minor radius a	0.45 m
Aspect ratio	2
Elongation K_{95}	1.7
Toroidal magnetic field B_T	1T
Plasma current I_p	0.75 MA
RF heating power P_a	5-7 MW
Pulse duration t_p	5 s
Plasma density n	$(3\text{-}5)10^{19}$ m^{-3}
Plasma temperature T_0	(1.5-3) KeV
Safety factor q_{95}	4-6
Triangularity δ	0.3-0.5
Power density on divertor tiles P_g	2-20 MW/m^2 up to 30

Vacuum chamber (VC) has a form of D-shape torus and consists of: all-welded shell with support structure, sleeves and flanged high-vacuum valves, in-chamber components (divertor, stationary limiter, plasma passive stabilization coils), components of VC heating system, detectors of electromagnetic and technological diagnostics system (TSD). All inner surfaces of vacuum chamber, including central column are faced with graphite tiles (graphite, grade F 479, made in Germany).

Movable -divertor device is a system meant for vertical and angle positioning of the divertor tiles, and allows for replacement of the tiles through a sluice without loss of vacuum.

Transport-sluice device is meant for loading in/unloading from vacuum chamber the replaceable MDD tiles without loss of vacuum in the tokamak chamber.

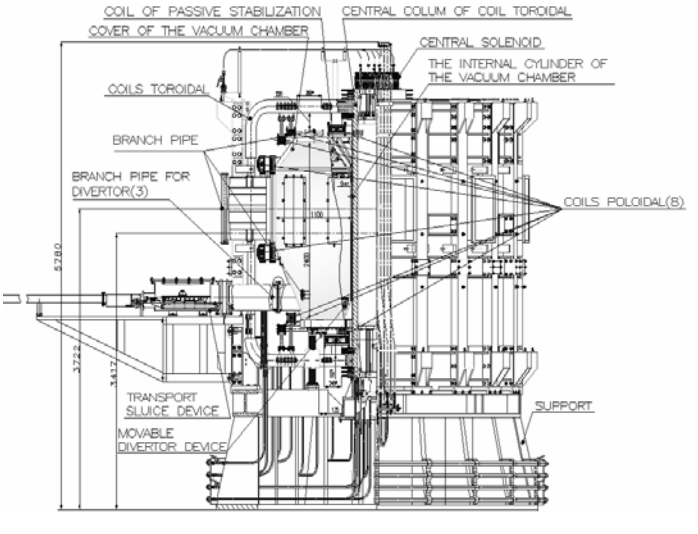

FIG. 1. Tokamak KTM Structure.

Central solenoid-inductor serves for excitation and maintenance of current and stable configuration of plasma column. Central solenoid consists of 430 coils wound by four layers on the central pin. Each layer has independent water cooling. Poloidal Field coils (PFC) located inside of toroidal field coil (TFC) form and confine plasma column configuration.

For plasma additional heating tokamak KTM will be equipped with RF-heating system. This system is based on the principle of auto-generation of oscillations in complex distributed circuit, which includes feeders and antenna, and powerful RF triode as a sole non-linear element. This approach differs from the approach used in foreign countries and based on use of cascade RF power amplifiers excited by independent oscillator and connected to the matched load. Fundamental feature of the proposed RF system is the fact that antenna and, therefore, impedance inserted by plasma are the component parts of complex distributed circuit, where self-excitation occurs at one of own circuit frequencies. It is planned to use four generators of 13 MHz frequency; power inserted into plasma will be 7 MW.

Power system of tokamak KTM is meant to supply electromagnetic system, balance coils, additional heating system, pre-ionization system, systems of vacuum pumping and conditioning, physics and technological diagnostics and engineering support system. The power system shall provide for frequency of tokamak operation to be up to 5 cycles per hour under nominal mode. Total short-term power rate of tokamak power system will reach 150-180 MW.

The experimental complex is being created thanks to the joint efforts of Kazakhstani and Russian organizations. In accordance with work distribution plan National Nuclear Center of the Republic of Kazakhstan (NNC RK) and Institute of Atomic Energy NNC RK are charged with construction and modernization of the KTM site, development and manufacture of vacuum system and some diagnostics systems; Kazakhstani organization “Promenergoproekt” is general designer of the complex and is responsible for systems of outer and pulse power supply. The work distribution among the Russian organizations is as follows: TRINITI – calculations of scenarios and manufacture of physics diagnostics; Efremov Institute – chief designer and manufacturer of KTM facility and RF-antennas of plasma additional heating system; VNIITVCh – development of additional RF-heating of plasma and manufacture of RF-generator; S.E.D. (Saint-Petersburg) – manufacture of lamps for RF-generator; Tomsk Polytechnic Institute – development and manufacture of control system and data acquisition and processing system.

3. KTM Experimental Complex Project Status

The following jobs have been completed or are in progress now:

3.1. Calculations of Physical Start-up and Plasma Column Control Scenario.

Scenario of physical start-up of KTM facility, namely plasma equilibrium evolution and energy balance, was calculated for the stage of plasma current ramp-up and its reaching of the plateau and under powerful additional heating. Plasma behavior during initial stage of discharge was described by code TRANSMAK; calculation of 1.5D evolution of equilibrium and energy balance was described by code DINA. Calculation of plasma burning scenario includes: initiation of breakdown and initial stage of current ramp-up, current input with obtaining the divertor configuration, maintenance of plasma at current plateau [6].

Firstly, static scenario of ohmic discharge for specific time points was calculated taking into account loss of poloidal flux for plasma current ramp-up and its maintenance at the plateau.
According to the scenario of discharge in KTM, the column shifts to the chamber center simultaneously with increase of plasma small radius and rise of discharge current. Such a scenario of discharge initial stage is proposed to be used as basic scenarios of ITER

discharges. The current radial profile is controllably formed by using the layer technique under coherent current ramp-up and increase of small radius of plasma column. This allows to avoid development of large magneto-hydrodynamic (MHD) disturbances of the column while reaching rational values q at the current ramp-up stage. The time of current ramp-up is sufficiently big and we can expect the absence of skinning. Transfer from limiter configuration to divertor one accompanying by decrease of plasma big radius ⟨R⟩ from ~ 116 cm to 90 cm occurs under value of plasma current to be ~ 90% of plateau current, i.e. 700 kA. Fast control of plasma vertical position is provided by the current in the HFC coils. The discharge scenario with additional heating under nominal current of 0.75 MA at plateau was developed. Rate of plasma current ramp-up at the stage of its input is dIp/dt ~ 2.5 MA/s.

Two disruption types were analyzed for tokamak KTM, namely, so-called “big” disruption and vertical disruption of the column or Vertical Displacement Events (VDE).

“Big” disruption in tokamak KTM (*see FIG. 2*) is characterized by rather fast attenuation of plasma current (~ 2,5ms). It is the result of the release of plasma thermal energy, and fast rise of its resistance due to abrupt decrease of temperature (up to ~ 10 eV). At that axis of plasma column shifts in vertical direction on ~ 10 cm upwards and in horizontal direction on ~ 40 cm inwards. Simultaneously current of ~ 450 kA is induced in the chamber. Halo-currents in toroidal and poloidal directions reach ~ 50 kA.

If the column disruption is due to vertical plasma displacement then plasma will rapidly move up and down along the vertical axis in KTM chamber due to a loss of the control over plasma position. Loss of control can be caused by failure in the control system, and kink and balloons modes (so called “small” disruption), MHD disturbances, or significant oblongness of the column.

If the “hot” plasma column bumps into chamber wall, diaphragm, passive stabilization coils, or divertor components then the column will be “cut” with simultaneous decrease of small radius under practically constant total current. The so-called “thermal disruption” and fast attenuation of plasma current will occur if stability factor decreases up to 2. As a rule, rates of column movement depend on resistive times of the chamber and passive stabilization coils.

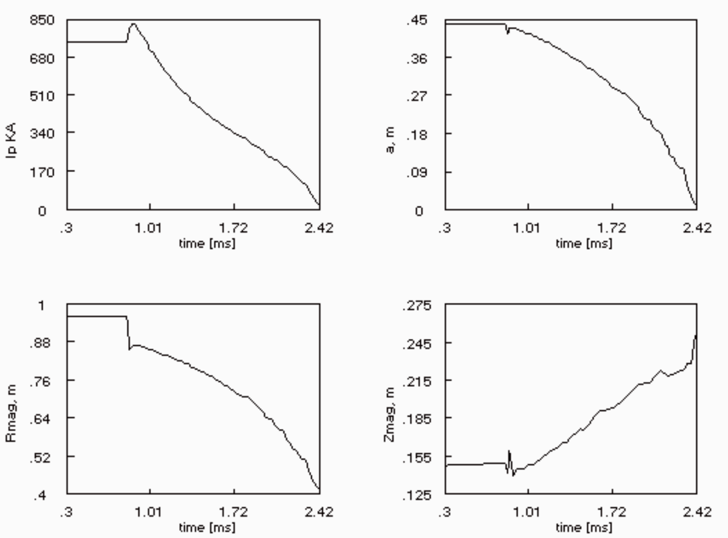

FIG. 2. Time dependencies of plasma parameters during “Big Disruption” (of plasma current Ip (KA), small radium a (cm), coordinates of magnetic axis Rmag and Zmag (m)

But sometimes the plasma column can gather the speeds comparable with “Alfven” ones. In this case VDE can be dangerous for divertor device, chamber walls and passive stabilization coils. Due to significant oblongness of the chamber and absence of special protection of the divertor VDE will represent the most danger if the column moves downwards to the divertor area. Calculation results (*see FIG. 3*) shows that during the period of ~8 ms plasma gathers speed up to 1 km/s at least. In case of collision with the divertor all the energy will be released at the divertor and collision may be a cause of its failure. In order to decrease loads on chamber structure and to protect divertor we propose to use injection of pellets during VDE.

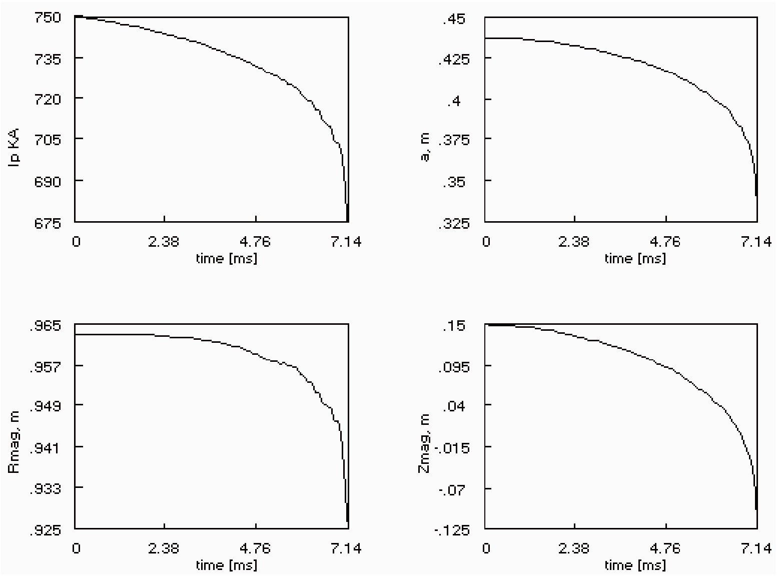

FIG. 3. Time dependencies of plasma parameters during “VDE” (of plasma current Ip (KA), small radium a (cm), coordinates of magnetic axis Rmag and Zmag (m)

3.2. Computer Simulation of Heating of Vacuum Chamber and Divertor of Tokamak KTM

As a result of numerical simulation of the heating mode of KTM vacuum chamber the optimal scenario of the process have been developed, which provides for uniform heating of chamber shell under required temperature irregularity ($\Delta t \leq 10 \div 20$°C), and parameters have been recommended for the source of induction heating system (inductor) of vacuum chamber (while only tokamak’s central solenoid is switched on).

The calculations were carried out for the models taking and not taking into account thermal radiation (*see FIG. 4*). It was showed that taking into account of radiation decreases temperature irregularity on ~ 12° along a perimeter of vacuum chamber.

It was showed that heating of divertor section is characterized by insignificant temperature irregularity at the graphite tiles while heating with standard ohmic heaters and inductor.

The numerical simulation of impulse heating of the chamber during current input into plasma was completed taking into account nonlinear properties of the material and thermal loads, which are time-varying. Temperature distribution at the divertor graphite tiles under impulse heating mode was analyzed. It was established that maximal temperature of graphite tiles during impulse is 1440^{o}C on internal surface and 2404^{o}C on external surface of the divertor.

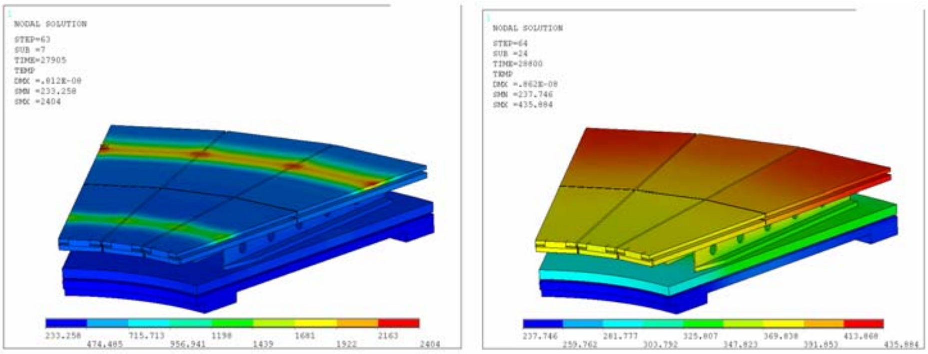

FIG. 4. Temperature state of divertor device in the end of
(a) 32nd impulse (27905th second), (b) 32nd pause (28800th second)

3.3. Activities at the Site of Experimental Complex KTM

At present the reconstruction of buildings and structures at the KTM site was completed (laboratory building, reactor building, complex physical protection system, engineering networks and communications: heating system, ventilation system, water supply system, sewage, and connection and communication system). Activities on creation of external power supply system were carried out as well: reconstruction of substations and mounting of substation at the site of KTM complex, power supply system of own needs, equipment was prepared for start-up activities. Creation of impulse power supply system is in progress. It is planned to begin free-standing tests of separate systems of impulse power supply and to complete manufacture, collection and delivery of equipment of some technological systems and control systems of tokamak KTM. Start-up activities on the external power supply system and preparation of the system for commissioning have been begun.

3.4. Manufacture of vacuum chamber with in-chamber components and electromagnetic system

In 2007, Efremov Institute plant completed the manufacture of KTM facility. Test assemblage of the facility was carried out at the plant and production tests of the KTM facility were conducted in accordance with the developed programs and techniques. The following tests were carried out: Vacuum chamber was tested on leakproofness under room temperature and under heating up to 200^{o}C; electromagnetic system was tested by using special diagnostics system, the integrated tests of transport slice device and movable divertor device were carried out. In December2007 the facility was successfully delivered from Saint-Petersburg to Kurchatov, Kazakhstan.

3.5. Diagnostics systems of tokamak KTM

Main part of physics diagnostics of KTM plasma was developed and manufactured in the institutes of Russian Federation (TRINITI, Kurchatov institute). In order to carry out physical start-up of tokamak KTM it is proposed to use first stage of physics diagnostics, which will be installed at the tokamak, tailored and integrated in information-measurement system of data acquisition system (DAS). These diagnostics include magnetic probes system, monitoring bolometer and multi-channel monitor of radiations (measurement of radiation losses), anti-fault interferometer of chord-average density and dual-frequency impulse reflectometer (measurement of density and density gradient), monitoring spectrometer and monochromator (transition L→H mode, impurity control), and high speed video camera. In 2009 the second stage of diagnostics will be manufactured. There are multi-channel anti-fault interferometer, impulse reflectometer with adjustable frequency (plasma density profile), spectrometer of high resolution (ion temperature control), multi-channel X-ray spectrometer (measurement of electron temperature profile), infrared pyrometer and four-channel detector of infrared diapason, Langmuir probes (scrap-layer diagnostic), etc.

3.6. RF-system KTM

System for additional heating of KTM plasma consists of 4 identical RF-systems; each system is an active oscillator, which resonance circuit consists of RF-generator, feeder, RF-antenna and KTM plasma. Each RF-generator is designed for power rate of 2MW, and total power rate induced into plasma shall be more than 5 MW. At present four RF-generators are being manufactured on the basis of generator lamps of 1200kW power rate each; feeders for power rate transportation and RF-antennas are being manufactured as well. Main components of RF-system will be delivered to Kurchatov, Kazakhstan, in 2009. In 2008 manufacture of the system for anode feeding of generator lamp has been begun. In 2009 one set of anode feeding (for one RF-generator) will be delivered to the KTM complex site and RF-system will be mounted at the site. In 2010 mounting of RF-generators and one channel of anode feeding of RF-generator will be completed. In 2011 the tests of one RF-generator with plasma will be carried out; on the basis of the test results the work on preparation and adjustment of RF-system of tokamak KTM will be continued.

3.7. Data Acquisition System (DAS) KTM

In 2008 the activities on production of blocks and cabinets of control automation system have been continued, as a part of these activities the following cabinets will be manufactured: cabinet for vacuum system control, second unit of data acquisition of electromagnetic diagnostics, data acquisition unit of physics diagnostics; data acquisition software for these units will be developed as well. Earlier the following elements were manufactured: control cabinets for water cooling system and plasmas control system, first unit of electromagnetic diagnostic data acquisition, as well as server. The information-algorithm program of TFC power source control was developed. The following components were developed and manufactured for the digital control system of PF1-PF6 coils power sources: algorithm and information software of the subsystem for collection, control and registration of power source parameters, cabinets for digital control of impulse power supply sources of tokamak KTM. In 2009 we planned to complete manufacture of synchronization cabinets and units of physics diagnostic data acquisition, software of DAS components and systems; and the adjustment of data acquisition system of tokamak KTM will be continued.

In 2008 we planned to complete mounting of tokamak KTM at the site, as well as to continue manufacture and kitting-up of plasma RF-heating system equipment, physics diagnostics of KTM facility, vacuum exhaust and cooling systems, gas intake and plasma quenching systems, and data acquisition system.

In 2009 system of RF-heating will be manufactured, delivered and mounted at the site; the following work will be completed: manufacture, kitting-up and delivery of the equipment, as well as mounting of tokamak KTM systems and their tests; the start-up activities will be carried out for all the systems.

Preparations and commissioning of all the system, preparation and physical start-up of tokamak facility is scheduled on 2010.

4. Scientific-Research Program and Prospects of International Cooperation

The main stages of scientific-research program are:

- Physics studies of tokomak plasma, including ohmic mode and modes with plasma additional RF-heating.
- Material studies and tests of first wall armor materials and receiving divertor tiles.
- Studies of possibilities to control processes at first wall, in boundary plasma, in divertor, equilibrium plasma, as well as to control fluxes in divertor area.
- Creation of physics and technological diagnostics of plasma column, processes in divertor area and boundary plasma.
- Creation and work-out of mockups of divertor components by using lithium capillary-porous system-technologies.

Activities on organization of international cooperation concerning joint development and realization of the scientific-research program, including physical start-up and operation of KTM complex have been begun. Memorandums on Cooperation were signed with JAEA (Japan) and CIEMAT (Spain). Memorandum on Cooperation with scientific center Culham, United Kingdom, is being prepared to be signed.

5. Conclusion

Commissioning of tokamak KTM before operation of ITER reactor allows for organization of wide international cooperation in the field of fusion material testing, including creation of new materials and development of innovative technological and design solutions.

6. References

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