Progress of Preparation for ITER Divertor Thermocouple in JADA[*)]

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The Japan Domestic Agency (JADA) is scheduled to procure the Outer Divertor Thermocouple (ODTC) system for the divertor outer vertical targets in the ITER project. The ODTC system is a diagnostic system that will directly measure the surface temperature of the divertor, a plasma-facing component, and will be installed on the surface of the divertors which are in the scope of JADA procurement sharing. A thermocouple itself is a conventional component used for measuring temperature; however, the ODTC system must take highly reliable measurements under the ultrahigh vacuum and high magnetic and radiation fields of the ITER environment. Therefore various advanced research and development is necessary. The ODTC Instrumentation and Control (I&C) system, which is based on ITER standards, should also be developed since it is included within the scope of JADA procurement. In this manuscript, we show the current status of research & development on the ODTC system, the TC component, and the I&C system.

Keywords: ITER, JADA, ODTC, Divertor, thermocouple, surface temperature, I&C system, data transmission, data processing

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1. Introduction

ITER is a tokamak thermonuclear experimental reactor and therefore requires super sensitive experimental measurements in extreme temperature conditions, ultrahigh vacuum, and high magnetic and radiation fields. The divertor is a plasma facing component that will have the highest heat flux in the reactor. Observing the divertor surface temperature is very important to avoid erosion and prevent damage to the machine and will be primarily measured by IR cameras using IR thermography. In addition, thermocouples (TC) will also be mounted onto the sides of the divertor targets for supplementary temperature measurement [1]. In the framework of the ITER project, the Japan Domestic Agency (JADA) has been assigned to procure the Divertor Outer Vertical Targets (OVT) [2], IR thermography and Outer Divertor Thermocouples (ODTC). The Inner Divertor Thermocouples (IDTC) will be procured by the European Domestic Agency (EUDA). In the scope of ODTC procurement, the system consists of TC components, cablings, and signal processing. The procurement arrangement (PA) for the ODTC system was decided to be functional specific, where the responsibility of the conceptual design belongs to the ITER organization (IO) and the preliminary and final designs belong to JADA. The conceptual design review (CDR) was performed in September 2011, and consequently category 1 chits that should be resolved before proceeding to the preliminary design were generated. Therefore some on-going technical issues have yet to be solved, such as validation of the TC attachment scheme, the effects of irradiation on the materials, distribution of TCs, which are to be followed with the subsequent revision of the system requirements. The CDR was prepared on the assumption that the plasma facing divertor OVT would have a carbon fiber reinforced carbon (CFC) monoblock segment in the lower part and a curved tungsten (W) monoblock segment in the upper part [3]. The details of the selection of divertor materials were reviewed in [4]. Nevertheless, a full tungsten divertor is most likely to be adopted in the project.

In the current ODTC system procurement schedule, the technical specifications are being prepared for the PA which is planned to be signed at the end of 2014 between JADA and the IO. JADA will conduct the preliminary design review (PDR) and final design review to determine the precise specifications after the PA is signed and manufacturing is scheduled to start in 2018. The ODTC components and in-vessel cabling will be shipped to the EUDA site for installation to the divertor cassettes in 2021. The ODTC Instrumentation and Control (I&C) system is scheduled to be shipped to the ITER construction site in France for installation in the diagnostic building during assembly phase 2 in 2022.

In this paper, an overview of the ODTC system and the preparation for scientific and engineering prospects for the TC components and the ODTC I&C system are described.

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2. ODTC System

The ITER Project requirements for the divertor diagnostic systems (IR camera, IR thermography, and inner and outer TCs) are to measure the maximum surface temperature of the divertor for machine protection and also to measure the power load for advanced control. The divertor surface temperature should be measured in the range of 200 °C to 3600 °C, with a time resolution of 0.02 ms by the diagnostic systems. A TC is a very simple and accurate temperature measurement device. However, the response time at 0.5 cm depth from the plasma facing surface on the monoblock is over 0.1 s which is much slower than the requirements. Therefore their role in measurement in ODTC system is defined as supplementary, and they will be mostly used for calibration of IR cameras and IR thermography. The TC positions should overlap with the IR coverage. During operation, it is expected that there will be very little variation in the divertor toroidal temperature, thus 3 divertor cassettes (#04, #28, #46) are to be equipped with 54 TCs, 27 fitted to the inner target and 27 fitted to the outer target. The total number of ODTC components is 81. TCs shall be mounted to the side of the target onto which the plasma impinges.

An investigation of inherent functions is very important for developing the ITER system design to reduce potential technical risks' impact on machine operation. The functional breakdown of the ODTC (and also IDTC) system is summarized in Table 1. The top function A-0 is derived from the ITER Project requirements. The 3 main functions, A1, A2, and A3 relate to TC components, cablings, and signal processing, respectively. A functional breakdown is used for the ITER RAMI (Reliability, Availability, Maintainability, and Inspectability) analysis to perform a technical risk assessment [5, 6]. The second and lower level functions will be revised and defined as the design progresses.

An investigation of the system overview is indispensable to ensure that the system design makes its way into equipment. A system overview of the ODTC system is shown in Fig. 1. The supplies of square boxes are in the scope of the ODTC manufacturing, and those of round boxes are specified only by the ODTC designer. TCs and mineral insulated (MI) cables form part of a cable harness assembly that terminates at a connector on the divertor cassette. The cassette's electrical connections interface with the lower port cable assembly. The vacuum boundary belongs to the divertor cassette and is out of the ODTC scope. Compensation lead wires connect from the feed-through connector to a signal conditioner. That is to say the cabling goes through the lower port from the tokamak building to the diagnostic building. The total path of the ODTC cabling has a measured analog voltage gradient reach over 100 m because of the requirement for the ODTC system design to avoid any electronics in the port cell. Therefore, the total impedance of the TC cable must be small compared to the input impedance of the TC signal processing unit so as not to draw significant current through the cable. In the diagnostic building, it connects to a local controller and transfers data to the CODAC (Control, Data Access and Communication) system, ITER's central I&C system.

Table 1 Functional breakdown of the ODTC systems.

A-0 To provide a supplementary facility for the measurement of divertor temperature, temperature profiles and power profiles		
	A1 To convert temperatures at contact points into potential difference	
		A11 To make strong thermal contact with CFC or W monoblock
		A12 To produce potential difference by TCs
	A2 To transfer potential difference from contact points to the data acquisition system	
		A21 To transfer potential difference in-VV
		A22 To transfer potential difference through vacuum feedthroughs
		A23 To transfer potential difference ex-VV
		A24 To fix cables onto supports
	A3 To execute data processing	
		A31 To execute signal conditioning
		A32 To access data
		A33 To configure data processing
		A34 To transfer data

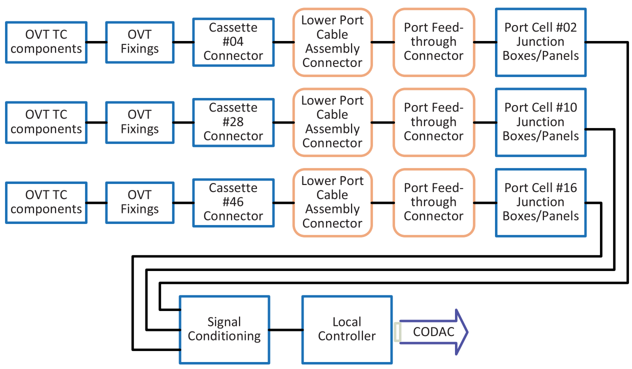

Fig. 1 System Overview of the ODTC system. There are 3 sets of TC components and cablings for 3 divertor targets, and one I&C system.

The divertor targets are planned to be replaced 3 times in their 20 year lifetime. The first target with CFC and tungsten monoblocks will be done before Deuterium - Deuterium operation. The TCs on the targets are disposable and will also be replaced along with the targets. The current specifications of the ODTC system are for the first lot since details of the replacements will be discussed during the operation phase.

3. TC Components

The TC components are installed in-vessel and will be subjected to an ultrahigh vacuum, high temperatures and radiation and therefore should have high durability. There are a variety of TCs which can convert a temperature gradient into electricity. The IO recommends type N (Nicrosil–Nisil) since they cover a temperature measurement range of −200 °C to 1200 °C. However, there is a possible issue that Cr vapor may lead to a measurement error when in vacuum and at high temperatures. A typical TC is assumed to have a pair of twisted 0.23 mm outer diameter metal wires inside a stainless steel sheath and covered with 1.5 mm outer diameter MI cable. The temperature measure point is at a so called reduced tip junction, in which the two wires are contacted for low mass and tough mechanical strength. The details will be optimized by making a prototype mounted to the monoblock during the design phases.

During normal plasma operation, a steady state design heat flux of (5 to 10) MW/m^2 is assumed for the divertor OVT. Furthermore, the capability to remove up to 20 MW/m^2 during transient events of 10 s must also be provided [2–4]. The temperature of the plasma facing surface of the OVT may exceed 2000 °C. Therefore the TCs should be placed where the temperature will not exceed the melting point (~ 1375 °C) of the stainless steel sheath. The TCs are mounted to a thin metal coating layer with a thickness of about 0.5 mm to the side of the monoblock. The details are not decided yet, and it will be developed during the design review phase. The standard method of embedding TCs into drilled holes was rejected because the holes would cause component failure via high heat flux. Direct spot welding TC tips to the monoblock was not adopted because of the difficulty of welding small metal tips with high temperature materials.

A cross-section and side view of ODTC components mounted on divertor monoblocks are shown in Fig. 2. A typical monoblock size is 3 cm in width, 3 to 4 cm in height and 1 to 2 cm in depth. There is a water channel in the middle of the monoblock and a metal support block at the bottom [7]. To take reliable temperature measurements, all of the TCs do not have to work simultaneously. Having a short distance from the surface to the TC contact point is an advantage to gain a short time response, but poses the risk of the TC being damaged by erosion. Therefore the TCs should be placed at varying levels with some placed closer to the plasma facing surface for more accurate temperature measurements, and some placed farther away to withstand erosion. Figure 2 shows an alternating upper, middle, and lower configuration proposed by the IO. The distances from the plasma facing top will lose their original arrangement due to erosion of the surface during operation. An ODTC self-adjustment scheme is recommended to be developed during the design phases.

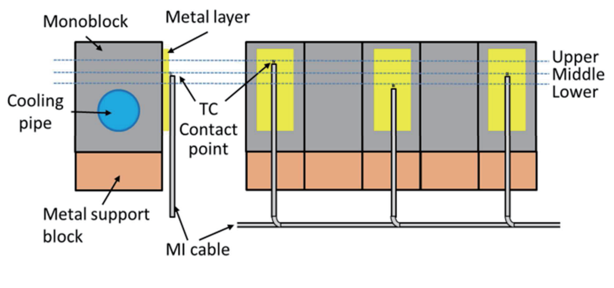

Fig. 2 Cross-section and side view of ODTC components mounted on divertor monoblocks. They are heated on the plasma facing top, and cooled by water through the cooling pipe.

The spatial distribution of ODTC components should be closer than those of the IR camera and the IR thermography for calibration. There are no specific measurement requirements for toroidal coverage, but it cannot be smaller than the monoblock depth (1 to 2 cm), which is reasonable for the IR view to adequately make an absolute 2 cm and relative 3 mm IR calibration. The distribution will also be developed during the design phases.

4. I&C System

All I&C systems of ITER have to be designed based on the ITER Plant Control Design Handbook (PCDH) which is a common guideline of the ITER project to ensure efficient data exchange between the central I&C system and plant systems. We designed a generic I&C system platform for the diagnostic systems in accordance with the PCDH [8]. The scope of the generic I&C system platform and sub-systems adapted for the ODTC system is shown in Fig. 3.

The supervisory sub-system for ODTC includes the functions specific to TC measurement such as TC health

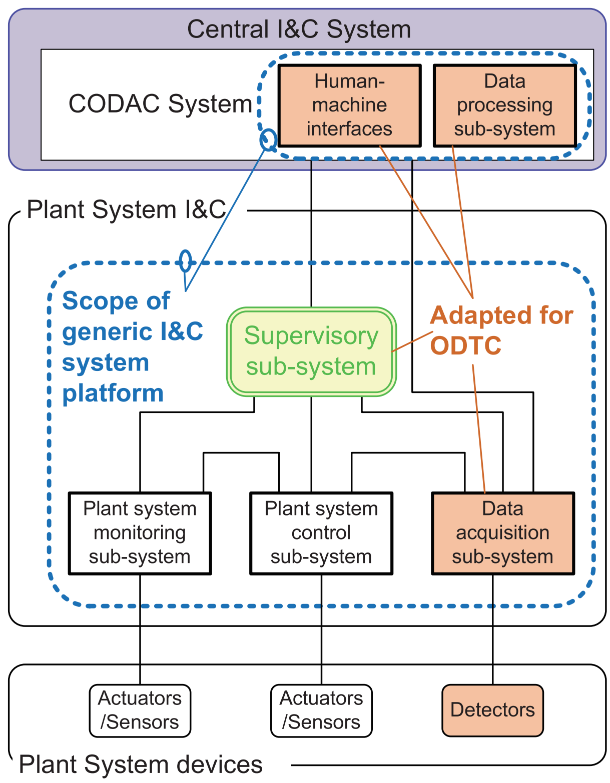

Fig. 3 Overview of the designed generic I&C system platform and sub-systems adapted for ODTC system.

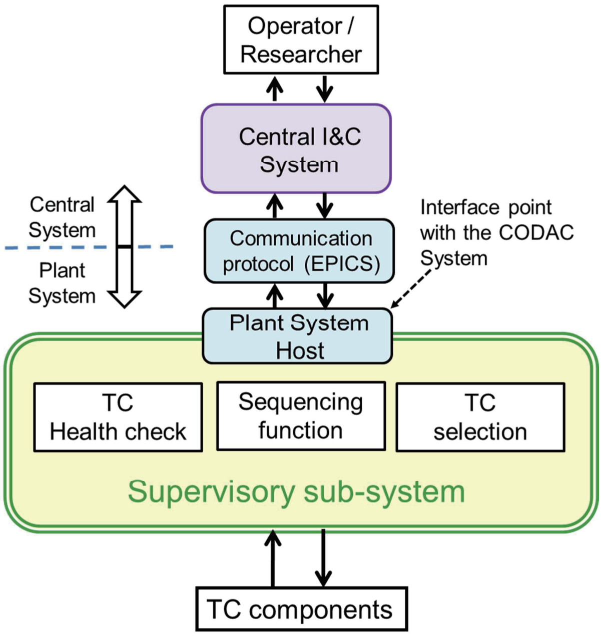

Fig. 4 Schematic view of the supervisory sub-system for the ODTC system.

check and selection of TCs for measurement. These two functions are integrated into a plasma pulse sequence or a calibration procedure by the sequencing function of the supervisory sub-system. Figure 4 summarizes the functions of the supervisory sub-system for the ODTC system. At the beginning of a pulse or calibration, the supervisory sub-system requests the TC health check function to check and report the TCs' faults such as wire break or short circuit. An operator can select the TCs to be used for measurement as pulse schedule parameters since some TCs may have failed due to erosion, physical stresses, or aging from the harsh high radiation and magnetic field environment. The pulse schedule is submitted to the ODTC I&C system and is checked against the results of the TC health check.

The divertor surface temperature is derived from temperatures measured by the ODTC system and the temperature of the divertor cooling water measured by the cooling water system. Since the calculation of the divertor surface temperature needs data from two different plant systems, we proposed that the data processing sub-system of the ODTC should be placed in the same level of the CODAC System. The calculation algorithm for the divertor surface temperature will be determined by the PDR of the ODTC system.

For the data acquisition and processing sub-systems, to verify our design of the ODTC I&C system, we developed a data processing system according to ITER standards and also evaluated whether the data processing model proposed by ITER satisfies the requirements of the ODTC system.

5. Summary

In the ITER project, JADA will procure the ODTC system that will satisfy all ITER requirements. The specifications have been summarized to prepare for the signature of the PA. The ODTC system functional breakdown and system overview were investigated. It was proven that the main functions correspond to TC components, signal transmission, and signal processing. The specifications of the TC components were proposed by the IO although there are still some technical issues to be solved before manufacturing. The design for the ODTC I&C system was prepared as a generic I&C system platform for diagnostic systems and sub-systems adapted for the ODTC system. There are also still many factors that need to be defined such as the divertor materials, cabling, interfaces, assembly and I&C systems. The procurement for a suitable ODTC system under these complex conditions while keeping within schedule is challenging.

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