Status of Design and R&D for the Korean ITER Diagnostic Systems

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Abstract. The ITER Korea (Korean domestic agency) will procure one diagnostic upper port plug, a neutron activation system (NAS), and three vacuum ultraviolet (VUV) spectrometer systems for main, edge, and divertor. Implementation activities in Korea including R&D on ITER diagnostics started shortly after procurement assignment in 2005. At present, the ITER Korea is conducting detailed design and engineering work to finalize the system specifications and to resolve technical issues, and also participating in joint activities for development of the documents for the procurement arrangement (PA). In this paper, the status of design activities and results of R&D for the Korean ITER diagnostic systems will be described including measurement requirements, design specifications, and outstanding R&D issues.

1. Introduction

Development and implementation of the ITER diagnostic systems have major challenges because of the harsher environment and stringent requirements for the plasma and first wall measurements compared to the present devices. [1] About 40 diagnostic systems will be implemented to provide accurate and reliable measurement for a wide range of plasma parameters (45 in total). [2] All ITER members are contributing various diagnostic systems and the ITER Korea (Korean domestic agency, KODA) will procure one diagnostic upper port plug, a neutron activation system (NAS), and three main, edge, and divertor vacuum ultraviolet (VUV) spectrometer systems. Implementation activities including R&D on ITER diagnostics in Korea started shortly after the procurement assignment. Currently, the ITER Korea is conducting detailed design and engineering work to resolve the outstanding technical issues and to finalize the specifications for development of the procurement arrangement (PA) documents. In this paper, the status of design activities and results of R&D for the Korean ITER diagnostic systems will be described including measurement requirements, design specifications, and outstanding R&D issues.

2. Vacuum Ultra-Violet Spectrometers (Main, Edge, and Divertor)

Spectroscopy has been an essential technique for measuring many critical plasma characteristics in fusion devices. In particular, vacuum ultra-violet (VUV) and extreme ultra-violet (XUV) spectroscopy has been a key diagnostic for the identification and monitoring of impurities in fusion plasmas, since the VUV/XUV spectral region (2 - 200 nm) contains most of the important emission lines of the light (Li, Be, C) and heavy metallic (Fe, Ni, Cu, W) impurities. [3] The plasma facing materials in ITER are beryllium-coated copper in the first wall, and carbon and tungsten in the divertor. Constant monitoring of these elements is essential not only for physics reason but also for the first wall protection. For example, the presence of the Cu spectral lines implies a possible damage of the first wall. So, the main mission of the VUV spectroscopy is to monitor the impurity behaviors through the core, edge and divertor plasmas, measuring a full coverage of spectrum emitting from most of impurity species of Be, C, Cu, W, etc. in ITER. Measurement of the absolute quantity of the species as well as their rate of increase is required. The measurement requirements related to the VUV system in the ITER diagnostic system requirement document (SRD) are shown in Table I, including the required time resolution and measurement accuracy to support the physics analysis and operation.

TABLE I: VUV MEASUEMENT REQUIREMENTS FROM ITER DIAGNOSTIC SRD.

Measurement	Parameter	Condition	Range Value	Resolution		Accuracy
				Time	Spatial	
Impurity Species Monitoring	Extrinsic (Ne, Ar, Kr) rel. conc.		$1x10^{-4}$ - $2 x10^{-2}$	10 ms	Integral	-
	Be, C, O rel. conc.		$1 x10^{-4}$ - $5 x10^{-2}$			
	Cu rel. conc.		$1 x10^{-5}$ - $5 x10^{-3}$			
	W rel. conc.		$1 x10^{-6}$ - $5 x10^{-4}$			
Impurity Density Profile	Fractional content, $Z\leq10$	r/a > 0.85	0.5 - 20 %	100 ms	50 mm	20 %
	Fractional content, $Z>10$	r/a > 0.85	0.01 - 0.3 %			

2.1. Design of the VUV Spectrometer Systems

For the goal of the impurity monitoring in ITER, three kinds of VUV spectrometer will be installed in the core, edge, and divertor. These are planned to be located at the upper port 18 and equatorial port 11 as shown in FIG. 1 and Table II.

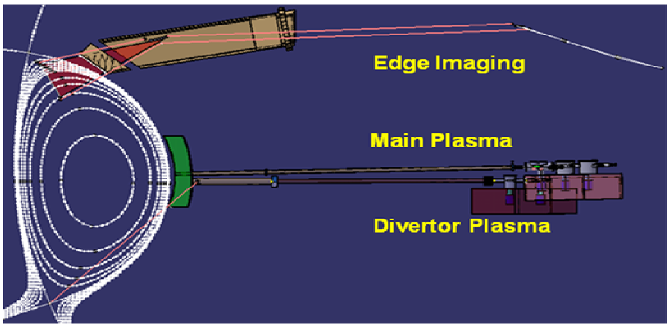

FIG. 1. Three ITER VUV spectrometer systems.

TABLE II: THREE ITER VUV SPECTROMETER SYSTEMS.

Subsystem	Main VUV Survey	Edge VUV Imaging	Divertor VUV
Function	Impurity species identification	Edge impurity profile	Divertor impurity influxes, particularly Tungsten
Wavelength (nm)	2.4 - 160.0	17.0 - 30.0	15.0 - 40.0
Resolving power ($\lambda/\Delta\lambda$)	~300	~400	~350
Gratings	5	1	2
Implementation	Slot in Eq11 port-plug Collimating mirror in port-cell	Slot in Up18 port-plug Field mirror in PP Col. mirror in port-cell	Slot in Eq11 port-plug Field mirror in PP Col. mirror in port-cell

a) Main VUV Survey Spectrometer

The main VUV survey spectrometer located at the equatorial port #11 will measure the line-integrated impurity emission lines through the core plasma, providing full coverage of most of the impurity lines with an appropriate spectral resolution. To achieve this, the design is based on a spectrometer with five spectral channels that cover the VUV spectrum ranging from 2.4 to 160 nm. This design will provide a high resolution along broad spectral bands, simultaneously. Each spectrometer channel is designed to use a holographic diffraction grating and an electronic detector in a flat-field geometry. Recently, the optical design of the system has been updated, as illustrated in Table III. [4]

TABLE III: OPTICAL DESIGN FOR FIVE CHANNELS OF VUV SURVEY SYSTEM.

Spectral Channel	1	2	3	4	5
Wavelength Range (nm)	2.4-7.8	7.0-16.2	14.4-31.8	29.0-60.0	55.0-160
Line Width (nm)	0.022	~0.039	~0.061	0.096	0.285
Spectral Resolution ($\lambda/\Delta\lambda$)	~232	~296	~382	~465	~377
Incidence Angle (degree)	86.5	83	70	62	45
Distance: Slit to Grating (mm)	650	500	543.5	400	300
Distance: Grating to Det. (mm)	~650	~500	~543.5	~400	~300

b) Edge VUV Imaging Spectrometer

The edge VUV imaging spectrometer in the upper port #18 is configured as a grazing incidence system using a field mirror in port plug, a collimating mirror in port cell, and a flat-field 2-D spectrograph. This system is optimized the measurement of the spatial distribution of impurities in the edge region of the plasma. For physics application, a high-resolution measurement of the selected representative impurity ions is additionally considered. Recently, the choice of wavelength range for the edge VUV spectrometer is selected for a high (spectral and spatial) resolution image to obtain radial profiles of impurities in the wavelength range from 17 to 30 nm, which will cover the important spectral lines from the light species (He, Be, C, O) to the heavier species such as Ar, Cr, Fe, Ni, and Cu impurities. A spectral resolving power is expected more than 400, while maintaining a high throughput in order to meet the ITER measurement requirements with respect to the time resolution and accuracy. In order to confirm the feasibility of the optics, a backward ray-tracing from the slit to the edge plasma region has been performed using the optical program (ZEMAX), as shown in FIG. 2. Five ray bundles are launched from the five positions in the slit of 10 mm length and their images at the edge plasma are calculated in the ray-tracing. A parabolic cylindrical mirror in the port plug is used as a field mirror and an ellipsoidal mirror in the port cell is used for collimation of the light. The spatial resolution is calculated to be about 3.5 cm, which is better than the measurement requirement (5 cm resolution) in the Table I.

FIG. 2. Backward ray-tracing from the slit of the spectrometer to the plasma edge region.

c) Divertor VUV Spectrometer

A basic system enabling full system implementation of the divertor VUV spectrometer will be installed in the equatorial port #11. This system is intended to measure the plasma impurities, especially tungsten, in the divertor region. Tungsten emission calculations along the simulated lines of sight indicated that the wavelength range of 15 to 40 nm is promising for monitoring of tungsten under ITER divertor plasma conditions. As a result, a design with a spectral range of 15 to 40 nm with the resolving power of ~350 is planned. The overall optical design is shown in FIG. 3, in which the front mirror is located at the front-end in the port plug to achieve a good throughput and grazing angle of ~20 degree.

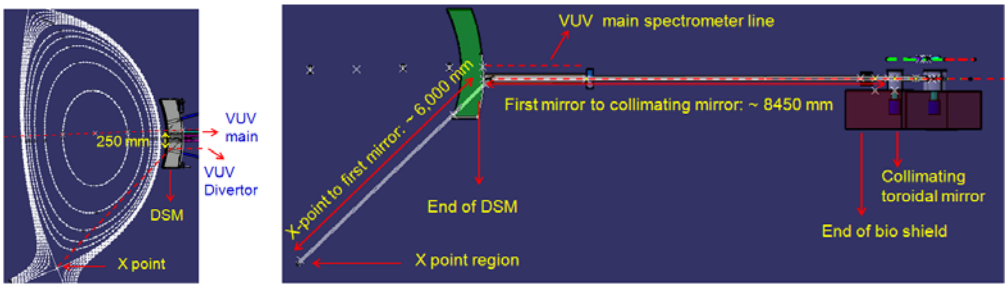

FIG. 3. Design of divertor VUV spectrometer system.

2.2. Design Issues and Proto-type System R&D

There are many practical issues for implementation of the ITER VUV system, such as calibration, alignment, degradation of the first mirror, etc. The calibration of VUV spectrometers is important and always challenging. The number of sources in this spectral region that can be used as either a transfer or absolute standard is quite limited. The wavelength is calibrated utilizing multiplet lines with referenced species from the plasma as a transfer standard. For sensitivity calibration, branching ratios from the plasma line referenced back to absolutely calibrated lines and overlapping lines of different spectral channels will be employed. The first mirror reflectivity change due to surface deposition is also a big issue, because it collects the VUV photons at the front and is exposed to the plasma through the slot in the diagnostic shield module. Consequently, the mirror surface will be deposited with the impurity species such as Be, C, and W. The reflectivity of the field mirror which is vulnerable to surface contamination will be calibrated by comparison with a reference line over time or with visible branching lines. An optical alignment technique that is simple and solid is also required. Additional R&D effort to address the resolution issue of the design is required during the preliminary and final design stage before system fabrication.

To verify the optical parameters, a prototype VUV system has been prepared to test the design performance in the laboratory. The system, composed of a toroidal mirror to collect the light from a hollow cathode source to slit, and two holographic diffraction gratings which are positioned at different optical distances and heights according to design parameters in a single vacuum chamber, is shown in FIG. 4. By using this system, two-candidate electronic detectors; a back-illuminated charge-coupled device (BI-CCD) and a micro-channel plate electron multiplier (MCP) have been studied. The test results showed that the BI-CCD has performed better than the MCP for ITER VUV system. [5]

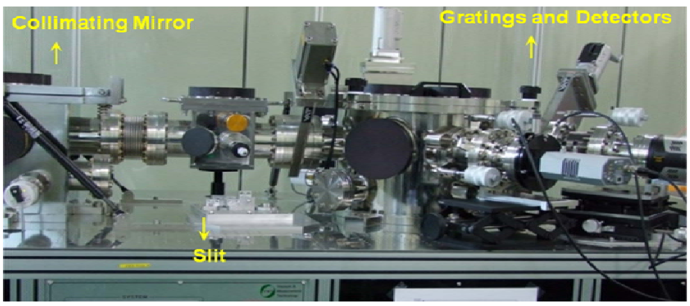

FIG. 4. ITER VUV prototype spectrometer with two gratings and detectors.

3. Neutron Activation System

In order to control the fusion reaction in ITER, the total neutron production should be measured with a high accuracy and reliability. Because of the harsh nuclear environment of ITER, a machine protection is high priority so that an accurate evaluation of the neutron fluence is an essential requirement in ITER, as listed in Table IV. The ITER neutron activation system (NAS) measures the total fusion power and neutron fluence to the first wall by using encapsulated metal specimens that are transferred pneumatically between the irradiation ends and a counting station. [6] The counting system measures gamma rays from metal specimens which are activated by the neutron flux. Some limitations in choosing irradiation locations and sample materials make the design challenging due to the extremely high neutron flux and fluence. After results of a few years of R&D, the irradiation ends are optimized to be installed in in-vessel and ports, which range about 50 - 130 meters to the counter station.

TABLE IV: NAS MEASUEMENT REQUIREMENTS FROM ITER DIAGNOSTIC SRD.

Measurement	Parameter	Condition	Range or Coverage	Resolution		Accuracy
				Time	Spatial	
Neutron flux and emissivity	Total neutron flux		1×10^{14} - 5×10^{20} n/s	10 s	Several poloidal points	10 %
In-situ calibration: neutron flux and emissivity	Total neutron flux	Before H, DD and DT phases	TBD	TBD	Several poloidal points	TBD
Neutron fluence	Neutron fluence on the first wall		0.1-1 MWy/m^2	Integral	Several poloidal points	10 %

3.1. Design of NAS

The ITER neutron activation system measures gamma radiation from specimens activated by the fusion neutron flux. Encapsulated specimens are transferred between the irradiation ends and counting station by the driving He gas. The air lock device separates the primary loops containing the irradiation ends from the secondary loop of the capsule loader. The tubes of inner diameter of 10 mm will be used for the transfer lines of the capsule. The design of the transfer lines of NAS is shown in FIG. 5.

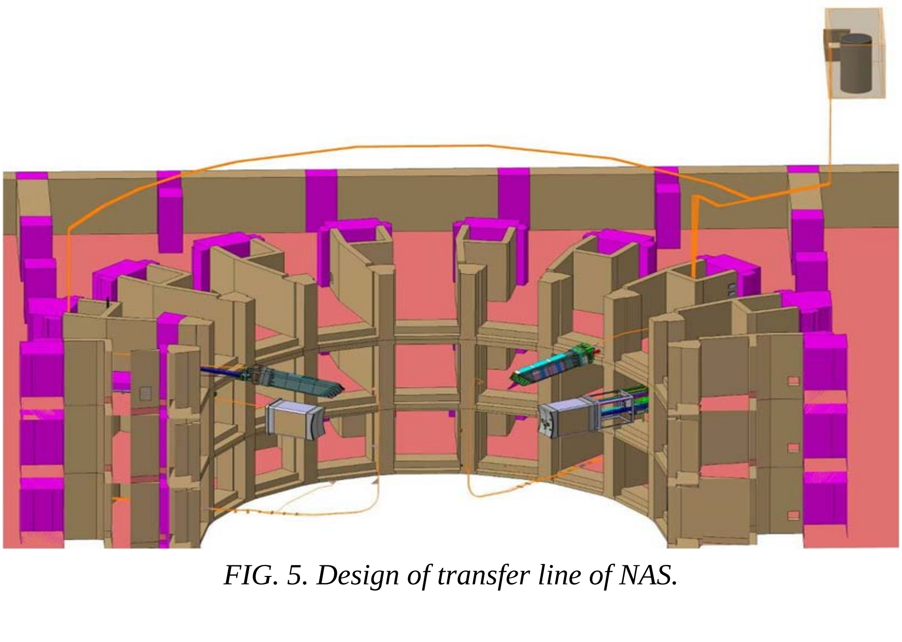

FIG. 5. Design of transfer line of NAS.

Due to the large size and elongated shape of the ITER plasma, multiple positions for the irradiation ends in each toroidal section are required for highly reliable measurements. At present, 7 irradiation end locations per toroidal section and 14 total locations are planned for ITER NAS taking into account the reliability of the measurement and redundancy of the system. FIG. 6 shows the current distribution of the irradiation ends in a toroidal section. It is required for the irradiation ends to be located as close as possible to the plasma for high accuracy of the measurement. Because of the high thermal and EM loads, and the high risk of damage during the blanket installation when the irradiation ends are very close to the first wall, the possibility of putting the irradiation ends around the vacuum vessel inner wall behind the blanket modules is investigated [7]. The result shows the scattered neutron effect on those locations is not serious because of the blanket acting as a neutron collimator.

The transfer station distributes capsules to the appropriate locations such as the irradiation end, counting station, or disposal bin. It consists of a capsule loader and a distribution 'carousel'. When the capsule is loaded on the carousel from the loader, the platter inside the carousel rotates to place the capsule to the point connected to the designated place. The capsule loader and carousel are separated by the air lock system to prevent the leakage of the driving gas. At every transfer line ends the air cushion technique will be implemented to prevent capsule breakage. A counting station will be located outside the bioshield of ITER where neutron flux effect on the detectors is negligible. Detectors such as HPGe will be used to count gamma rays from the activated specimens. Total neutron source strength will be evaluated from the gamma spectrum considering the location of the irradiation end, specimen material, its mass, irradiation and cooling time.

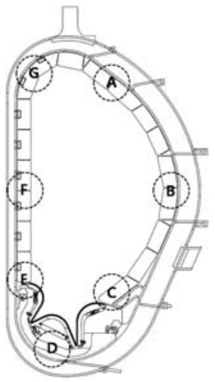

FIG. 6. Irradiation ends in a toroidal section.

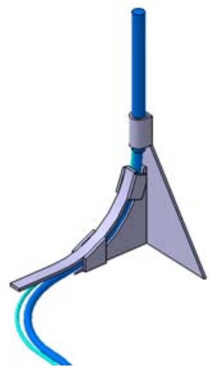

FIG. 7. Design of irradiation end and its support.

3.2. Design Issues and Proto-type System R&D

Because of the long pulse length of ITER, the NAS is expected to measure two different parameters: neutron flux with a rough temporal resolution about 10 seconds and neutron fluence for an entire ITER operation time. Neutron flux measurement by the NAS is achieved by the specimen irradiation relatively in short period of time compared to the ITER discharge length, and plays a supplementary role of the data from other neutron flux monitors. On the other hand, measurement for the long irradiation period covering the entire discharge of ITER is required for the neutron fluence. This is the primary role of the NAS. Because of the irradiation time difference between two measurements, careful selection of the specimen material is necessary for the activation of the specimen to be in appropriate range. Radioactivity calculation for various candidate specimens (Al, Si, Ti, Cu, Nb, etc.) has been performed for this purpose [8]. It was found that some materials such as Si are difficult to use as specimens for measuring neutron fluence because of the activation saturation problem.

High thermal load on the irradiation end limits the selection of the capsule material such as polyethylene. Temperature of the irradiation end around the midplane of the tokamak is estimated to be about 600°C. Appropriate selection of the capsule material which endures the high temperature of the irradiation ends and does not hinder the accurate measurement of the activation of the specimen is required. Very thick blanket shield modules are implemented in ITER to shield high neutron flux from the plasma. As the in-vessel transfer lines are routed on the inner wall of the vacuum vessel, some of the irradiation ends are designed to be stuck out from the wall in the direction of the plasma. If the image currents are induced along the transfer tube during plasma disruption, very high EM load can bend these irradiation ends. To prevent the bending, supports for the irradiation ends are designed as shown in FIG. 7. These supports also can help to cool down the irradiation end by direct contact with the vacuum vessel.

Accurate transfer of the specimens to the designated place is a key performance requirement for the successful operation of NAS. In 2009, a prototype specimen transfer system was designed and developed to optimize the design of the ITER NAS to verify the feasibility of the NAS transfer system. As shown in FIG. 8, the prototype system is composed of 10 irradiation ends, 4 counter ends, carousel, and disposal bin, in which the specimens are transferred pneumatically between the sub-components. An air cushion scheme is applied to prevent possible sample breakage from abruptly stopping the capsules at the irradiation ends.

FIG. 8. Prototype system of NAS.

4. Upper Port Plug

The KODA will procure the port plug #18 which employs two irradiation ends of NAS and one field mirror of VUV spectrometer. As all diagnostic upper port plugs have common structural features, the generic plug structure has been developed in collaboration with IO and other DAs. Since 2006, the KODA has participated in engineering work for the design completion, especially contributing to the cooling channel design [9] and thermo-hydraulic analysis. [10] After the preliminary design review in June 2010, the KODA has a plan to study a real-size mock-up of ~4 m long trapezoidal section of the generic upper port plug. It is anticipated that several key manufacturing techniques would be verified through this mock-up fabrication: electron beam welding of the trapezoidal section within 5 mm tolerance, 4 m long gun-drilling of 25 mm diameter water channel, and TIG welding of the plug to cover the drilled water channels.

The diagnostic shield module should be customized to accommodate the diagnostic components as well as to shield the neutrons generated. The KODA has started to design the integration of components contained in the port plug structure, as shown in FIG. 9. The first mirror of the VUV image spectrometer is installed with a supporting frame, which will allow easy maintenance without removing the whole port plug. The design of the supporting frame is evolving to achieve a robust support and easy installation compatible with remote handling.

For the neutron activation system, two tubes are also integrated to pneumatically transfer the capsule to the irradiation ends located just behind the diagnostic first wall.

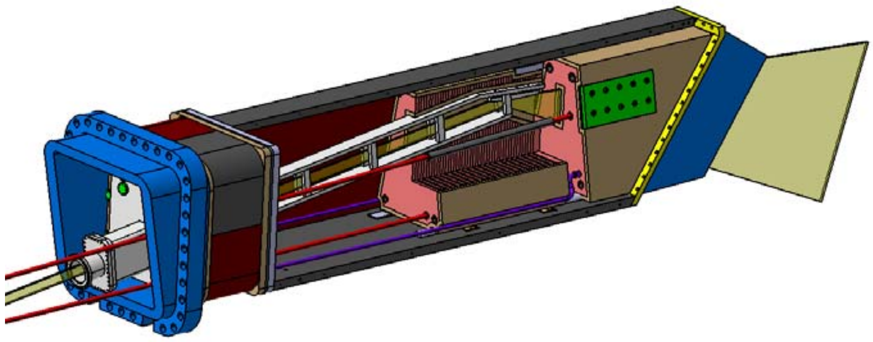

FIG. 9. Integration of diagnostic upper port plug #18.

5. Conclusions and Future Work

The status of design and results of R&D for the Korean ITER diagnostic systems was described along with the measurement requirements, design specifications, and outstanding R&D issues. To verify design parameters, ITER proto-type diagnostic systems are developed and tested. Recently, to support the VUV diagnostics, a modeling study on impurity transport and dynamics in ITER has been launched in Korea. Also, a study of sample capsule materials and in-situ methods of sample tracking by using a supersonic wave or microwave technique in case of a capsule-loss event has been launched taking into account the ITER environment of high thermal flux as well as high magnetic field.

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