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# DESIGN AND DEVELOPMENT OF ITER VUV SPECTROMETERS WITH PROTOTYPE TESTING

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**Abstract**

Development of ITER VUV spectrometers are in the final design stage, and the manufacturing has partially been started from the in-port-plug components. From the study with various mock-ups and prototypes, the design of ITER VUV spectrometer could be verified to proceed the development and procurement to the next stage. Especially, the prototype divertor VUV spectrometer installed at KSTAR was modified in the year of 2023 to accommodate the design update of ITER divertor VUV spectrometer replacing the collimation mirror with the space-resolved slit, and the initial data could be obtained with this spectrometer at KSTAR with upgraded tungsten divertor. By employing the space-resolved slit, 1-D profile of impurity emission lines in the wavelength range of 5 nm – 18 nm including tungsten lines could be observed showing the shape different from the Oxygen line. The real size mock-up for the field mirror box was manufactured and tested to check the manufacturability and also to assess the remote handling maintenance scenario. In addition, a set of bellows as safety important components was manufactured to check the design value of the allowed operation cycles derived from the structural analysis.

## 1. INTRODUCTION

The primary role of ITER vacuum ultraviolet (VUV) spectrometer is the monitoring of all the relevant impurity ion species in plasmas of ITER, registered as a nuclear facility INB-174 [1-3]. Three VUV spectrometers, core survey (2 – 160 nm), edge imaging (17 – 32 nm, 1-D profile), and divertor VUV (15 – 32 nm) are proposed to be operated in ITER tokamak to facilitate the measurement in different regions of plasmas with relatively high spectral resolution of $\lambda/\Delta\lambda = 200 – 500$ [4-6]. Currently these ITER VUV spectrometers are in the end of the final design, and the manufacturing of in-port-plug components was started.

Two prototype ITER VUV spectrometers, core survey VUV spectrometer and divertor VUV spectrometer were installed at KSTAR in the year of 2012-2014, and they have been tested to verify or improve the design of ITER VUV spectrometers. From the year of 2021, following the design update of ITER divertor VUV spectrometer, the divertor VUV spectrometer at KSTAR has been upgraded by replacing the collimation mirror with the space resolved horizontal slit positioned in front of the normal vertical slit. The initial data from the upgraded divertor VUV spectrometer are reported in the paper from the experimental campaign at KSTAR in 2023-2024. 1-D tungsten emission profile could be measured from the upgraded tungsten divertor at KSTAR, while further upgrade of the instrument is necessary such as blocking the stray light, and this is remained as future work.

Mock-up tests were also performed for several components of the ITER VUV spectrometer such as bellows, slit, and the field mirror box. Especially different kinds of mock-ups for double wall bellows classified as safety important components in ITER were manufactured and their designs were verified from the test.

## 2. OPTICAL COMPONENTS

### 2.1. Overview of Optical Design

The ITER vacuum ultraviolet (VUV) spectrometer consists of three systems as shown in Fig. 1. The VUV core survey spectrometer located in the equatorial port consists of 5 spectrometers with different wavelength ranges of 2.4 – 7.7 nm, 7.1 – 16.1 nm, 14.6 – 32 nm, 29.7 – 59.2 nm, and 56 – 160 nm [6]. Divertor VUV spectrometer and VUV edge imaging spectrometer can provide 1-dimensional spatial profile for the wavelength range of 15 – 32 nm (17 – 32 nm for VUV edge). These spectrometers consist of the field mirror in the port plug, the collimation mirror (or space-resolve slit for Divertor VUV), and the spectrometer in the port cell surrounded with the vacuum chambers. The geometry of the collimation mirrors is ellipsoid, and that of the field mirror is ellipse cylindrical to provide good imaging resolution and also to minimize the slot opening in shield module of the port plug structure for the light path. Several safety important components such as the rotary feedthrough and the bellows forming vacuum boundary are currently under development including mock-up tests. For example, the mock-up of the rotary feedthrough necessary for the shutter actuation to protect the field mirror (the first mirror) was manufactured to check the manufacturability, and the mock-up for the DN65 ITER standard flange to mount the rotary feedthrough was also successfully tested. Those results are planned to be reported in a separate paper in the future.

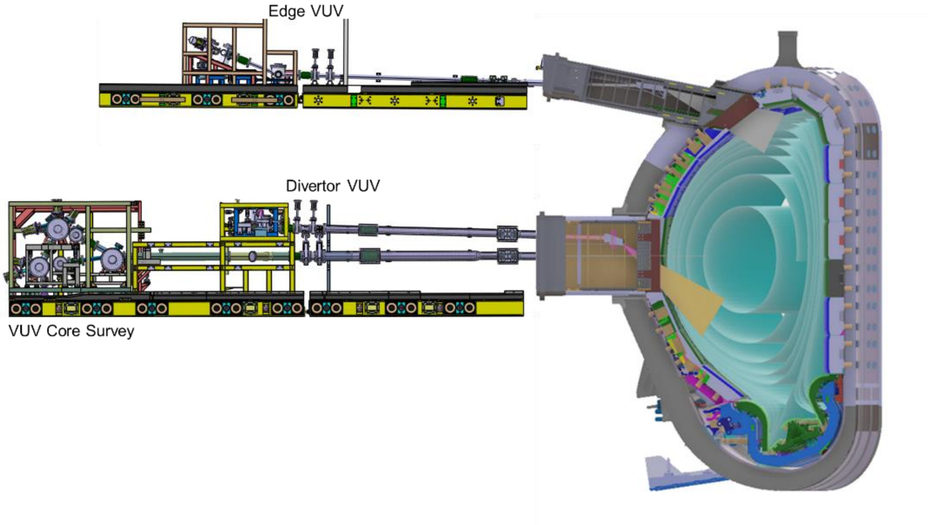


*FIG. 1* Overview of ITER VUV spectrometers. From the top, VUV edge imaging spectrometer, Divertor VUV spectrometer, and VUV core survey spectrometer with 5 wavelength channels.

### 2.2. Prototype spectrometer test at KSTAR

To validate the optical design of ITER VUV spectrometers, two prototypes of VUV core survey and divertor VUV spectrometers was manufactured and installed at KSTAR. The VUV core survey spectrometer has been operated at KSTAR from the year of 2012 in the wavelength of 15 nm – 50 nm composed of two spectrometers in a common set of chambers [6]. The divertor VUV spectrometer consists of one field mirror inside the middle port cassette of KSTAR, and one spectrometer chamber outside of the cassette flange as shown in Fig. 2 [5]. This divertor VUV spectrometer was upgraded in the years of 2021-2023 to accommodate the design update of ITER divertor VUV spectrometer replacing collimation mirror with the space-resolved slit due to the lack of space in ITER port cell. (Fig. 2)

As the first data, the acquired spectrum from the campaign of 2023-2024 for the shot #33372 is shown in Figure 3. Tungsten quasi-continuum emission lines of 5 – 7 nm could be observed originated from the tungsten divertor of KSTAR installed replacing carbon divertor in the year of 2023. By employing the space-resolved slit, 1-D profile of impurity emission lines for the wavelength range of 5 – 18 nm could be observed. Different 1-D profiles between W (~ +20 - ~ +44) and O VIII emission lines could be identified, and those peaks could be cross-checked with the different VUV survey spectrometer at KSTAR, so called CAES with the wavelength of 2 - 8 nm [7]. The upper region of CCD image of Figure 2 corresponds to the divertor plasma region through the line of sight in lower edge region of the plasma, while the lower region of CCD image corresponds to the plasma core region.

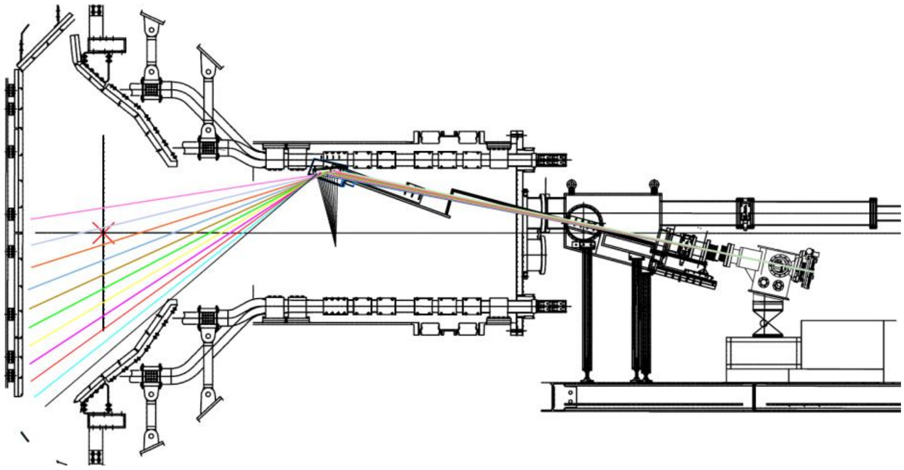

*FIG. 2* Divertor VUV spectrometer at KSTAR with lines of sight.

A series of spectra of Fig. 3, was obtained with a time resolution ~ 1 s. The limitation of the time resolution is primarily due to the time required for data readout of the employed CCD, and the replacement of CCD with the different model is currently in progress. As shown in Fig. 3, W unresolved lines array 4.5 - 7.5 nm, O VIII 10.24 nm, O VI 17.3 nm, O VI 18.4 nm and C VI 13.49 nm lines could be identified. To increase the signal-to-noise ratio of the acquired data, the vertical slit was opened in its maximum width, therefore the line width of the obtained spectra in Fig. 3 is thick compared to general spectra.

A stray light was detected in the wavelength range 13 – 19 nm as shown in right upper region of Fig. 3. This stray light is expected to be the visible light, and an additional baffle near the slit is planned to be installed to resolve this issue as future work. Because there is no stray light in the wavelength range of 4 – 12 nm, detail analysis of 1-D profile was conducted on lines emission in this range. The distribution of tungsten unresolved lines array near 6 nm and oxygen O VIII 10.24 nm was mainly investigated. Figure 3 shows that impurity emission lines have a cut-off in the lower region, and this indicates that there is obstruction hindering the lines emission in this position. As shown in Fig. 2, the ray with higher incidence angle than 79.6 ° (dark pink line of Fig. 2) would be blocked by the backside of the mirror or double reflected with lower reflectivity. As a result, the image area below the ray with incidence angle around 79.6 ° (bottom of CCD image in Fig. 3) did not appear in the 1-dimensional imaging spectra because it is out of the position of the reflecting mirror surface.

The mirror reflectivity (Au coated, roughness ~3 nm r.m.s., ~ 16 deg. grazing angle) should be multiplied to derive the line integrated emission intensity from the impurity species, and this reflectivity is orders of magnitude higher in the line of sight through the plasma core region compared to that of the divertor region. This reflectivity difference become much higher in the lower wavelength region [8]. Therefore, it is deduced that the tungsten emission in the divertor region is orders of magnitude higher than that of the plasma core region, while this difference of spatial distribution for O VIII 10.24 nm line is much smaller. Detailed investigation of this acquired data is to be reported in the separate paper. Stray lights on the upper right corner are to be removed by installation of appropriate blocking plate in front of the grating in the next experimental campaign.

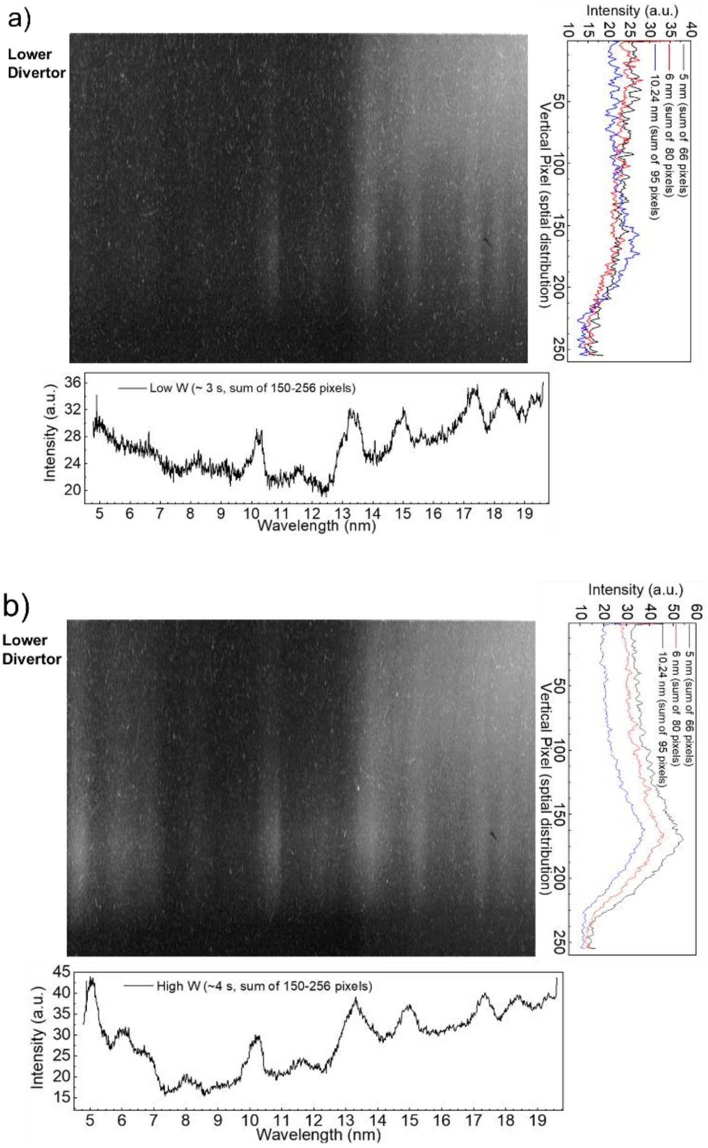


*FIG. 3* VUV spectra obtained in the image mode for the shot #33372 at KSTAR (a) at discharge time around 3 s, relatively lower tungsten emission and (b) at discharge time around 4 s, relatively higher tungsten, an array of unresolved lines (4.5 – 7.5 nm) was measured. The wavelength was calibrated by the 3$^{rd}$ order polynomial fit for identified lines. The images are compressed horizontally for a better view. Upper part of CCD image corresponds to the line-integrated emission from lower divertor region.

### 2.3. Slit design and prototyping

The general slit design with two sliding plates in a relatively small angle was adopted for the slit of VUV spectrometer as shown in Fig. 4. Linear motion guide bearings were attached to each sliding plate. Two plates are moved by the actuator driven by pico-motor (piezo-electric motor) as shown in Fig. 4. The candidate model of the pico-motor is 8302-UHV from Newport *co. ltd.*, and this model provides the maximum stroke of 25 mm. Based on this design, the slit functional test was performed to check the linearity of the slit opening via the motor rotation step number.

Piezo-type pico-motor attached to the top of the slit of Fig. 4 facilitates the micro-meter scale manipulation of the slit. The average step size that affects the variance in slit width should be validated through laboratory experiment with the mock-up as shown in Fig. 4 (middle). The variance in the slit aperture was investigated with a high-resolution microscope every time the pico-motor was controlled. Length-scale on microscope images was calibrated using a standard measuring specimen.

It was found that there is a difference between opening and closing the slit aperture with pico-motor. (Fig. 4, right) As the pico-motor went forward 27500 steps and then backward 2500 steps, there is the offset ~ 0.1 mm from the original position. Therefore, the slit should be opened to recover original reference open position (e.g. 3 mm) using a kind of the limit switch sensor. After that, by moving the slit to the closed position, the target slit width can be adjusted in proportion to the number of pico-motor step by the linearity between the step of motor and the slit width could be reproduced.

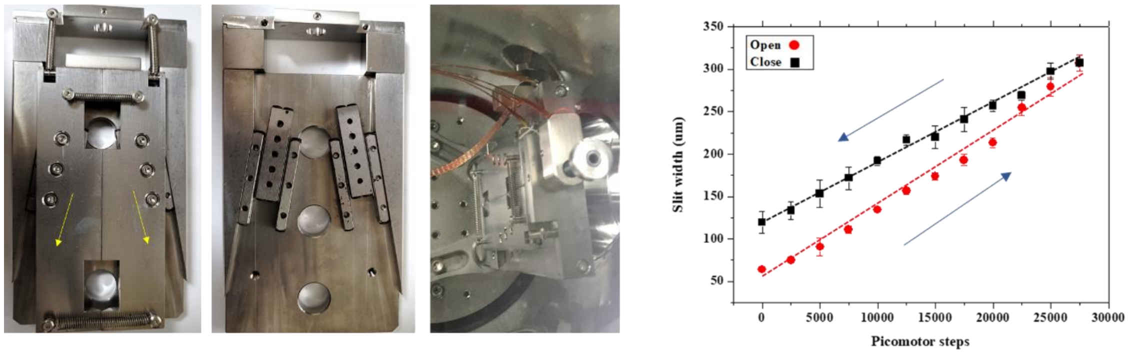


*FIG. 4* Slit prototype for ITER VUV spectrometer using roller linear motion bearings. There is hysteresis of the slit width between slit widths in opening and closing motion implying that the baseline position needs to be defined by the limit switch sensor on the reference position (e.g. 0.3 mm).

## 3. MECHANICAL COMPONENTS

### 3.1 Remote Handling Compatible Design and Mock-up of the field mirror box

To optimize the design of ITER VUV spectrometers, various studies for several key components have been performed. A mock-up for the field mirror box with shutter for divertor VUV spectrometer was manufactured as shown in Fig. 5. To check the remote handling scenario for the replacement of the mirror box, the dynamic movement of this box on the base plate was tested. From the test, it was found that a remote handling tool such as a lab-jack is necessary for disengagement of the mirror box because the friction on the connection area of the dowel and guide pins are not negligible. Two guiding rollers with ball bearings are attached to the remote handling adaptor for guiding motion on the channels on the base plate.

Two CuCrZr bushing blocks are designed for smooth rotation of the shutter rod located on the channel hole of the structure. The bushing block consists of CuCrZr bushing ring and intermediate stainless steel ring. This stainless steel ring is assembled to CuCrZr by shrink fit through rectangular feature. The end of the CuCrZr bushing has Metric 6 thread, and this thread is attached to the other stainless steel ring by the threaded connection. After this assembly, two adjacent stainless steel rings are orbital welded, and the other end of the stainless steel ring is welded to the pipe of the shutter rod. Vent hole was implemented in each block to prevent trapped volume with regard to high vacuum requirement.

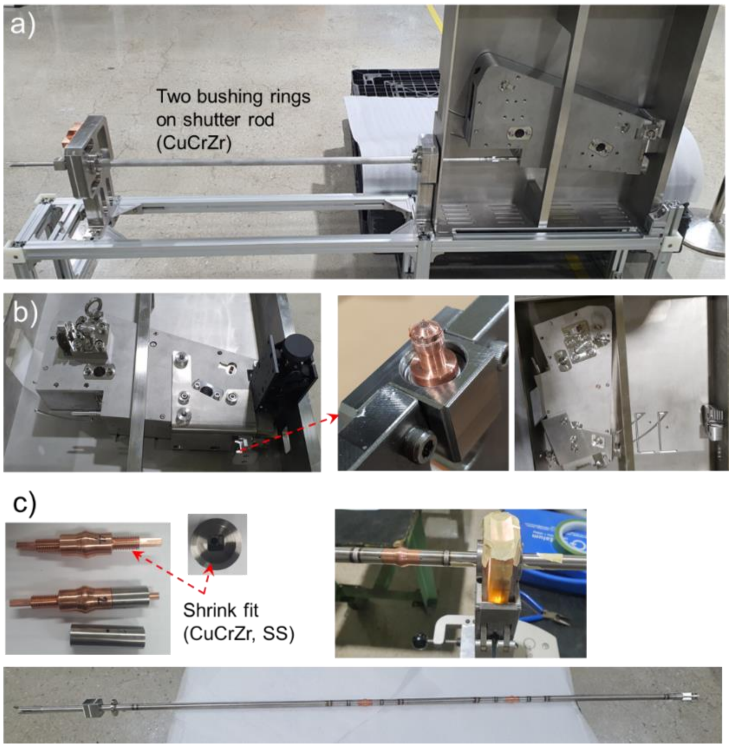


*FIG. 5* a) Mockup for the field mirror box with shutter for Divertor VUV spectrometer b) Check for remote handling replacement of the mirror box. A lab-jack like tool is necessary for disengagement of the mirror box (friction of the dowel/guide pins are not negligible). Guiding roller with ball bearings are attached to the remote handling adaptor. c) Shrink fit was used for the CuCrZr bushing block assembly on the shutter rod.

### 3.2 Bellows Prototyping

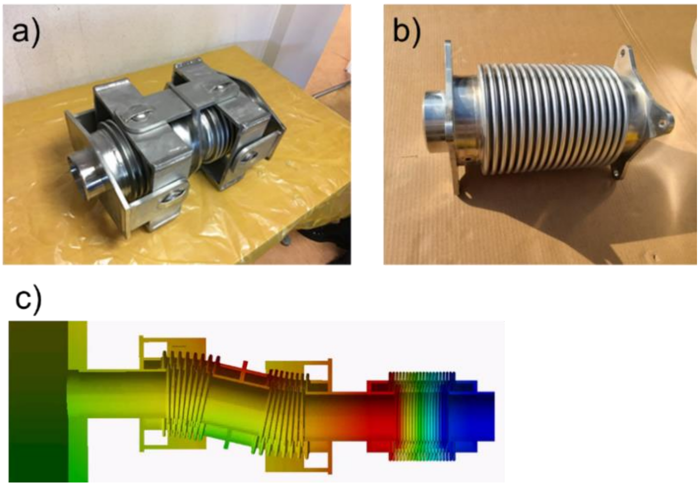


*FIG. 6* a) Gimbal double wall bellows for lateral movement b) Axial double wall bellows DN150, and c) Displacement schematic for ITER environment.

To absorb the relative movement between the port plug on the tokamak and the spectrometer chamber on the building (conservatively max. ~ 69 mm in one direction), one gimbal bellows and one axial bellows are employed for each vacuum extension pipe as shown in Fig. 6. The structural integrity of each bellows wasverified by the dedicated structural analysis following codes and standards. The double pipes with rings were manufactured by machining the forged block without welding between pipe and ring. Only bellows are welded to the pipe rings.

The number of fatigue cycle of the bellows was assessed by the test of mock-up as well as the structural calculation with finite element modelling. The dimensions of the mock-up of Fig. 6 are the same as those of ITER VUV spectrometers, but the manufacturing procedure did not followed exactly the procedure of ITER (such as vacuum handbook).

Axial bellows and gimbal bellows were tested and passed for its life time for the lateral movement. Total 5 gimbal bellows and two different sizes of axial bellows (DN100 and DN150) were manufactured. Beyond its designed value of operation cycles of ~ 600 (lateral 69 mm max. in load spec.), its actual test for each bellows was performed to 1200 cycles passing vacuum leak test. Furthermore, in the case of gimbal bellows, the life time test was performed until fracture of bellows as detailed for the gimbal bellows test in Ref. [9]. The fracture signal was detected in 4000 cycles or 6000 cycles for two same prototypes of gimbal bellows, respectively.

## 4. CONCLUSION

From the series of R&D with Mock-ups and prototypes, the design of ITER VUV spectrometer could be verified to proceed the development in the next phase of the procurement. The prototype divertor VUV spectrometer at KSTAR was modified in the year of 2023 following design update of ITER divertor VUV spectrometer replacing collimation mirror with the space-resolved slit. By employing space-resolved slit, 1-D profile of impurity emission lines for the wavelength range 5 nm – 18 nm including tungsten lines could be observed showing pattern different from the Oxygen line. Bellows and slit mock-ups were manufactured and their design could be verified from the test.

## ACKNOWLEDGEMENTS

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