VUV spectroscopy of high Z impurity ions in KSTAR plasmas using prototype ITER VUV spectrometers and development of 2-D VUV tungsten camera

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Introduction: A prototype ITER VUV survey spectrometer has been developed adopting channel #3 (14.4 nm –31.8 nm) and channel #4 (29.0 nm – 60.0 nm) among the five channels (2.4 nm – 160 nm).[1, 2] This prototype spectrometer has been installed and operated from KSTAR campaign of 2012 year. Another prototype of ITER VUV spectrometers, VUV imaging (1-D profile) spectrometer has been also installed at KSTAR during 2014 -2017. This VUV imaging spectrometer employs an ellipsoidal mirror and a concave field mirror to provide one-dimensional profile of lower part of plasmas. (see Fig. 1)

For 2-D detection of impurity emission, VUV camera system to detect 6.5-6.8 nm wavelength range of tungsten ion emission has been developed for KSTAR campaign of 2017 year. Preliminary result obtained from the 2-D camera with optical components for visible lines is to be presented.

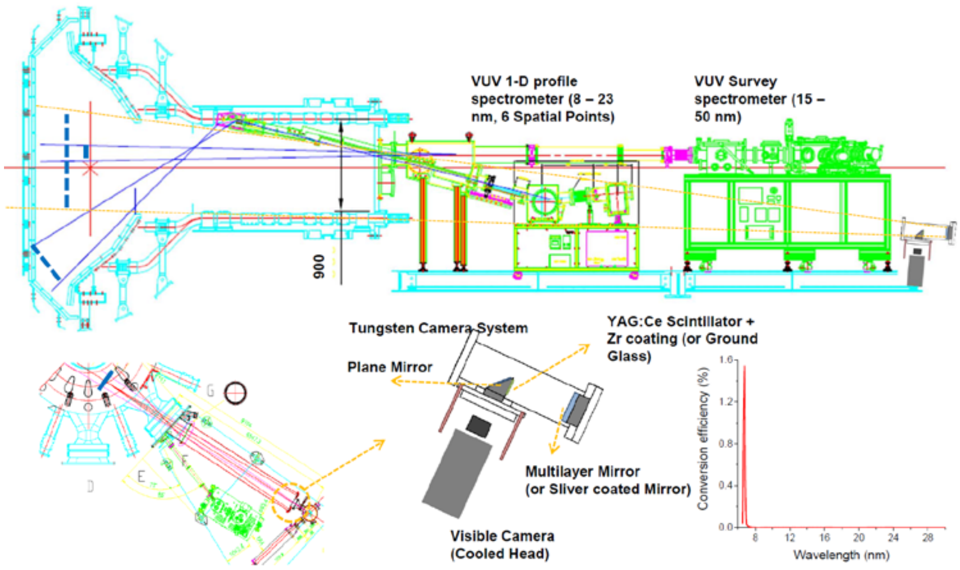

Fig. 1. Sketch of VUV survey spectrometer, VUV 1-D profile spectrometer, and tungsten EUV movie camera mounted on KSTAR F-port.

VUV spectroscopy of high Z impurity ions: Impurity transport and seeding experiments using inert gases and tungsten powder at KSTAR has been performed and studied by KAIST University team from 2012 year. In order to study Z (atomic number) dependence of impurity transport, gas feeding system for neon and krypton, and tungsten powder injector system were installed at KSTAR in 2015. From the krypton injection experiments such as #18399 shot, Kr XXV line of 15.8 nm and Kr XXVI line of 17.9 nm are measured from the VUV survey spectrometer as shown in Fig. 2. VUV 1-D profile spectrometer also provides the same emission lines of Kr ions. The spatial resolving power of current VUV 1-D profile spectrometer is expected to be 3 points for line of sights in Fig. 1. Because this VUV 1-D profile spectrometer consists of a concave grating and a horizontal slit, the spatial resolving power can be improved by adjusting the position of the horizontal slit. In case of ITER VUV imaging spectrometer, we plan to use a custom-made grating for imaging of slit to the detector in vertical (sagittal) direction. Therefore, the spatial resolving power of ITER VUV imaging spectrometer is expected to be much better than that of the current KSTAR VUV 1-D profile spectrometer. From the measurement of Kr lines using channel #4 spectrometer at KSTAR, small peaks like Kr XXIV 31.6 nm and Kr VI 35.8 nm are also identified. (Fig. 2) From tungsten dust injection experiment, multiple overlapped spectral lines around 15 – 22 nm are successfully measured as shown in Fig. 2.

Optics design of 2-D tungsten camera: A sketch of the tungsten VUV movie camera consisting of a LaN/B multilayer mirror, a YAG:Ce scintillator, and an EM-CCD camera is shown in Fig. 1. The optics design is inspired by the ultra-fast VUV movie camera developed at Caltech [3]; this camera can capture 20-40 nm VUV images at $>10^6$ frames per second and is used to study magnetic reconnection associated with a Rayleigh-Taylor instability [4]. Since VUV photons cannot penetrate the glass and is severely attenuated in the air, the entire optics must be installed inside the vacuum chamber.

A concave LaN/B multilayer mirror is used to focus VUV photons onto the YAG:Ce

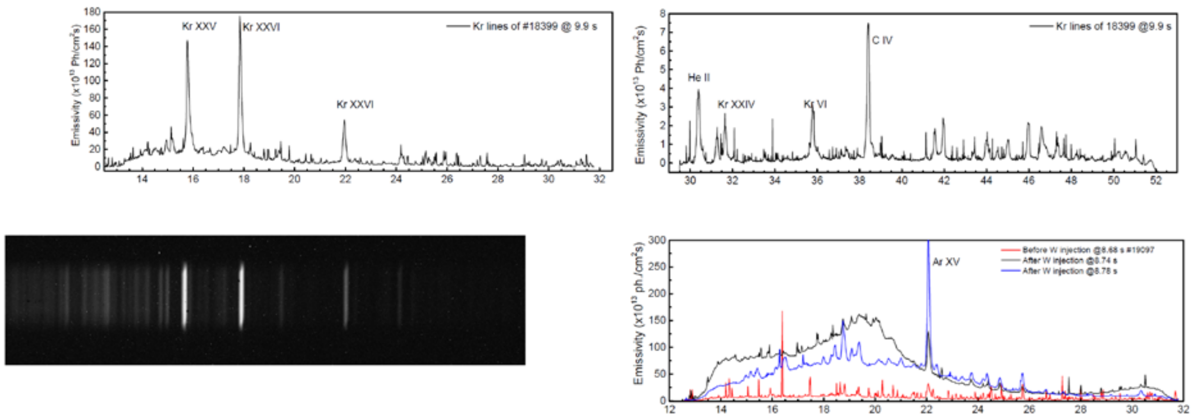

Fig. 2. VUV spectra from Kr and W injection experiments. From VUV survey and 1-D profile spectrometers, Kr lines can be identified. Unidentified line array of W is observed with time evolution.

scintillator. This mirror was custom-fabricated by Fraunhofer IOF and has alternating layers of LaN and B. The diameter and focal length of the mirror are 75 mm (d_1) and 150 mm (f_1), respectively. The reflectivity of the multilayer mirror has a maximum value of 25% at 6.75 nm and the FWHM is 0.2 nm. The distance between the KSTAR plasma and mirror is expected 850 cm (p_1) and so the distance between the mirror and scintillator is 15.3 cm (q_1). The solid angle subtended by the multilayer mirror is $\Omega_1 = \pi(d_1/2)^2 / 4\pi p_1^2 = (3.75\ \text{cm})^2 / 4(850\ \text{cm})^2 = 4.8\times10^{-6}$ Sr and the demagnification is $q_1/p_1=1/56$.

A YAG:Ce scintillator having 70 ns decaying time converts VUV photons into 550 nm visible photons. We chose a crystalline scintillator because it has better spatial resolution than a powder-type scintillator. The scintillator is also custom-made by Crytur Ltd. The diameter and thickness of the scintillator are 25 mm and 15 μm, respectively. One side of the scintillator is coated with Zr film (100 nm) to block visible light photons while not attenuating the desired VUV photons. The transmission of Zr film is 70% for 6.5-7 nm VUV photons while $< 10^{-6}$ for visible photons. The conversion efficiency of the crystalline YAG:Ce scintillator for 6.5-7 nm VUV photons into visible photons is not available at this time, but is assumed to be similar to the efficiency of a powder-type YAG:Ce scintillator; ~ 8% (see Fig. 4 in Ref. [5]).

An Andor Newton 971 EM-CCD camera placed outside the vacuum chamber captures visible light images formed on the scintillator through an f/1.2 lens (d_2=41.7 mm, f_2=50 mm). The solid angle subtended by this lens is $\Omega_2 = \pi(d_2/2)^2 / 4\pi p_2^2 = (2.1\ \text{cm})^2 / \{4(45\ \text{cm})^2\} = 5.0\times10^{-3}$ Sr. The demagnification is therefore 1/8 ($=q_2/p_2$). The temporal resolution of our tungsten camera up to few tens of fps and is currently limited by the EM-CCD camera; in principle, our EUV movie camera is able to take a movie at 10^7 fps.

The photon conversion efficiency of the combined multilayer mirror, Zr filter, and YAG:Ce scintillator, defined as incoming VUV photons divided by output visible light photons is shown in Fig. 1; the reflectivity of the LaN/B multilayer mirror is provided by Fraunhofer IOF, the transmittivity of a 100 nm Zr film is obtained from CXRO website [6], and the conversion efficiency of YAG:Ce scintillator is taken from Ref. [5]. As seen in Fig. 2, the peak efficiency is shown at 6.75 nm and is about 1.5%.

The total demagnification of our camera is 56×8=448 and the pixel size of the EM-CCD camera is 16×16 μm^2. Thus, one pixel corresponds to 7.2×7.2 mm^2 of actual plasma. The emission intensity of the highly-charged tungsten ion lines at around 6.75 nm is expected to be in the order of 1 W Sr^{-1} m^{-2} a (0.1 - 1000 depending on impurity contents) according to the previous VUV study on KSTAR. Assuming all the photos have the same wavelength (6.75 nm) and considering the solid angle subtended by the multilayer mirror and the fact that the multilayer mirror is blocked by scintillator support structure by 50%, 4.3×10^6 photons will reach the mirror per a second. Using the VUV to visible photon conversion efficiency, the number of visible light photons generated by the scintillator is 6.4×10^4 photon/s. Taking into account the solid angle subtended by the f/1.2 lens on the visible light camera, there will be

320 visible light photons will hit the single pixel of the EM-CCD camera per a second. If we set the exposure time at 100 ms and bin 2×2 pixels we will get 120 photons on a binned pixel.

Test of spatial resolution and preliminary result with visible optics: In order to check the spatial resolution of our tungsten VUV camera, we took pictures of several target images using visible optics; a silver mirror was used instead of the multilayer mirror (same diameter and focal length) and the YAG:Ce scintillator was replaced by a ground glass screen. As seen in Fig. 3, the camera can resolve 0.5 line pairs per cm in the horizontal direction. Note that since our EM-CCD camera does not have a global shutter at present, the images are smeared.

As a next step of test, this camera system with visible optics was installed at KSTAR as shown in Fig. 1. For the proof of concept in view of optical performance, we installed 465-475 nm bandpass filter in front of the CCD camera to observe Ar II 472 nm, Kr II 468 nm, C III 466 nm, and et. al.. The viewing area is about 90 cm (height) x ~60 cm (width) region of central plasmas. (Fig. 1) Due to the lack of available ports at KSTAR, the viewing angle is 30 deg. from the poloidal view. In D-shaped plasmas, straight C III lines are observed as seen in Fig. 3 (b). Brighter image in left side is the emission from the inboard side of KSTAR. In tungsten and argon injection experiment (#19097), some localized emission from the central part was observed as shown in Fig. 3 (c).

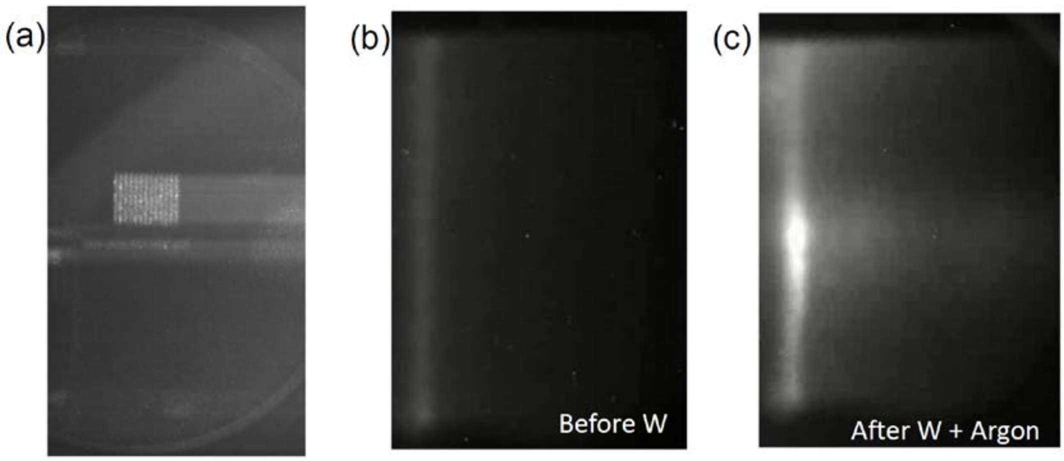

Fig. 3. Resolution test results with (a) horizontal line pairs (0.5 line pairs/cm). Preliminary result at KSTAR with visible optics: (b) steady state plasma with C III emission and (c) a impurity mixed image with Ar, C, and W.

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