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Upgrade of the tangentially viewing vacuum ultraviolet (VUV) telescope system for 2D fluctuation measurement in the large helical device

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A high-speed tangentially viewing vacuum ultraviolet (VUV) telescope system, using an inverse Schwarzschild-type optic system was developed to study fluctuations in the Large Helical Device (LHD). However, for the original system, the sampling rate was restricted to below 2000 Hz due to the low signal to noise (S/N) ratio in the experiment. In order to improve the S/N ratio, upgrade of the system was made. With this upgraded optical system, the maximum framing rate is improved to 6000 fps with a similar spatial resolution. Rotation of the m = 2 structure caused by the magnetohydrodynamic (MHD) instability is measured by the upgraded system. The spatial structure of the image is consistent with the synthetic image assuming the interchange mode type displacement of the flux surfaces. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4959951]

I. INTRODUCTION

Physics of fluctuations in magnetically confined plasma is extremely complicated. If we resolve the spatial structure of the fluctuations, our understanding of the fluctuations will be improved. Since the phases of the fluctuations on a magnetic field line are almost the same, we can obtain a greater part of the information from two dimensional (2D) structures of the fluctuations in toroidally confined plasmas. In addition, an advantage of the 2D imaging is that this type of diagnostics can measure fluctuations with a higher mode number. Therefore, 2D imaging diagnostics, such as the tangentially viewing soft X-ray (SX) camera system,[1] have been developed. However, no optical components, e.g., lenses, are available in the energy range of SX. A pinhole should be used for the image formation. It is not easy to improve the optical system of a pinhole camera. If we go to lower energy radiations, Mo-Si multi-layer mirror which can reflect photons of 13.5 nm can be used. The reflectivity of the material is up to ~65% and is close to the theoretical limit of the multi-layer mirrors. The carbon VI line (n = 4-2 transition) falls into this energy range. Therefore, vacuum ultraviolet (VUV) telescope system has been developed in large helical device (LHD) since 2008.[2,3] The framing rate was restricted to under 2 kHz due to poor signal to noise (S/N) ratio. Though we have successfully measured magnetohydrodynamic (MHD) instabilities in this low frequency range, an upgrade of the system is required for studying the edge MHD instabilities whose typical frequency is 1–5 kHz. In this article, an upgrade of the VUV telescope system and preliminary results are reported.

II. UPGRADE OF THE VUV TELESCOPE

An inverse Schwarzschild-type optical configuration, consisting of two multi-layer mirrors, is used to form the image of the plasma. The mirrors are made of layers of molybdenum and silicon. VUV light with a wavelength of 13.5 nm ($\Delta\lambda \sim 1$ nm) is reflected. The telescope is made from the combination of the concave/convex mirror (see, Fig. 1), of which curvature length is 213.3 mm and 79.53 mm, respectively. The distance between the mirrors is 133.8 mm. The diameters of the mirrors are enlarged from 23.2 mm to 34.0 mm (1st mirror) and 102 mm to 147 mm (2nd mirror) in the upgrading. A larger number of photons are thus collected by this upgraded system. Image magnification factor is decreased to ×80 from ×60, as well. The effective resolution at the focal point is changed from 3 mm/pixel to 4 mm/pixel. In order to exclude the low-energy VUV light, a Zr film of 200 nm thickness is inserted. Since the number of photons per pixel N is proportional to $d\Omega$, where $d\Omega$ is the solid angle of the 1st mirror viewed from the plasma. The number of photons per pixel is about 5.5 times larger from the improvement of the optics. The maximum framing rate about 3 times higher (6 kHz) than that of the old system (~2 kHz) can be achieved. Images are detected by a two-stage micro-channel plate (MCP) with a phosphor screen (PHOTONIS, APD 2 PS 18/6/5/560:1 EDR 4.5″ FM P47 type). A Vision Research Phantom V4.2 type CMOS camera is used to record the 2D image on the phosphor screen. Normally, images are recorded with 256 × 256 pixels. The observable diameter in the plasma is enlarged from 0.6 m to 1.0 m, as shown in Fig. 2. Setting the telescope close to the plasma makes this enlargement of the viewing field. Since LHD is a helical system, the shape of LHD is a kind of twisted torus. In the experiments, the emission profile is usually peaked in the edge region (around $\rho = 0.9$). An “X”-like structure (bright region) can be seen in the left side. Emission very close to the last closed flux surface produces

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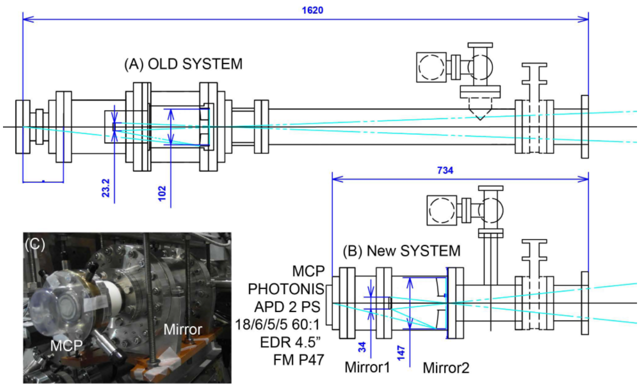

FIG. 1. Schematic diagram of the old (a) and the upgraded (b) system. Distance to the LHD plasma is reduced by 0.9 m, as well. Photograph of the upgraded system is shown in (c).

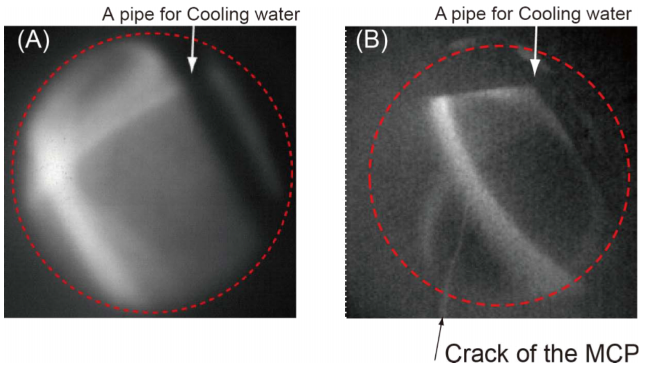

FIG. 3. An example of 2D VUV emission measured by old (a)/upgraded system (b). “X”-like structures can be seen in the left side. Emission very close to the last closed flux surface makes this kind of pattern since the shape of the LHD is a kind of twisted torus as shown in Fig. 4.

this type of image. Comparison of the images measured by the old/new system is shown in Fig. 3. It can be seen that the observing region is expanded. This is confirmed by the fact that the cross-like structure moves to the center area of the image. The quality of the image is also improved. Unfortunately, there is one crack on the MCP, which stays from the center to the left-bottom region. The images shown in this article are affected by this defeat. In Sec. III, an example of measurement where MHD instabilities are measured by this upgraded system will be introduced. The system is operated with a framing rate of 2000 kHz to keep reasonable brightness. Since the S/N ratio is improved, a rotating structure (f ∼ 0.8 kHz) is clearly measured. This measurement also shows that the system is improved from the original system. That will be beneficial for the MHD instability research in the future.

III. EXPERIMENTAL IMAGE AND COMPARISON WITH THE SYNTHETIC IMAGE

The LHD device[4] is a heliotron device and the shape of the magnetic surface is quite complex. It is not straightforward to estimate the 2D image when the plasma is observed tangentially. Here, the flux surfaces are approximated by the triangular mesh for generating the synthetic image of the VUV light emission from plasma. From this approximation, the calculation of the crossing point of the sight line with the flux surfaces becomes simple. The contribution to a pixel from the emission in a layer between the flux surfaces can be obtained (see, L1, L2,... shown in Fig. 4). Thereby the relation of the radial emission profile and the 2D image is expressed by the matrix form.[5] In order to interpret the images measured in the experiment, the synthetic image is obtained by integrating the VUV-light emission from the deformed magnetic surface with the radial plasma displacement ξ_r.[5,6] Moreover, the deformed structure is also rotated numerically and the fluctuation component is separated by the singular value decomposition (SVD).[7]

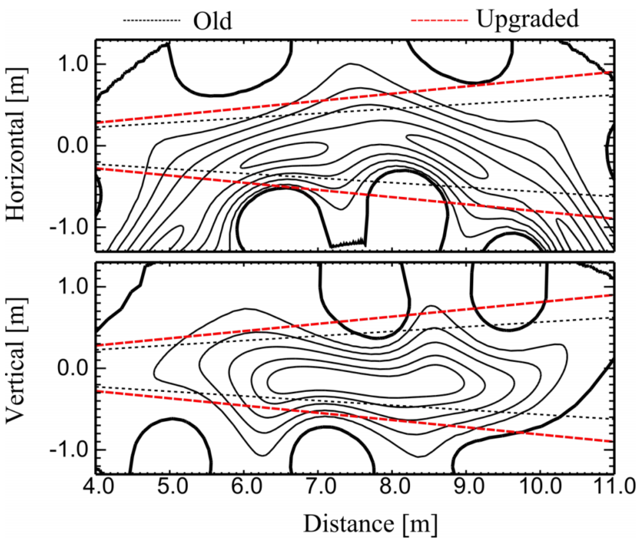

FIG. 2. Viewing field of the VUV telescope system.

In the low magnetic field experiment with $B_t = 0.9$ T, strong MHD activities are observed by the magnetic probes. Because the instability shows an m/n = 2/1 helical structure (m, n: poloidal and toroidal mode number), this activity is considered to be the core MHD mode. Owing to the low electron temperature in this shot, even the fluctuation localizing in the plasma core is detected by the VUV telescope system. The measured tangential images have been analyzed as follows. First, the images are averaged over every 4 × 4 pixels. The averaging not only reduces the noise but also improves the dynamic range of the camera image. Therefore, image size is changed to be 64 × 64 pixels rather than 256 × 256 pixels per frame. The unnecessary part is also removed,

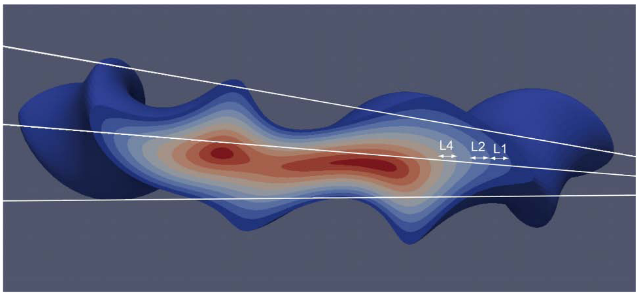

FIG. 4. Schematic drawing of the surface of LHD and sight lines.

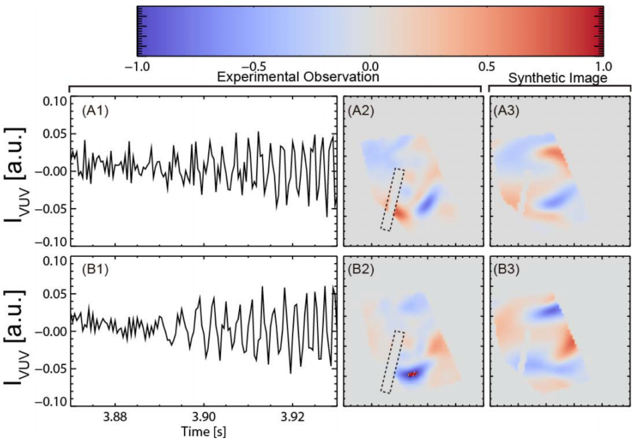

FIG. 5. Eigenfunctions of the chronos ((a1) and (a2)) and topos ((a2) and (b2)) are shown. Dashed box shown in a2 and b2 is the area where MCP is damaged. Synthetic image assuming that the radial displacement localized on the rational surface with the parameters $\rho_r = 0.4$ and $w = 0.15$ and poloidal/toroidal mode number is $m/n = 2/1$ is shown in a3 and b3.

for example, the black strip lies in the top-right corner of the image, which is the shadow of the cooling pipe in the vacuum vessel. Then, the SVD method is used to decompose the fluctuations into the temporal (chronos) and spatial (topos) components. The derived singular value (SV) components of both time (Figs. 5(a1) and 5(b1)) and space (Figs. 5(a2) and 5(b2)) are shown. Since this mode is rotating, two orthogonal components having different phases are obtained simultaneously. From the chronos components, it is found that the MHD oscillation occurs from 3.88 s to 3.90 s. From the topos components (Figs. 5(a2) and 5(b2)), it is realized that MHD instability has an m = 2 poloidal spatial structure. The phase reversal is observed, but there is no phase shift of the pattern. Finally, these experimental images are compared with synthetic images obtained numerically. In this case, plasma displacement ξ_r with a Gaussian function is assumed, i.e., $\xi_r = c \exp\left(-\left(\frac{\rho-\rho_r}{w}\right)^2\right)$ where, c, ρ_r, and w are amplitude, peak position, and the radial width of the mode, respectively. The best agreement with the experimental image is achieved by using $w = 0.15$, $\rho_r = 0.45$ (Figs. 5(a3) and 5(b3)). It is worth pointing out that the plasma displacement assuming an even function (interchange-type) fits the experimental better than an odd function (tearing-type), suggesting that the observed MHD instability may be the interchange mode. This is consistent with the previous experiments using a 2D SX camera system.[6]

IV. SUMMARY

After upgrade of the VUV camera system on LHD, MHD activities up to 3 kHz can be studied by the improved optic system. In a preliminary experiment MHD instabilities having m = 2 structure are observed. The spatial pattern is consistent with the interchange mode localized on the iota = 1/2 rational surface. Unfortunately, capabilities to detect higher mode number fluctuations have not been demonstrated in the LHD. This camera will be moved to KSTAR tokamak, where the shape of the plasma is much simpler and more suitable for 2D imaging diagnostics.

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