# Performance improvement of two-dimensional EUV spectroscopy based on high frame rate CCD and signal normalization method


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**Abstract**

In the Large Helical Device (LHD), the performance of two-dimensional (2-D) extreme ultraviolet (EUV) spectroscopy with wavelength range of 30–650Å has been improved by installing a high frame rate CCD and applying a signal intensity normalization method. With upgraded 2-D space-resolved EUV spectrometer, measurement of 2-D impurity emission profiles with high horizontal resolution is possible in high-density NBI discharges. The variation in intensities of EUV emission among a few discharges is significantly reduced by normalizing the signal to the spectral intensity from EUV_Long spectrometer which works as an impurity monitor with high-time resolution. As a result, high resolution 2-D intensity distribution has been obtained from CIV (384.174Å), CV (2×40.27Å), CVI (2×33.73Å) and HeII (303.78Å).


## 1. Introduction

In LHD, the core plasma is surrounded by ergodic layer, which is formed by the presence of higher-order Fourier components in the magnetic fields created by the helical coils. Since the ergodic layer has 3-D structure, 2-D measurement is at least necessary for the impurity transport study in the ergodic layer [1]. A 2-D space-resolved EUV spectrometer has been developed to measure the 2-D distribution of impurity emissions from the ergodic layer. The 2-D profile from several impurity species, i.e. carbon, helium and iron, has been measured and analyzed [1-3]. In LHD two positive-ion-source-based NBIs (p-NBI) and three negative-ion-source-based NBIs (n-NBI) are operated at energies of 40 and 180 keV for plasma heating, respectively. The ECH with injection power up to 4 MW and two perpendicularly injected p-NBIs with total input power up to 10 MW are used for electron and ion heating, respectively. High-density discharges in ranges of $10^{13}$-$10^{15}$ $cm^{-3}$ are mainly sustained and heated by three tangentially injected n-NBIs with total input power up to 20 MW. As the pulse length of LHD discharges heated by n-NBIs is normally limited to 3-5s, it is necessary to improve the performance of 2-D EUV spectrometer to measure the 2-D distribution of impurity emissions from high-density plasmas heated by the n-NBI. In 2013 LHD campaign, the performance of 2-D EUV spectrometer greatly improves by installing a new high frame rate CCD and applying a signal intensity normalization method in the 2-D distribution analysis. In this report, the EUV spectroscopy in LHD and the principle of 2-D measurement are introduced in section 2. The performance improvement of 2-D spectroscopy on horizontal resolution and time resolution are shown in section 3. The intensity normalization method is also presented in section 3. Typical high-resolution 2-D distributions from impurity carbon are shown in section 4. The report is summarized in section 5.

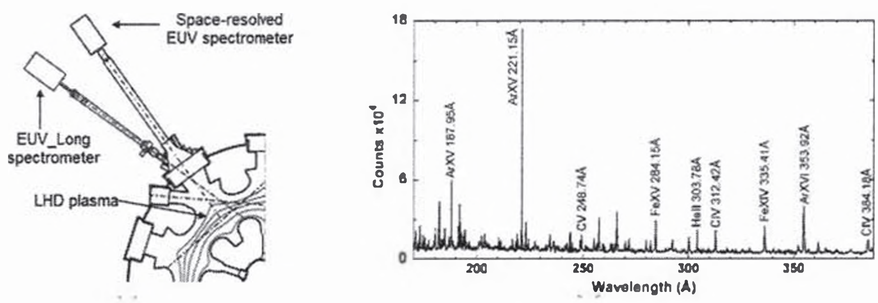


Figure 1. (a) Schedemic view of EUV spectroscopy in LHD with EUV_Long spectrometer and space-resolved EUV spectrometer and (b) typical spectrum measured with EUV_Long spectrometer in range of 170-390Å.

## 2. EUV spectroscopy in LHD

As shown in Fig. 1(a), two EUV spectrometers working in wide wavelength range of 30 to 650Å, which are named as EUV_Long spectrometer and space-resolved EUV spectrometer, are installed on 10-O port in LHD. The performance of two spectrometers is separately described in papers of [5] and [6] in detail. The EUV_Long spectrometer is developed as an impurity monitor to measure the time behavior of impurity emissions with sampling time of 5ms. A typical spectrum measured by EUV_Long spectrometer is shown in Fig. 1(b), and the time behavior of impurity emissions measured with the EUV_Long spectrometer, which is used for the intensity normalization method, is shown in Fig. 7 (d). As shown in Fig. 2, the space resolved EUV spectrometer observes s vertical profile of impurity emissions at horizontally elongated plasma cross section when the observation chord is fixed at the center of LHD port ($\theta=0°$). The vertical observation range is about 550mm. The full vertical profile form Z=-550mm to 550mm can be observed by changing the vertical angle of space resolved EUV spectrometer with a vertical stepping motor two or three times. The elliptical shape of the LHD plasma rapidly rotates in the poloidal direction as the toroidal angle $\theta$ is changed. The change in the poloidal cross section of the LHD plasma is also shown for different toroidal angles of $\phi = +2°$, $\phi = 0°$ and $\phi = -2°$ in Fig. 2. The vertical profiles of impurity emissions as a function of toroidal angle $\theta$, which results in the 2-D distribution measurement, can be measured by horizontally scanning the observation chord with a horizontal stepping motor. A good separation in the impurity emission location between inboard and outboard X-points can be easily obtained when the 2-D distribution is measured [2].

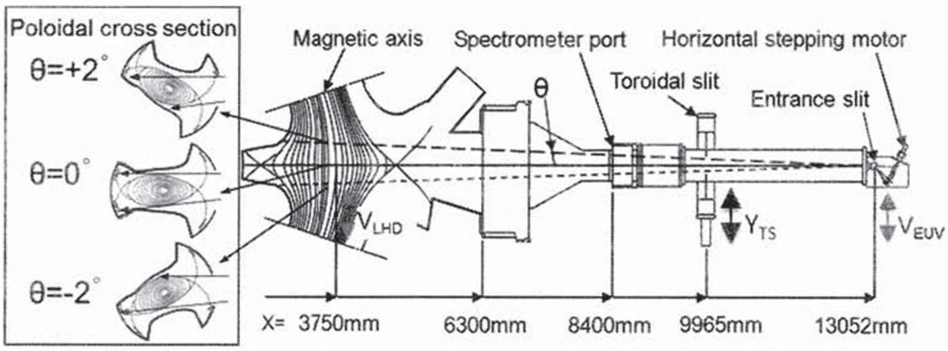


Figure 2. Schematic view of space-resolved EUV spectrometer. Horizontal scanning of space-resolved EUV spectrometer is carried out with a horizontal stepping motor. $V_{EUV}$ is horizontal scanning speed of space-resolved spectrometer and $V_{LHD}$ is horizontal scanning speed of observation chord at magnetic axis of R=3.75m. $Y_{TS}$ is the horizontal distance between toroidal slit and central optical axis. The poloidal cross section of LHD plasma at toroidal angle of $\theta = +2°$, $\theta = 0°$ and $\theta = -2°$ is shown at rectangular frame.

## 3. Improvements of 2-D data performance

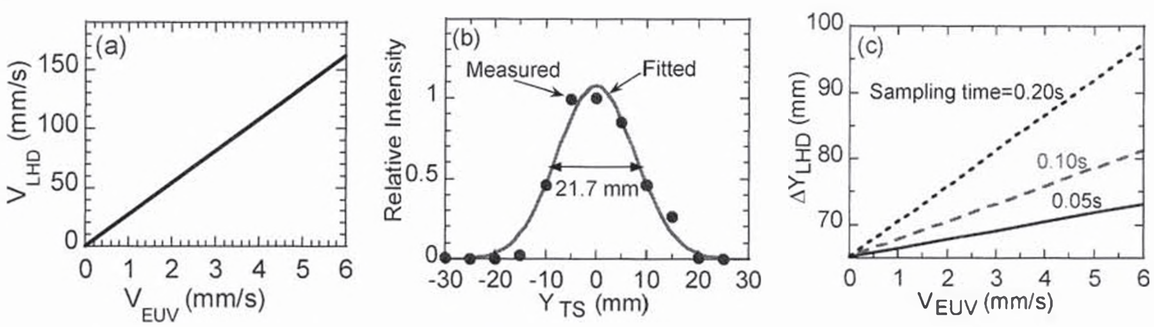


Figure 3. (a) $V_{LHD}$ as a function of $V_{EUV}$, (b) relative spectral intensity as a function of $Y_{TS}$ and (c) horizontal resolution ($\Delta Y_{LHD}$) against $V_{EUV}$ as a parameter of sampling time

A back-illuminated CCD (Andor DO420-BN) with 1024 × 256 pixels was used in the space-resolved EUV spectrometer to detect the impurity emission until 2012 LHD experimental campaign. The active area of the CCD is 26.7 × 6.7 mm$^2$ with a pixel size of 26 × 26 μm$^2$. The CCD is usually operated at -20°C, where the thermal noise can be sufficiently reduced. 51×204 subimage mode is usually used for profile measurement with readout time of 63ms and sampling time of 200ms [2]. In 2013 LHD experimental campaign, the CCD was replaced by a new CCD (Andor DO920P-BN). The pixel size and active pixel number of the new CCD is the same as that of the old one. But the readout time of the new one is improved to 16.8ms under the same 51×204 subimage mode. Therefore, the new CCD can be operated with sampling time of 50ms or 100ms [2].

The toroidal resolution of space-resolved EUV spectrometer at $V_{EUV}$ = 0, which is basically a function of the angle of incidence and the grating size and curvature, is experimentally determined using a toroidal slit (TS). As shown in Fig. 2, the toroidal slit, which can be horizontally moved, is installed between the LHD plasma and the space resolved EUV spectrometer. Distance between the toroidal slit and the LHD plasma is about 2 times longer than the distance between the toroidal slit and entrance slit of space resolved EUV spectrometer. The spectral intensity changes when the toroidal slit is horizontally scanned. Figure 3 (b) shows a relative spectral intensity as a function of the horizontal position of toroidal slit, $Y_{TS.}$ which means the horizontal distance between toroidal slit and central optical axis. The relative spectral intensity profile is fitted with Gaussian function and the full width at half maximum of the Gaussian curve is determined to be 21.7mm. Since the distance between the entrance slit and the LHD plasma is about 3 times longer than the distance between the entrance slit and the toroidal slit, the horizontal resolution can be estimated to be 65mm at the position of R=3.75m [6].

As shown in Fig. 3(a), the horizontal scanning speed of observation chord at the position of magnetic axis ($V_{LHD}$) is approximately linear against the horizontal scanning speed of space-resolved spectrometer ($V_{EUV}$). The horizontal resolution in 2-D measurement shown in Fig. 3 (c) is a function of sampling time and scanning speed. Under the same scanning speed, the horizontal resolution is improved as the CCD sampling time decreases. Fig. 4 (a) and (b) show comparison of the 2-D distribution measured by old CCD with sampling time of 200ms and new CCD with 50ms, respectively. It clearly shows the horizontal resolution is significantly improved.

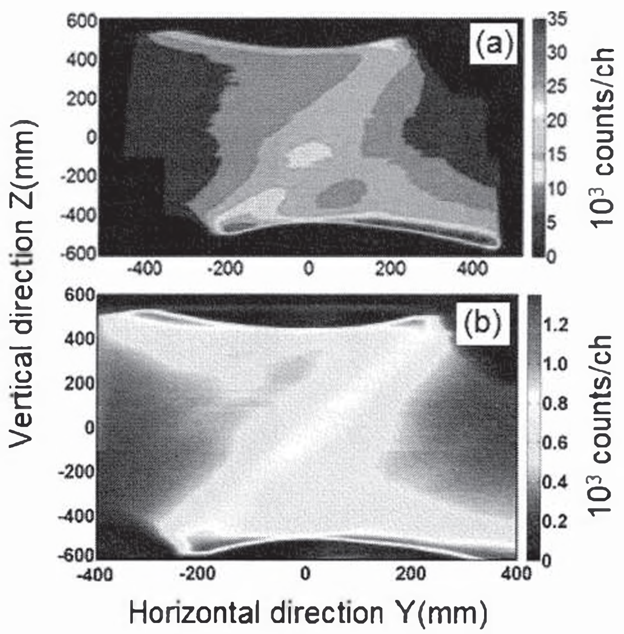


Figure 4 2-D profiles of HeII (303.78 Å) measured by (a) old CCD with $V_{LHD}$ = 135mm/s and sampling time = 200ms and (b) new CCD with $V_{LHD}$ = 162mm/s and sampling time = 50ms

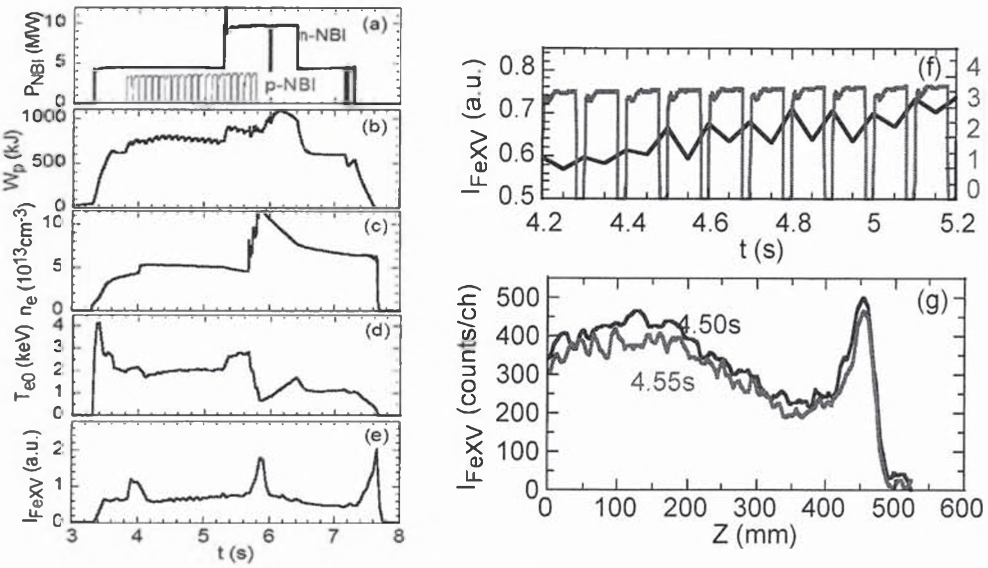


Figure 5 Time behaviors of (a) n-NBI (tangential injection) and p-NBI (perpendicular injection) port-through power, (b) plasma stored energy, (c) line-integrated electron density, (d) central electron temperature and (e) intensity of Fe XV (284.147Å) measured by space-resolved EUV spectrometer, (f) enlarged time behavior of Fe XV (284.147Å) with modulated p-NBI port-through power and (g) vertical profiles of FeXV (284.147Å) at t=4.50s (blue) and 4.55s (red).

For examining the time resolution in the upgraded system, time behavior and vertical profiles of FeXV (284.147Å) are measured during the NBI modulation phase. The interval of NBI modulation is 100ms and the sampling time of CCD is 50ms. As shown in Fig. 5 (f), a good correlation between the emission intensity of FeXV (284.147Å) and the p-NBI port-through power can be clearly observed. Figure 5 (g) shows the vertical profile of FeXV at t=4.50s and 4.55s. The two vertical profiles can be clearly distinguished each other indicating a good time resolution.

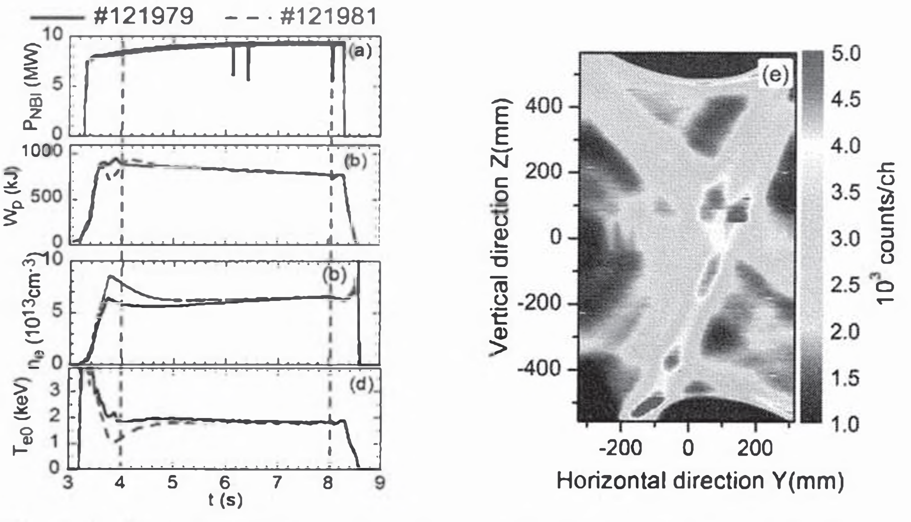


Figure 6. Time behaviors of (a) n-NBI port-through power, (b) plasma stored energy, (c) line-averaged electron density, (d) central electron temperature and (e) 2-D distribution of CIV (384.174Å) from short pulse NBI discharge. The 2-D profile is obtained through horizontal scanning during 4s oft=4s to 8s.

With the new CCD, it is possible to obtain the high-resolution 2-D distribution from high-density discharges. As mentioned above, the pulse length of high-density discharges heated by n-NBI is limited to several seconds. High horizontal scanning speed is required to complete the 2-D measurement during n-NBI pulse. The 2-D distribution of CIV (384.174Å) shown in Fig. 6 (e) is obtained from high-density NBI discharges with scanning speed of $V_{LHD}$= 162mm/s and sampling time of 100ms. The horizontal resolution is sufficiently good because two X-point diagonal traceries can be clearly observed.

A new method of normalizing the 2-D signal intensity by the spectral intensity from EUV_Long spectrometer is used for the 2-D data analysis to reduce the effect of shot-to-shot variation in the EUV emission during horizontal scan of the space-resolved EUV spectrometer. A steady discharge longer than 4s is required to complete the 2-D measurement. However, EUV emissions during the scanning often temporally change at each discharge. A typical example is shown in Fig. 7. Figure 7 (e) shows CIV 2-D distribution analyzed without intensity normalization using three discharges (#122454: upper trace, #122455: middle trace and #122456: lower trace). The new method is attempted using the time behavior of CIV measured with EUV_Long spectrometer, as shown in Fig. 7(d). The 2-D distribution is analyzed from 2s to 10s. A temporal variation is clearly seen in the emission intensity. The signal level is also changes among three discharges. All these variations in the emission intensity can give a clear influence to the quality of analyzed 2-D distribution. The 2-D distribution after intensity normalization is shown in Fig. 7 (f). When Fig.7(f) is compared with Fig.7(e), we clearly see the effect of intensity variations is almost invisible.

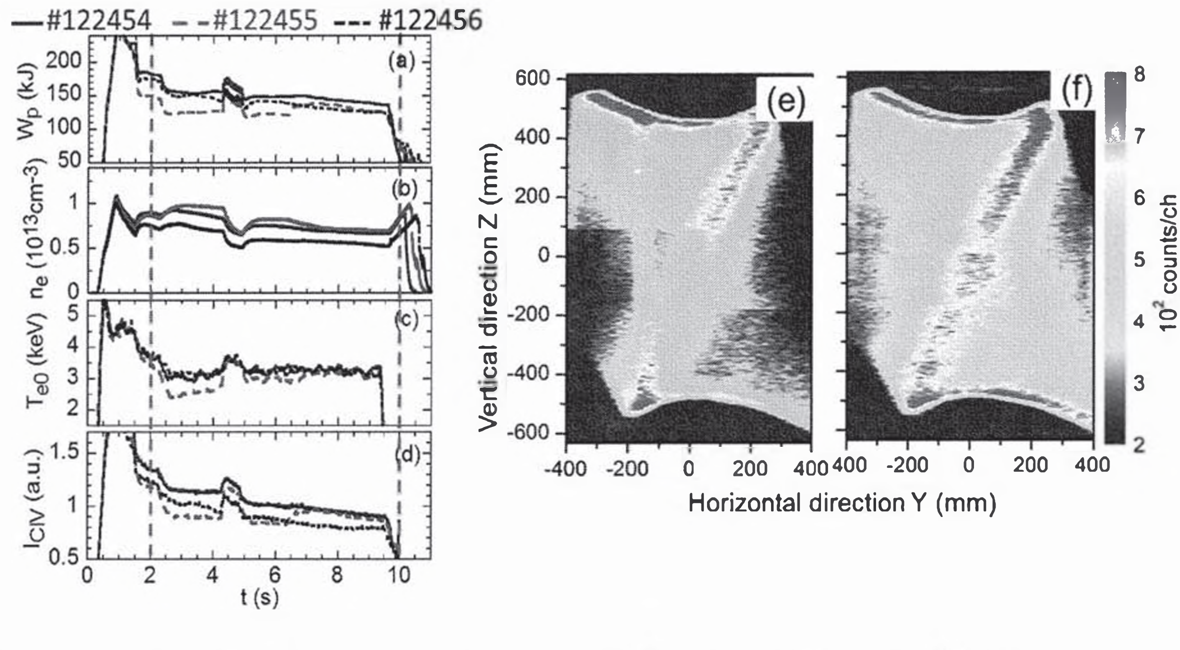


Figure 7. Time behaviors of (a) plasma stored energy, (b) line-averaged electron density, (c) central electron temperature, (d) CIV (312.4 Å) intensity measured from EUV_Long spectrometer, (e) 2-D distribution without intensity normalization and (f) 2-D distribution with intensity normalization.

### 4. Typical result of 2-D impurity emission distribution

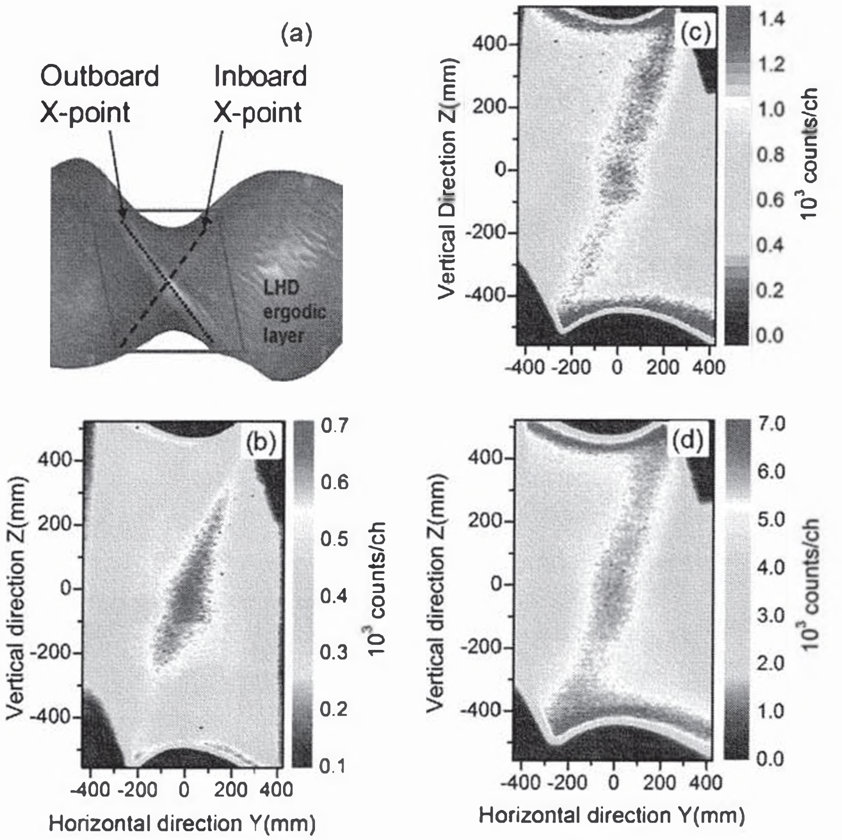


Figure 8. (a) Schematic view of LHD ergodic layer and 2-D distributions of (a) CIV (384.174Å), (c) CV (2×40.27Å) and (d) CVI (2×33.73Å). Observation range of space-resolved EUV spectrometer is denoted with a diamond-shape solid line in Fig.8(a) in addition to diagonal trajectory of inboard (dashed line) and outboard (dotted line) X-points.

The 2-D distribution of CIV (384.174Å), CV (2×40.27Å) and CVI (2×33.73Å) is observed from ICRF discharges at line-averaged density of $n_e = 1\times10^{13}$ cm$^{-3}$. Data are taken with sampling time of 0.1s and horizontal scanning speed of $V_{LHD}$=162mm/s. The figures indicate that the carbon emissions are localized in two parts, i.e. the top and bottom edges and the vicinity of inboard X-point. The line-integrated impurity line intensity is usually enhanced in the plasma edge as seen at the top and bottom emissions in the figures because the observation chord length passing through an impurity emission contour reflecting magnetic surface structure is considerably long at the plasma edge. The carbon emission is also enhanced along inboard X-point. It indicates a 3-D structure of the impurity distribution in the ergodic layer, reflecting a specific impurity transport in the ergodic layer.

### 5. Summary

The performance of 2-D space-resolved EUV spectrometer has been successfully improved without reduction of signal-to-noise ratio by installing a high frame rate CCD. It becomes possible to measure the 2-D distribution of impurity emissions from high-density short-pulse NBI discharges. Shot-to-shot intensity variation during horizontal scan can be significantly reduced by normalizing the 2-D impurity signal to the spectral intensity from EUV_Long spectrometer. As future work, 2-D distribution will be analyzed against different density ranges.

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