§4. First Performance of Energy Resolved X-ray Video Camera in LHD

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To study impurity behavior in magnetically confined plasma by injecting tracer-encapsulated solid pellet (TESPEL), new kind of X-ray detection system is required. The detector must measures the radial profiles of time-resolved soft X-ray spectra emitted from high temperature plasmas in LHD. The plasmas emit strong soft x-ray in an energy range from 1.0 keV to 10 keV. The spectra consist of continuum as bremsstrahlung emitted from electrons and K_α lines emitted from the impurities such as ionized argons and transition metals.

In the second fiscal year, we start to measure soft x-ray with using a Silicon-on-Insulator pixel detector (SOIPIX) installed at 7-O horizontal port in LHD. The SOIPIX has both thick high-resistive radiation sensor and CMOS readout circuit in a single chip[1]. The signal is read out in the fast time of 1 μs/pixel. The detector at the port is 264×264 pixels of 14 μm square. The thickness of the sensor is 500 μm to obtain the x-ray in the range from 1.0 keV to 10 keV, effectively. The data and control signals are transferred through an Ethernet I/F consisting of an on-board FPGA. The detector is cooled to less than -10 °C to reduce leakage current.

In the present research, the soft x-ray emitted from LHD is measured by means of an in-vacuum-pinhole camera to obtain the x-ray distribution. The pinhole is a diameter of 100 μm at a 200-μm-thick stainless plate. The plate is manually motional in the vertical direction. The precision of the motion is 10 μm. The x-ray through the pinhole and a 250-μm-thick beryllium filter is measured with the SOIPIX. The filter separates vacuum between LHD and the detector system, and reduces the flux of low-energy x-rays. For example, the transmission of argon K_α (E = 3.2 keV) and iron K_α (E = 6.7 keV) emitted from high temperature plasma are 18.4 % and 85.4 %, respectively. The distances between the pinhole and the plasma center (R_{ax} = 3600 mm), the pinhole and the sensor are 16.9 m and 65.5 mm, respectively. The sensor is 437 mm higher than LHD equator. At the plasma center the sensor approximately covers a 0.8-m-square region.

The measurement of an x-ray image has been tried at the last cycle (17th LHD experimental campaign). Figure 1 shows the first image obtained from a long pulse heated plasma of approximately 40-minutes pulse duration (LHD#124530, $T_e^{center} \approx 3.0$ keV). The total exposure time of the SOIPIX is 16 sec. The square frame means the whole region covered with the sensor. In the present measurement, the relative position of the sensor against the pinhole is fixed in the horizontal direction. From the experimental results, it is suggested that the sensor has horizontally shifted approximately 1.7 mm toward 6-O direction, at which the view frame has approximately shifted 400 mm towards 8-O direction. The pinhole exits at the higher position of 387 μm, at which the center of the view frame is corresponding to be 100 mm higher than the plasma center. In addition, the image is reversed due to the pinhole camera. Accordingly, the x-ray seems to come from the upper and 8-O sides of the 7-O port.

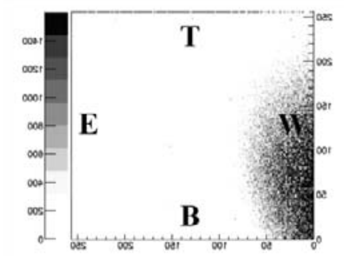

Fig.1. First x-ray image detected with the SOIPIX. The vertical and horizontal axes are corresponding to the Z and toroidal direction of the plasma, respectively. The signs of "T", "B", E", and "W" mean the top, bottom, 6-O side, and 8-O side of the sensor. At the sensor the x-ray image of LHD plasma is reversed due to the pinhole camera.

Figure 2 shows the comparison between the spectra obtained with the Si(Li) x-ray pulse-height analyzer (PHA) at 2-O port and the SOIPIX at the 7-O port. These ports are mutually facing in LHD. In the figure the surface intensities are equal around iron K_α. The peak intensities are proportional to the energy resolution of $E/\Delta E$, where ΔE is the width of the lines. Then, the energy resolution of SOIPIX is approximately 70 % in compared with the PHA.

The impurity transport has been studied by using the PHA system installed at 2.5L port[2]. The typical time resolution of the transport study is 50 ms, since more than 100 photons are necessary to obtain x-ray spectrum as shown in Fig.2. Serious drawback of this system is that the number of sightlines is limited to only three.

On the other hand, the SOIPIX makes it possible that the number of sightlines is effectively improved 32 times owing to its small pixel size. Therefore, it becomes possible to measure the impurity transport in a single shot of LHD. In this measurement, the readout region is assumed to be 256×8 pixels. While the readout time becomes longer (~2.05 ms) due to its large number of readout pixels, this time will be reduced significantly by introducing double-buffered pixel detector being developed.

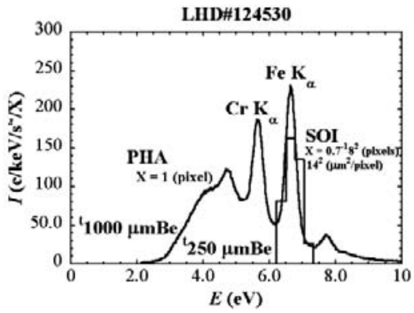

Fig.2. Spectra measured with the SOIPIX and the conventional PHA in LHD. The horizontal and vertical axes mean the photon energy and the intensities, respectively. The solid curve and line represent the spectrum measured with the PHA and the SOIPIX, respectively. It yields a high statistical error of approximately 25 % that the spectrum of the SOIPIX is an experimental result from a single pixel. The surface intensities are equal around iron K_α. The thicknesses of the beryllium filters are 1000 μm for the PHA and 250 μm for the SOIPIX, respectively. The spectral intensity of the SOIPIX is reduced to compare with that of the PHA, exactly.

1) Y. Arai, *et al*., Nucl. Instr. and Meth A. Vol. 636, Issue 1, Supplement, pp. S31-S36. DOI:10.1016/j.nima. 2010.04. 081.
2) S.Muto and S. Morita, Plasma and Fusion research **2,** S1069, 2007. DOI: 10.1585/pfr.2.S1069.