Design of an Automated Calibration Stage for the Detectors in KSTAR SXR Diagnostic System

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*Keywords: Soft X-ray, SiPM, AXUV, detector calibration

1. Introduction

Soft X-ray (SXR) measurement systems are among the essential diagnostics in fusion plasma research, as they are widely used for studying instabilities and impurity transport within the fusion plasma [1,2]. Thanks to their simple hardware structure, SXR diagnostics can be easily implemented as a multi-channel system. Fusion plasmas are optically thin to SXR [3] so that the local emissivity can be reconstructed from line-integrated signals measured by multi-channel SXR arrays. Since this procedure is valid only if the sensitivities of the detectors are identical, inter-channel calibration is necessary to obtain reliable reconstruction results. This calibration must be performed periodically, as direct exposure to the harsh vacuum environment can cause detector sensitivity changes across channels over time, even if they were initially calibrated [4].

To ensure that calibration is performed under controlled and consistent conditions, the calibration stage system has been used for the KSTAR SXR system. The current stage system, however, is manually operated, making the calibration procedure labor-intensive and prone to human error. Moreover, it was originally designed exclusively for Absolute eXtreme Ultra-Violet (AXUV) photodiode-based detectors and is mechanically incompatible with Silicon Photomultiplier (SiPM)-based detectors, which have recently been adopted for SXR diagnostics in KSTAR [5].

To address these issues, we have designed a fully automated photodetector calibration stage with enhanced reliability, detector compatibility, and user convenience, ultimately ensuring more accurate and consistent SXR measurements. A detailed discussion of the calibration procedure is presented in Section 2. The system design to meet the requirements of the proposed calibration procedure is explained in Section 3.

2. Development of a Reliable Calibration Procedure

As aforementioned, in the current calibration system, we manually adjusted the stage to locate the laser spot on each channel by the naked eye. To improve this cumbersome and inaccurate process, a motorized stage is applied. The overall calibration procedure using a motorized stage can be summarized as follows: First, the SXR detector to be calibrated is mounted on a two-axis motorized stage. Next, the stage is moved along a predefined path so that each channel is aligned with a 532 nm laser spot of constant intensity to scan the entire active area of the detector array. The approximate positions of the maximum signal intensity of each channel are obtained from the initial coarse scan, after which a fine scan is conducted near that position, yielding N 2D signal intensity maps. If the sensitivities of the channels differ, the maximum signal intensity for each channel will also differ. By selecting one channel as a reference and multiplying the other channels by calibration factors to match their sensitivity to that of the reference channel, the calibration procedure is completed.

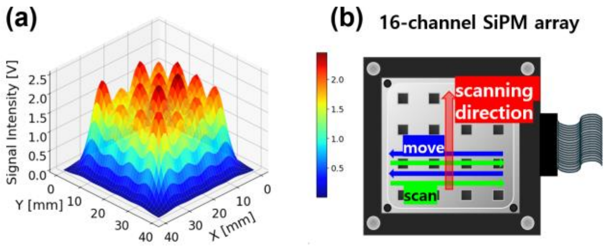

Fig. 1 (a) Example 2D signal intensity map of SiPM detector; (b) Schematics of the scan process of SiPM detector.

To elaborate, the scan process is divided into two subprocesses: the coarse scan and the fine scan. The approximate position of each channel can be found from the signal intensity map obtained from the coarse scan. The positions are determined as the locations where each channel has its maximum signal intensity, as exemplified by the red area in Fig. 1(a). Then, in the fine scan, the stage is moved to that position to perform a fine scan within a square region centered on that position. Using this method, we can reduce the overall calibration time while still achieving precise calibration.

In the coarse scan, the interval between each scan line was determined as one-quarter of the channel size to ensure that at least three scan lines pass through each channel size. Considering a one-way scan, the interval between each path line is half that of a scan line. For example, SiPMs have a channel with a 4 mm × 4 mm active area, whereas AXUVs have a 1 mm × 5 mm channel. The interval between each path line of the coarse scan for SiPMs and AXUVs is 0.5 mm and 0.625 mm, respectively.

In the fine scan, the size of the square-shaped scan region is the same as the interval of the coarse scan. Also, the interval between each path line in the fine scan is fixed at 100 μm, which is one order of magnitude larger than the unidirectional positioning accuracy of the motorized stage (several tens of μm).

To prevent positioning errors caused by backlash, the scan should be one-way. In Fig. 1(b), the green lines represent stage motion during scanning, and the blue lines represent motion without scanning.

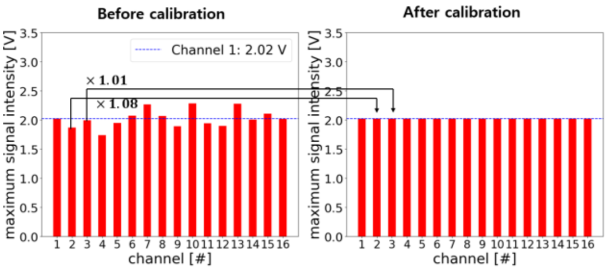

Fig. 2 Examples of measured maximum signal intensity and calibrated result.

After two scan subprocesses, we obtain the position of the N maximum sensitivities for each N channel, respectively. As the final process, the stage moves to each position of maximum signal intensity in order, and stops for 5 s to acquire a time-series signal. Averaging each time-series data over time, the maximum signal intensity is obtained. Finally, the calibration factors are calculated for each channel based on the reference signal intensity as exemplified by channel 1 in Fig. 2. This calibration procedure ensures that all channels in one array have identical signal intensities for a constant light input, i.e., equal sensitivity, by multiplying the signal of each channel by its corresponding calibration factor.

3. System Design

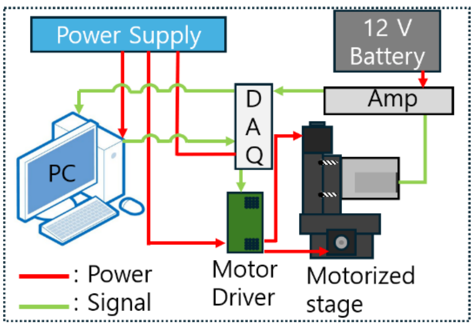

Fig. 3 Schematic of the SXR photodetector automated calibration system.

We designed the hardware as a platform to implement the calibration procedure proposed in Section 2 as follows. First, a two-axis motorized stage is used to move the detector module so that it aligns with the fixed 532 nm laser point as a light source. The DAQ (Data Acquisition) module is used not only for data acquisition but also for step motor control to simplify the system. We applied NI USB-6423 DAQ model to meet the requirements of the number of analog input pins for each multi-channel array and the counter pins needed to generate step motor control pulses. Also, a 12 V battery is used with the detector amplifier to prevent it from being affected by external noise. We perform the entire calibration procedure through a user interface based on LabVIEW software on the PC, which sends control signals and collects measurement signals.

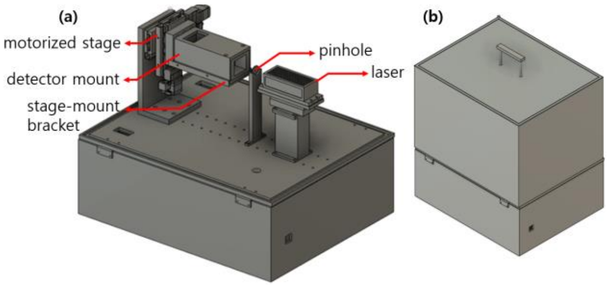

Fig. 4 (a) Assembly of the automated calibration stage system without the light-shielding cover; (b) With the light-shielding cover.

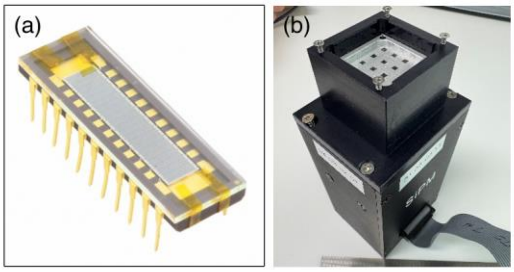

Fig. 5 (a) AXUV detector; (b) SiPM detector with a light guard.

Figure 4(a) shows each component of the stage system, and Figure 4(b) shows the stage with an acrylic light-shielding cover containing an inner light-absorbing film to block ambient light. In the system, two-axis motorized stages are combined together with a stage-to-stage mount. The combined motorized stage is mounted on the base plate using the stage-mount bracket. To accommodate detectors of various sizes and shapes, as shown in Figs. 5(a) and (b), we designed a detector mount that can securely hold each type on the stage. For ease of assembly, we designed not only the detector mount but also the stage-mount brackets.

The detector mount is not directly installed on the stage but rather mounted on the bracket, allowing the mount to be easily replaced and reassembled, as presented in Fig. 6. All of these components of the system were designed to ensure that the distance between the detector and the laser remains constant, independent of the detector type. In addition, they were made of anodized aluminum to minimize reflected light. The pinhole mount was also added to adjust the size of the laser spot using a pinhole in case the laser spot is larger than the detector channel.

The space below the base plate is designed to accommodate the required electronic components, such as the DAQ, motor driver, battery, power supply, and amplifier. The USB-6423 DAQ model used in the system is sufficiently compact to be packaged within the stage assembly.

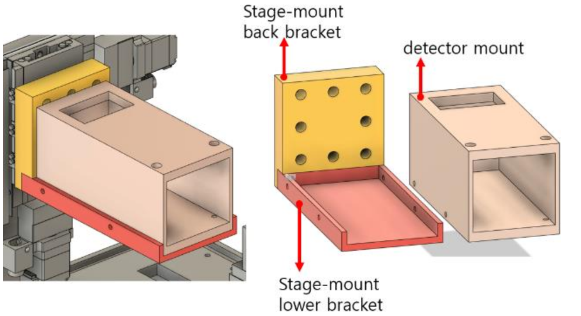

Fig. 6 Assembly of the detector mount and the stage-mount brackets.

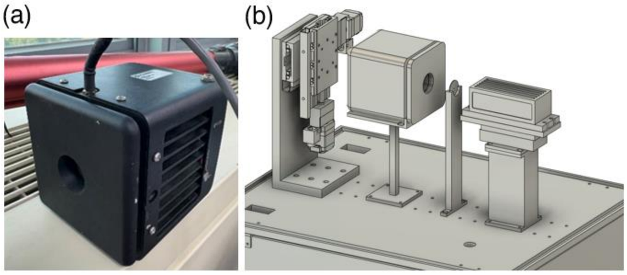

Fig. 7 (a) Powermeter; (b) Assembly with the powermeter.

The laser may slowly degrade over time, and although the calibration among the channels is relative, it is hard to expect that the sensitivity of the detector remains linearly proportional to the light intensity. For high-fidelity calibration, the light intensity at the light–capturing position should be kept constant across all calibration events. We designed a powermeter mount, as illustrated in Fig. 7(b), to position the powermeter at the same location as the active area of the detector when measuring the absolute intensity level of the laser. Using the manual stage beneath the laser module, we can adjust the absolute intensity of the laser at the active area to maintain its level across calibration events.

4. Summary

In this study, we established a reliable calibration procedure for SXR arrays, comprising three steps: First, the motorized stage moves the detector array along the predetermined path to coarsely scan the entire active area of the detector. Second, based on the information on the positions of the maximum signal intensity for each channel obtained from the first coarse scan, the stage moves the detector array to these positions and performs a fine scan within a square-shaped region. After the two scanning processes, we obtain the relatively accurate position of the maximum signal intensity for each channel. Finally, the stage moves the detector array to these final positions and the signal is measured and averaged over time. The time-averaged maximum signal intensities for each channel are then used to calculate the calibration factor.

To implement the proposed calibration procedure, a calibration stage system was designed. This detector-type-independent, fully automated system consists of a two-axis motorized stage, a 532 nm laser as a light source, a light-shielding cover, and multiple mounts and brackets to secure each component in the correct place. A DAQ is employed for both data acquisition and step motor control, thereby simplifying the system.

We have completed the system design and are currently in the fabrication process, and we plan to conduct an operational test once fabrication is complete. After the test, the improved calibration procedure using the automated system will contribute to studies of instabilities and impurity transport based on the KSTAR SXR data.

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