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R&D OF AN ULTRAFAST X-RAY BEAM SIZE MONITOR FOR SuperKEKB

R. Nomaru[†,1,2], G. Mitsuka[2], M. Andrew[3], K. Yoshihara[3], C. Driver[3], L. Ruckman[4]
[1]The University of Tokyo, Tokyo, Japan
[2]High Energy Accelerator Research Organization, Ibaraki, Japan
[3]University of Hawaii, Honolulu, HI, USA
[4]SLAC National Accelerator Laboratory, Menlo Park, CA, USA

Abstract

At SuperKEKB, sudden beam loss (SBL)—a beam instability that develops within several tens of microseconds—has become a major obstacle to higher luminosity. Observations have indicated that the beam size can expand abruptly during SBL, highlighting the need for ultrafast diagnostics. To address this, we are developing a bunch-by-bunch beam size monitor using synchrotron X-rays and a 128-channel silicon strip detector. Initial tests with a pulsed laser confirmed proper detector and readout operation, and gain calibration is underway. The monitor will be installed for beam measurements in the next SuperKEKB operation beginning November 2025.

INTRODUCTION

The SuperKEKB accelerator [1] is a high-luminosity electron–positron collider employing 4 GeV positrons and 7 GeV electrons. In December 2024, it achieved a world-record peak luminosity of 5.1×10^{34} cm^{-2}s^{-1}. The ultimate goal is to exceed this record by more than an order of magnitude, and accelerator operations are ongoing toward this achievement. However, a phenomenon known as Sudden Beam Loss (SBL) has emerged as one of the critical obstacles to further luminosity upgrades [2]. SBL refers to a beam instability that rapidly develops over an extremely short timescale of several tens of microseconds, causing severe beam losses and ultimately leading to beam aborts. These aborts not only damage accelerator components and detectors, but also hinder increases in beam current and reduce the effective collision operation time.

Understanding the mechanism of SBL is essential for realizing higher luminosity at SuperKEKB. Previous observations suggest that the beam size can increase abruptly during SBL events [3], indicating the necessity of accurately capturing beam-size variations on such short timescales. Although SuperKEKB is equipped with a beam size monitor capable of turn-by-turn measurements, no existing system provides the faster time resolution required for SBL studies.

To address this limitation, we are developing and testing a novel beam size monitor capable of bunch-by-bunch measurements. In addition to enabling detailed investigations of SBL, this monitor is also expected to serve as a valuable tool for studying other beam instabilities, such as electron cloud effects, which have long been recognized as issues in collider operation.

† nomaru@post.kek.jp

BEAM SIZE MEASUREMENT METHOD

In the SuperKEKB main ring, the beam size is measured using synchrotron X-rays emitted when the beam is deflected by a bending magnet. The X-rays pass through a coded-aperture slit, and the resulting image is recorded. By fitting the obtained pattern, the beam size is extracted [4]. A schematic view of this method is shown in Fig. 1.

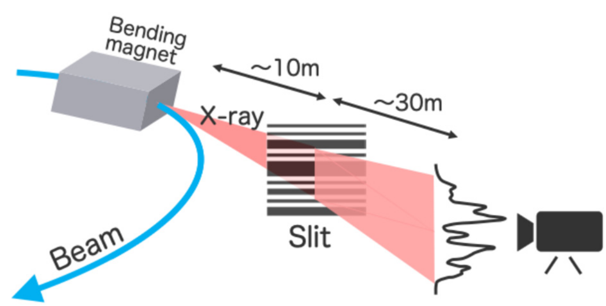

Figure 1: Concept of the X-ray beam size monitor.

The fastest imaging device employed at SuperKEKB has been a CMOS camera, which enables turn-by-turn measurements with a sampling rate of approximately 100 kHz. In this study, we introduce a silicon strip detector as a new imaging device. By sampling synchrotron X-ray images at 2.7 GSa/s, the system achieves bunch-by-bunch beam size measurements, corresponding to a minimum bunch spacing of 4 ns.

CONFIGURATION OF THE ULTRAFAST BEAM SIZE MONITOR

We are currently conducting performance tests of the ultrafast beam size monitor jointly developed by KEK, the University of Hawaii and SLAC. A photograph of the monitor is shown in Fig. 2. The system consists of three main components: a sensor board equipped with a 128-channel silicon strip sensor, a preamplifier board for signal amplification, and a DAQ board responsible for digitization and data transfer. Each DAQ board can process signals from 32 channels, and by stacking four layers, the system records all 128 channels at a sampling rate of 2.7 GSa/s. The DAQ board employs the same readout circuit developed by the University of Hawaii for the Belle II TOP detector [5].

An enlarged view of the silicon strip sensor is presented in Fig. 3. The sensor was fabricated at the Stanford Nanofabrication Facility and contains 128 cathode strips with a pitch of 50 μm. The depletion layer depth is 75 μm,

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and the sensor is typically operated at a bias voltage of −40 V. Currently, only 42 of the 128 channels were connected to the downstream electronics for the initial test, and we report the results obtained with this configuration.

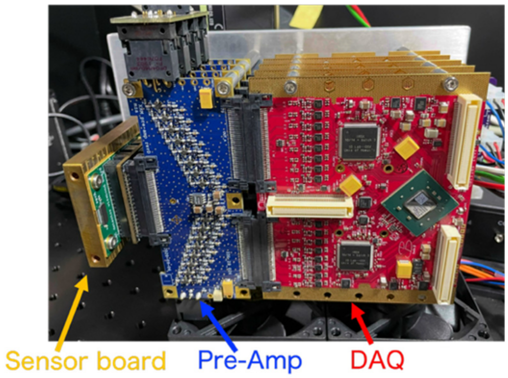

Figure 2: Photograph of the ultrafast beam size monitor.

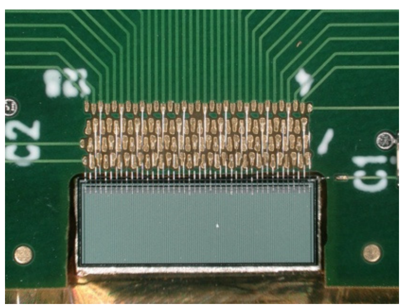

Figure 3: Enlarged photograph of the silicon strip sensor. The X-rays enter from the bottom of the image.

TEST BENCH CONFIGURATION

To verify the operation of the monitor, we conducted laser illumination tests of the silicon strip sensor using a pulsed laser as a substitute for synchrotron X-rays. A schematic of the test bench setup is shown in Fig. 4. Inside a light-tight enclosure, both the pulsed laser source and the complete sensor system were installed. The laser was mounted on a motorized vertical stage, enabling remote adjustment of the irradiation position on the sensor. Data acquired by the DAQ system were transferred to an external computer via optical fiber, and the sensor bias voltage was also controlled externally.

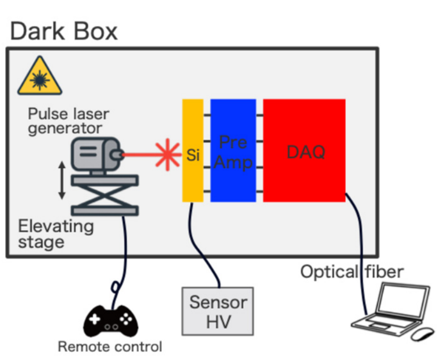

Figure 4: Test bench configuration using a pulsed laser.

The pulsed laser employed in this study was the NPL98B model from Thorlabs [6], which provides laser light at a wavelength of 980±10 nm with five selectable pulse widths. For the present tests, we used the shortest available pulse width of 6 ns (see Ref. [6] for detailed pulse characteristics).

LASER IRRADIATION TESTS

Sensor Response Characteristics

We first evaluated the response of the silicon strip sensor to pulsed laser irradiation. Figure 5 shows the output waveform from one channel for a single laser pulse, observed directly with an oscilloscope. The sensor produced an output pulse with a temporal width comparable to that of the incident laser pulse. The pulse height was defined as the voltage difference between the baseline and the peak of the waveform, as indicated by the arrow in Fig. 5.

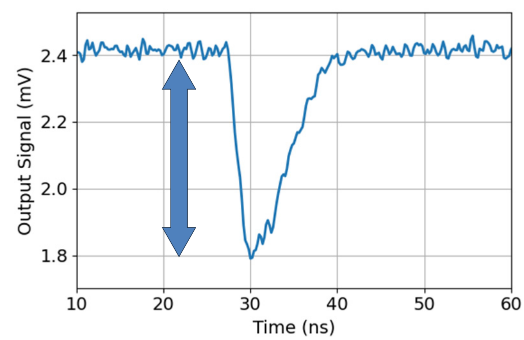

Figure 5: Output waveform of one channel of the silicon sensor for a single pulse irradiation. The arrow indicates the definition of pulse height.

Figure 6 presents the dependence of the pulse height (blue) and bias current (red) on the applied bias voltage. Both quantities increased as the magnitude of the bias voltage was raised. In particular, the increase in pulse height exhibited a tendency to saturate at higher bias voltages.

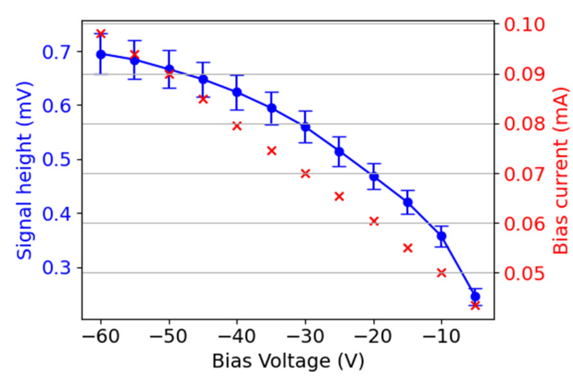

Figure 6: Relationship between bias voltage and pulse height (blue) / bias current (red).

Preamplifier and DAQ Response

Next, waveforms were recorded using the preamplifier and DAQ system for signal amplification and digitization. Figure 7 shows the overall response of the silicon strip

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sensor to a single laser pulse. An enlarged view of the waveform from channel 89 is provided in Fig. 8. In this measurement, signals were clearly observed in the region around channels 60–110, indicating that the laser was irradiating this portion of the sensor.

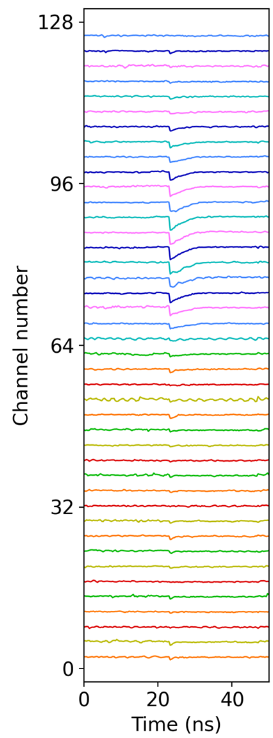

Figure 7: Overall response of the silicon strip sensor to a single laser pulse recorded by the DAQ. Only 42 out of 128 channels are shown.

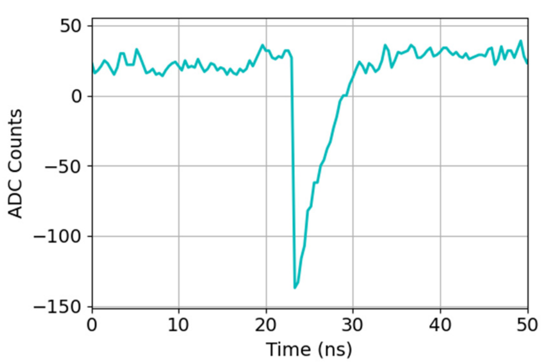

Figure 8: Single-pulse response of channel 89 recorded by the DAQ.

By moving the laser vertically with the motorized stage, the range of channels showing signals was expected to shift accordingly. Figure 9 shows a heatmap of pulse height distributions across the channels as a function of the laser's vertical position. A clear linear relationship was observed, in which the channels recording the signal moved consistently with the change in irradiation position.

These results confirm that both the sensor and the downstream readout electronics are functioning properly. This provides a foundation for subsequent gain calibration of individual channels in preparation for beam-based measurements.

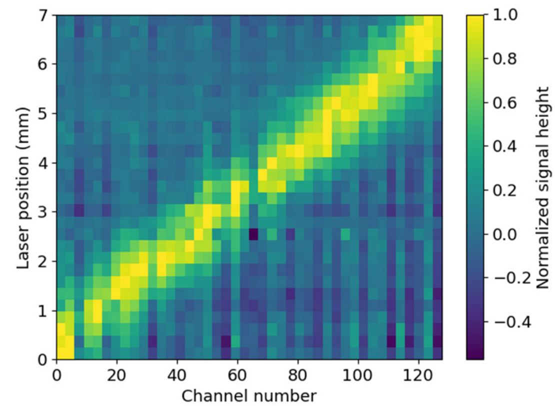

Figure 9: Relationship between laser vertical position and pulse height in each channel.

CONCLUSION AND FUTURE PROSPECTS

We have been developing and testing a novel beam size monitor capable of bunch-by-bunch measurements to investigate beam instabilities at SuperKEKB, such as Sudden Beam Loss (SBL) and electron cloud effects, in greater detail. The monitor employs a silicon strip detector to capture synchrotron X-ray images with high speed, enabling beam size measurements for bunches arriving at intervals as short as 4 ns. Through irradiation tests using a pulsed laser, we confirmed that both the sensor and the associated electronics function properly. The monitor is scheduled to be installed in the SuperKEKB main ring for beam observations during the next operation period beginning in November 2025.

Several technical challenges remain. For example, the sampling clock is not synchronized with the accelerator RF signal, and the DAQ boards lack onboard memory, limiting the ability to record large numbers of bunches simultaneously. To overcome these limitations, we are leveraging our previously developed RFSoC-based bunch-by-bunch BPM system [7-9] to upgrade the beam size monitor with a renewed readout design. Beam size measurements using this enhanced system are expected to begin in the fall of 2026.

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