

Visualizing the three-dimensional shape of a high-energy particle beam using a position-sensitive photodiode

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We describe a simple and robust method for particle beam visualization using a general-purpose position-sensitive photodiode as a time- and position-sensitive particle detector. The detector and data acquisition system were characterized using an Am-241 source and tested in an accelerator experiment using a high-energy ion beam at beam intensities of 10^4 s^{-1} region. With an FPGA-based digital signal processing, the pulse height and timing of the photodiode signal allow the observation of the spatial and temporal profile of the beam, i.e., the real-time movie of the particle beam, with fairly good spatial and temporal resolutions. The 3D imaging of the beam clearly visualized the temporal profile of the beam spill as well as the long-term shot-by-shot stability of the beam without significant damage on the detector. This simple technique is quite useful for beam diagnosis in high-energy beam experiments and a variety of applications.

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I. INTRODUCTION

The visualization of temporal and spatial beam profiles is one of the key technologies in many applications using particle beams, ranging from atomic, nuclear, and particle physics, material analysis, medical diagnosis and treatment, semiconductor industries, and so on. Numerous varieties of beam profile monitors have been developed for different applications, which are classified into two types: scanning or multiplexing one-dimensional (1D) detectors and using two-dimensional (2D) detectors. Generally, the use of metal wires is relatively robust to a wide range of beam energies and intensities. Scanning or multiplexing the wires gives the 1D beam profile at a position resolution determined by the wire diameter, typically from $10 \mu\text{m}$ to 1 mm [1,2]. Instead of wires, the use of scintillating fibers [3] helps improve time resolution to the nanosecond scale. For 2D detectors, the simplest solution is to use 2D scintillation materials, which visualize the beam by converting the particle kinetic energy into visible light. The light can be observed even by human eyes if the beam intensity is sufficient. In many cases, using appropriate optics the light is detected in a position-sensitive manner, most simply by a

camera, with photomultiplying devices if required. The sensitivity and efficiency of these detectors are usually determined by the signal-to-noise ratio and the quantum efficiency of the photon detector, respectively. For moderate beam intensities, coupling of cameras with single-particle detectors such as microchannel plates (MCP) provides a good position and time resolutions better than $100 \mu\text{m}$ and 1 ns , respectively [4,5]. The MCP with a delay-line anode [6] also delivers an equivalent performance, which is in particular use in the keV energy region.

For MeV or higher-energy particles, one can use semiconductor detectors, which convert the particle kinetic energy directly into the proportional electronic charge signals [7–9]. The semiconductor detectors have advantages over the fluorescence and MCP detectors in terms of quantitativity of the beam intensity and particle energy. The use of materials like diamond [10] and silicon carbide [11] has been shown to provide improved performance than silicon in terms of fast operation and radiation hardness. Recent rapid advances in 2D semiconductor detectors have been driven by the micropixelization of the semiconductor sensors and the development of pixel readout ASICs (see the review literature [12,13] and references therein). The latest technology achieves a readout of more than 200 k pixels at a pitch of $55 \mu\text{m}$ with a subnanosecond time resolution [14]. Such techniques have also been applied to time-resolved imaging of high-energy particle beams [15,16], although the positional resolution is not simply determined by the pixel size since the high-energy particle generates multipixel events.

On the other hand, nonsegmented 2D sensors are still extremely useful in terms of its robustness and simplicity,

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which have two pairs of electrodes on a single semiconductor detector. A continuous position information is obtainable by only four readouts with an excellent position resolution competitive to the pixel detectors. The four-channel output signals can be processed by common laboratory electronics. Moreover, position-sensitive photodiodes (PSD) based on such operation principles are now widely used in optoelectronic devices and are commercially available at very low costs. The performance of 2D position-sensitive photodiodes in particle detection has been tested in several earlier works in terms of position resolution and linearity [17–25]. These studies observed the 2D position of the incident MeV particles from the Am-241 radioactive source or accelerator beams with several tens to hundreds of micrometer resolutions depending on the detector specification and subsequent pulse-processing electronics. The application of these detectors was demonstrated in material analysis using the Rutherford back-scattering (RBS) and channeling experiments [26,27]. Other than MeV ions, the application in electron detection was also examined using the Cs-137 source [28]. Nevertheless, the feasibility of time-resolved particle detection using position-sensitive photodiodes has yet to be verified. In this study, using a general-purpose position-sensitive photodiode, we demonstrate the three-dimensional (3D) visualization of particle beams and their application to the spatial and temporal diagnosis of accelerator beams.

II. DETECTOR AND DATA ACQUISITION

We used a 20×20 mm² duolateral type position-sensitive photodiode (PSD), DL-20C from OSI Optoelectronics, which

has a pair of electrodes on the front and rear surfaces as shown in Fig. 1(a). This type of diode features a higher position resolution compared to those with four electrodes on one side, i.e., the tetralateral type. A glass window of the photodiode was removed for particle detection. The charge carriers created by a particle are driven to the four electrodes through the resistive layer of the diode. Because the charge amount collected at each electrode is inversely proportional to the incident position, the relation is given by

$$x = \frac{L_x}{2} \frac{Q_{x2} - Q_{x1}}{Q_{x2} + Q_{x1}}, y = \frac{L_y}{2} \frac{Q_{y2} - Q_{y1}}{Q_{y2} + Q_{y1}}, \quad (1)$$

where $Q_{x1}, Q_{x2}, Q_{y1}, Q_{y2}$ are the charges from each electrode, L_x, L_y are the distances between two electrodes, respectively. In the normal use as a photodetector, the carriers are recorded as photocurrents using current amplifiers and give the center-of-mass position of the incoming light. In particle detection, the carriers have to be recorded through charge-sensitive amplifiers. The total amount of charge carrier Q_{tot} created by the incident particle is proportional to its kinetic energy loss in the depletion layer of the diode.

To visualize the 3D shape of a particle beam using Eq. (1), it is necessary to determine the relative signal intensity from the four signals with the time when the event was triggered. To achieve this with minimal dead time, we developed data acquisition electronics composed of analog amplification and digital signal processing parts, as shown in Fig. 1(b). In the analog part, the charge signal from each electrode was integrated at the

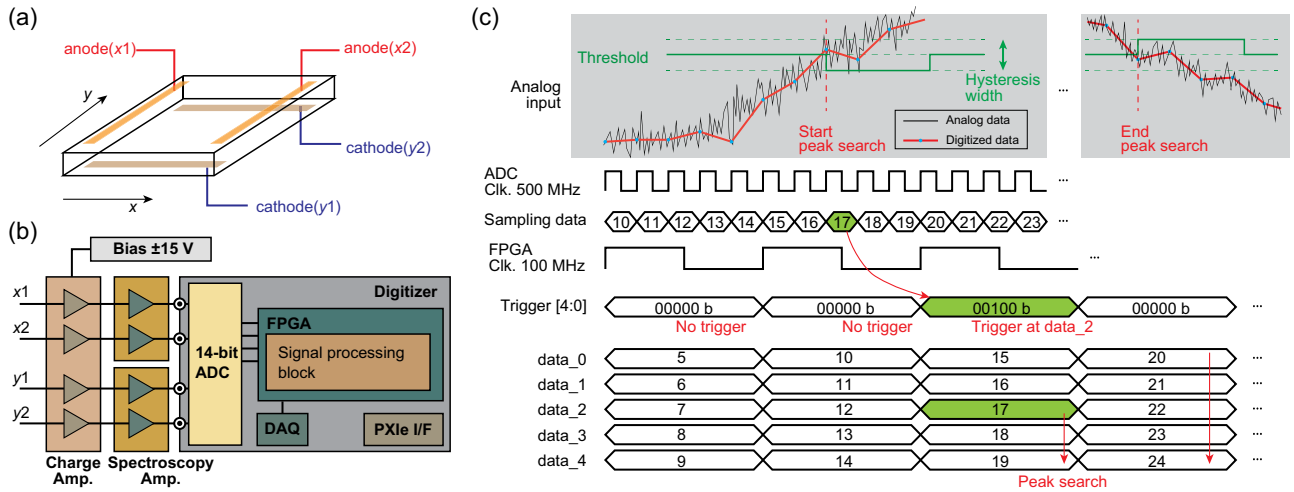


FIG. 1. (a) Structure of the duolateral position-sensitive photodiode and the xy coordinate system. (b) A schematic diagram of the data acquisition system, which consists of an analog four-channel charge-sensitive preamplifier, dual-channel spectroscopy amplifiers (Amp.), and a four-channel 14-bit digitizer with an on-board customizable FPGA. (c) A simplified signal and timing diagram of the digitizer: on the top, the input analog signal (black line) and digitized samples (blue dots) are presented. The green line shows trigger threshold for peak detection, to which hysteresis behavior is implemented to realize a Schmitt trigger. The lower part shows the timing of the ADC sampling and subsequent data processing at the FPGA.

four-channel charge-sensitive preamplifier (CAEN A1422) and shaped into a semi-Gaussian unipolar pulse by a spectroscopy amplifier (ORTEC 855). The preamplifier's gain was 5 mV/MeV, and charge collection time was approximately 20 ns for the given detector capacitance of 600 pF. A bias voltage of ± 15 V was applied to the cathode and anode surfaces of the detector, respectively, through the preamplifier. Increasing the bias voltage can shorten the charge drift time in the diode; however, the overall charge collection time is constrained by the surface resistance and capacitance of the PSD, as discussed later. For the spectroscopy amplifier, the input polarity was set to positive and negative for signals from anodes and cathodes, respectively. The gain and shaping time were chosen appropriately depending on the situations. A key advantage of the present method is that it employs general-purpose analog amplifiers and does not require specialized electronics, making it highly versatile and widely applicable. Although the maximum count rate is limited to the order of 10^4 cps, the method remains suitable for various experiments operating within this intensity range, including those that do not necessarily use a primary beam.

These analog pulses from the amplifier were fed to a 14-bit four-channel digitizer (Keysight M3102A). It is currently a popular way to record all the triggered waveforms and extract detailed information by off-line analysis. However, the data transfer rate becomes a bottleneck as the count rate increases. In this study, we do not save the waveform but only the peak height and the time stamp using the onboard FPGA (Xilinx Kintex-7). The FPGA's pipelined parallel processing allows a continuous data stream through the multiple stages of signal processing without causing any input dead time. We developed a dedicated logic circuit using Verilog HDL and Keysight Pathwave FPGA software. A simplified timing diagram is shown in Fig. 1(c). The input signal is digitized by the Analog-to-Digital Converter (ADC) interface at a 500 MHz sampling rate and transferred to the FPGA block. Because the FPGA operates at 100 MHz, five sampling data are processed in parallel at each clock. Each event is detected on its rising edge by a Schmitt trigger block, in which the threshold level is shifted up and down for a certain period after the rising and falling edge trigger, respectively, to stabilize the trigger against noise. When the event is detected, the signals are sent to the peak-searching block in which the peak heights of four signals are saved to the register of the FPGA. The event-by-event data of the four signal heights and the 100-MHz time stamp are transferred to a data-acquisition PC through a PXIe interface. Note that the actual sequence is a bit more complicated than Fig. 1(c): the FPGA includes the sum, delay, and walk-averaging blocks programmed for triggering events on a smoothed Q_{tot} signal, which has the same pulse height independent of the hit position.

III. CHARACTERIZATION USING ^{241}Am SOURCE

Characterization of the PSD was performed using a 5.4 MeV α particles from an Am-241 source. First, we examined the response of the photodiode to particle incidence and the performance of the data acquisition system described in the previous section. The detector was mounted on a universal printed circuit board using pin sockets and installed in a vacuum chamber. The four output pins of the photodiode were connected to the preamplifier through coaxial cables and a vacuum feed-through. The α source was placed in front of the detector at approximately 100 mm distance. A mask with $\varnothing 1$ mm holes in 2.54-mm pitch was set on the entrance surface of the detector. Figures 2(a)–2(c) upper panels are the 2D images obtained with different shaping times at the spectroscopy amplifier; $\tau_{\text{Amp}} = 0.5, 1.0$, and 3.0 μs . Each image shows the dot pattern of the mask but with a considerable distortion, especially at the edges of the active area when the shaping time is short. This is known as a pincushion distortion caused by the ballistic deficit of the charge carriers, which arises when the pulse shaping time τ_{Amp} is not sufficient compared to the charge collection time constant RC [23]. The surface resistance and capacitance of the present detector were 10 k Ω and 600 pF, respectively, resulting in the time constant RC on the μs order. In addition, the capacitive coupling between the anode and cathode surfaces causes a bipolar behavior of the charge signal, which also contributes to the ballistic deficit [19,29]. The deficit of the charge carrier is obviously observed in the total charge $Q_{\text{tot}} = Q_{x1} + Q_{x2} + Q_{y1} + Q_{y2}$ histogram. The lower panels in Figs. 2(a)–2(c) show the relations between Q_{tot} and the x position of the detector corresponding to the 2D images. When the shaping time $\tau_{\text{Amp}} = 0.5$ and 1.5 μs , the total charge Q_{tot} is lower near the center of the detector. Although the number of charge carriers created by the α particle is the same, the observed Q_{tot} depends on the hit position, leading to the distortion of the image. These effects have been investigated over a long period, and several algorithms have been proposed to correct the distortion [30–34]. However, when $\tau_{\text{Amp}} = 3.0$ μs , the total charge Q_{tot} appeared to be almost constant around the ADC channels 30 to 35 independent of the x position. The 2D image was obtained with good linearity and negligible distortion in this condition. The size and position of the available 7×7 dots in Fig. 2(c) were analyzed using Gaussian functions fitted to each dot. A linear fit of the dot positions estimated the calibration factor as 0.0781 ± 0.0004 mm/channel with a coefficient of determination $R^2 = 1.0017$.

The position resolution of the presented method was evaluated from the analysis of 2D image of the mask pattern obtained with the shaping time $\tau_{\text{Amp}} = 3.0$ μs .

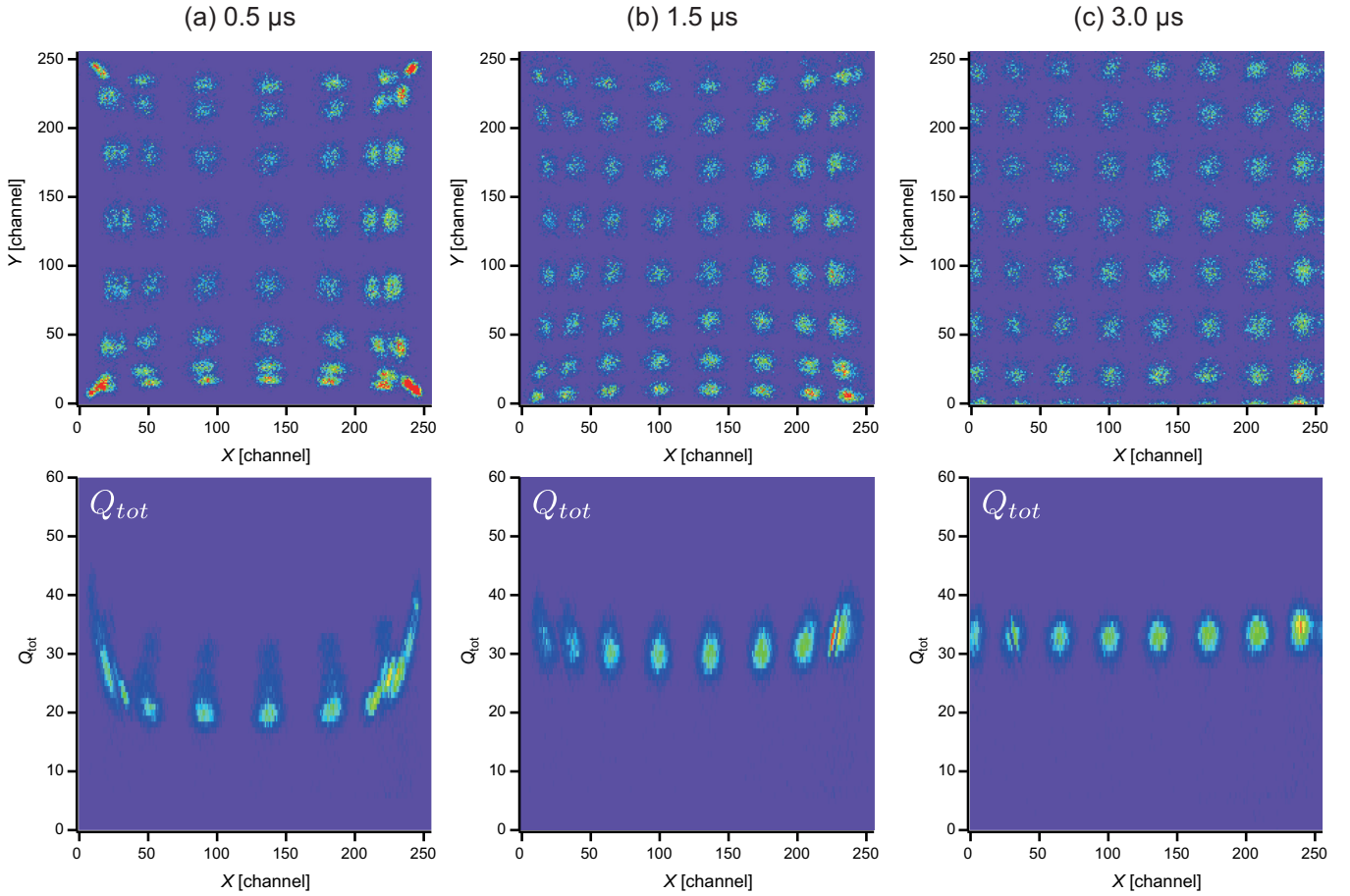


FIG. 2. The upper panels are 2D images of the mask pattern observed using an Am-241 α source. The shaping times of the amplifier τ_{Amp} were (a) 0.5, (b) 1.5, and (c) 3.0 μs . The effect of pincushion distortion is prominent when τ_{Amp} is small. The relation of x position and the total charge Q_{tot} corresponding to the 2D images are shown in the lower panels. The histograms are normalized to the total number of detected particles.

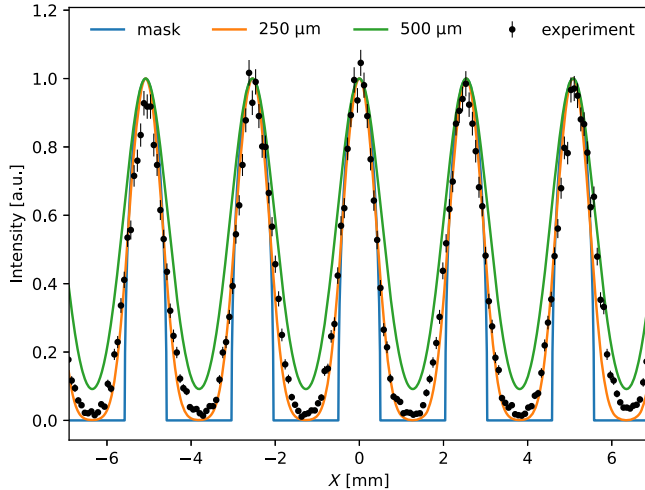


FIG. 3. Projection of the 2D mask image observed using an Am-241 α source with the shaping time of the amplifier $\tau_{\text{Amp}} = 3.0 \mu\text{s}$. The solid lines show the theoretical model curves for the raw mask image and those convolved with different detector resolutions, 250 and 500 μm .

In Fig. 3, the x projection of the 2D image is shown with model curves for different position resolutions. The curves represent the projection of the raw mask pattern and those convolved with Gaussian functions with standard deviations $\sigma = 250$ and $500 \mu\text{m}$. The experimental data and model curves are normalized to their peak heights, exhibiting a clear changes in the pattern contrast depending on the position resolution. From this comparison, we estimated the position resolution of the PSD for this α particle measurement to be 250 μm . A possible resolution improvement for higher-energy ions may be expected due to the large signal-to-noise ratio of the output signal. However, the obtained position resolution is already close to the systematic position detection error of 200 μm specified for the DL-20C photodetector. The energy resolution can be estimated to be $\sim 820 \text{ keV}$ at 5.4 MeV from the FWHM of the Am-241 line in the Q_{tot} spectrum. Although this is not as good as high-resolution semiconductor detectors, the double-hit events and possibly background signals can be eliminated by setting an appropriate window to the Q_{tot} value.

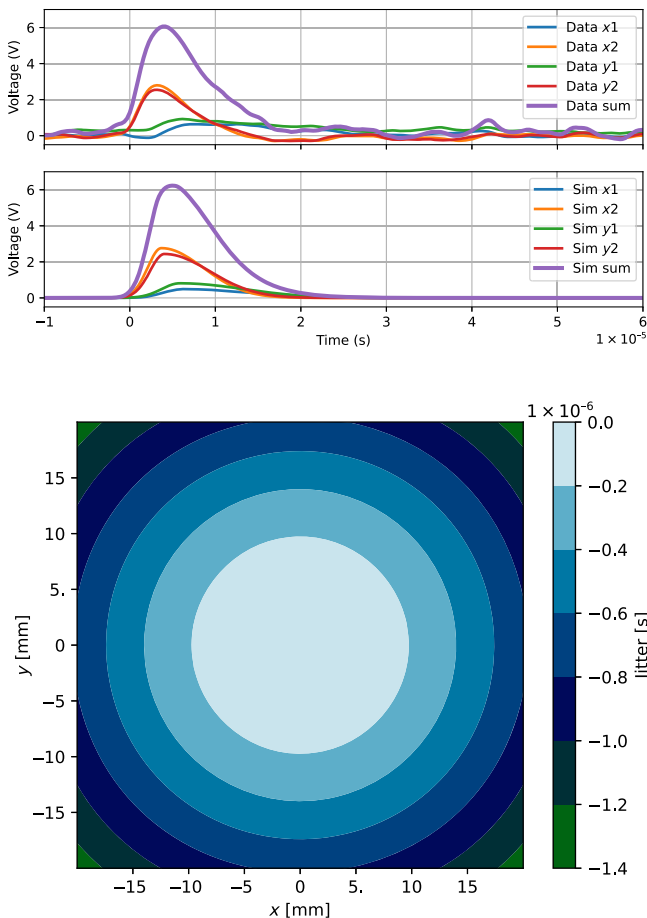


FIG. 4. Top and bottom waveforms: the experimental data (“Data”) and simulation (“Sim”) for the signals from four electrodes of the PSD and their sum, respectively. Two-dimensional map: timing jitter calculated from the simulated waveforms at various hit positions on the PSD.

To evaluate the accuracy of the time information obtained, we also performed an analysis of timing resolution. The resolution of the digitizer is 2 ns, but the time resolution of the present method is rather limited by the timing jitter of the detector signal. Due to the capacitive behavior of the detector, the hit position affects not only the pulse height but also the rising time of the signal and consequently the timing jitter of the sum signal. We have conducted a timing simulation based on earlier studies [23,35,36], and analyzed the timing jitter and its position dependences. The top and bottom waveforms in Fig. 4 show the experimental and simulated signals for an α particle hit event at $(x, y) = (7 \text{ mm}, 5 \text{ mm})$. For the experimental data, four outputs x_1 , x_2 , y_1 , and y_2 from the spectroscopy amplifiers and their sum signal are presented. The waveform simulation assumed an asymmetric Gaussian function

with a position-dependent rise and fall time constant to reproduce the experimental data. The position-dependent time delay of the signal was assumed to be proportional to the propagation distance d on the resistive surface [23] and included as $0.3 \text{ RC}(d/L)$ in the present simulation. We calculated the position-dependent timing jitter assuming that the trigger threshold is set at 50% of the peak height of the sum signal. Taking the timing at the PSD center as a reference, the calculated jitter is shown as a 2D map in Fig. 4. The jitter is at most approximately $1 \mu\text{s}$ within the central 90% region of the detection area. This time resolution may be further improved by correcting the position dependence of the timing, if the signal waveform is well characterized.

IV. 3D IMAGING OF HIGH-ENERGY ION BEAM

We used a 465 MeV/nucleon Ar^{16+} beam from the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS), Japan. The beam was slow extracted from the heavy ion synchrotron HIMAC as a spill with approximately 1.0 s duration over a 3.3 s repetition period using the double RF-KO method [37]. The beam intensities were set to be between 10^2 and 10^4 particles/spill at the detector. A silicon foil of 1.5- μm thick was inserted in the beamline as a charge stripper, and the beam was charge separated by a dipole magnet before entering the detector. Using Eq. (1) for x (horizontal) and y (vertical), and the timestamp for z (longitudinal) positions, the 3D structure of the ion spill was reconstructed and shown in Fig. 5(a). The 3D image was created by integrating 74 spills for clarity. In this experiment, the beam had a negligible divergence, smaller than 0.05 mrad evaluated from the beam size at the PSD and the configuration of the beam transport, and thus the particle velocity was approximated parallel to the beam axis z . The beam spill was separated in three charge states, Ar^{16+} , Ar^{17+} , and Ar^{18+} , owing to the electron loss in the stripper. The x – y projection of the image, which is the ordinal observation using 2D detectors, clearly shows the charge separation of the beam. The full width at half maximum (FWHM) beam size was 2.9 mm (horizontal direction x) and 3.8 mm (vertical direction y). The charge fractions of Ar^{16+} , Ar^{17+} , and Ar^{18+} were obtained as 45.9%, 38.3%, 15.8%, respectively. These fractions were in reasonable agreement with an estimation using the ETACHA4 code [38]. In addition to these, 3D imaging allows the evaluation of the temporal structure of the beam spill as observed in the t – x and t – y projections. It was deduced that the x position of the beam fluctuates within the spill duration, whereas the y position remains stable. This can be explained by the fact that the beam was slow

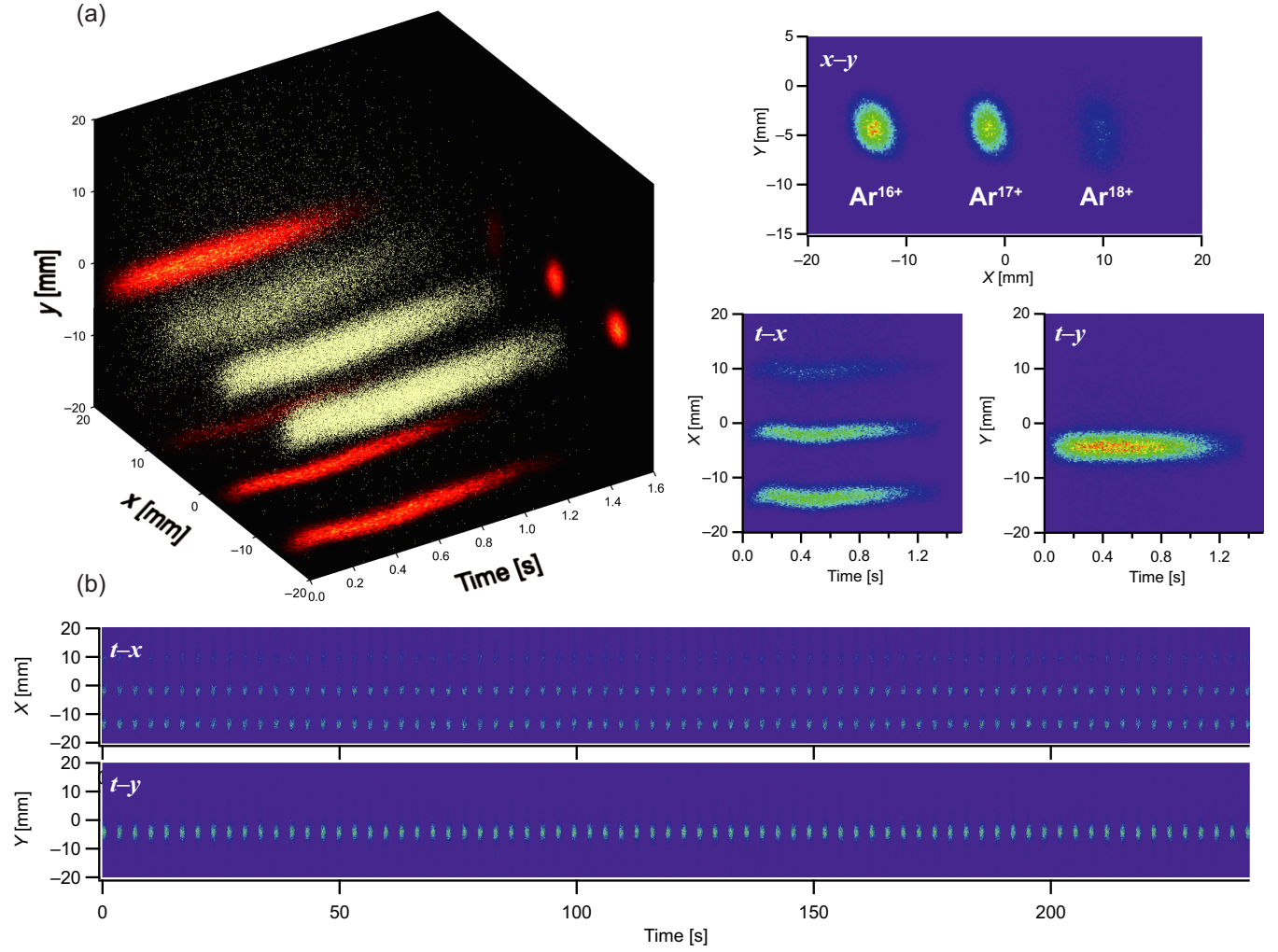


FIG. 5. (a) Reconstructed 3D image of the 465 MeV/nucleon Ar^{16+} , Ar^{17+} , and Ar^{18+} beam spill integrated for 74 spills. The beam was transported as Ar^{16+} and charge separated by a magnet after passing through a stripper foil. The projection of the 3D image into the $x-y$, $t-x$, and $t-y$ planes are shown as 2D images. (b) The long-term $t-x$ and $t-y$ projections of the beam showing the shot-by-shot behavior of the beam spill.

extracted from the synchrotron in the x direction, giving a positional fluctuation to the spill. We confirmed that this behavior is dependent on the beam-extracting parameters and can be compensated by optimizing the extraction. It should be stressed that these temporal behaviors are normally undetectable from the integrated 2D beam image but become apparent in 3D beam imaging by time-resolved data processing.

Another critical property of the beam that has to be diagnosed is the stability of the beam on a longer time scale. Figure 5(b) represents the $t-x$ and $t-y$ projections without integration, which visualize the 3.3 s repetition cycle of the beam spill. Such representations of the time-series data enables demonstration of the shot-by-shot analysis of the beam in terms of both the beam intensity and positions. Figure 6(a) shows the number of

particles detected in each spill. The error bar shows the Poisson standard deviation σ of the counts. The shot-by-shot fluctuation of the beam intensity, i.e., the standard deviation about its mean, was evaluated to be $\sim 1.2\sigma$. This suggested that the fluctuation is primarily statistic, possibly with little contribution from other factors coming from the beam acceleration and transport. The position of the center of mass of the beam in x and y is plotted in Figs. 6(b) and 6(c) for each spill, respectively. The filled area shows the FWHM of the beam size. The shot-by-shot fluctuation of the beam's center-of-mass position was $\sigma_x = 0.17$ mm and $\sigma_y = 0.11$ mm. Thus, these fluctuations were significantly smaller compared to the beam size in the current condition. The reconstructed real-time movie of the beam image can be found in Supplemental Material [39].

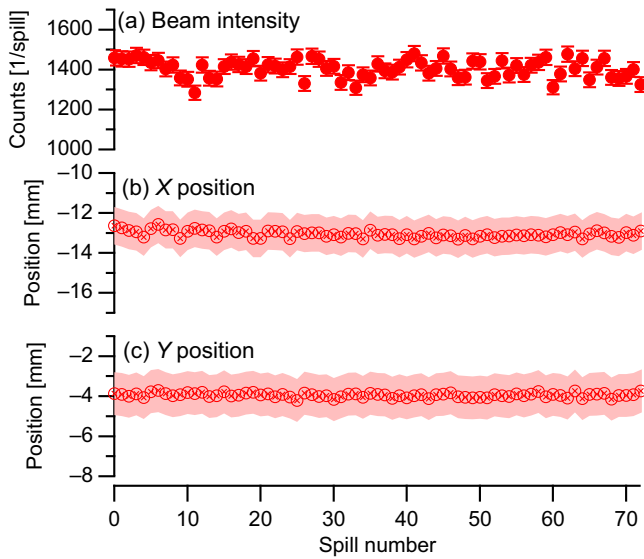


FIG. 6. The shot-by-shot analysis of the (a) beam intensity, (b) x position, and (c) y position shown for 74 spills recorded using the PSD. The filled region in (b) and (c) shows the FWHM of the beam size.

V. SUMMARY

The 3D visualization of a high-energy particle beam was accomplished by using a position-sensitive photodiode with a high-speed digitizer implemented with an on-board FPGA. The sum, delay, walk average, Schmitt trigger, and peak-search functions were programmed in the FPGA block, which finally outputs the peak height of the four signals with a time stamp for each event. Prior to the beam experiment, a characterization measurement was performed with an Am-241 α source, which showed that the pin-cushion distortion by the ballistic deficit is negligible when an appropriate pulse shaping time τ_{Amp} is chosen. By analyzing the experimental data obtained using the α source, the position and time resolution of the present measurement were estimated to be 250 μm and 1.0 μs , respectively. The imaging of the beam spill revealed both (i) the three-dimensional profile of the single spill, and (ii) the long-term shot-by-shot stability of the beam intensity and positions. In both cases, it was demonstrated that the proposed method serves as an extremely powerful beam diagnostic technique for examining ripple effects and stability of the beam spill.

Since the pipelined signal processing in the FPGA does not cause input deadtime unlike the analog peak holding circuits, the data acquisition system did not show pileup behavior in the measurement range up to 10^4 count/s. Regarding the radiation hardness, we have confirmed that irradiation with approximately 10^{10} particles/ cm^2 of high-energy ions did not result in any noticeable increase in dark current or localized degradation in detection efficiency at the beam spot. This indicates that the observed level of

radiation hardness is sufficient for the intended use of the PSD in low-current beam applications. These newly available diagnoses are potentially useful in many experiments and applications, which would benefit from knowing the temporal behavior of the beam in addition to the hitherto observed time-integrated 2D images.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [40].

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