

Advanced muon-spin spectroscopy with high lateral resolution using Si-pixel detectors

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Muon-spin spectroscopy at continuous sources has stagnated at a stopped muon rate of ~ 40 kHz for the last few decades. The major limiting factor is the requirement of a single muon in the sample during the typical $10\ \mu\text{s}$ data gate window. To overcome this limit and to be able to perform muon-spin relaxation/rotation (μSR) measurements on millimeter-sized samples, one can use vertex reconstruction methods to construct μSR spectra. This is now possible thanks to the availability of very thin monolithic Si-pixel chips, which offer minimal particle scattering and high count rate. Here, we present results from a Si-pixel-based spectrometer that utilizes vertex reconstruction schemes for the incoming muons and emitted positrons. With this spectrometer, we were able to obtain a first vertex reconstructed ($\text{vx-}\mu\text{SR}$) spectrum. The unique capabilities and benefits of such a $\text{vx-}\mu\text{SR}$ spectrometer are discussed.

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I. INTRODUCTION

Measuring submillimeter samples using μSR is a dream for material scientists, in particular, in the field of quantum materials that are difficult to produce in large quantities. In addition, data collection rates at continuous muon sources, which offer high time-resolution measurements, have stagnated at a stopped muon rate of $40\ \text{kHz}$ since the development of the technique. In this paper, we have developed a prototype muon-spin relaxation/rotation (μSR) spectrometer, which breaks these limitations, ushering in a new era for muon-spin spectroscopy and its applications. With recent developments in silicon pixel detector chips used in particle physics experiments, such a concept becomes possible for the first time, benefiting from an excellent single hit spatial resolution of $23\ \mu\text{m}$ and a combined timing resolution better than $15\ \text{ns}$ [1].

Other potential breakthroughs for the μSR technique [2] include (1) the ability to obtain magnetic and electronic properties of materials on the submillimeter lateral resolution, (2) measure multiple samples in parallel allowing, e.g., fast and efficient exploration of the phase space of a family of materials, (3) perform pump-probe and transient measurements benefiting from the high data collection rate, and (4) measurements of μSR signals with lower uncorrelated background,

allowing longer measurement time windows beyond the current $10\ \mu\text{s}$ limit, without sacrificing the high time resolution or data rate.

Here, we demonstrate the feasibility of utilizing the MuPix11 [3–9] chip—a thin high-voltage monolithic active pixel sensor [10]—to construct a prototype μSR spectrometer. This prototype is designed to operate efficiently in a high-rate continuous muon beam at the Paul Scherrer Institute (PSI). The technology has been developed in the context of the Mu3e experiment [11], currently under construction at PSI. This work demonstrates two key performance aspects of the design: First, acquiring μSR spectra with submillimeter lateral resolution from the sample region. This will allow the separation of regions (on the scale of hundreds of micrometers) with different magnetic properties in the samples as well as the measurement of multiple samples in parallel. Second, the superb spatial resolution will be used to identify multiple muons implanted in the samples at the same time, enabling an increase in the incoming muon rate by more than tenfold, and therefore, make more efficient use of the highly oversubscribed μSR spectrometers/beamlines at μSR user facilities.

II. EXPERIMENTAL

We have fabricated “Quad” modules consisting of four MuPix11 Si-pixel chips [3] mounted on a single printed circuit board [PCB, Fig. 1(a)]. The chips were glued onto a $20\ \mu\text{m}$ thick polyimide foil to provide mechanical stability. The thickness of the MuPix11 chips used in the modules varied between 50 and $100\ \mu\text{m}$, which was sufficient for a first prototype aimed at exploring the general capabilities of this technology (see Sec. III). For the reported measurements,

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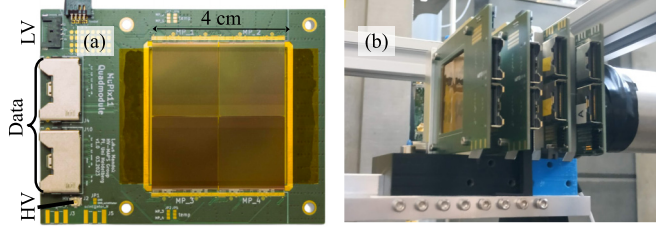


FIG. 1. (a) A photo of a Quad hosting four Si-pixel chips showing the HV, LV and data connectors. (b) The arrangement of the Quads in the prototype spectrometer at the π E3 beamline at PSI with two upstream, two downstream, with the investigated sample in the middle.

we used four such Quads to construct a basic μ SR spectrometer, with two Quads forming the upstream detector set and two forming the downstream detector set [Figs. 1(b) and 2]. The measured samples were suspended on a frame using aluminized mylar tape and mounted in the middle between the two detector sets. The design of this spectrometer allows for a flexible positioning of both Quads and the sample relative to each other. However, for the reported measurements in this work, the Quads were placed at distances of $z = \pm 10$ mm and $z = \pm 30$ mm at either side of the sample at $z = 0$.

The electronics and data acquisition (DAQ) software for the spectrometer were adapted from the Mu3e collaboration [12,13]. The Quad PCB was fed by a low voltage (LV, typically 1.9 V) to operate the Si pixels and a high voltage (HV, typically -30 V) to bias their substrate [Fig. 1(a)]. The data were read using a custom-made front-end board [12,13], converted to optical signals, and then fed into the DAQ PC hosting the DE5a-NET development board [14]. All our measurements were performed with a muon-spin polarization perpendicular to the beam direction, as indicated in Fig. 2.

III. SIMULATIONS

At the energy scales relevant for μ SR measurements (surface muons at ~ 4.1 MeV), the primary source of uncertainty in the vertex reconstruction of particle trajectories is predominantly due to multiple Coulomb scattering within

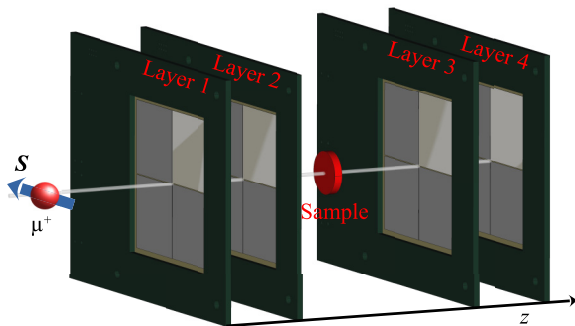


FIG. 2. A schematic of the spectrometer prototype that consists of four layers with the sample in the middle. The gray line indicates the beam propagation direction (along z) and the blue arrow denotes the initial muon spin direction, perpendicular to the beam.

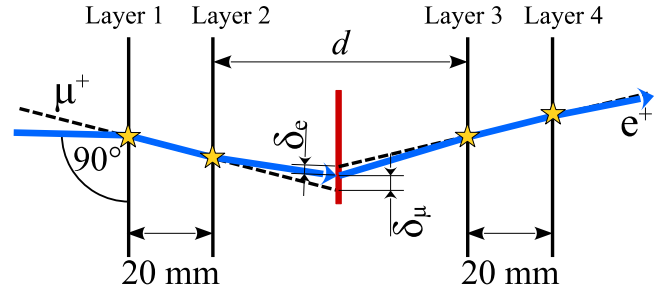


FIG. 3. The actual (blue solid lines) and reconstructed (dashed lines) trajectories of an incoming muon and an emitted positron as they pass through the Si-pixel chips. The red line represents the sample centered between layers 2 and 3.

the inner silicon chips, i.e. layers 2 and 3, as illustrated in Fig. 3. Such scattering introduces an uncertainty δ_μ and δ_e in determining the trajectories of incoming muons and emitted positrons, respectively. However, $\delta_\mu \gg \delta_e$ due to the relatively high kinetic energy of the positrons. Therefore, δ_μ can be considered as an upper limit on the resulting lateral resolution of the vertex reconstruction scheme.

To estimate this uncertainty, we employ *muSRsim* simulations [15,16], based on GEANT4 [17]. We model the scattering behavior of muons traversing a four-Si-pixel layer configuration (Fig. 3), each with a thickness of $100\ \mu\text{m}$. We also take into consideration the polyimide foil ($25\ \mu\text{m}$) onto which the chips are glued. A pointlike muon beam (10 million particles) incident perpendicular to layer 1 is used with a sample of 20 mm diameter. The simulations provide the coordinates of the muon hits on each layer, $\mathbf{r}_i$, as well as the actual landing coordinates at the sample, $\mathbf{r}_s$. We use the hit coordinates in the upstream set to perform a linear extrapolation to the sample position, $\mathbf{r}_s^{\text{ext}}$. Finally, we calculate the distance between the actual and extrapolated muon positions at the sample, i.e., $\delta_\mu = |\mathbf{r}_s - \mathbf{r}_s^{\text{ext}}|$ for all incoming muons. The standard deviation of δ_μ was used as a measure of the uncertainty and evaluated from simulations with varying distances, d , between layers 2 and 3. As seen in Fig. 4, the standard deviation of δ_μ increases linearly with d at a rate of ~ 0.03 mm per mm spacing. However, it remains below ~ 1.5 mm up to $d \simeq 40$ mm. In our configuration with $d = 20$ mm, this uncertainty is calculated to be less than 0.7 mm (dashed line in Fig. 4). Further reduction of uncertainty can be achieved by combining the extrapolated tracks of the muon and its matched positron, since the high-energy decay positrons scatter even less than muons. More details on these simulations can be found elsewhere [18]. Efficient track extrapolation for both muons and positrons depends critically on the ability to distinguish between them. From the simulations, we note that the energy deposited in the Si layers strongly depends on the particle species. In particular, we find that muons deposit a significantly higher energy compared to positrons (see Fig. 5). Therefore, this opens the possibility of an effective method to distinguish between particle species. Since the measured time over threshold as implemented on the MuPix chip is proportional to the deposited energy of the hit, one can use this parameter in the future to identify muon and positron hits.

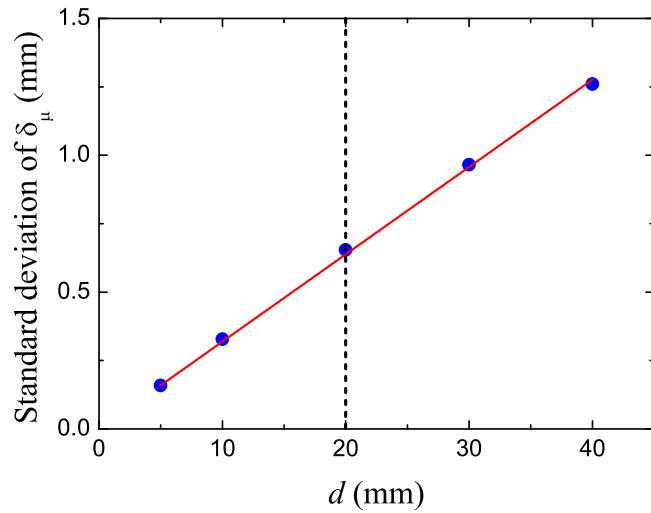


FIG. 4. The standard deviation of the distance between the actual and extrapolated muon positions on the sample as a function of the distance between layers 2 and 3. The solid line is a linear fit of the data. The vertical dashed line marks the experimental conditions used here.

IV. DATA ANALYSIS

The data obtained from the MuPix11 chips are a stream of detected hits with their lateral coordinates (x, y) on the chip and the corresponding time stamp t of the hit. There are two types of valid hits, (1) an incoming muon that stops in the sample and (2) an emitted positron from the sample. Both must have coincidence hits in two layers, either the upstream set (layers 1 and 2) or the downstream set (layers 3 and 4). Any coincidence hits in more than two layers represent either a muon missing the sample or a positron that does not originate from a muon stopping in the sample and are therefore ignored.

Using the Corryvreckan software framework [19,20], the raw data of the recorded hits were filtered to obtain only such valid events. These were then used to construct tracklets, i.e., two points $\mathbf{r}_i^1 = (x_i^1, y_i^1, z_i^1)$ and $\mathbf{r}_i^2 = (x_i^2, y_i^2, z_i^2)$ representing

the coordinates of the hit i in layers 1 and 2 (or layers 3 and 4), respectively, both having the same time stamp t_i . Here, the coordinate z represents the position of the layer along the beam direction as shown in Fig. 2.

In order to generate the μ SR histograms, we used a simple algorithm, where we identify an incoming muon trajectory as a hit in layer 1 with coordinates (x, y) that fall within a 4 mm diameter from the center of the beam collimator (a Pb cylindrical collimator with a 3 mm diameter hole). Using $\mathbf{r}_i^1$ and $\mathbf{r}_i^2$ of such hits, we extrapolate the trajectory to the sample position at $z_i^s = 0$, $(x_i^s, y_i^s, 0)$. Then, we open a software data gate of 13 μ s and look for another trajectory within this time window that can be extrapolated to the vicinity of $(x_i^s, y_i^s, 0)$. More specifically, the distance between the two trajectories at $z = 0$ must be less than or equal to d_{match} with a typical value of 1 mm. If a matching trajectory, j , is found, we record the time difference $t_j - t_i$ in the corresponding upstream or downstream histogram. Otherwise, we move on to the next muon trajectory candidate. Note that during the data analysis, for incoming muon rate of ~ 40 kHz, we only find very few events with two positron trajectories that match the same incoming muon candidate. This is to be expected since the probability of two muons landing within ~ 1 mm from each other is $\sim 0.6\%$ at this rate. The algorithm described above, although very simple and can be improved in the future, was sufficient to enable measurements of vertex reconstructed μ SR (vx- μ SR) signals accurately, reproducing measurements performed on the “conventional” general purpose surface-muons (GPS) [21] spectrometer at PSI as described below.

V. RESULTS

A. vx- μ SR spectra

Since our prototype spectrometer does not have a magnet, we use permanent magnets placed above and below a 6 mm diameter Al disk to generate a magnetic field that is perpendicular to the initial muon-spin polarization (see inset of Fig. 6). Measurements of this sample using the GPS spectrometer as a reference show a clear precession signal in an applied field of ~ 6.3 mT, as seen in Fig. 6.

We detect the same precession signal (with a different phase due to the different geometries) in the GPS and the Si-pixel prototype spectrometers. Both spectra were fit (single histogram fits, solid lines) using

$$N(t) = N_0 e^{-t/\tau_\mu} (1 + A \cos(\omega t + \phi) e^{-(\sigma t)^2/2}) + B, \quad (1)$$

where N_0 is the initial counts, A is the asymmetry parameter, $\tau_\mu = 2.197 \mu$ s is the muon’s lifetime, ω is the precession frequency, ϕ is the phase, σ is the damping rate, and B is the accidental background counts. The results of these fits give an equal precession frequency (Si pixel: 0.85 ± 0.01 MHz, GPS: 0.855 ± 0.001 MHz) and damping rate (Si pixel: 0.323 ± 0.055 1/ μ s, GPS: 0.285 ± 0.007 1/ μ s) within the error bar. For completeness, we also note that $N_0 = 153(1)$ for the Si-pixel spectrometer and 8246(16) for the GPS spectrometer. It is important to point out here that the algorithm used to create the μ SR histograms from the Si-pixel spectrometer has (by design) a negligible accidental background, B , compared to the currently used spectrometer technology

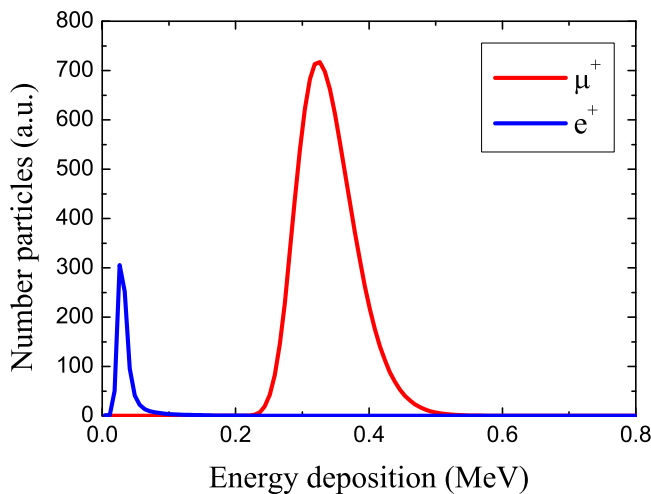


FIG. 5. The deposited energy of muons and positrons in the first layer of the simulated spectrometer.

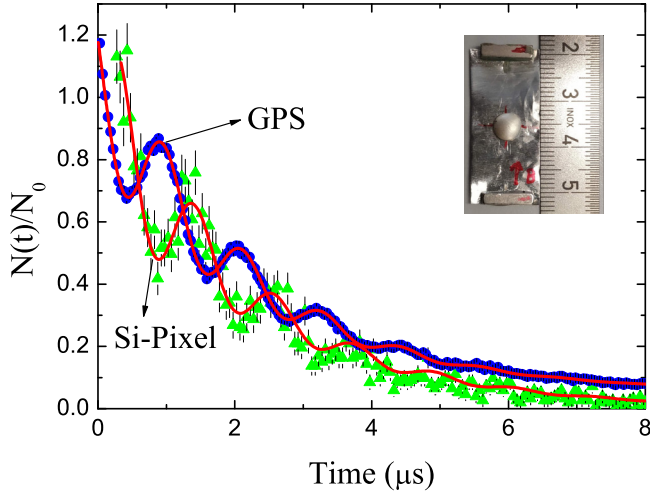


FIG. 6. A first vx- μ SR signal measured from a 6 mm diameter Al disk placed between two permanent magnets producing a transverse field of ~ 6.3 mT at the center (inset). The number of counts as a function of time measured in the upstream detector of the Si-pixel spectrometer (green triangles). This is compared to the counts in the upstream detector of GPS (blue circles) measured on the very same sample. The solid lines are fits as described in the main text.

(Fig. 6). This is because good events associate each muon with a single corresponding positron. Therefore, we conclude that vertex reconstruction schemes enable measurements with much longer data windows without reducing the data rate or compromising time resolution. We also note that the signal in the Si-pixel detector is from a dataset of ~ 35 s duration only as opposed to the ~ 14 min measurement time at GPS. The limited run time on the Si-pixel spectrometer was due to DAQ software issues during the reported measurements, which caused data corruption beyond that time. These issues have been fixed recently and unlimited run times can be now performed.

B. Lateral resolution at the sample

In order to explore the lateral resolution limits from vertex reconstruction schemes on the sample size and geometric features, we inspect the lateral distribution of vertices of valid events. For this purpose, we use a silver plate with various cutouts as a sample [Fig. 7(a)]. The vertices are defined as the intersection points [within a distance of d_{match} ; see Fig. 7(b)] of an incoming muon trajectory and a corresponding emitted positron trajectory at the sample position, $z = 0$. We can clearly resolve details as small as ~ 0.6 mm on the sample, as can be seen in Figs. 7(c)–7(e). Moreover, we vary the value of d_{match} to study the impact of our selection criterion. As an example, we show the vertices using $d_{\text{match}} = 0.3, 0.5$, and 1.0 mm in Figs. 7(c)–7(e), respectively. In order to quantitatively evaluate the width of the features in Fig. 7(a), we plot the number of reconstructed vertices, N_v , along the corresponding cross section, as shown in Figs. 7(f)–7(h) for $d_{\text{match}} = 1.0$ mm. The main peak across the corresponding sample's feature is then fit using a Gaussian function and used to evaluate the full width at half maximum (FWHM). The smaller peaks in N_v are attributed to other features

TABLE I. The actual feature width (left column) for different d_{match} values (top row) compared to the FWHM of the number of vertices of good events along the corresponding feature's cross section.

Actual (mm)	Estimated for d_{match} (mm)		
	0.3	0.5	1.0
1.6	2.19(10)	1.98(5)	1.95(3)
1.1	1.60(7)	1.62(5)	1.62(2)
0.6	1.30(17)	1.25(10)	1.41(5)

along the same cross section. As summarized in Table I, we find that the FWHM values increase with the width of the feature, while overestimating it by ~ 0.4 mm. We believe that these overestimated values are simply due to poor statistics in these measurements as well as a possible misalignment of the cuts.

However, the estimated width does not vary much regardless of d_{match} . The main difference is the number of events that decreases significantly with decreasing d_{match} . This indicates that, at least at an incoming muon rate of 40 kHz, our algorithm manages to select good events very efficiently and accurately even for $d_{\text{match}} \sim 1$ mm. We note that for higher rates d_{match} may need to be reduced to allow for a good separation of individual muons.

VI. SUMMARY AND CONCLUSIONS

We have built a μ SR spectrometer prototype based on MuPix11 Si-pixel chips that provide information about the lateral position of the particle hits as well as their time. Using this information to obtain the landing position of an incoming muon on the sample and the corresponding emitted positron, we are able to construct vx- μ SR histograms using vertex reconstruction schemes. With this added information compared to conventional μ SR, we are able to perform measurements on samples of submillimeter size that are not possible using current spectrometer technology. In addition, this method opens the possibility of performing μ SR measurements on multiple small samples simultaneously or measuring a single large sample at rates more than 10 times higher than currently possible at continuous muon source facilities. This can be done by accepting an incoming muon rate of 40 kHz for individual areas of $\sim 1 \times 1$ mm² in the sample. We note that a rate of at least 1 MHz per pixel is possible for MuPix11 chips [22].

The presented prototype is operated in air, without a cryostat to host the sample and without the possibility to apply an external magnetic field. Operation of the Si-pixel detectors in vacuum, to allow the introduction of a cryostat, is crucial for future utilization of this technology for standard μ SR measurements. The use of a cryostat will introduce additional sources of scattering, most notably due to windows in the radiation shield, the effects of which on the tracking capabilities and hence the standard deviation of δ_μ and δ_e need to be assessed. In addition, to allow extrapolation of muons' and positrons' trajectories in a magnetic field, a three-layer configuration may be needed for accurate vertex reconstruction [18]. These issues are currently being addressed at PSI.

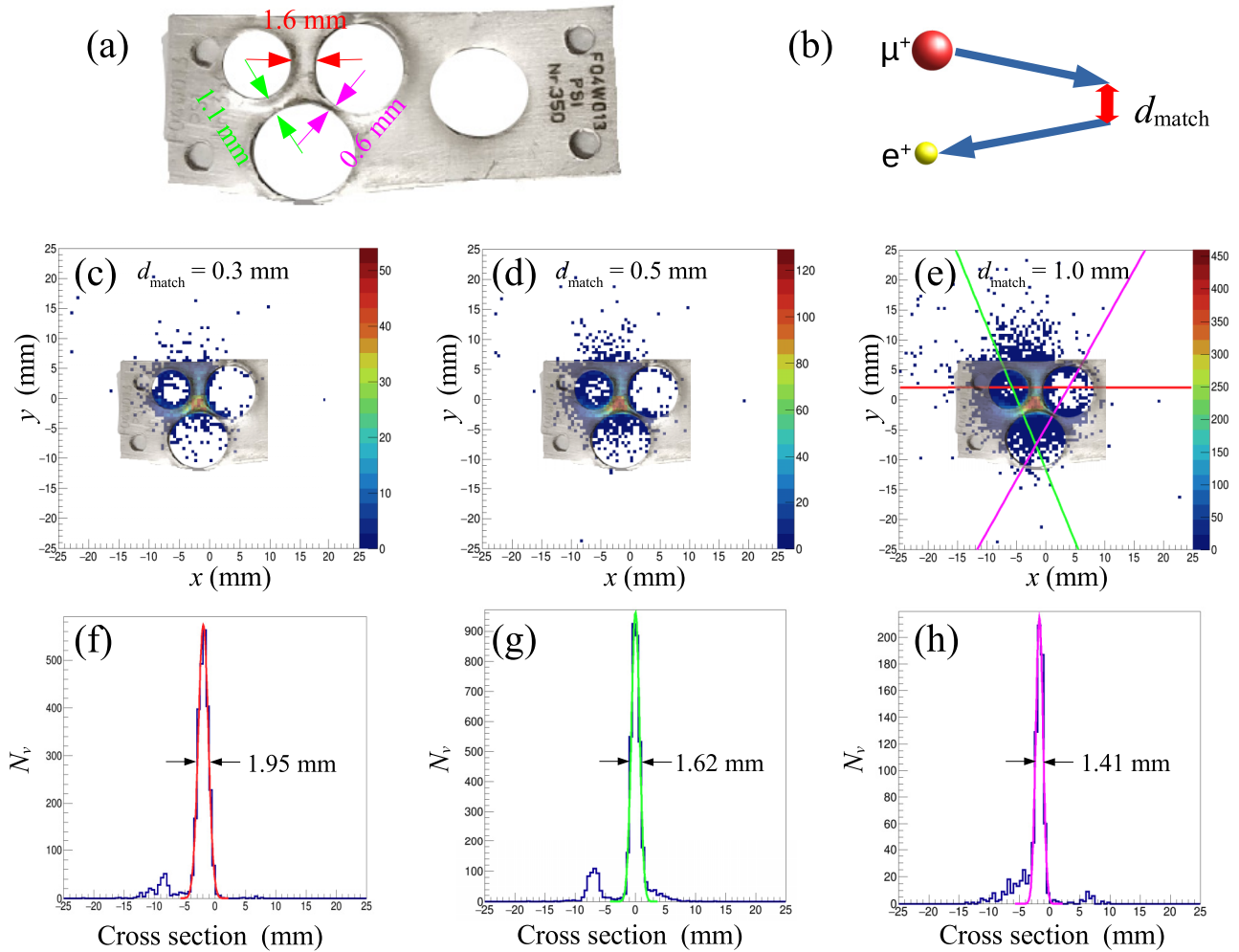


FIG. 7. (a) The measured silver sample with indication of the typical sizes of its features. (b) A schematic showing the condition for matching an incoming muon to an emitted positron. The two-dimensional histogram of the coordinates of vertices of good muon-positron events at the sample position using a d_{match} of (c) 0.3 mm, (d) 0.5 mm, and (e) 1.0 mm. The sample image is scaled and overlaid on the plots showing that the vertices reflect the sample shape. The number of detected vertices, N_v , along the (f) red, (g) green, and (h) magenta cross sections in panel (e). The solid lines in panels (f)–(h) are fits of the peaks in N_v using a Gaussian curve with the corresponding FWHM. The nonfitted peaks in panels (f)–(h) originate from sample features along the indicated cut in panel (e) further away from the beam spot centered at $(-2, -1)$.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [23]; embargo periods may apply.

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