Position Sensitive APDs for Small Animal PET Imaging

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Abstract— In this paper, an investigation of position sensitive avalanche photodiodes (PSAPDs) as optical detectors for reading out segmented scintillation arrays of LSO in high-resolution PET modules is reported. PSAPDs with 8 x 8 mm^2 have been characterized with single LSO crystals and arrays. Energy resolution of 19% (FWHM) for 511 keV γ-rays and coincidence timing resolution of ~3 ns (FWHM) have been recorded with PSAPD coupled to 1 x 1 x 20 mm^3 LSO detectors. Flood histogram studies have been successfully conducted by coupling multi-element element LSO arrays (1 mm pixels, 20 mm tall) to the PSAPDs. Finally, depth of interaction (DOI) resolution of < 4.5 mm (FWHM) has been measured by coupling two PSAPDs on opposite ends of a 20 mm long LSO crystal with a 1 x 1 mm^2 cross section. Based on these results, PSAPDs appear to be promising for high resolution PET. An important advantage of these PSAPDs is significant reduction in electronic readout requirements.

I. Introduction

Positron emission tomography (PET) is becoming an increasingly popular tool in cancer detection and research. Small-animal PET imaging opens up new avenues for studying novel cancer treatment models by allowing individual animals to be tracked longitudinally in vivo.

A new generation of high resolution, high sensitivity, small animal PET detectors need to be developed to allow the early stages of cancer development to be studied in mouse models. The main challenges are to achieve high spatial resolution and sensitivity, while minimizing cost to enable more widespread use of the technology. A number of groups have made significant advances in small animal PET imaging technology in recent years [1]-[7]. Many new small animal PET systems use very small scintillator elements, typically lutetium oxyorthosilicate (LSO), read out by position-sensitive or multi-channel photomultiplier tubes to achieve high spatial resolution.

Other readout technologies such as silicon avalanche photodiodes (APDs) are also being considered in small animal PET designs. One of the primary motivations for using APDs is that these silicon-based detectors could ultimately be made very cheaply in high volumes. APDs also offer high optical quantum efficiency (up to a factor of 4 higher than PMTs), wide spectral response, and insensitivity to magnetic fields. Due to these factors, APDs are being actively investigated for small animal PET [3], [8]-[10]. In all such efforts, individual APD pixels are coupled to scintillation crystals to determine the crystal of interaction and provide energy and timing information and there is no multiplexing of signal.

In this paper, an APD design that provides intrinsic position sensing capability and therefore can provide significant reduction in the number of electronic channels that are required is discussed. This is particularly important now, because newer design of high resolution, small animal PET systems have a large number of LSO crystals (10,000 to 20,000), which can have severe impact on the electronic readout requirements for APD-based PET system. The new position sensitive avalanche photodiodes (PSAPD) would simplify the readout requirements in such PET designs and thereby reduce cost as well as complexity of small animal PET systems.

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II. Position Sensitive Avalanche Photodiodes

A new approach of using the high gain planar APD technology to produce position sensitive avalanche photodiodes has been explored. This involves modification in the design of the back contact structure of the APD in order to enable determination of the position of interaction. A variety of anode structures, all of which involve charge sharing, have been explored with other detectors such as microchannel plates and silicon p-i-n detectors to provide position sensitivity [11]-[15]. For our investigation, we have selected a simple design where four contacts are placed on a resistive layer at corners as shown in Fig. 1 and geometric considerations are used to compute position (based on signal collected at each corner contact). In this design, the signal from the top contact is the sum of the signal from the four bottom contacts. The top contact is used to generate energy and timing information for an event while the bottom four contacts provide the position of an event.

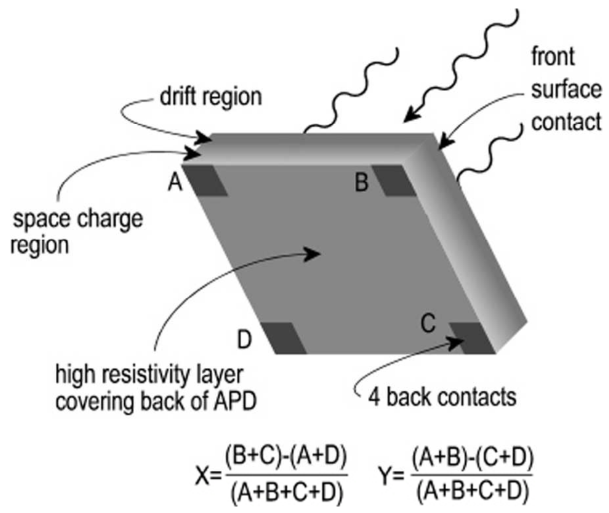

Fig. 1. Schematic diagram of a position sensitive avalanche photodiode (PSAPD) with four corner contact design.

Such PSAPDs were fabricated with areas of 8 x 8 mm^2 and 14 x 14 mm^2 using the planar process and were packaged on ceramic substrates. We have characterized gain and noise properties of these devices. The operating gain (where the signal to noise ratio is optimized) was ~1000 at ~1750 V for both PSAPD sizes, while the corresponding noise was 200 and 300 electrons (FWHM) for 8 x 8 mm^2 and 14 x 14 mm^2 devices, respectively. The quantum efficiency for these devices was measured to be ≥ 60% in the 400 to 700 nm region. The intrinsic spatial resolution of these devices was measured to be < 1 mm (FWHM) and their risetime was ~1 ns [16]. The imaging response of these devices shows pincushion distortion, which is an intrinsic property of a device with four corner anode design. This distortion can be corrected by processing the image using a previously generated spatial response for the device [16]. For imaging segmented scintillation arrays, this distortion is not critical as long as individual scintillation segments are correctly identified. Thus, PSAPDs are attractive for PET imaging and these devices have been evaluated for PET imaging by coupling them to LSO crystals and arrays. In this paper, 8 x 8 mm^2 PSAPDs are evaluated for use in high-resolution PET systems.

III. EVALUATION OF PSAPD-LSO PET DETECTOR MODULES

PET detectors and modules were constructed by coupling PSAPDs to single LSO crystals and arrays and their energy resolution and timing resolution were measured when irradiated with 511 keV γ-rays. Flood histogram studies were also conducted with PSAPDs coupled to LSO arrays (under illumination with 511 keV γ-rays). Finally, depth of 511 keV γ-ray interaction in LSO crystals was measured by comparing the signal measured with two PSAPDs coupled to opposite faces of the LSO crystals.

For PSAPD evaluation, a five-channel readout system was used. Each channel consisted of a pre-amplification stage (Cremat #101D), a shaping stage (Canberra #2020), and a sample-and-hold stage. The static detector signals were sampled by a 12-bit analog conversion card. Upon a lower-level-discriminator trigger on the 5th input (top contact), the digitizer simultaneously captured and converted all 5 signals from the PSAPD readout sample-and-hold circuitry. Four of the signals (from bottom contacts) were used to generate position and the fifth, the trigger signal, was used for pulse-height and timing analysis. The digitizer was installed in a laboratory computer running Microsoft (MS) Windows 98. MS Visual BASIC and DriverLINX were used to control the I/O card, and to manipulate, display and store the results.

A. *Flood Histogram Studies*

Imaging studies have been conducted by coupling an 8 x 8 mm^2 PSAPD to segmented LSO arrays with 1 mm pixels that were 20 mm thick. The LSO array had 8 x 8 element format. The pixel pitch of the LSO array was ~1.27 mm and as a result, the PSAPD covered 6 x 6 elements of the LSO array. 511 keV gamma rays (^{22}Na source) irradiated the LSO array and the resulting flood histogram, acquired at room temperature is shown in Fig. 2 in a three-dimensional representation. This data was taken with a custom 16-channel ASIC, designed specifically for APD-based PET applications. As seen in the figure, all pixels of the 6 x 6 LSO array are well identified and the average peak to valley ratio for the imaging data is ~6 as shown in Fig. 3. Pincushion distortion can be seen in the histogram, which is an inherent property of the device with four-corner anode design. Such distortion can be readily corrected using a previous calibration map of the device. Overall, these γ-ray imaging studies confirmed that

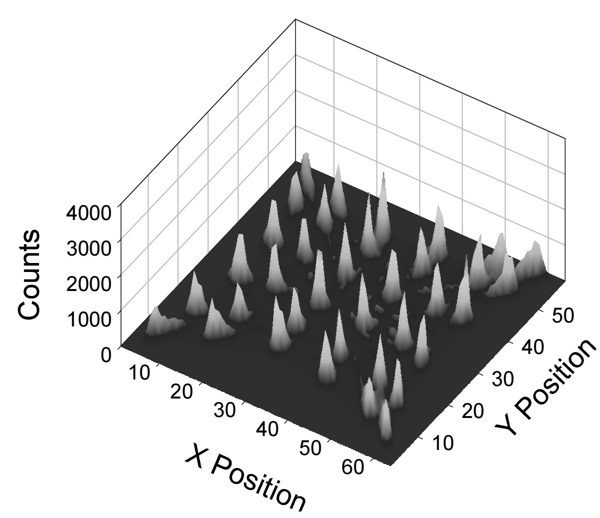

Fig. 2. Three dimensional plot of the flood histogram data collected upon coupling a 8 x 8 mm^2 PSAPD to an LSO array (1 mm pixels, 20 mm tall) at 20° C. ^{22}Na source (511 keV gamma rays) was used.

PSAPDs are capable of providing very high spatial resolution.

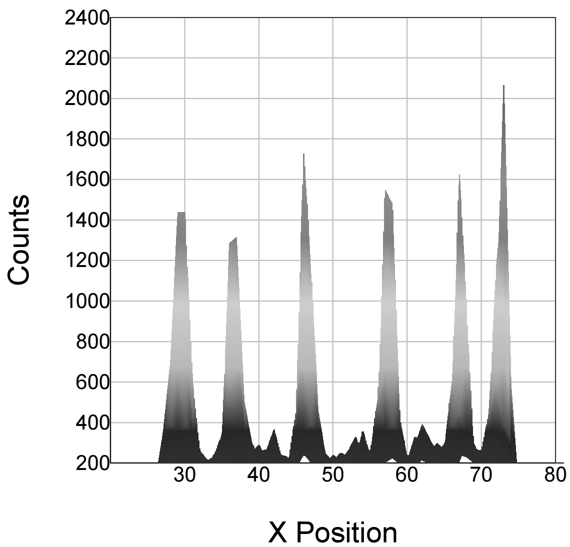

Fig. 3. Line profile of a center row of pixels from Fig. 4. The average peak-to-valley ratio is ~6.

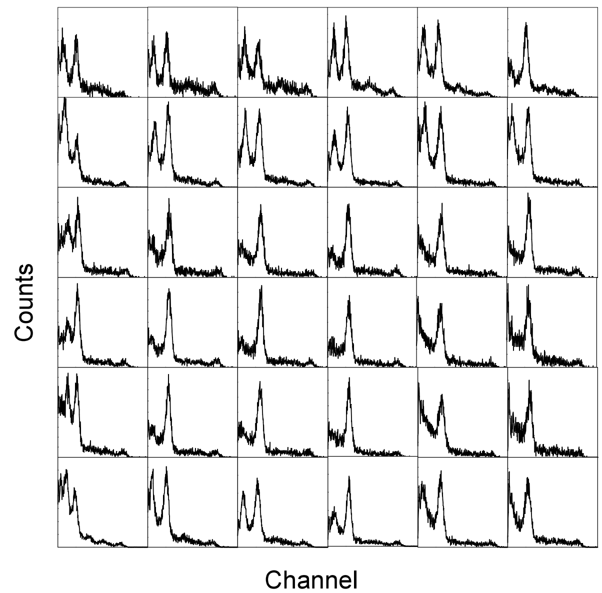

Fig. 5. ^{22}Na spectrum of each crystal of the 8 x 8 – 1 x 1 x 20 mm LSO array shown in Fig. 2.

B. Energy Resolution Measurements

We coupled an 8 x 8 element LSO array (1 x 1 x 20 mm^3 pixels) to the 8 x 8 mm^2 PSAPD and acquired ^{22}Na spectra (see Fig. 4) at room temperature. The energy resolution of the 511 keV photopeak was 19% (FWHM) at 20° C. The spectrum for each LSO crystal in the 3D plot (Fig. 2) is shown in Figure 5 and have an average energy resolution of 16% FWHM. Overall, these results are promising and indicate that high-energy resolution is achievable with LSO crystals coupled to PSAPDs including LSO samples having 1 mm^2 cross-section.

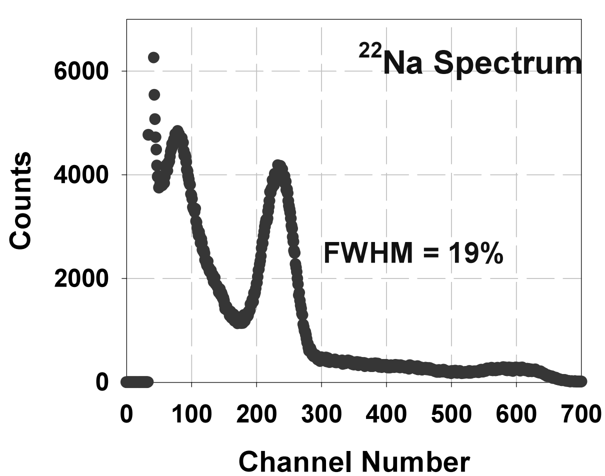

Fig. 4. ^{22}Na spectrum collected with 8 x 8 element LSO array (1 x 1 x 20 mm pixels) mated to 8 x 8 mm^2 PSAPD at 20° C.

C. Timing Resolution Studies

Coincidence timing resolution studies have also been performed with the PSAPDs coupled to LSO samples. Two 8 x 8 mm^2 PSAPDs, each coupled to 1 x 1 x 20 mm^3 LSO samples were operating in a coincidence timing circuit. The signal from each channel was processed with a timing filter amplifier (TFA), constant fraction discriminator (CFD) and gate/delay generator and then fed to a time-to-amplitude converter (TAC). These detectors were irradiated with 511 keV positron annihilation γ-ray pairs and a coincidence-timing spectrum, with resolution of 3.2 ns (FWHM) acquired at 20° C is shown in Fig. 6.

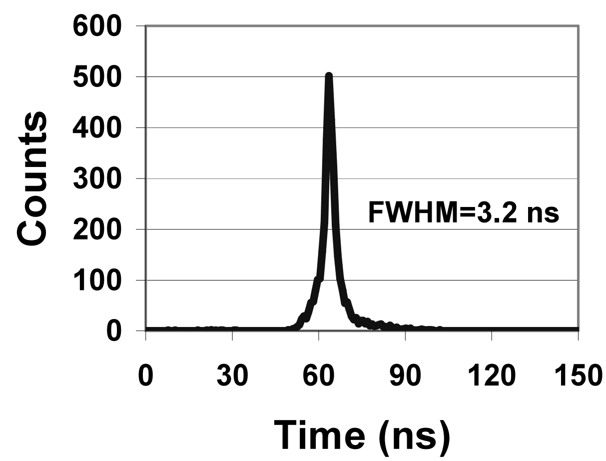

Fig. 6. Timing resolution with two 8 x 8 mm^2 PSAPDs (each coupled to 1 x 1 x 20 mm^3 LSO) operating in coincidence at 20° C.

D. Depth of Interaction Measurements

Depth of interaction (DOI) measurements have been made with two 8 x 8 mm^2 PSAPDs. DOI information can be used to correct parallax errors at the edges of the imaging volume that can result in poor spatial resolution.

One approach to estimate the depth of interaction involves collecting optical signal from both ends of the LSO crystals and comparing their relative magnitude [17]. This can be

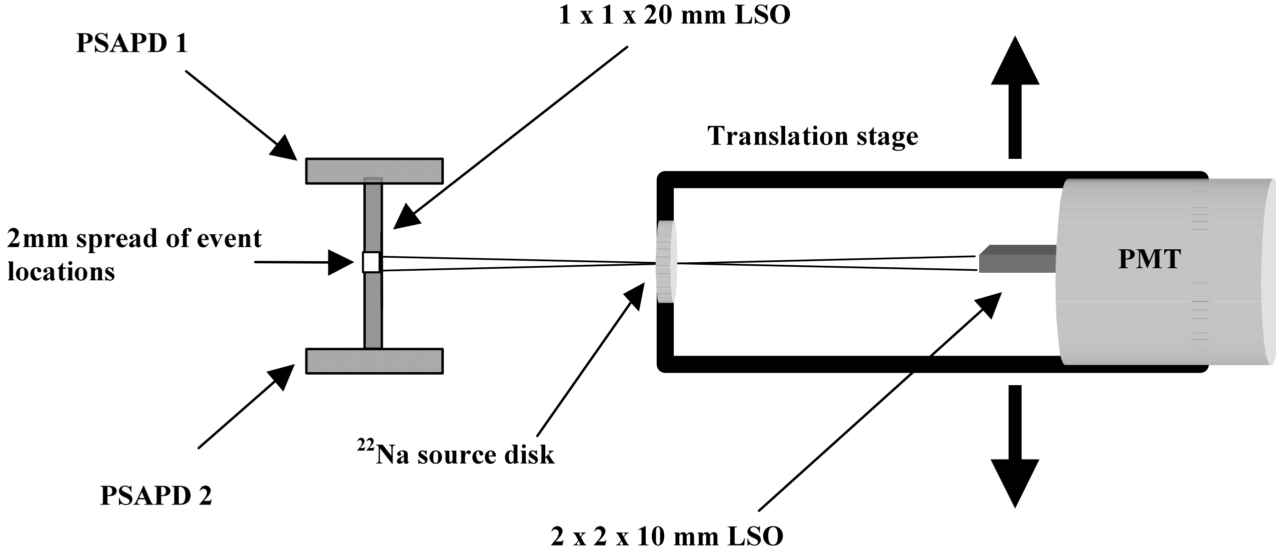

Fig. 7. Schematic representation of the experimental setup used to collect DOI data with two PSAPDs.

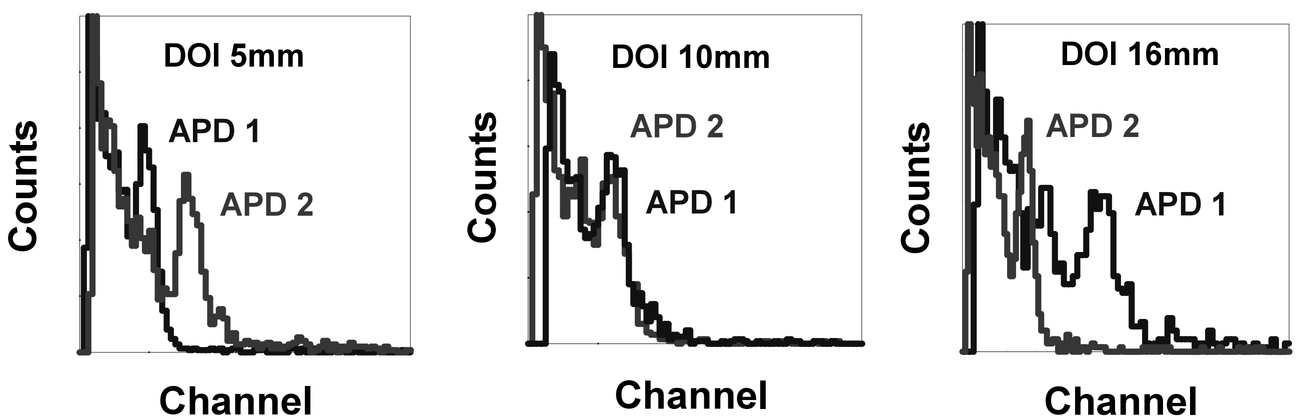

Fig. 8. 511 keV energy spectra collected with two PSAPDs coupled to opposite ends of a test LSO crystal (1 x 1 x 20 mm) at room temperature. Gated spectra are collected at different DOI (which represents distance from PSAPD2). For DOI location near center, peak positions for both PSAPDs are similar, while the peak position is higher for both PSAPDs when the DOI location is closer to them, confirming that our approach can provide high DOI resolution.

accomplished by placing two PSAPDs on opposite ends of the LSO crystal. The thin cross-section of PSAPDs ensures that there is minimal attenuation of the incoming gamma-ray flux. The ratio of the PSAPD signals can be used to determine DOI, where the high gain and high signal-to-noise characteristics of these PSAPDs are very important. Fig. 7 shows a schematic representation of the experimental setup that was used to perform DOI measurements.

A special holder was used to perform these measurements which required very careful alignment of the detectors and the source. Both ends of the test LSO crystal (1 x 1 x 20 mm^3) were coupled to PSAPDs that were read out by charge sensitive pre-amplifiers (Cremat #101D). A second LSO crystal (2 x 2 x 10 mm^3) was coupled to a 1.5" diameter single channel PMT for electronically collimating the interactions at different DOI positions. This second detector was mounted on a translation table for 3D positioning with respect to the test LSO crystal that was coupled between the PSAPDs. A ^{22}Na point source (1 mm diameter), which was located inside a source holder attached to the translation table, was placed between the two crystals, 35 mm from each crystal. The holder ensured reproducible positioning of the detectors and source for test crystals. By moving the translation table, interactions at different DOI locations in the test LSO crystal were selected by acquiring coincidence events between the two LSO crystals. The energy thresholds were set just above the noise level. The data acquisition trigger was generated from coincidences between the PSAPD signals and the PMT signal. During the measurement, all electronics settings, including amplifier gains, were kept the same in order to measure the signal change due to scintillation light collection. Data were collected at five DOI locations (2.5 mm, 5 mm, 10 mm, 12.5 mm and 16 mm) on the test LSO crystal at 20° C. These DOI locations represent distances from PSAPD2. Energy spectra were acquired from both PSAPDs (in coincidence with the PMT) for each DOI location. Gated energy spectra at three central DOI locations (5 mm, 10 mm, and 16 mm) are shown in Fig. 8. The peak 511 keV positions for both PSAPDs at all five DOI locations are plotted in Fig. 9.

The trends in the plot clearly indicate that this approach would allow estimation of DOI with good accuracy. Quantification of DOI resolution has been performed using the data shown in Fig. 8 and 9. The DOI location is proportional to the parameter - APD1/(APD1+APD2), where APD1 and APD2 refer to the signals from two PSAPDs. The error in the parameter - APD1/(APD1+APD2) has been estimated using measured 511 keV peak positions and peak broadening for both PSAPDs at all five DOI locations. Gaussian fits to the 511 keV peaks were used to estimate broadening for each spectrum. By performing propagation of error analysis, we estimate the DOI resolution to be < 4.5 mm (FWHM) over the measurement range, which is consistent with the data shown in Fig. 8 and 9.

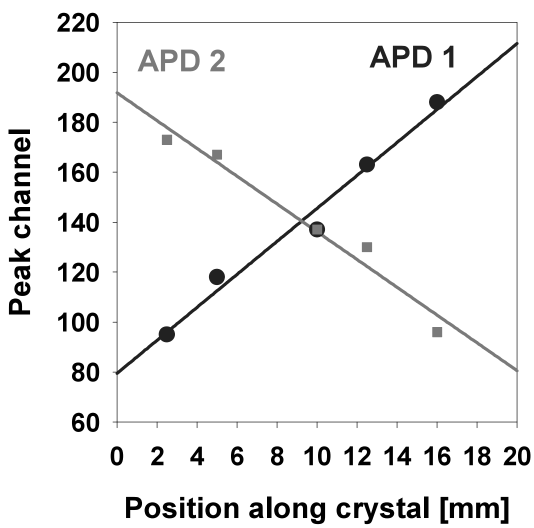

Fig. 9. 511 keV peak position with two PSAPDs versus DOI location for 1x1x20 mm LSO crystal. Data are shown for five DOI locations and the solid lines are linear regression fits to the data points.

Overall, these studies indicated that the approach of coupling an avalanche photodiode at either end of a LSO crystal allows accurate estimation of depth of interaction, even for LSO samples with 1 mm cross-section. This in conjunction with high energy, timing, and position resolution obtained with PSAPDs indicates that these devices can be used to build a high resolution, high sensitivity PET system.

IV. SUMMARY

Position sensitive avalanche photodiodes have been investigated for high resolution PET imaging applications. A PSAPD design with four corner contacts has been fabricated using planar process with device areas of 8 x 8 mm^2 and 14 x 14 mm^2. Such PSAPDs have shown high gain, low noise, and high quantum efficiency, which are characteristic of deep diffused APDs. Good energy, timing, DOI, and position resolution has also been observed with such PSAPDs. Furthermore, the electronic readout requirements for such PSAPDs is minimal. In addition to PET and other nuclear medicine imaging applications, PSAPDs are also promising for nuclear and high energy physics research, non-destructive evaluation, materials science studies, and geological exploration.

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