Effects of Dark Counts on Digital Silicon Photomultipliers Performance

Radosław Marcinkowski, Samuel España, Roel Van Holen, Stefaan Vandenberghe

***Abstract*–Digital Silicon Photomultipliers (dSiPM) are novel light detector that integrates single-photon avalanche photodiodes and CMOS logic into a single silicon chip and have been used for developing new, high performance detectors for Positron Emission Tomography (PET). As a solid-state devices they suffer from thermal excitation what leads to the appearance of noise events called dark counts. However, it is unclear what effect the dark counts have on the count rate performance of dSiPM. Therefore, it is necessary to investigate the event loss caused by these dark counts and to come up with optimal configuration of these devices. Here, the effects of dark counts on the performance of are evaluated.**

Due to the trigger architecture of dSiPM, dark counts cause start of acquisition sequence of the device. Processing of these dark counts leads to dead time of dSiPM what cause the loss of true gamma events. We studied how trigger level, validation level and validation length influence the loss of events due to dark counts. We found that validation time should be kept long (40 ns) to minimize the loss of events. Use of high trigger level and validation level also reduce the event loss caused by dark counts. However, with the high validation level, detection of events with low number of optical photons is reduced as it more difficult for these events to pass the validation threshold. The RTL refresh option was also tested to reduce the effect of dark counts. We found that this option resulted in the achieving maximum sensitivity, i.e. the highest fraction of correctly recorded true events, of dSiPM regardless of used validation and trigger levels. In cases when the scintillation light is spread over several dies, we found that the use of RTL refresh option combined with a low validation level in order to guarantee the individual validation of all required dies ensures higher sensitivity than the use of Neighbor Logic (NL). Finally we verified the dead time of dSiPM and found that is longer than specified and equal to 50 ns.

I. Introduction

A. Digital Silicon Photomultipliers

DIGITAL Silicon Photomultipliers (dSiPM) are solid-state single-photon sensitive devices made of arrays of Geiger-mode avalanche photodiodes. In contrast to analogue SiPM, these devices integrate CMOS electronics into a silicon photomultiplier chip for early digitization of Geiger-cell output resulting in fully digital readout. As a result, they achieve gain-independent photon counting with accurate photon arrival time information. This makes them very promising devices for the next generation of detectors for medical imaging applications [1]. Due to the novel architecture, the dSiPM contains a set of configurable parameters that must be well understood for the optimal use of this device as a gamma photon detector. The optimal configuration parameters for each application vary depending on the energy of the gamma, the light output, time response of the scintillator and the spread of the scintillation light over the sensor. In particular, dark counts can lead to partial or complete loss of gamma events or give rise to noise events, uncorrelated with gamma events.

Since dSiPMs are solid-state devices, they generate dark signal due to thermal excitation. Thermally generated carriers can fire the avalanche process, what leads to the firing cells of the device even in the absence of light. These noise events are referred as dark counts. The amount of dark events generated per second is referred as dark count rate and depends on the temperature of the device. The higher the temperature, the higher the dark count rate.

To explain loss of gamma events due to dark counts we will first give a brief introduction to the operation principles of the dSiPM. The dSiPM device consists of 16 independent units, called dies. Each die contains 4 SiPM pixels (active area: 3.2x3.8 mm^2) with each pixel further split into four sub-pixels. Each die contains individual trigger and validation logics, which are based on different Boolean interconnection of pixels and sub-pixels. A trigger is produced when the configured trigger level is met [2]. At that moment a configurable time (validation time) is started during which a certain validation level (i.e. a certain number of light photons) must be reached in order to start recording the event. The die is reset if the validation level is not reached. During this reset, the cells are recharged and are therefore not able to detect any arriving light photons. According to specification, the recharge time is ~20 ns. The acquisition sequence of the dSiPM is presented in Fig 1.

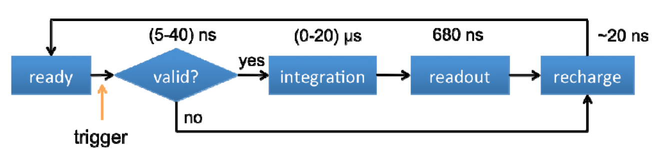

Fig. 1. Acquisition sequence of dSiPM sensor.

B. The influence of dark counts on the dead time and the spectrum of dSiPM

With the lowest trigger level (1) only one fired cell is needed to trigger the die. When combined with a high

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validation level, the trigger caused by the dark count fired cell will probably not be validated and recharging will start after the validation time. Therefore, the higher the dark count rate, the longer the fraction of time during which the die will be inactive. This inevitably will lead to longer dead time and to the higher loss of real gamma events. This is illustrated in Fig. 2.

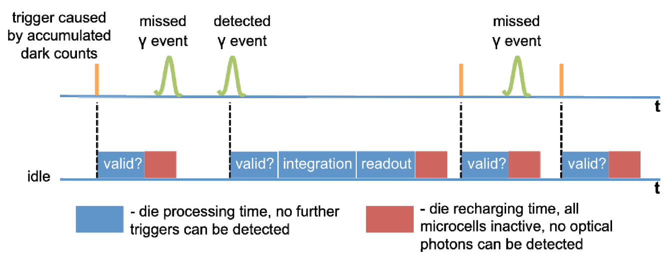

Fig. 2. Illustration how dark counts can lead to the loss of gamma events in a dSiPM.

At a higher trigger level, cells fired due to dark counts accumulate until the trigger level is met. In that way, at the same dark count rate, the dark count trigger rate is reduced but will still have a significant influence. On the other hand, when we use a higher trigger level it will be more likely that the trigger produced by dark counts will also meet the validation level. This would then result in events in the energy spectrum formed by a combination of dark counts; these will be called dark count events. To prevent this effect there is an option, called RTL refresh, that allows for fast reset of full cell rows of sub-pixels (row-trigger-lines; RTL), where one or more cells have been fired but no die trigger has been generated after a predefined time (~ 20 ns). Thus, this feature avoids the dark counts to accumulate. During this RTL reset, only cells in one particular RTL line are recharged while all other cells are kept active. This allows the entire die to remain in an active state and detect incoming gamma events. This feature can obviously not be used for trigger level 1 as each fired cell already generates a trigger.

For several configurations it is necessary to have light spreading over different dies. Typical examples are detectors employing monolithic crystals [3], [4] or pixelated crystal arrays with pixel size not matching the light sensor pixelization [5], [6]. In these cases it is required to simultaneously read out several dies in order to process the event. As the light is spread onto several dies there is a higher probability that one or more of dies, which are supposed to collect light from an incoming gamma photon, are in the recharge phase after being triggered by dark counts. Such situation is presented in Fig. 3.

In dSiPM devices there are two ways to detect light spread over several dies. The first approach is to set the validation level to a low value such that all dies measuring a significant amount of light will independently start their readout. The second approach is to force the readout of all the dies in the devices by using the Neighbor Logic (NL) option. NL is a feature of dSiPM that allows a first successfully triggered and validated die to become a 'master die', forcing all other dies to start acquiring data.

In this work we studied different DPC configurations in order to quantify events loss of the dSiPM device due to dark counts and to provide guidelines on the optimal configuration for different detector designs and applications.

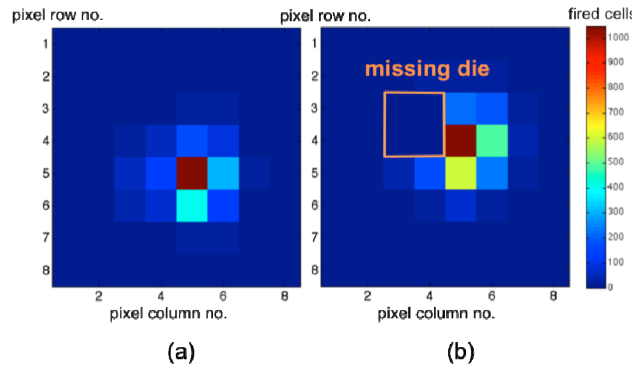

Fig. 3. Example of recorded light distribution of 511 keV interaction where all dies of dSiPM array were available (a) and where one die was missing (marked by the orange box) due to undergoing recharge (b). Color scale represents number of recorded optical photons in dSiPM's pixels.

II. Materials and Methods

In this study a single dSiPM array DPC3200-22-44 (Philips Digital Photon Counting) was used. In order to control the expected output in terms of events count rate and number of detected optical photons per event a pulse light emitting diode (LED) was used as a source of optical photons. The LED was placed 7 cm from the detector so that the whole surface of dSiPM was illuminated by light produced by the LED. The LED was driven by Agilent Function/Arbitrary Waveform Generator, type 33220A-ABA, which was set to output pulses 100 ns width, 5 ns both rising and falling edge at a frequency of 10 kHz. Since the main scintillator of interest to use with the detector is LYSO, the amplitude of generated pulses was set to match LED light output with the number of optical photons registered by a DPC for a 511 keV gamma interaction in LYSO (~3000 registered photons per die). The whole setup was placed in a temperature chamber where the working temperature of dSiPM during measurements was kept within 3.5°C to 5°C. The schematic of measurement setup is shown in Fig. 4.

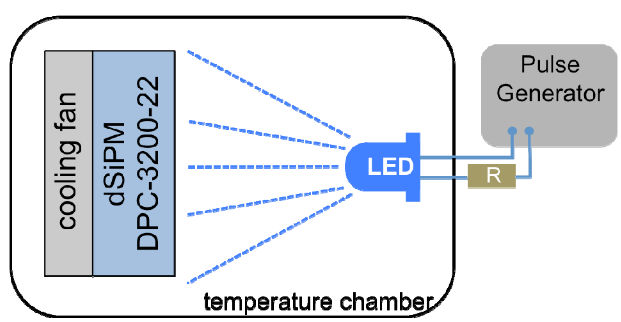

Fig. 4. The schematic of measurement setup.

For all measurements a fixed integration time length of 165 ns (similar to setting used for LYSO) was used for dSiPM device. Furthermore, 10% of the most active cells were disabled in order to reduce dark count rate (DCR) in the detector. At the given working temperature, this resulted in a cumulated DCR of about 3.1 MHz per die. Fig. 5 shows the measured cumulated DCR of a single die (active area: 7.15x7.87 mm^2) at 4°C as a function of the percentage of active cells.

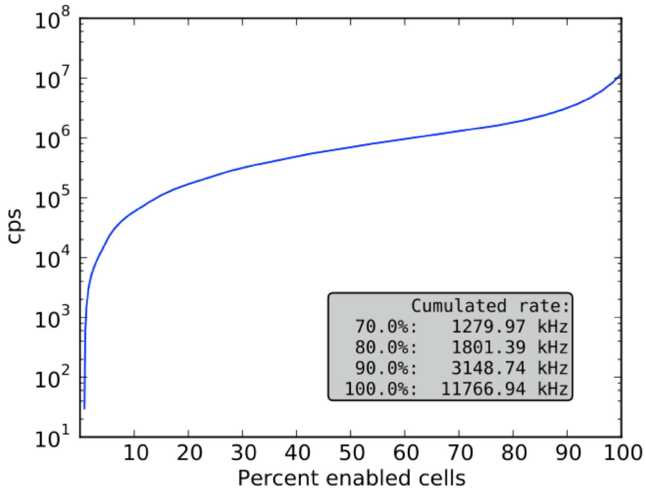

Fig. 5. Cumulated dark counts rate (DCR) of a single die at 4°C. Values in the box show cumulated DCR for 100%, 90% 80% and 70% of active cells.

To quantify the event loss for different dSiPM configurations and to determinate which configuration provides the highest sensitivity of the device a fixed number of light pulses was generated with the LED. In order to filter LED events from other types of events (dark counts or false events) a histogram of the number of fired cells per event was obtained and only the events contained in the photopeak were selected for further processing (see figure 6 in the next paragraph). Subsequently the number of recorded LED events by the DPC was compared to the number of generated light pulses and the fraction of lost events was calculated.

For the first results only one of the central dies of dSiPM tile was activated. First the fraction of recorded LED events was measured for different validation time length (validation level set to 8 and trigger level was set to 4 for this measurement). Second, the fraction of recorded events was determined for varying validation level (validation time set to 40 ns and trigger level was set to 4 for this measurement). Finally, the percentage of recorded events was measured for different trigger levels (1, 2, 3 and 4). Validation time and level for this study was chosen based on the previous measurements to provide the highest fraction of correctly recorded LED events. These three measurements were performed both with RTL refresh option switched on and off to evaluate its efficiency to reduce the influence of dark counts on dSiPM.

Next, different combinations of RTL refresh and NL options were studied for cases where the simultaneous readout of multiple dies is required to process a single event. For this study trigger level 4, validation level 8 and validation time of 40 ns were used. All dies were active and all four combinations of RTL refresh and NL were studied (on/off). An event with one or more missing dies was considered as an invalid event.

Finally, the event loss of the dSiPM was quantified for situations where multiple dies were required to record a single event. For this purpose a different number of dies (1, 2, 4 and 16) was activated per acquisition and the fraction of recorded LED events was measured in each case. As in the previous studies, measurements were performed for RTL refresh turned on and off and events with at least one die missing were considered as invalid. The NL option was turned off. Trigger level 4, validation level 8 and a validation time of 40 ns were used.

Furthermore the actual length of recharge time of dSiPM was verified. For this, the fraction of recorded events for different trigger rates of dSiPM was measured. Different trigger rates were acquired by deactivating a different fraction of dSiPM's cells for each acquisition. Monte Carlo simulations of the dSiPM acquisition chain were performed with different dead times (non-paralyzable model). The results obtained with simulations were fit to the measured data. From a comparison of the simulated and the measured data, the real dead time of the device was obtained. For this study only one die was activated and trigger level 1, validation level 8 and validation time of 40 ns were used.

III. Results

A. Quantification of events loss

Table I shows the percentage of recorded LED events for different validation time lengths for both RTL refresh turned on and off. It can be clearly seen the percentage of recorded events increases with the validation time.

Table I. Percentage of recorded LED events for different validation time (settings used: trigger level 4, validation level 8)

Validation time	RTL	
	ON	OFF
5 ns	12.01 %	8.58 %
10 ns	58.85 %	46.35 %
20 ns	99.29 %	98.09 %
40 ns	99.31 %	98.48 %

Table II shows the percentage of recorded LED events for different validation levels for both RTL refresh turned on and off. In case of RTL refresh turned on the percentage is constant for all validation levels while with RTL refresh off the percentage reduces at lower validation levels.

The percentage of recorded LED events for different trigger levels is presented in Table III. For RTL refresh on, the percentage is almost constant with the slight reduction at trigger level 2. For RTL refresh turned off a slight decrease of recorded events can be observed for lower trigger levels with a significant drop for trigger level 1.

TABLE II. PERCENTAGE OF RECORDED LED EVENTS FOR DIFFERENT VALIDATION LEVELS (SETTINGS USED: TRIGGER LEVEL 4, VALIDATION TIME 40 NS)

Validation level	RTL	
	ON	OFF
2	99.46 %	53.62 %
4	99.15 %	97.61 %
8	99.31 %	98.48 %

TABLE III. PERCENTAGE OF RECORDED LED EVENTS FOR DIFFERENT TRIGGER LEVELS (SETTINGS USED: VALIDATION LEVEL 8, VALIDATION TIME 40 NS)

Trigger level	RTL	
	ON	OFF
1	-	86.29 %
2	98.88 %	96.84 %
3	99.41 %	97.66 %
4	99.31 %	98.48 %

Table IV shows the percentage of LED events recorded by all 16 dies for different combinations of RTL refresh and NL options. The highest percentage of recorded events was observed for RTL refresh turned on and NL turned off while the highest loss of events was observed when both options were enabled.

TABLE IV. PERCENTAGE OF RECORDED LED EVENTS FOR DIFFERENT RTL & NL CONFIGURATIONS (SETTINGS USED: TRIGGER LEVEL 4, VALIDATION LEVEL 8, VALIDATION TIME 40 NS)

Neighbor Logic	RTL	
	ON	OFF
ON	37.83 %	65.78 %
OFF	99.00 %	89.83 %

Table V shows the percentage of recorded LED events in the situation where multiple dies are needed for event detection. For RTL refresh enabled, the fraction of recorded events was constant irrespective of number of dies required. For RTL refresh disabled, the fraction of recorded events decreases as the number of required dies increased.

TABLE V. PERCENTAGE OF RECORDED LED EVENTS FOR DIFFERENT NUMBER OF DIES NEEDED TO RECORD A SINGLE EVENT (SETTINGS USED: TRIGGER LEVEL 4, VALIDATION LEVEL 8, VALIDATION TIME 40 NS)

Number of dies	RTL	
	ON	OFF
1	99.31 %	98.48 %
2	99.64 %	97.69 %
4	99.57 %	98.36 %
16	99.00 %	89.83 %

B. *False events caused by RTL refresh*

In the histograms of the number of recorded optical photons per event, for both cases of RTL refresh (on/off), peaks at low values were observed (Fig. 6). It was observed that with RTL enabled, this low energy peak contained more counts than in case of RTL refresh turned off. Also the number of optical photons recorded per event for this peak was much higher in case of RTL refresh. All recorded events forming this peak at low values for RTL refresh turned on had a repeating pattern of fired cells in a die. In each event one pixel of a die had very high number of fired cells (even few hundreds) while rest of die's pixels had just a few fired cells.

This is depicted in Fig. 6. The peaks at higher values correspond to correctly recorded LED events for RTL refresh turned on (blue) and turned off (red). In case of disabled RTL refresh, the low energy peak obtained at lower values corresponds to events caused by accumulated dark counts that managed to fulfill the validation level. For RTL refresh turned on the low values peak corresponds to previously described events with repeating pattern of fired cells. As the RTL refresh prevents accumulation of dark counts and the pattern of fired cells indicates that, these events were considered as an undesirable side effect of using RTL refresh option.

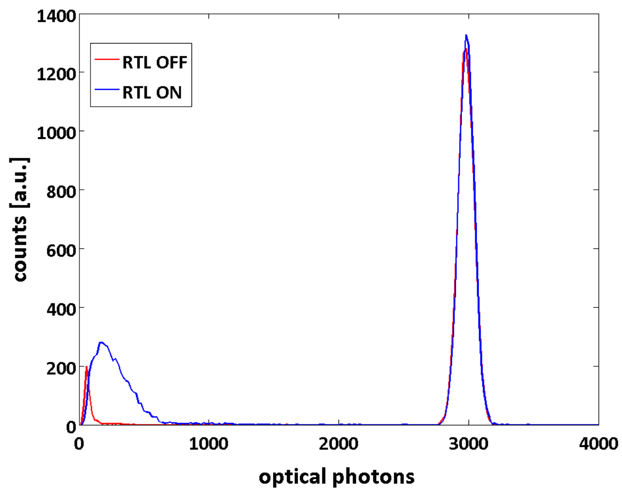

Fig. 6. Spectrum of recorded LED pulse by dSiPM for RTL refresh turned on (blue) and RTL refresh turned off (red).

C. *Verification of the dead time of the DPC*

Fig 7. shows the percentage of recorded LED events for different trigger rates (blue plot) fitted with the results of Monte Carlo simulations of dSiPM acquisition chain for different lengths of dead time according to a non-paralyzable model (red plots). The percentage of recorded events increases with the decrease of trigger rate caused by dark counts. The drop in the fraction of recorded events for very low trigger rates is caused by the fact that in these cases, a very limited number of cells was left active to acquire such low trigger rates. It can be observed that the best match between the measured data and the outcome of simulation is achieved for the case when dead time was assumed to be equal to 50 ns.

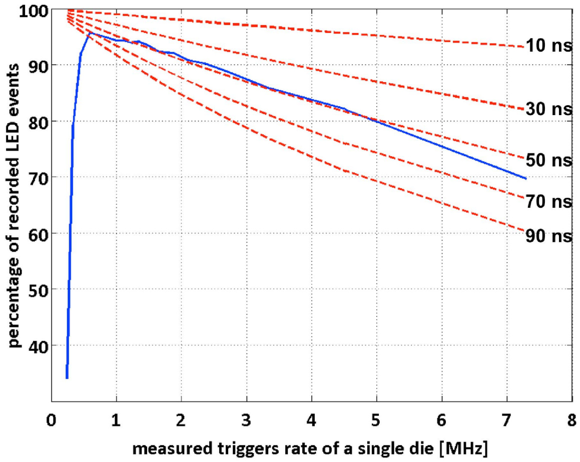

Fig. 7. Fraction of recorded LED events as a function of dark counts trigger rates (blue) with fit of simulated number of recorded events according to non-paralyzable dead time model for different dead time lengths (red).

IV. Discussion

We observed that the RTL refresh option allows recording almost 100% of the events while completely removing the accumulated dark count events for trigger level 2, 3 and 4. RTL refresh also allows achieving maximum sensitivity in terms of correctly recorded events regardless of used validation level as presented in Table II. This allows the dSiPM sensor to correctly validate events with a low number of optical photons. In Table V it is shown that RTL refresh can be efficiently used to achieve maximum sensitivity with any number of dies needed to record a single event.

We also observed that using the RTL refresh option causes appearance of false events (see Fig. 6). These events have a repeating pattern with one pixels of the dSiPM die containing a very high value of fired cells (even a few hundred) while other pixels have just a few fired cells. The cause of these events is RTL's fast recharge of cells. During this fast recharge there is a probability that photon avalanche are generated in the pixel of dSiPM. This is why one pixel, in which such avalanche was generated, has so high number of fired cells while other not. Due to the pattern of these events they can be efficiently filtered out from the data however for the detection of low energy gamma photons the filtering might be more challenging. For efficient filtering, the light distribution of low energy gamma photons in the detector should be carefully studied in order to distinguish them from false RTL events. Also at the high dark count rates the false RTL events can cause a slight drop in detector sensitivity as each acquisition of these false events is finished by die recharge phase, which contributes to the dead time of the detector.

RTL refresh should not be combined with NL as shown in Table IV. The loss in the sensitivity in case of using NL is due to two factors. First, the dies that are recharging due to their own unsuccessful validation are still ignoring the master trigger signal, which needs up to 20 ns to propagate from the master die to other dies. Therefore, a die, that is already in the recharge phase before the master trigger reaches, will not record incoming photons and will be missing. Second, due to internal processing in the current version of the dSiPM, it can happen occasionally, that the valid master signal is generated although the master die invalidated the event and it is recharging. In this case the master die will be missing and other dies will be recording an invalidated event. These two factors combined with the appearance of false RTL events cause a significant drop in dSiPM sensitivity when both RTL and NL options are combined.

When comparing the fraction of recorded events for RTL refresh enabled and disabled for some cases the difference might appear to be insignificant. However one should remember, that this study was based on a very simplified scenario (LED light) when each event contains a high number of optical photons recorded by each die of the sensor. In real applications this is not the case and events with a lower number of optical photons are more probable. In the case of light spreading, some dies are illuminated by a much lower number of optical photons than the other dies. In this situation RTL refresh combined with lower validation level will give a much better result than the use of NL and higher validation level.

When using trigger level 1 and a single die active, we found the fraction of recorded events to be 86.29 %. The loss of events was caused by the dark counts triggers, which measured rate was ~3.3 MHz, and the expected recharge time of a die ~20 ns. From Monte Carlo simulation of the dSiPM acquisition chain we expected this value to be 93.6 %. To verify the recharge time of dSiPM, which is the dead time of the sensor, we measured the fraction of recorded events as a function of the trigger rate (see Fig. 7). Then we repeated the Monte Carlo simulations for different lengths of recharge time for acquired trigger rates and fitted the results to measured data. From the fit, based on non-paralyzable dead time model, we concluded that the actual dead time of dSiPM is around 50 ns instead of just 20 ns stated in the device's specification. Repetition of the simulations with dead time of 50 ns resulted in a fraction of recorded events equal to 86.7 %. This difference of dead time length might be caused by internal excess delays in the device between switching from recharge state to active state in the acquisition chain. This effect should be taken into account when evaluating the sensitivity of detector based on dSiPM working at a given dark count rate.

V. Conclusions

We have found that RTL refresh is an effective option to reduce dark counts and to ensure maximum sensitivity of the detector regardless of trigger level, validation level and number of dies needed to record an event. Therefore, in cases when the scintillation light is spread onto several dies, the use of RTL refresh option should be employed and combined with a low validation level in order to guarantee the individual validation of all required dies. This approach ensures higher sensitivity of the detector than employing NL.

When trigger level 1 is required for accurate timing measurements [5] the following strategies can be followed to reduce the loss of events. First, the dark count rate can be reduced by lowering the working temperature of dSiPM and by deactivating a larger fraction of the most active cells of the device. Second, the light can be focused in a small area of the dSiPM tile so less dies are needed to process the incoming event.

Furthermore we found that the dead time of dSiPM is longer than just recharge time of this device and is around 50 ns instead of 20 ns.

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