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Empirical dead-time corrections for energy-resolving detectors at synchrotron sources

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ABSTRACT

We examine the high count-rate performance of an energy-resolving detector in the three operating modes of the Advanced Photon Source (APS). Specifically, we present the optimal dead-time corrections for the SII Vortex silicon drift diode (SDD) detector using a digital pulse processor, highlighting the differences in operation between the 24-bunch, 324-bunch, and hybrid singlet modes of the APS. We analyze the input count rate (ICR), output count rate (OCR), and several regions of interest (ROIs). We find that the correct formula for dead-time correction can extend the use of the detector to significantly higher count rates.

1. Introduction

Detector performance is, historically, one of the major limitations to synchrotron-based experiments. Limiting the count rate of a detector to its linear response regime often defeats the advantages of working at a high-brightness source. Techniques which expand a detector's practical count rate range will improve the detector's overall usefulness. Dead-time corrections account for the detector response when photons arrive faster than they can all be counted. Here we report on the dead-time response of a silicon drift diode (SDD), commonly used for X-ray fluorescence experiments, specifically, the Vortex series of detectors by SII Nanotechnology USA, Inc. Recently, the performance of this detector was extensively reviewed by Woicik et al. [1], including energy resolution and general dead-time characteristics. We focus specifically on the effect of the X-ray bunch pattern on the dead-time properties of the Vortex SDD.

An SDD is a paralyzable detector [2], i.e., each incident photon will reset the time, τ_d, that the detector is "dead." In this case, for a general count rate N, the observed count rate N_O is related to the true count rate N_T by

$$N_O = N_T \exp(-\tau N_T). \quad (1)$$

Strategies for numerically solving Eq. (1) have been given by several authors [3,1]. In Eq. (1), τ is the effective dead-time parameter, which depends on the intrinsic detector response time τ_d and the spacing of X-ray pulses T. For a synchrotron fill pattern with evenly spaced bunches, the expected value of the dead-time parameter

$$\tau = T[\mathrm{Int}(\tau_d/T)+1] \quad (2)$$

where $\mathrm{Int}(x)$ is the nearest integer less than or equal to x. For an asymmetric fill pattern T is not well-defined; however, under certain conditions a weighted average of the different bunches can be numerically constructed [4]. In such situations Eq. (1) may still be applicable, using an empirically determined dead-time parameter τ [3].

Fluorescence detectors are commonly used with multichannel analyzers which provide the input and output count rates (ICR and OCR, respectively) along with the binned spectrum of data. One dead-time correction scheme which is often applied to the fluorescence signal is simply to multiply the signal of a fluorescence line of interest, as defined by a region of interest (ROI), by the ratio of the observed input to output count rates. However, ICR and OCR both suffer from dead-time effects [5]; simply scaling raw data by ICR_O/OCR_O may not yield the most accurate data. In the following section we describe our measurement and the fill patterns of the APS, and in Section 3 we present our results.

2. Measurements

Measurements were performed at beamline 7BM-B of the APS. 10-keV X-rays from a multilayer monochromator (1.5% bandwidth) were incident on a copper foil. The detector was placed at a 90° scattering angle to minimize the scattered beam signal. The shortest available peaking time, 0.25 μs, was used. The gap time was set to 0.2 μs. A manufacturer-supplied digital pulse processor (from XIA LLC), integrated within the detector power supply/electronics box, served as the multichannel analyzer. The incident

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intensity was scanned by opening the gap of slits placed upstream of the Cu foil. At each point in the scan, the ICR and OCR were recorded, as well as two ROIs. One ROI covered the whole spectrum; in fact, the signal from this ROI was essentially identical to the OCR in all cases, so we will not refer to this further in this paper. The other ROI was given an upper limit ~ 11 keV, i.e., windowed against pile-up pulses; this ROI was dominated almost exclusively by the Cu $K\alpha$ and $K\beta$ fluorescence signals. The FWHM of the fluorescent lines were 320 eV, with no shift in position for count rates up to the maximum of the observed ROI signal. An ion chamber served to normalize the incident beam flux. A scale factor, as determined from the low-count rate range, was applied to the ion chamber signal to determine the true count rate of a measurement. Different SDD units were used in the measurements, according to availability from the APS Detector Pool. A Vortex EX unit was used for two fill patterns (24-bunch and 324-bunch), while a Vortex Single Element was used for hybrid singlet mode. The difference between these models is simply in the length of the detector snout. Preliminary measurements with a four-element Vortex ME4 unit gave similar results to those shown below, with a variation in τ of a few percent between the elements.

These measurements were performed in each of the three operating modes of the APS. Two of the fill patterns (24-bunch and 324-bunch) have equal gaps between electron bunches in the accelerator (153 and 11.4 ns, respectively). Nominally, each bunch in these modes is filled with the same amount of current for a total of 100 mA, although bunch-to-bunch variations on the order of 10% are common. The third fill pattern, known as "hybrid singlet mode," consists of one 16-mA singlet isolated from eight septets, which hold the balance of the current. The septets are 51 ns long with 17 separations between them; the separation from the singlet to the nearest septets is 1.59 μs.

3. Results and discussion

Fig. 1 shows data in 24-bunch mode. Fig. 1a–c show the dead-time effects on ICR, OCR, and ROI, respectively. The figures show the linear response (dashed line) as well as the best fit to the data according to Eq. (1). The source of dead-time for ICR is the fast filter of the digital X-ray processor [5], while the OCR and ROI dead-time

Table 1
Comparison of measured dead-time parameters in each APS operating mode, with times in μs. Uncertainties for each measurement are about 3%. Also shown is the spacing between bunches.

T	24-bunch 0.153	324-bunch 0.0114	Hybrid singlet (asymmetric)
ICR	0.068	0.054	0.60
OCR	1.20	1.277	2.17
ROI	1.32	1.451	2.69

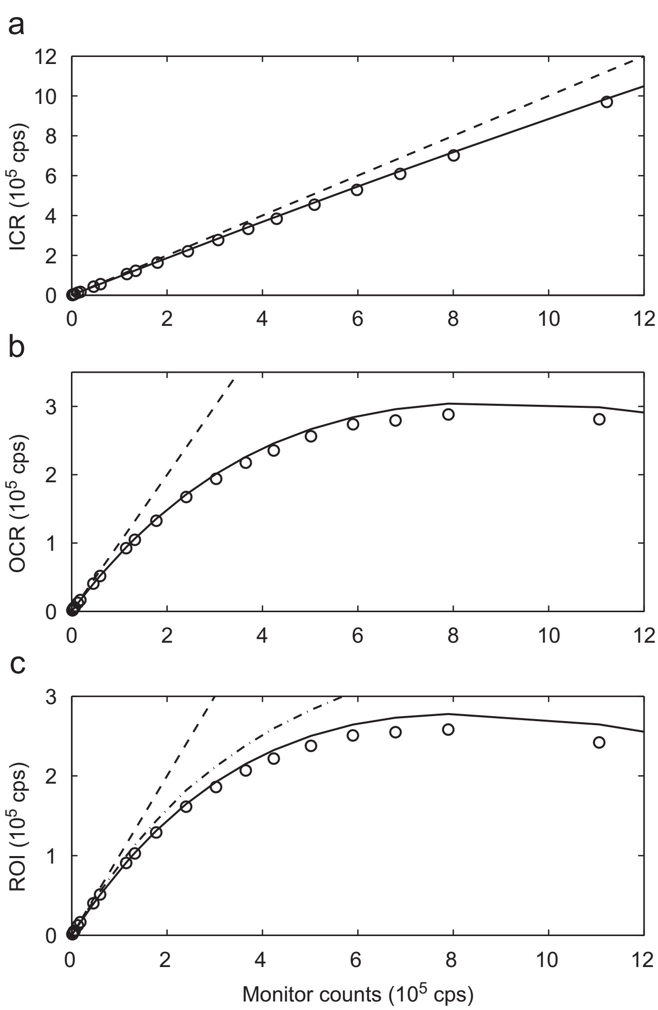

Fig. 1. Dead-time results for 24-bunch mode for (a) ICR, (b) OCR, and (c) ROI. For each set, data are shown as circles, fit to Eq. (1) as solid lines, and the linear response as a dashed line. In (c), the correction of ICR_O/OCR_O is shown as the dashed-dot line.

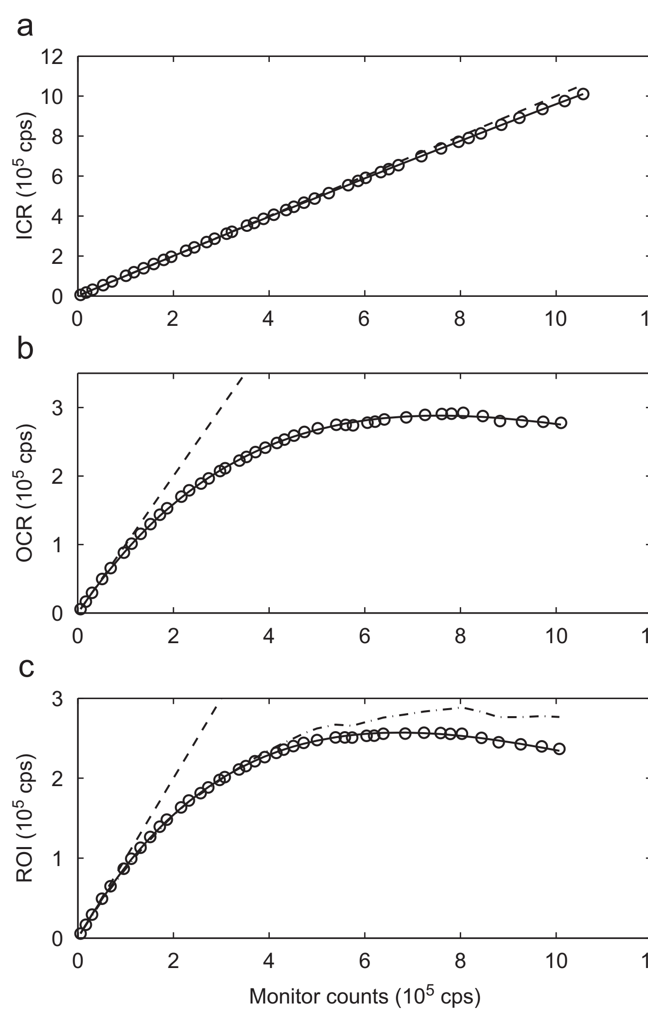

Fig. 2. Dead-time results for 324-bunch mode. Symbols are the same as in Fig. 1.

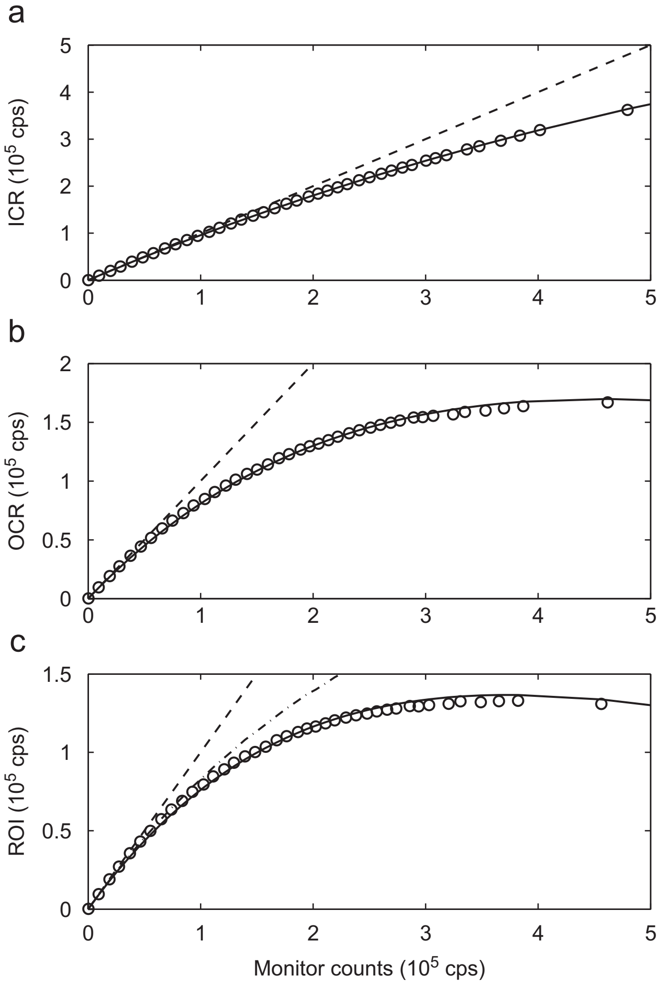

Fig. 3. Dead-time results for hybrid singlet mode. Symbols are the same as in Fig. 1.

characteristics will depend on the shaping time used. Fit results for each dead-time parameter, τ_{ICR}, τ_{OCR}, and τ_{ROI}, are summarized in Table 1. With no dead-time correction, errors in the measured count rate in the ROI quickly become significant. A 10% deviation from linearity occurs at $ROI_T \sim 30$ k counts per second (cps) for the uncorrected data. Correcting with the factor ICR_O/OCR_O seems to systematically overestimate the correction, but stays within 10% for all count rates. Correction via Eq. (1) might, in principle, make the whole range of data usable. In practice, corrections would be difficult to properly implement at count rates approaching $1/\tau$ (750 kcps), where the detector is insensitive to small changes in count rate [6].

The response of the Vortex SDD in 324-bunch mode (Fig. 2) is similar to that in 24-bunch mode, although the ICR response is notably more linear. A similarity is expected; the intrinsic detector response time τ_d is substantially longer than the bunch separation, so the source in either mode appears quasi-continuous. However, according to Eq. (2), one would expect shorter values of τ for the mode with shorter T. Correction using ICR_O/OCR_O is also more accurate in this mode than the others.

Compared to operation in the other modes, the SDD performance is significantly degraded in hybrid singlet mode. As seen in Fig. 3, even with dead-time corrections, the maximum usable count rates are about half of what is possible in the modes with regularly spaced bunches. The Vortex SDD is too slow to resolve the septets in hybrid singlet mode; this essentially results in the detector seeing two groups of well-separated X-rays, with about a factor of 5 difference in flux between the groups.

In conclusion, we have demonstrated the means by which dead-time corrections can substantially improve the operation of a SDD fluorescence detector. Use of Eq. (1) is a more accurate correction than simply scaling the raw data by the factor of the observed ICR/OCR. These results are readily generalizable to other synchrotrons with any given fill pattern, if τ is accurately known.

Acknowledgments

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