complexity of pile-up decomposition. SDDs can bring significant contributions at FELs in (1) photon counting, (2) spectrum measurements, and (3) background measurements and set-up optimization.

We present a pulse processing method based on fitting individual, overlapping pulses with pulse functions (a combination of gradual step function and exponential decay) which allows extracting (in the time domain) precise amplitude and timing information in the presence of pulse pile-up and clipping.

We demonstrate that, for individual pulses, the pulse amplitude is not an optimal estimator for signal amplitude (due to variation in peaking times); instead, the pulse amplitude and peaking time are obtained for each pulse by fitting. This removes the need for pulse shaping and takes into account pulse pile-up.

Avoiding pulse shaping reduces peaking times to tens of nanoseconds, resulting in reduced pule pile-up and allowing decomposition of remaining pulse pile-up at photon separation times down to $100\,\mathrm{ns}$ while yielding time-of-arrival information with precision of $10\,\mathrm{ns}$ and allows measurements of higher photon rates, compared to typical pulse shaping approaches.

While we demonstrate the usage of this pulse processing method with an SDD and pulsed FEL source, it can be extended to any detector with rapid response (e.g., SDD, transition edge sensors) and x-ray source (e.g., FEL, synchrotron, x-ray tube). In SDDs at pulsed sources, the timing can be used to recover the interaction radii.

At pulsed sources, or at short time intervals between two photons, photon pile-up occurs and the photon rates are not accurately described by the standard proxy, i.e., area of one photon peaks.

Instead, the photon pile-up of a discrete detected spectrum can be accurately described and fitted with the photon pile-up model presented here, yielding precise estimates of the photon rates in individual lines and effectively decomposing the spectrum. We also extended the model to include the stretching of the Poissonian statistics of pile-up introduced by sources with variable intensity (e.g., FELs).

We present a Bayesian decomposition approach which allows accurate decomposition of individual photon energies in single pile-up events, and estimating its error rate in the order of $1\,\%$ ($99\,\%$ accuracy) for the spectrum discussed in this paper (average rate $\lambda = 1.78$ photons/event, with pile-up of up to 6 photons from 6 monochromatic lines).

The photon pile-up and Bayesian decomposition presented here are useful not only for SDDs but for any applications of pile-up decomposition (e.g., spectroscopy with transition edge sensors [31], low-noise spectroscopic imaging with integrating pixel detectors [32]), or even usual pulse processing with pile-up rejection (two photons with small differences in time-of-arrival will not be distinguished by the pile-up rejection, resulting in pile-up).

The usefulness of silicon drift detectors will continue into the x-ray FEL era of science. Their successors, the ePixS spectroscopic, hybrid pixel detectors already offer hundreds of pixels with similar performance in a compact, robust and affordable package, particularly useful in x-ray FELs [33].

Glossary

ADC:	Analog-to-digital converter
CSPAD:	Cornell-SLAC pixel array detector
CXI:	Coherent X-ray Imaging instrument at LCLS
DAC:	Digital-to-analog converter
ePix:	SLAC hybrid pixel detector platform
ePixS:	Spectroscopic pixel detector in the ePix family
FEL:	Free-electron laser
FWHM:	Full width at half maximum ($\approx 2.355\ \sigma$)
LCLS:	Linac Coherent Light Source at SLAC
PDF:	Probability density function
r.m.s.:	Root mean square
SDD:	Silicon drift detector
SLAC:	SLAC National Accelerator Laboratory
XPP:	X-ray Pump-Probe instrument at LCLS

Acknowledgment

Use of the Linac Coherent Light Source (LCLS), SLAC National Accelerator Laboratory, is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF00515.

We applied the SDC approach for the sequence of authors [34]. Statement of authorship: conception, C. J. Kenney and G. Blaj; LCLS beamtime principal investigator, G. Carini; ePixS ASIC design, A. Dragone; design and acquisition of data, all authors; analytical methods, G. Blaj; analysis, G. Blaj; drafting the manuscript, G. Blaj; revising the manuscript: C. J. Kenney.

References

[1] E. Gatti and P. Rehak, "Semiconductor drift chamber — an application of a novel charge transport scheme," *Nuclear Instruments and Methods in Physics Research*, vol. 225, no. 3, pp. 608 – 614, 1984. [Online]. Available: https://dx.doi.org/10.1016/0167-5087(84)90113-3

[2] P. Emma, R. Akre, J. Arthur, R. Bionta, C. Bostedt, J. Bozek, A. Brachmann, P. Bucksbaum, R. Coffee, F.-J. Decker, Y. Ding, D. Dowell, S. Edstrom, A. Fisher, J. Frisch, S. Gilevich, J. Hastings, G. Hays, P. Hering, Z. Huang, R. Iverson, H. Loos, M. Messerschmidt, A. Miahnahri, S. Moeller, H.-D. Nuhn, G. Pile, D. Ratner, J. Rzepiela, D. Schultz, T. Smith, P. Stefan, H. Tompkins, J. Turner, J. Welch, W. White, J. Wu, G. Yocky, and J. Galayda, "First lasing and operation of an ångström-wavelength free-electron laser," *Nature Photonics*, vol. 4, no. 9, pp. 641–647, 2010. [Online]. Available: https://dx.doi.org/10.1038/nphoton.2010.176

[3] H. Graafsma, "Requirements for and development of 2 dimensional x-ray detectors for the European x-ray free electron laser in Hamburg," *Journal of Instrumentation*, vol. 4, no. 12, p. P12011, 2009. [Online]. Available: https://dx.doi.org/doi:10.1088/1748-0221/4/12/P12011

[4] G. Blaj, P. Caragiulo, G. Carini, S. Carron, A. Dragone, D. Freytag, G. Haller, P. A. Hart, R. Herbst, S. Herrmann, J. Hasi, C. J. Kenney, B. Markovic, K. Nishimura, S. Osier, J. Pines, J. Segal, A. Tomada, and M. Weaver, "Detector development for the Linac Coherent Light Source," *Synchrotron Radiation News*, vol. 27, no. 4, pp. 14–19, 2014. [Online]. Available: https://dx.doi.org/10.1080/08940886.2014.930803

[5] G. Blaj, P. Caragiulo, G. Carini, S. Carron, A. Dragone, D. Freytag, G. Haller, P. Hart, J. Hasi, R. Herbst, S. Herrmann, C. J. Kenney, B. Markovic, K. Nishimura, S. Osier, J. Pines, B. Reese, J. Segal, A. Tomada, and M. Weaver, "X-ray detectors at the Linac Coherent Light Source," *Journal of Synchrotron Radiation*, vol. 22, no. 3, pp. 577–583, 2015. [Online]. Available: https://dx.doi.org/10.1107/S1600577515005317

[6] B. Nasri, C. Fiorini, A. Grande, F. Erdinger, P. Fischer, and M. Porro, "A front-end stage with signal compression capability for XFEL detectors," *Journal of Instrumentation*, vol. 10, no. 01, p. C01022, 2015. [Online]. Available: https://doi.org/10.1088/1748-0221/10/01/C01022