Characterization of energy-resolving hybrid pixel detectors with reference beam qualities for medical applications

C. Bailat[a], M. Campbell[b], J. Damet[a], E. Fröjdh[b,c], W.S. Wong[b]

[a]Institute of Radiation Physics, Lausanne University Hospital, Lausanne 1007, Switzerland
[b]CERN, European Organization for Nuclear Research, CH-1211, Geneva 23, Switzerland
[c]Mid Sweden University, SE-851 70 Sundsvall, Sweden

1. Introduction

The characterisation of radiation fields in radiology is a crucial issue for radiation safety surveillance and the improvement of dose monitoring of medical staff. Energy-resolving hybrid pixel detectors have unique properties for the characterisation of radiation fields and provide a significant new technology for radiation protection. In this work we study the response of two hybrid pixel detectors, Timepix [1] and Dosepix [2], to beam qualities recommended by the International Electrotechnical Commission (IEC) for medical applications. Specifically, we use the reference beam qualities RQR5, RQR7, and RQR9[3]. This work is the first phase of a project that aims to measure the scattered radiation in a medical CT scan room.

2. Measurement instrument: hybrid pixel detector

"Integrated electronics will make electronic techniques more generally available through all of society, performing many functions that presently are done inadequately by other techniques or not done at all."

Intel founder Gordon Moore, 1965

A hybrid pixel detector consists of semiconductor sensor, such as a silicon diode, segmented into pixels and electrically connected to an equally segmented application-specific integrated circuit (ASIC) via bump bonds. This modularisation and independent optimisation of the sensor and ASIC permits:

- Application-specific sensor materials: e.g. Si, CdTe, CZT, GaAs, etc.
- Photon processing electronics that are optimised for speed, power consumption, and functionality
  - 100% fill factor and 100% usage of pixel area for the realisation of circuits (e.g. photon counting and time over threshold measurement)

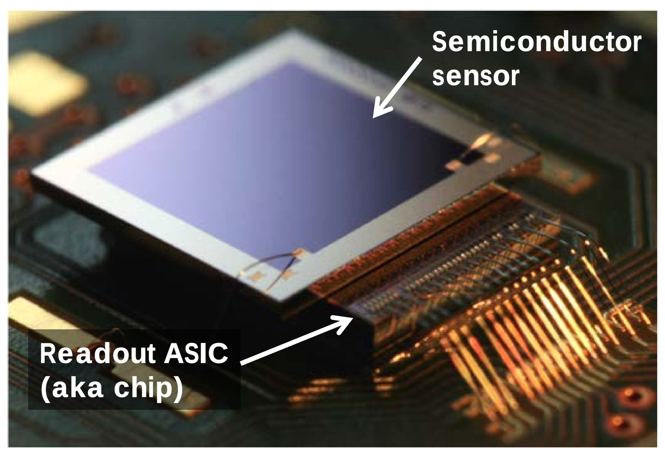

Figure 1. Photograph of the Dosepix hybrid pixel detector (courtesy of ECAP, Erlangen)

Hybrid pixel detectors make excellent X-ray detectors:
Small pixels → small input capacitance → low noise
→ small area → reduced input flux
Analogue threshold → background suppression (see box below)
Digital energy measurement through ToT (see box below)

3. Measurement technique: time-over-threshold (ToT)

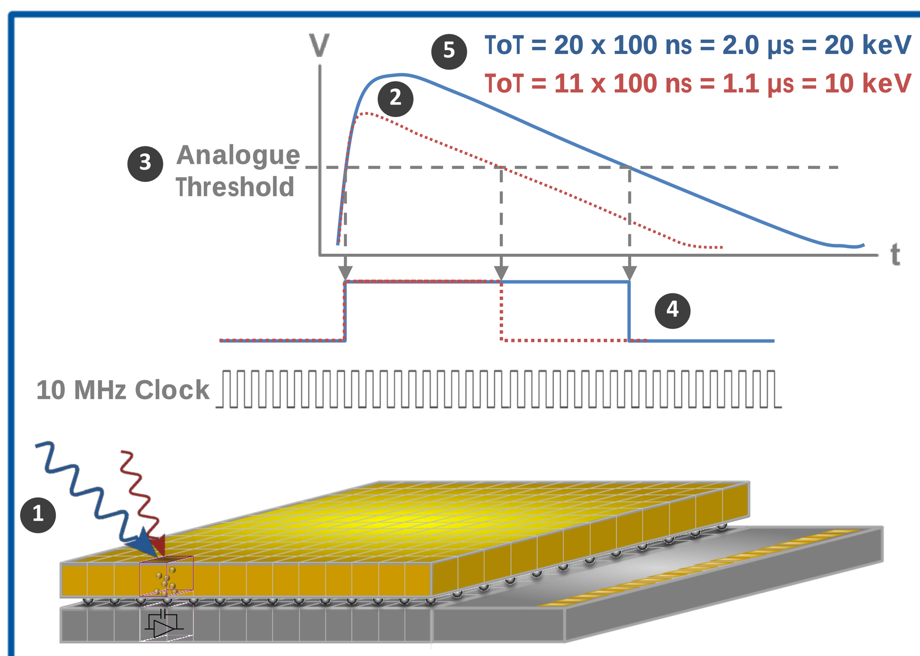

Figure 2. Illustration of ToT measurement in a hybrid pixel detector

1) When an ionising particle or photon impinges on the sensor, the absorbed energy creates electron-hole pairs through the photoelectric effect.
2) The generated charge induces a signal in the associated pixel frontend electronics. **The signal is amplified into a voltage pulse whose height and width are proportional to the energy absorbed by the sensor.**
3) The circuits compare the voltage pulse to an analogue threshold voltage which is set above background noise and low energy signals.
4) This results in a digital pulse whose width corresponds to the time-over-threshold (ToT).
5) Counting the number of reference clock periods coincident with the pulse provides a digital measurement of photon energy.

4. Timepix and Dosepix

Timepix and Dosepix are energy-resolving hybrid pixel detectors that use time-over-threshold to measure X-ray energy. Both systems are portable, using a USB connection to a laptop for power and control.

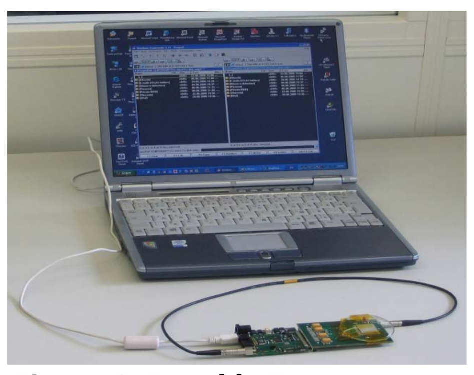
Figure 3. Portable Timepix system (photo courtesy of IEAP, Prague)

Timepix was designed to track charged particles with high spatial resolution. The detector has a matrix of 256 x 256 square pixels of 55 μm pitch. Each output frame contains a single ToT measurement per pixel, thus many frames are needed to construct an absorbed X-ray spectrum offline.

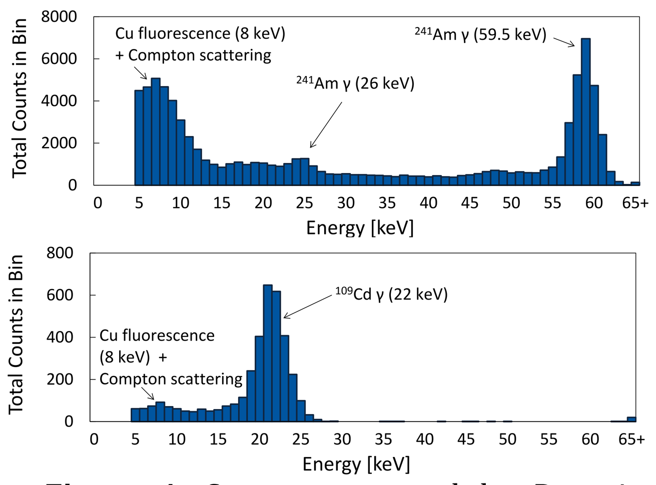

Figure 4. Spectra measured by Dosepix exposed to ^{241}Am (top) and ^{109}Cd (bottom)

Dosepix provides data that can be used to calculate the dose of ionising photon radiation (i.e. X-ray and γ), particularly in pulsed X-ray environments. It contains 12 x 16 square pixels of 220 μm pitch, and 4 x 16 pixels of 55 μm pitch. Each pixel automatically sorts up to 1 million ToT measurements into 16 energy bin registers. Rather than record an image frame, the Dosepix pixels act as 256 parallel processors that measure X-ray spectra.

Table 1 reports of the energy resolution measured using the γ sources ^{55}Fe (5.8 keV), ^{109}Cd (22 keV), and ^{241}Am (59.5 keV). Both chips can be also be operated in photon counting mode, which counts the photon intensity.

	Timepix (ToT mode)	Dosepix (energy binning mode)
Sensor material	300 μm-thick silicon p-on-n sensor biased with 90 V	
Data storage per pixel	1 ToT measurement per pixel	16 x 2^{16} binned ToT measurements per pixel
Minimum detectable energy	~3.6 keV	~ 4 keV
Energy resolution [FWHM]		
@ 5.8 keV	1.36 keV (23%)	2.28 keV (39%)
@ 22.2 keV	5.68 keV (26%)	3.97 keV (18%)
@ 59.5 keV	6.3 keV (11%)	3.76 keV (6%)

Table 1. Properties of the hybrid pixel detectors used in this work

5. Measurement setup

We placed the Timepix and Dosepix detectors side by side, perpendicular to a Toshiba KXO-80G X-ray generator with a tungsten anode. We measured the spectra of five consecutive 2-second X-ray pulses, varying the tube voltage: 69 kV (RQR5), 92 kV (RQR7) and 124 kV (RQR9), and also varying the tube current to study the influence of flux on the measurements.

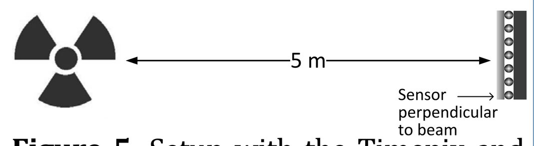

Figure 5. Setup with the Timepix and Dosepix detectors placed directly in the X-ray beam, 5 m from the tube.

6. Measurement results

Figure 6 shows the raw spectra measured by Dosepix placed directly in front of the primary beam without any additional filtering or collimation. The shapes of the left parts of the spectra nicely represent the spectra absorbed in silicon (see simulation results below). However, at high fluxes, "pileup" occurs when multiple photons impinge on the same sensor segment during the time to process a photon (of the order of a few μs). This overlap results in a single combined ToT count. While the ToT value remains proportional to the total amount of energy deposited by the multiple photons, that total energy is binned once as a single high energy event, thus creating false counts in the high energy regions of the spectrum. Pileup is worse in Timepix (Figure 7) because the circuits count the ToT of all photons during the acquisition time (thus there is digital as well as analogue pileup). Pileup poses a challenge in our spectrum analysis as photon attenuation in silicon depends on energy [4]. By varying the tube current, we observe that pileup increases with flux, which suggests that we could remove pileup effects if we sufficiently decrease the flux impinging on the sensor. Unfortunately our existing setup of the primary beam measurements limits our ability to reduce the flux further.

Regardless of the pileup issues, the measured spectra demonstrate the potential to use Dosepix and Timepix to provide new information for radiation measurements. We can, for example, see the effects of characteristic X-rays from the 124 kVp spectra of Dosepix (Figure 6, bottom left). Moreover if we only consider the spectra above a threshold of, e.g. 50 counts, the intersection of the spectrum with the count threshold provides an indication of the X-ray tube settings (Figure 6, bottom right). Although Dosepix is better suited for the measurement of spectra, when operated in photon counting mode, Timepix can be used to monitor beam intensity (see Figure 7, left).

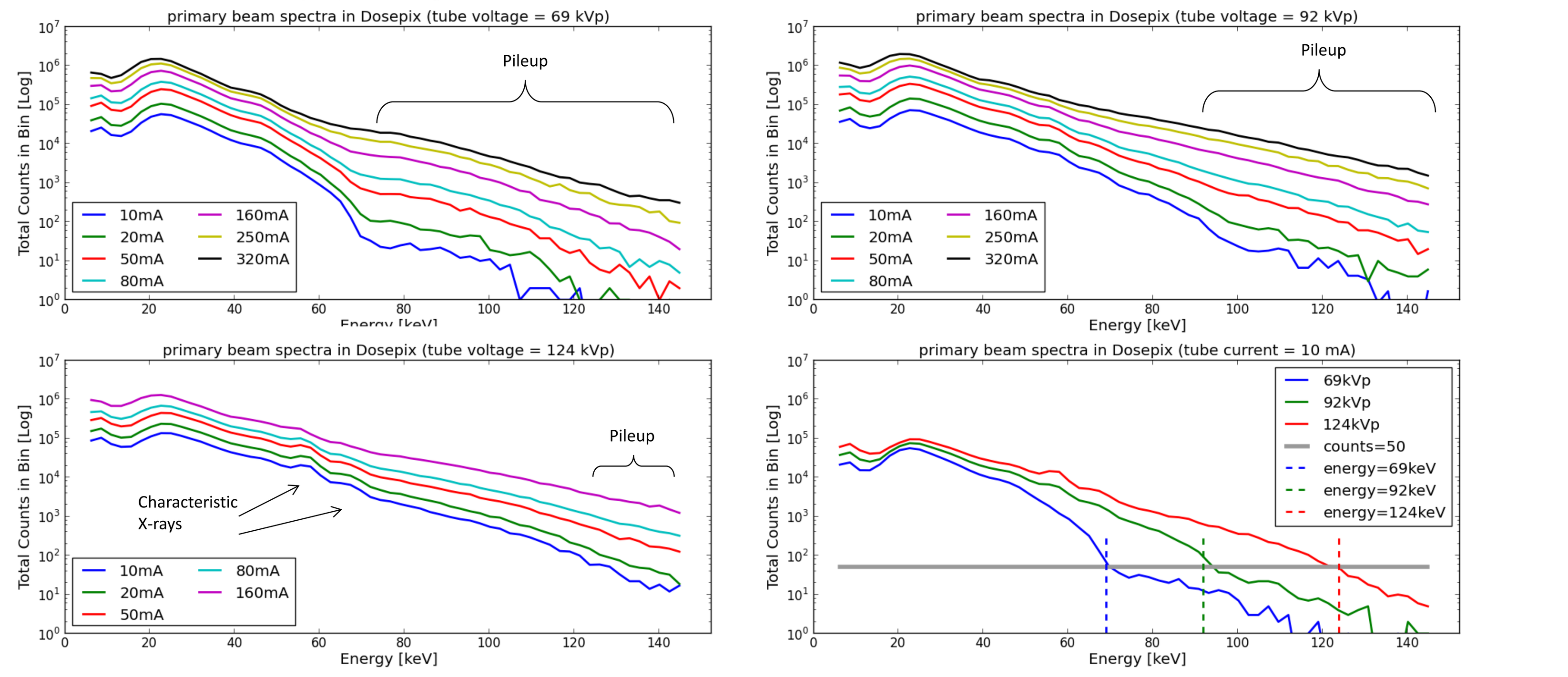

Figure 6. Dosepix measurements of the primary beam spectra, with the beams programed with: 69 kVp and varying tube current (top left), 92 kVp and varying tube current (top right), and 124 kVp and varying tube current (bottom left), and 10 mA tube current and varying tube voltage (bottom right). The data shown here has not been processed; energy binning was done on-chip.

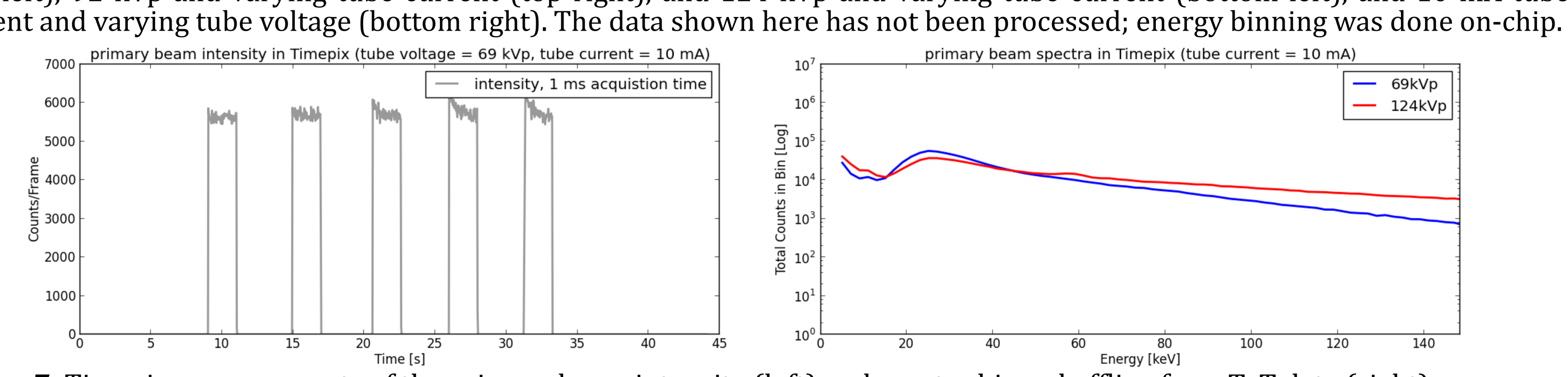

Figure 7. Timepix measurements of the primary beam intensity (left) and spectra binned offline from ToT data (right).

7. Simulation results

To independently validate our measurement results, we simulated the interaction of the X-ray beam with the materials of the various detector components: 300 μm Si sensor, Cu bump bonds and materials of a printed circuit board. We used Geant4 [5] to simulate the radiation interactions and an additional simulation framework to model charge transport by drift and diffusion.

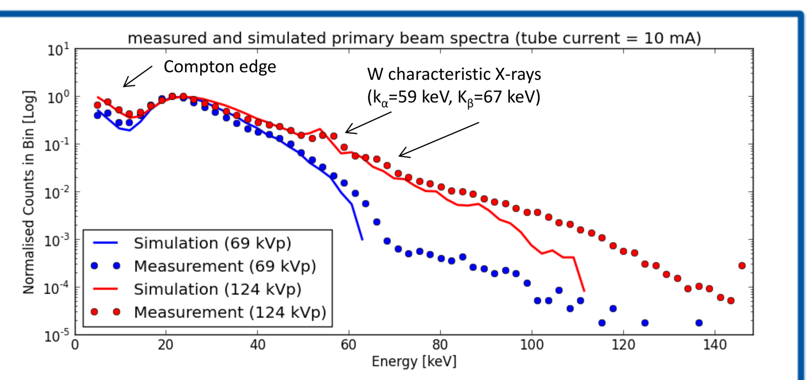

Figure 8. Simulated spectra of the primary beam absorbed by the detector materials. Spectra measured by Dosepix are included for comparison.

Figure 8 shows the simulated X-ray interaction spectra, overlaid with the spectra measured by Dosepix. Note that the simulations study purely the absorbed energy spectra and do not include models of the ASIC circuits. For energies below the maximum beam energy, the measured spectra are in very close agreement with the simulated absorbed energy spectra.

8. Conclusions and future outlook

In this work, we have demonstrated the feasibility of using the energy-resolving hybrid pixel detectors, Dosepix and Timepix, to measure X-ray information. Characterisation of the energy response of these two detectors, and development of detailed simulation models of X-ray interactions with the detector materials, are vital steps in the process to accurately reconstruct spectra impinging onto the detectors and assess the radiation field. The ability to measure X-ray spectra with Dosepix and X-ray intensity with Timepix gives us a potential new tool for the quality assurance of X-ray medical imaging systems. The measurement of the spectra of scattered radiation gives us a new tool for the radiation protection of patients and medical staff.

Our next steps are to resolve the effects of pileup in our measured spectra, and to measure the radiation scattered by X-rays during medical imaging. To demonstrate these next steps, Figure 10 shows X-rays scattered by a water phantom. For these measurements, pileup may no longer pose a problem as the scattered flux is much lower than the flux of the primary beam.

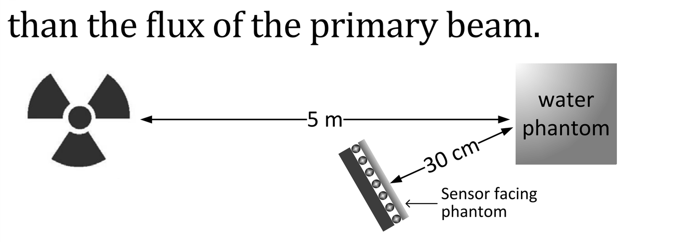

Figure 9. Setup with the Timepix and Dosepix detectors placed at an angle facing an irradiated water phantom.

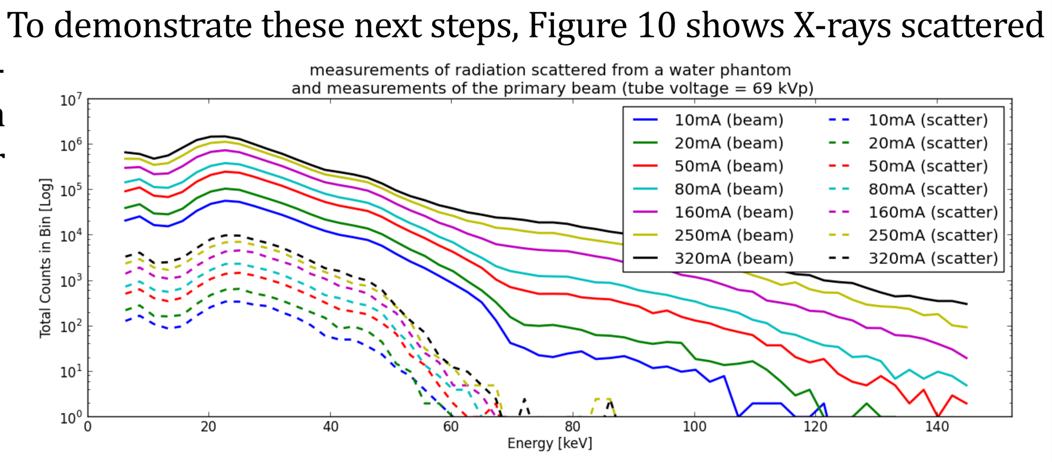

Figure 10. Dosepix measurements of radiation scattered from a water phantom. Measurements from the primary beam are included for comparison.

Acknowledgements and works cited

The authors would like to thank the Medipix2 and Medipix3 Collaborations, IBA Dosimetry GmbH, and the ARDENT Marie Curie ITN project for their support of this work. We would like to especially thank David Krapohl and Armin Schuebel for the use of their simulation code.

[1] X. Llopart et al., "Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements," NIM A, vol. 581, 2007.
[2] W. Wong et al., "A pixel detector ASIC for dosimetry using time-over-threshold energy measurements, Radiation Measurements," vol 46, 2011.
[3] IEC, "Medical diagnostic X-ray equipment – Radiation conditions for use in the determination of characteristics," IEC 61267 ed 2.0, 2005.
[4] "XCOM database of the National Institute of Standards and Technology," http://physics.nist.gov.
[5] S. Agostinelli et al., "GEANT4-a simulation toolkit", NIM Section A, vol. 506, 2003.

Poster contact: winnie.wong@cern.ch