Timepix3 as X-ray detector for time resolved synchrotron experiments

H. Yousef, G. Crevatin,E. Gimenez,I. Horswell, D. Omar,N. Tartoni

Diamond Light Source, Harwell Science and Innovation Campus, Didcot, Oxon OX11 0DE

Abstract

Time Resolved experiments are becoming more and more important in research carried out at synchrotrons. Timepix3 is a 'data driven' ASIC that place a time stamp for every event. The resolution of the time stamp is 1.5625 ns. It enables accessing the nanosecond regime potentially revolutionizing time resolved experiments at synchrotron facilities. The timepix3 ASIC flip chip boned to a 300 µm thick Si detector.

We will report the results of the characterization of Timepix3 with synchrotron X-ray beam with particular reference to timing characteristics.

In the DLS hybrid mode of operation, the electron beam circulating in the storage ring is made of 686 contiguous bunches spaced 2 ns apart, then a gap of 500ns. In the middle of the gap, it was placed an isolated bunch. Since the FWHM of this bunch is of the order of 50 ps when the data acquisition was triggered by the machine clock, the isolated bunch becomes an ideal tool to determine the actual time resolution of the detector. Histograms of the time of arrival (TOA) of the photons were built leading to an estimate of the time resolution of the isolated bunch. When the beam was stopped down to 20 µm x 20 µm and impinged in the centre of the pixel it was obtained a time resolution of 10.21 ns for 20 keV photons,20% signal threshold and 110 V bias voltage. A time resolution of 8.07 ns for 12 keV photons and 30% signal threshold is achieved when increasing the bias voltage to 350 V.

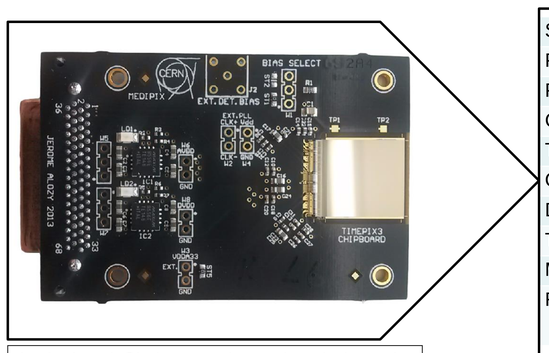
Timepix3 Overview

Timepix3 is a hybrid pixel ASIC developed by CERN within the Medipix3 Collaboration. The ASIC chip is bump-bonded to a Silicon sensor of 300 µm substrate thickness [1].

Pixels are organized in 128 double columns; each double column is divided in 64 blocks of 4 by 2 pixel groups called super-pixels.

Timepix3 measures : [1] **The Time of Arrival** (**ToA**): A measure of the interaction time of the impinging photo.
[2] **The Time over Threshold** (**ToT**): A measure of the photo energy.
[3] **The number of impinging photons**.

Three independent modes of operation can be set : [i] **ToA only.** [ii] **ToA & ToT.** [iii] **Event Count & Integral ToT.**



A pixelated Si detector bump-bonded on the Timepix3 ASIC readout (shiny area) which is wire-bonded on CERN chipboard.

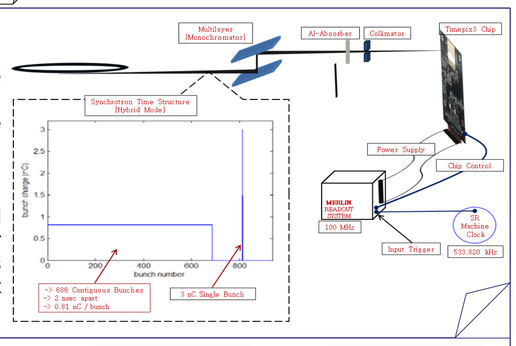
Sensor substrate	300 µm Silicon
Pixel matrix	256 x 256
Pixel size	55 x 55 µm^2
Chip active area	1.98 cm^2
Total chip area	2.29 cm^2
Operation Temperature	Room
Deadtime	475 ns/pixel (pulse measuement & packet transfer)
Time resolution	1.5625 ns
Minimum detectable charge	500 e-
Readout Type	1) Frame Based Zero Suppressed 2) Data Driven Zero Suppressed

Timepix3 physical parameters

Experimental Setup

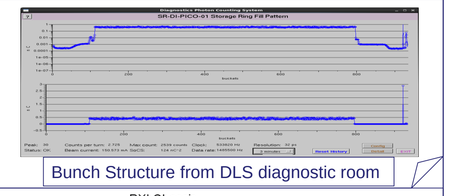
Synchronization and Acquisition

- The system is triggered by the machine clock.
- MERLIN system is synchronized with the approximate revolution period of 1.873 µs.
- Data collected in frames of 11 µs.
- Photon flux range between 10-20 Khits/pixel.
- The acquisition starts once the trigger signal is reached and the shutter keeps opened for 11 µs. The system then await for 0.97 ms before the system is ready for the next input trigger



DLS Hybrid Mode Time Structure

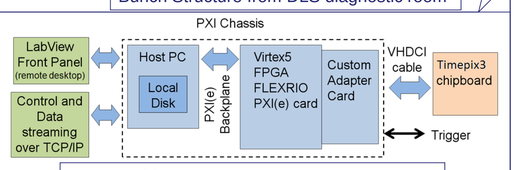
- 686 contiguous bunches, 2 ns apart and charge of 0.4 ns.
- Single bunch of 3ns & 50 ps FWHM.
- 1.873 µs (53380 Hz) revolution period in the ring.



Bunch Structure from DLS diagnostic room

Merlin System

Merlin is a Medipix3 readout system developed by Diamond. It represents the starting point for the characterization of the new Timepix3 readout system. It is based on a National Instruments™ PXI/FlexRIO system running a Xilinx Virtex5 FPGA [2].



Merlin system block diagram
(image courtesy of Richard Plackett)

Experimental Results

Time Resolution

Analysis Overview

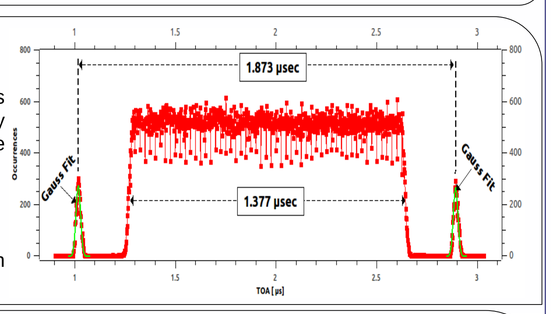
A collimated beam of 20µm x 20µm is aligned in the center of a pixel. Different photon energies and signal thresholds have been used.

The ToA histogram has been created from the data using bin size of 1.5625 ns. The time resolution of the detector system is determined by applying a Gauss fit on the isolated bunch and extracting the sigma value.

The Measured Bunch Structure

The figure shows the ToA histogram for 16 keV photons and signal threshold of 8 keV. The sensor is biased by 110 V. Comparing the histogram with the one from the DLS diagnostic room, one can find the following :

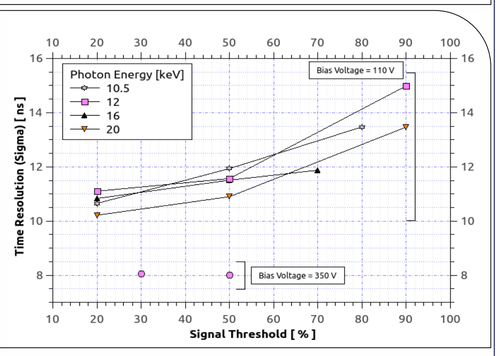
- Contiguous bunches within 1.377 µs .
- revolution time is 1.873 µs.
- Gauss fit can be applied on the isolated bunch.
- Glitches between the bunches due to the interaction of several clocks in the synchronization process.



The Time Resolution For Different Photon Energies And Bias Voltages

Two separate measurements have been made using 110 V bias voltage and 350 V. The graph shows :

- Time resolution of 8 ns when using 350 V, 12 keV photons and either 3.6 keV or 6 keV signal threshold.
- The higher the photon energy, the better the time resolution at the same signal threshold.
- Increasing the signal threshold for the same photon energy worsen the time resolution.



Reconstruction Of The Analogue Pulse

The shape of the preamp output pulse has been studied using several photon energies and step-wise increment in the signal threshold.

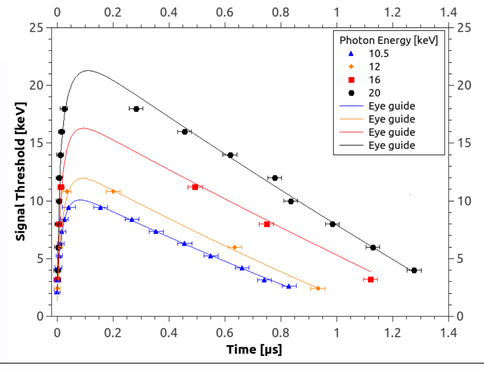
The reconstructed pulse is composed of two parts:

[1] the leading edge which is the ToA mean value of the Gauss fit on the isolated first bunch.

[2] The falling edge which is the time of the ToA added to the ToT mean value from the photo peak of the energy.

The results show:

- The pulse shape is triangular.
- The pulse height is proportional to the photon energy.
- The ToT is proportional to the photon energy.

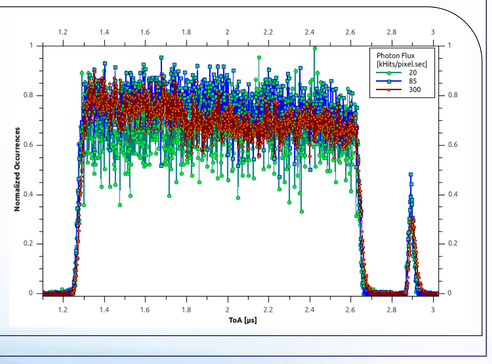


Photon Flux And Signal Overlapping

Pileup effect for 20 keV photons has been studied for three flux rates: 20, 85 and 300 kilo-hit/pixel/sec. Signal threshold of 10 keV and bias voltage of 110 V are used.

The time resolutions for flux rates of 85 and 300 are 10 and 12.5 ns, respectively.

The highest flux rate shows counts loss between the rising edge and the falling one due to the signal overlapping.



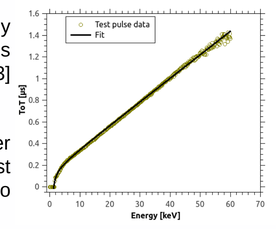
Energy Resolution

Analysis Overview

In the measurements, the ToA and the ToT can be measured concurrently. Despite the fact that the photon energy can independently be defined and measured in the beamline ahead of starting, the ToT-to-energy behavior is nonlinear particularly at low energy range below 20 keV. The behavior can be described by a surrogate function [3] depending on four parameters as follows :

$$ToT(E) = a * E + b - \frac{c}{E - t}$$

Parameters 'a' and 'b' are related to the linear region of the calibration curve at high energies. While , the parameter 'c' affects the curvature and parameter 't' is the threshold level. This calibration can be made in the lab using test pulses as in the side figure. The histogram can be built from the raw ToT data using a bin size of 25 ns. The photo peak can be fitted with what is called model *M* [3] since Gauss function does not fit the data due to the nonlinearity.



Charge Sharing - Double Split Events

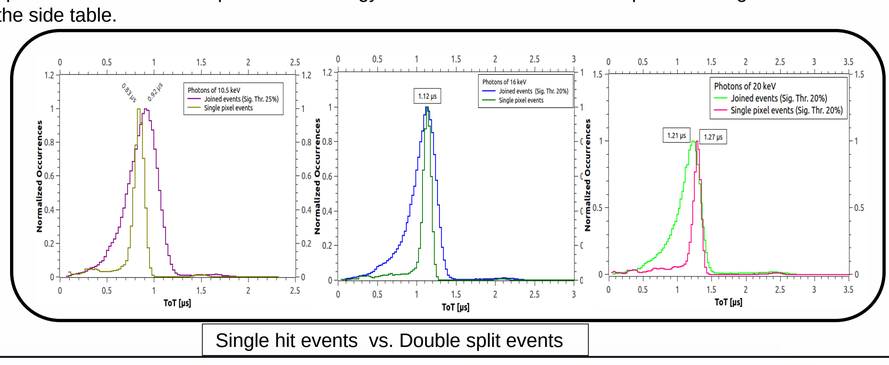
In this measurement, the beam is centered between two neighboring pixels and collimated to a spot size of 40µm x 20µm. Signal threshold of 20% of photon energy has been applied and bias voltage of 110V. The histogram has been built considering those hits falling in the same frame and having a ToA difference of maximum the leading edge of the analogue pulse of 50 ns.

The graph on the right side shows an example of fitting the M-model to the 10.5 keV photo peak in the ToT histogram.

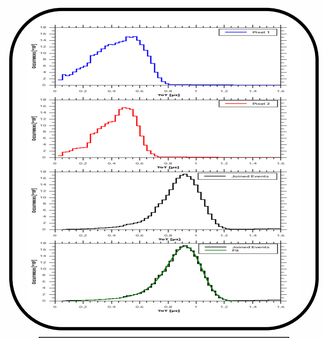
The figure below compares histograms for single hit events, independent measurements, and double split events between two pixels. The energy resolution for the measured photon energies are shown in the side table.

Measured energy resolution

Energy [keV]	FWHM [keV] Single	Double
10.5	2.19	5.92
16.0	2.65	6.32
20.0	3.64	7.27



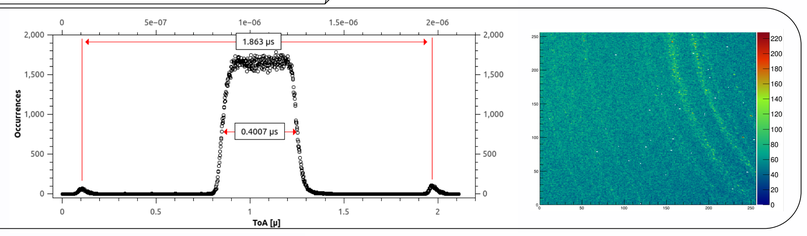
Single hit events vs. Double split events



Joining the shared events

Fluorescence Measurement

- Synchrotron bunch pattern : Low-alpha mode (200 bunches).
- Foil : Zirconium.
- Energy/Signal threshold: 18 keV & 3.6 keV.



Summary and Future Work

Timepix3 chip offers dual possibility for measuring simultaneously the arrival time and the energy of the impinging photons. The experimental results help in understanding the behavior of the detector system and its limitations. Further study includes time resolved experiments is to be performed in the future. The overall contributions will be placed in building an overview of how multichip detector system can be developed and the associated challenge given by the huge amount of data produced.

Acknowledgments

The author would like to acknowledge the Medipix3 collaboration for the fruitful discussion and their feedback. Many thanks to DLS beamlines I-19 and B-16 for offering the opportunity to perform this work.

References

[1] T. Poikela et al. - Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout - 2014 JINST 9 C05013 - doi:10.1088/1748-0221/9/05/C05013

[2] G. Crevatin et al. - Development of a Timepix3 readout system - 2015 JINST 10 C03042 - doi:10.1088/1748-0221/10/03/C03042

[3] Jan Jakubek ,Precise energy calibration of pixel detector working in time-over-threshold mode.Nucl. Instr. Methods A 633,S262-S266 (2011)