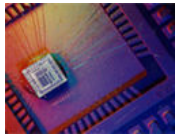
BROOKHAVEN NATIONAL LABORATORY



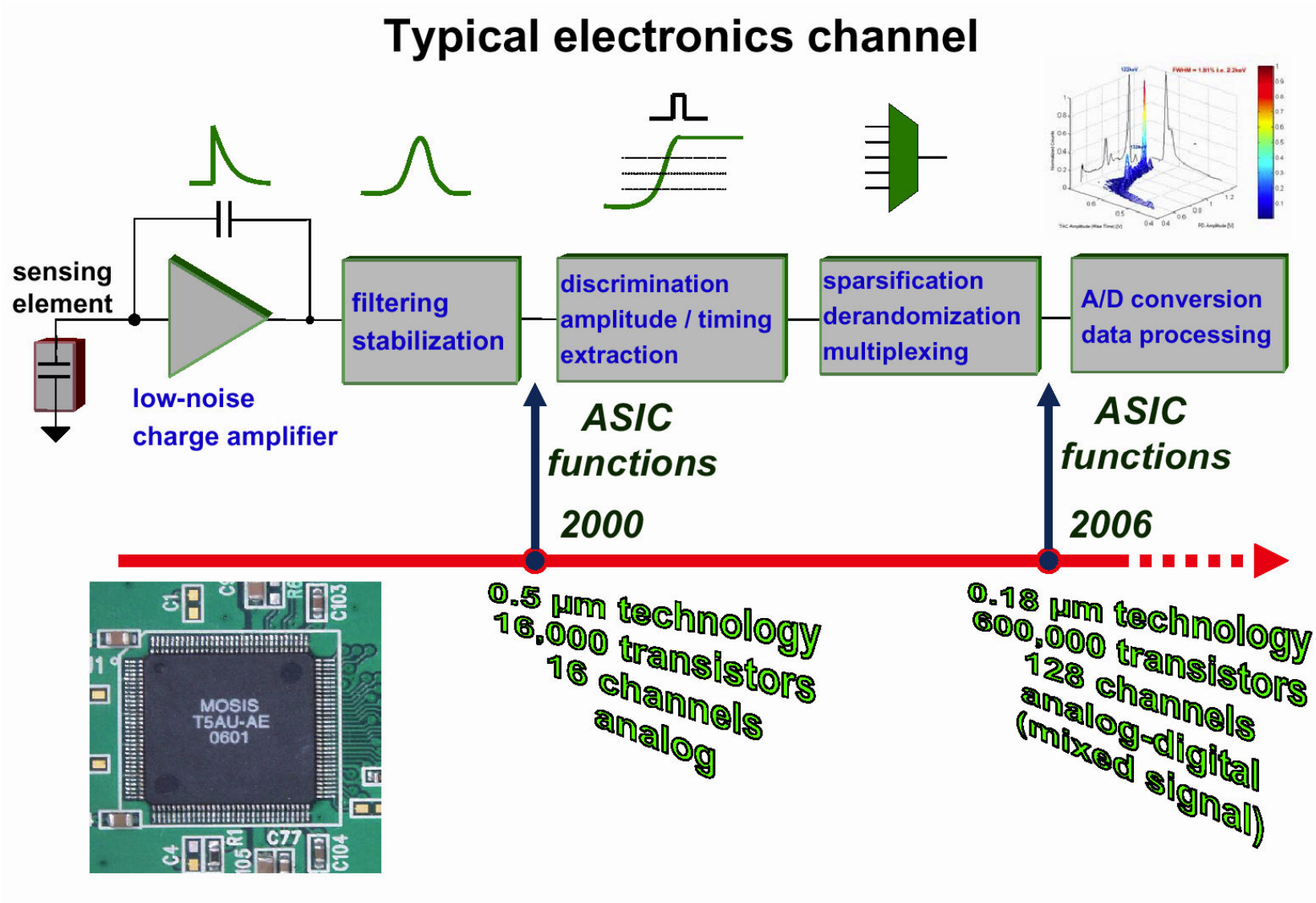
Microelectronics Group
Instrumentation Division

Monolithic Signal Processing for Solid State Detectors:
late developments at BNL

Angelo Dragone

Fermilab November 8th 2007

Integration



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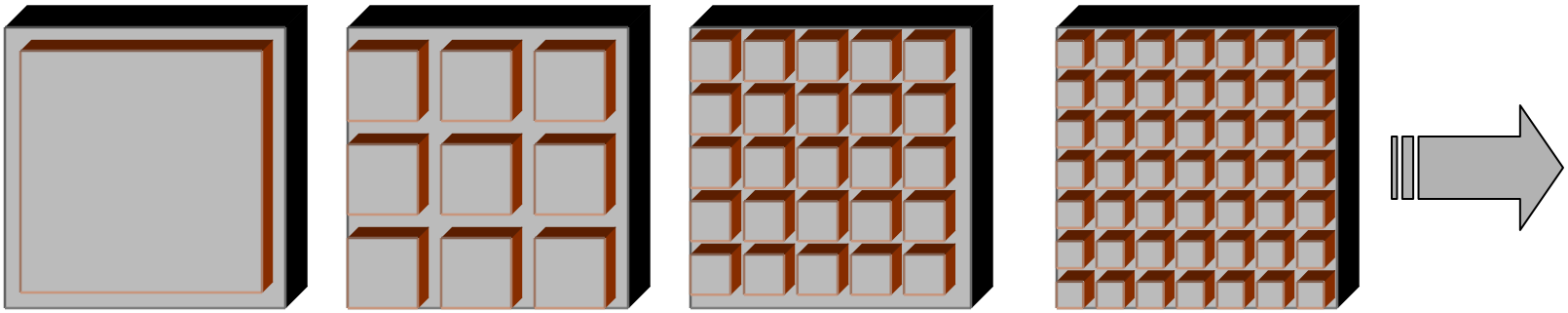
Microelectronics Group
Instrumentation Division

The Peak Detector Derandomizer ASIC:

a High Rate Readout System for Multichannel Detectors

G. De Geronimo, A. Dragone, J. Fried, A. Kandasamy, P. O'Connor, D.P. Siddons, E. Vernon

Highly segmented detectors



N=1 *N=9* *N=25* *N=49*

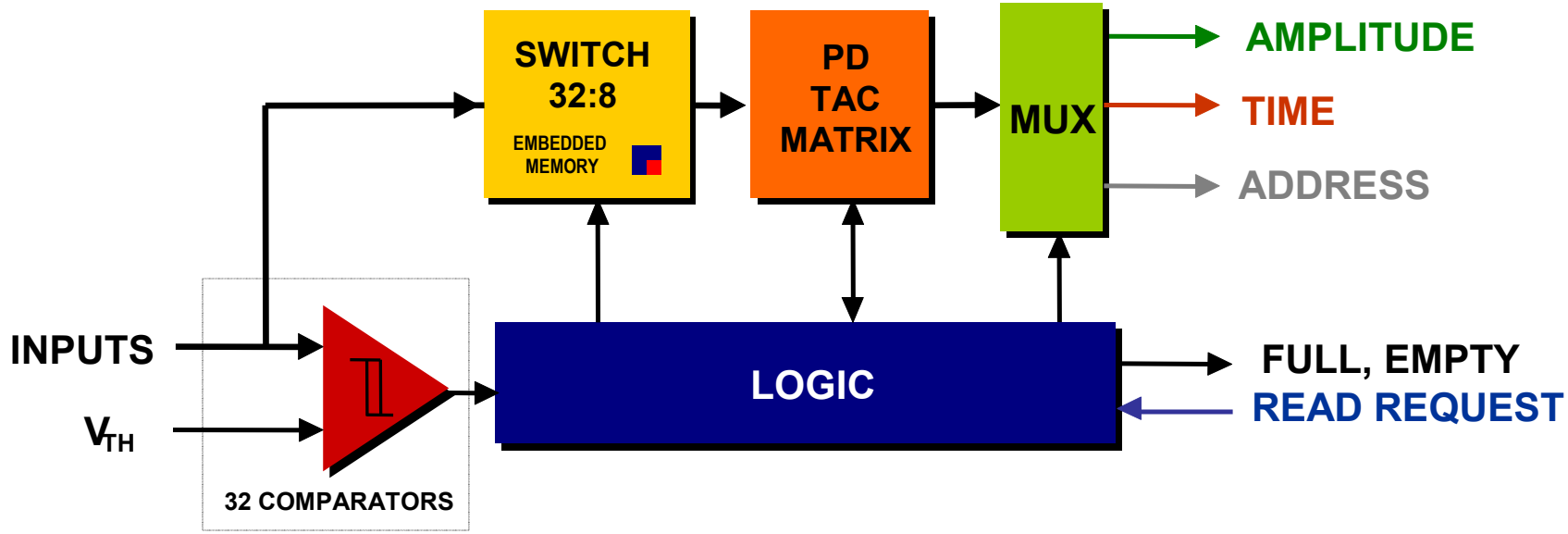
Benefits:

- Position Resolution
  - pixel pitch ~ $1/\sqrt{N}$
- Energy resolution:
  - C_{DET} ~ 1/N
  - I_{DARK} ~ 1/N
  - pulse shaping time ~ N
- Rate capability
  - pileup ~ 1/N
- "Small pixel" effect
  - improve energy resolution in detectors with poor hole transport

Drawbacks:

- Interconnect density
  - density ~ N
- Electronics channel count
  - cost ~ N
  - power ~ N

The Peak Detector Derandomizer ASIC Architecture



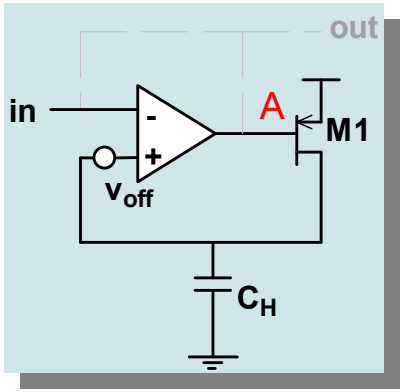
- New architecture for efficient readout of multichannel detectors
  - *Self-triggered and self-sparsifying*
  - *Simultaneous amplitude, time, and address measurement for 32 input channels*
  - *Set of 8 peak detectors act as derandomizing analog memory*
  - *Rate capability improvement over present architectures*
- Based on new 2-phase peak detector combined with Quad-mode TAC
  - *High absolute accuracy (0.2%) and linearity (0.05%), timing accuracy (5 ns)*
  - *Accepts pulses down to 30 ns peaking time, 1.6 MHz rate per channel*
  - *Low power (2 mW per channel)*

P. O'Connor, G. De Geronimo, A. Kandasamy, *Amplitude and time measurement ASIC with analog derandomization: first results*, IEEE Trans. Nucl. Sci. 50(4), pp. 892-897 (Aug. 2003).

CMOS PD Using Two-Phase Configuration

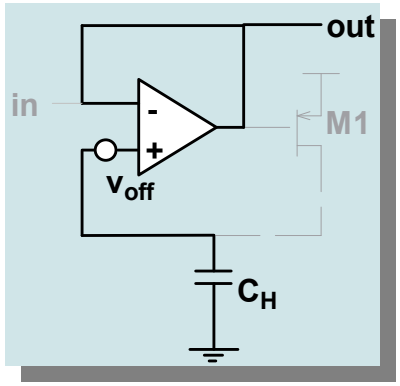
Write phase

- conventional peak detector
- M1: unidirectional current source
- voltage on C_H includes op-amp errors (offset, CMRR)



Read phase

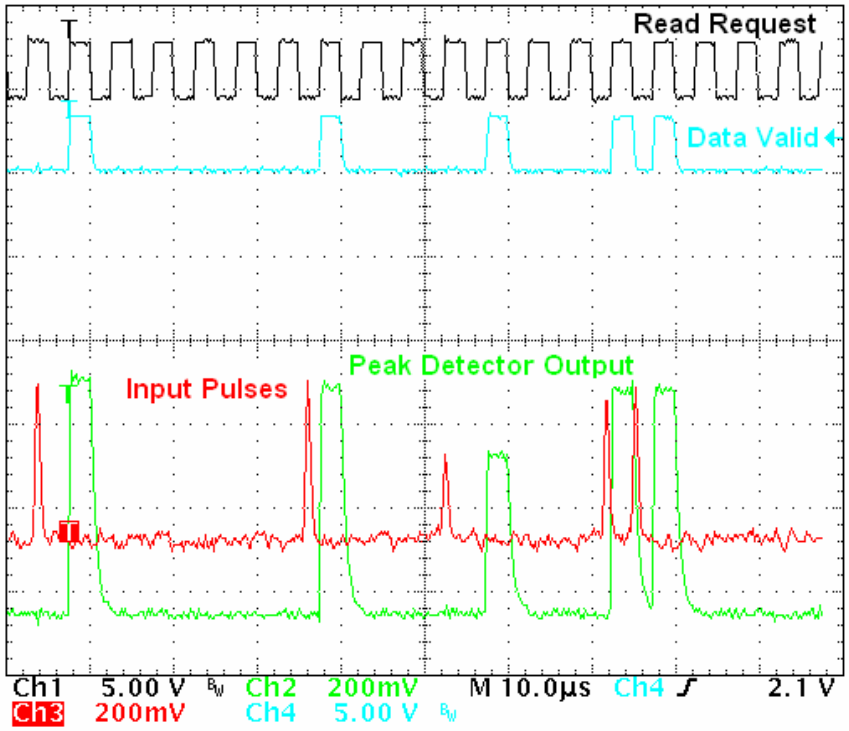
- same op-amp re-used as unity-gain buffer
- same CM voltage
- ***op-amp errors cancel***
- enables rail-to-rail sensing
- provides good drive capability

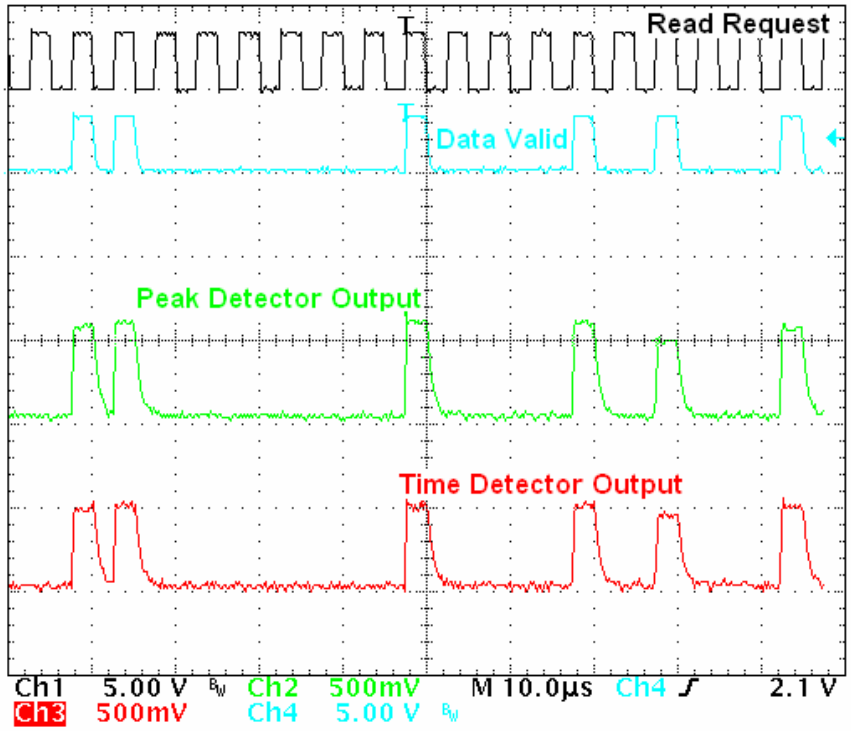


Parameter:	Value: PDD-1 (PDD-2)
Technology	0.35 um CMOS DP4M
Supply voltage	3.3V
Input voltage range	0.3 - 3.0 V
Minimum pulse width	500 (50) ns
Absolute accuracy	0.20%
Linearity	0.05%
Droop rate	250 mV/s
Timing accuracy	5 ns
Power dissipation	3.5 (2.0) mW/chan

G. De Geronimo BNL U.S. Pat. 6,512,399

PDD ASIC waveforms



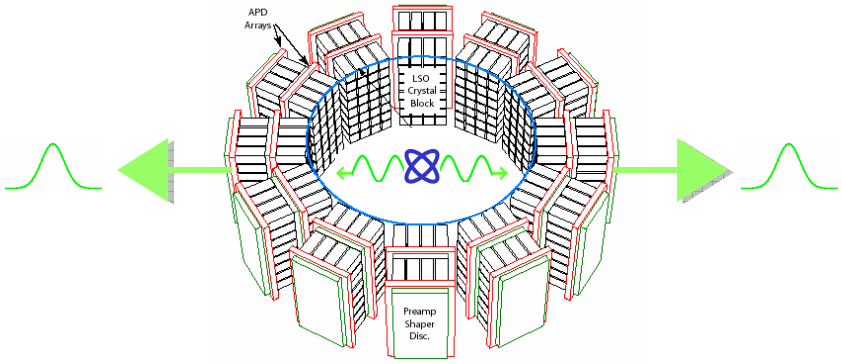


The PDD for Simultaneous Events

Simultaneous events = events that cross the threshold within a time window of about 10ns

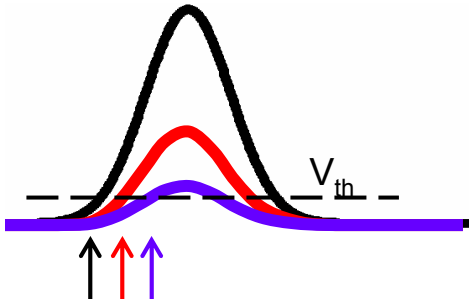
Coincident detection (e.g. PET)

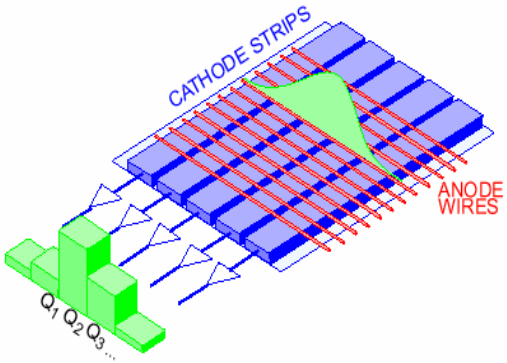
- similar amplitudes
- typically only two channels
- usually non-neighboring



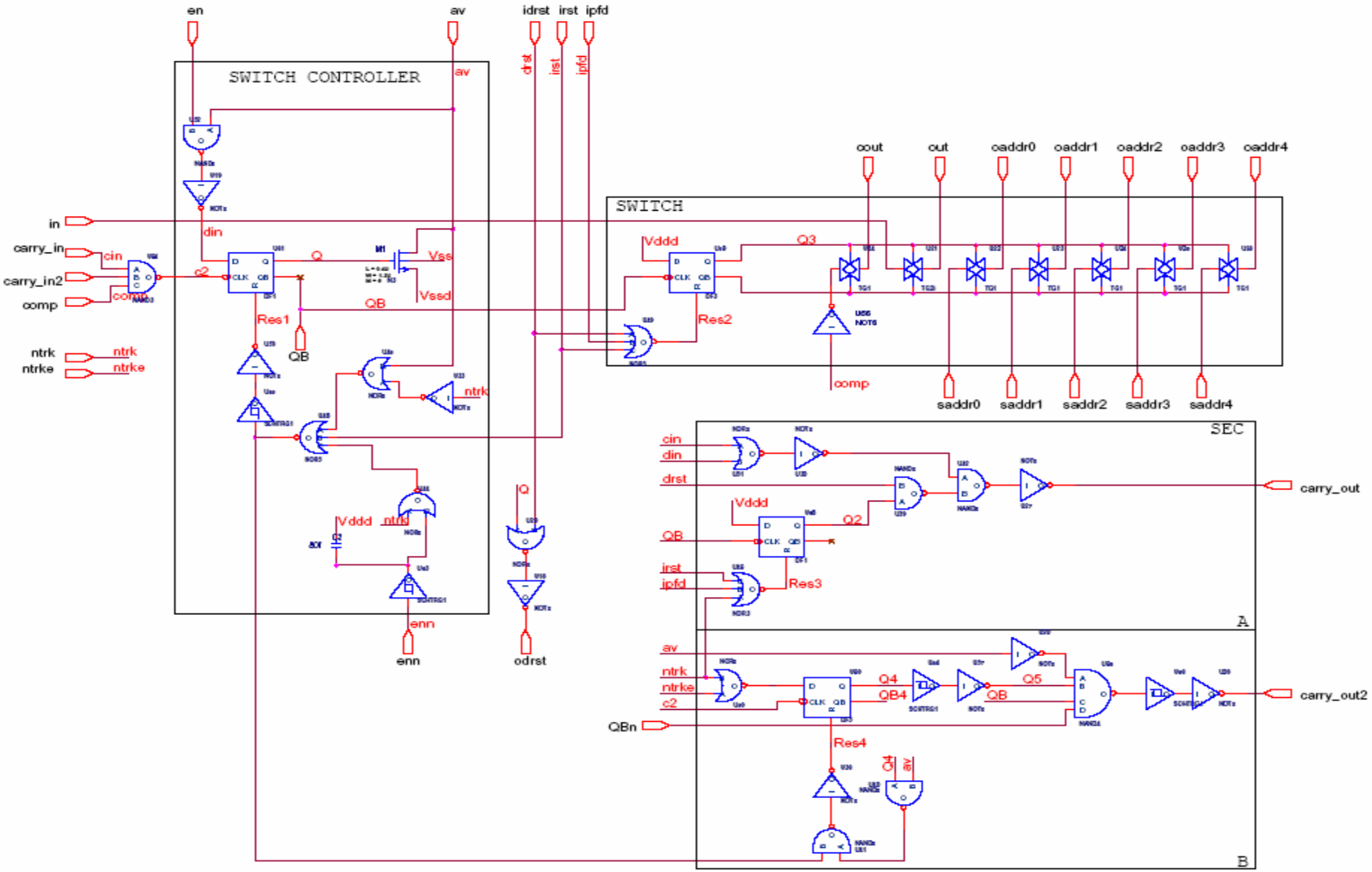
Charge-shared events (e.g. pad and strip MWPCs)

- occur in neighboring channels
- different amplitude (typically)
- more than 2 channels (often)

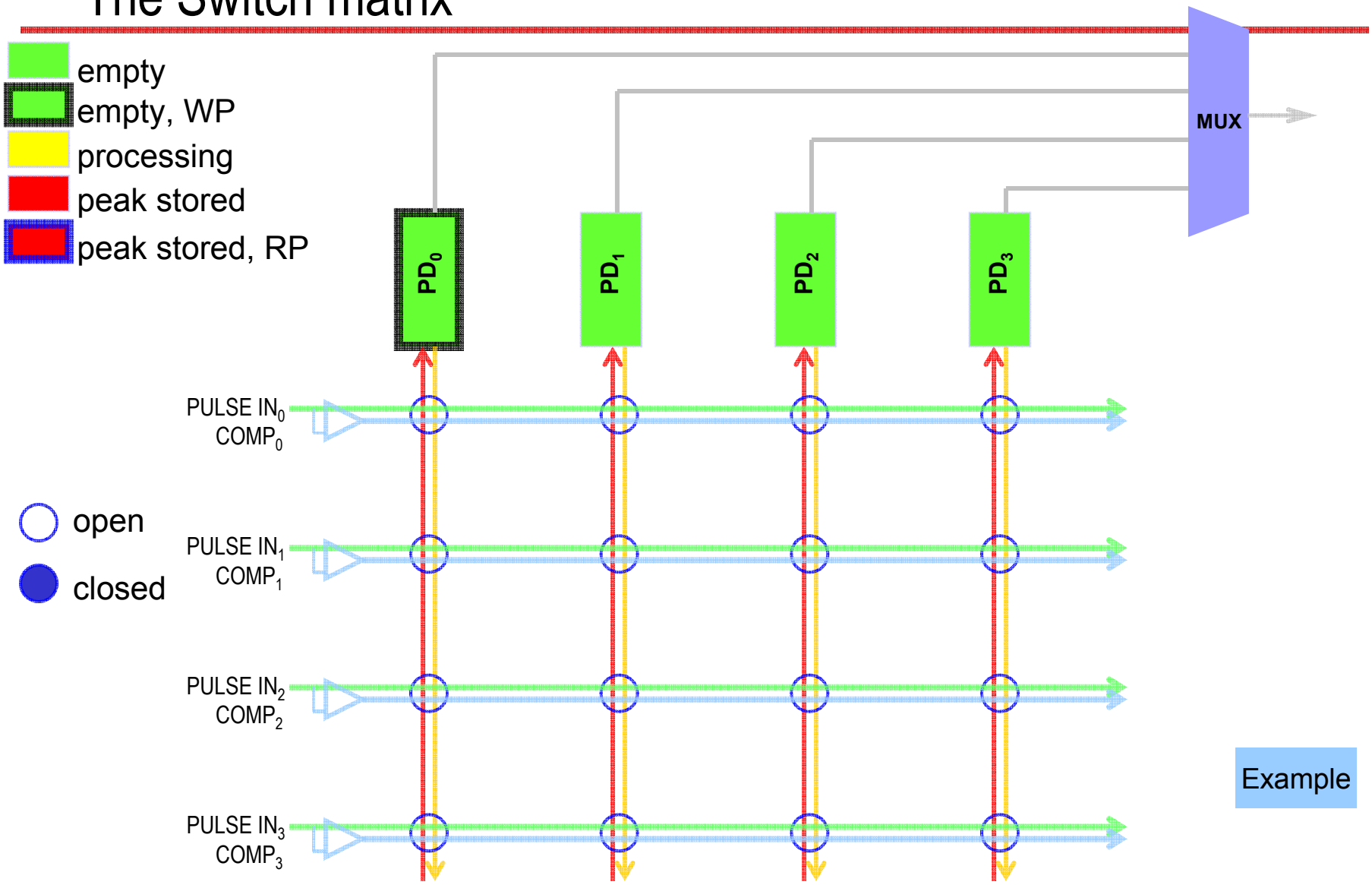




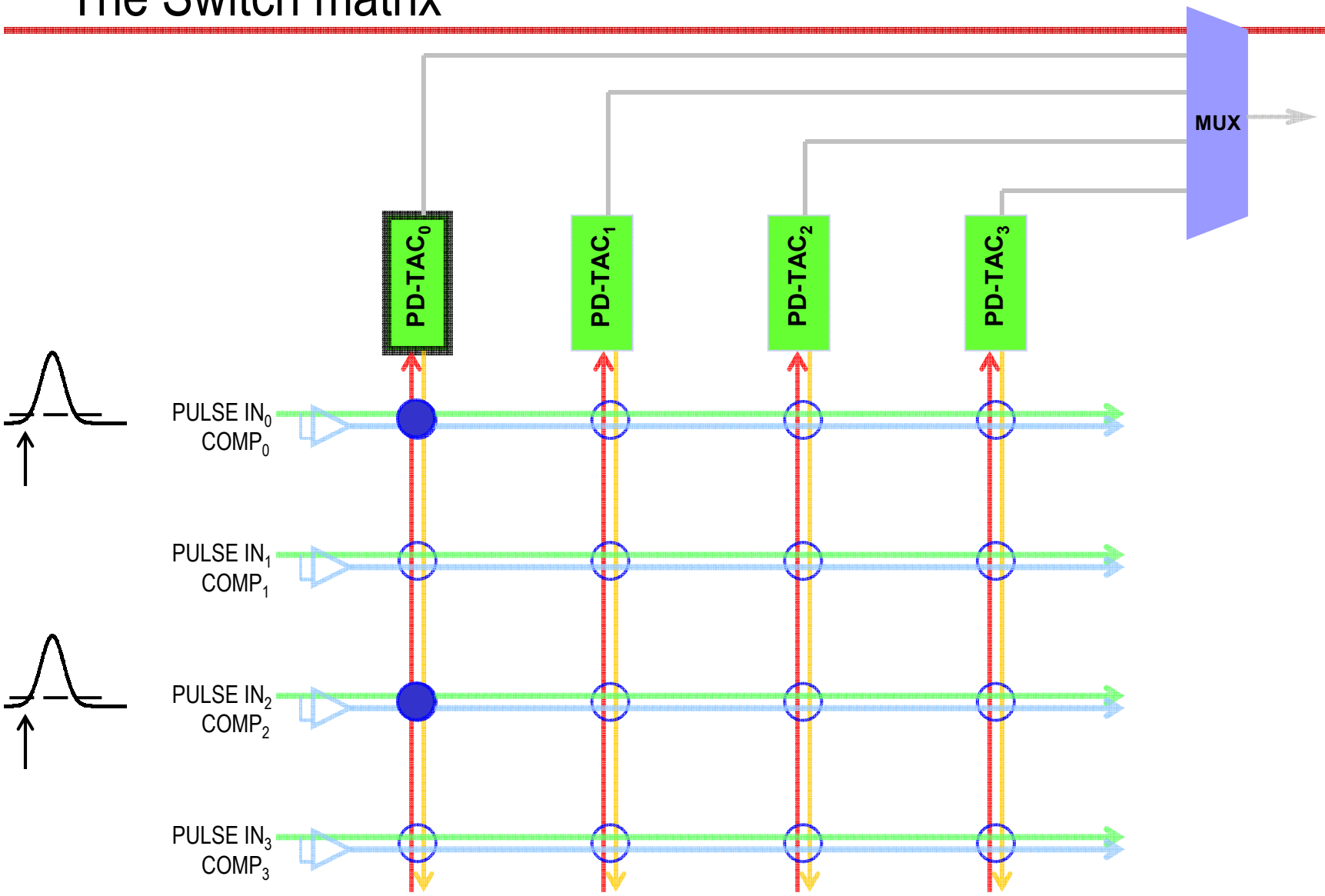
Matrix cell schematics



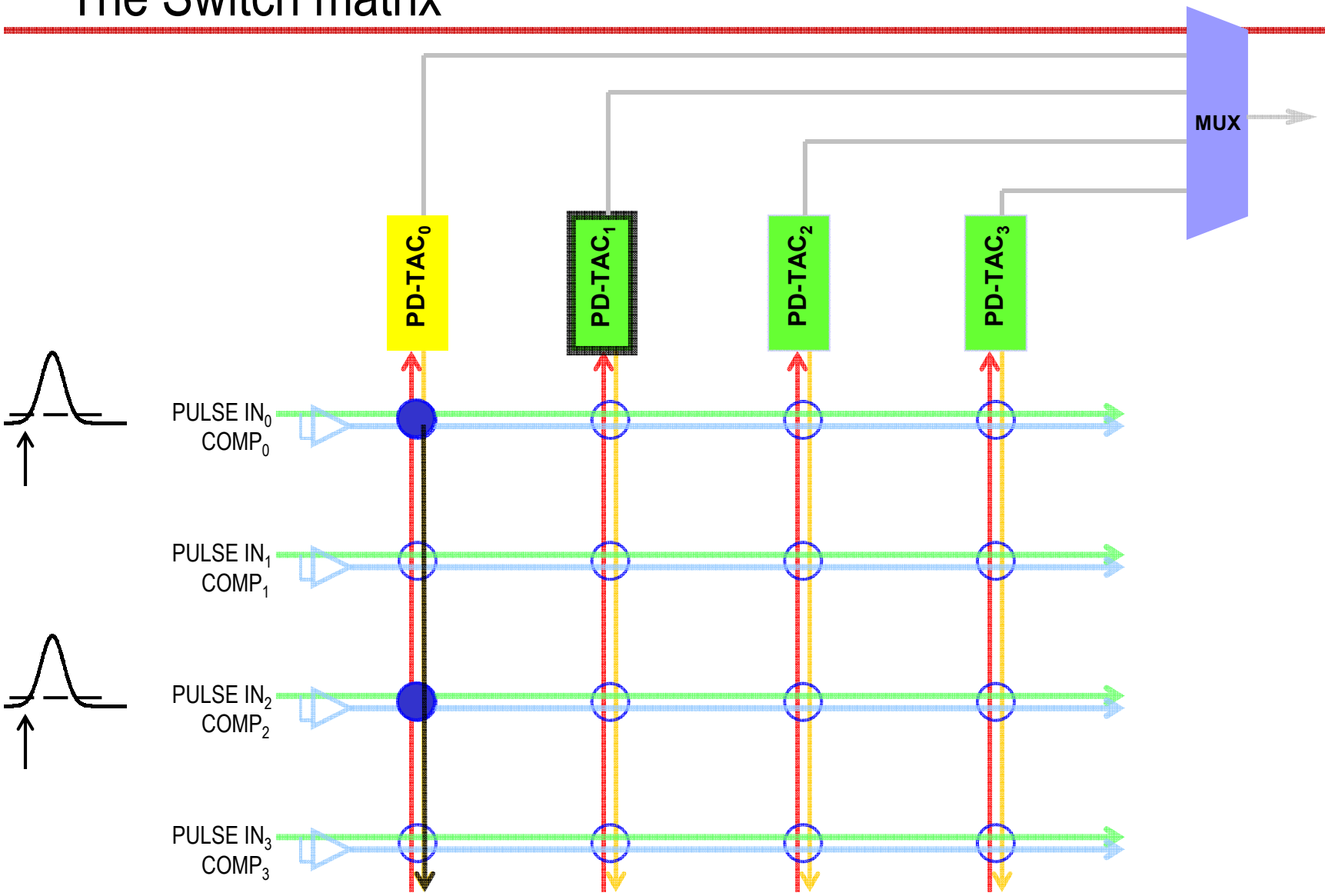
The Switch matrix



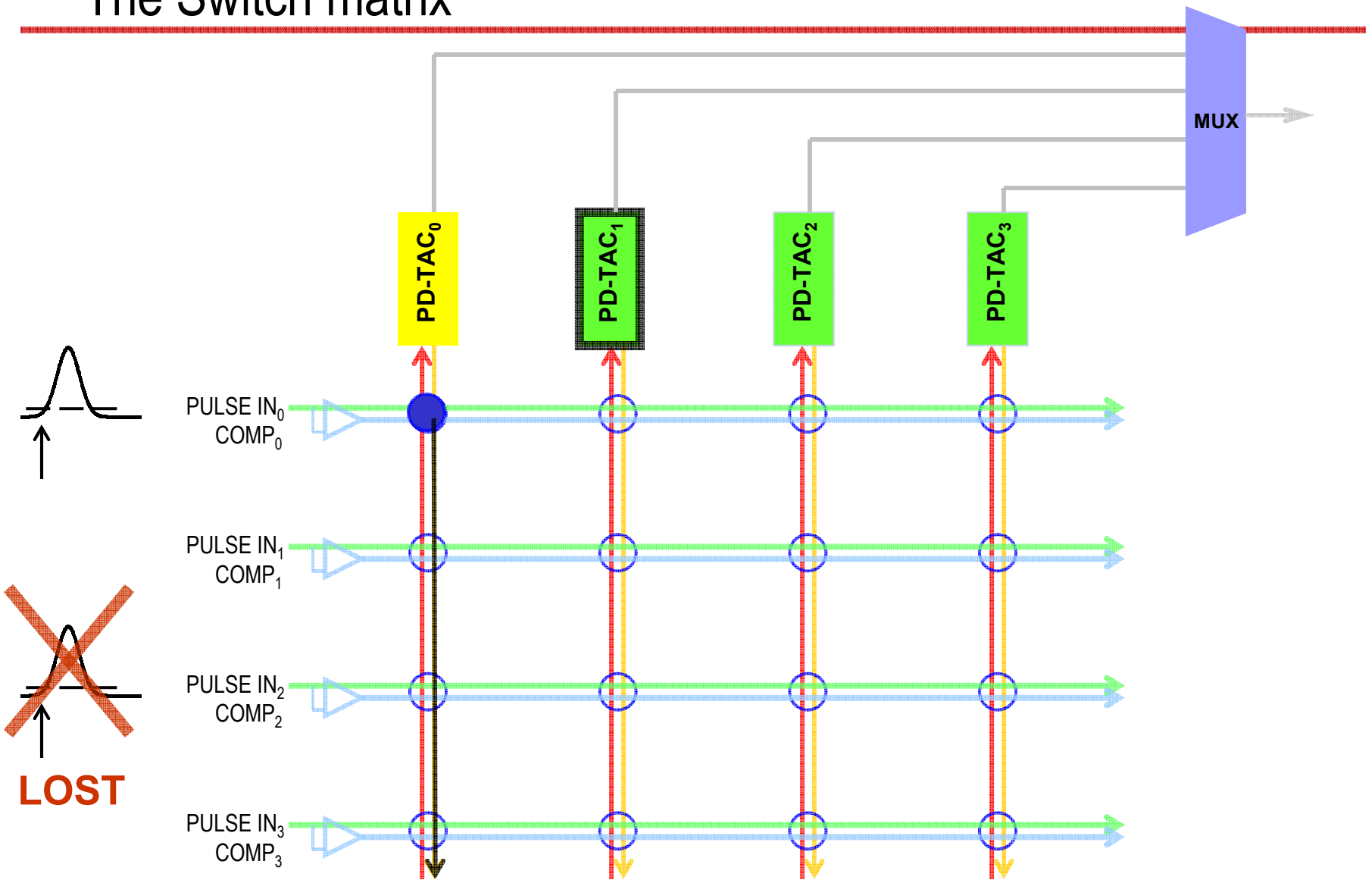
The Switch matrix



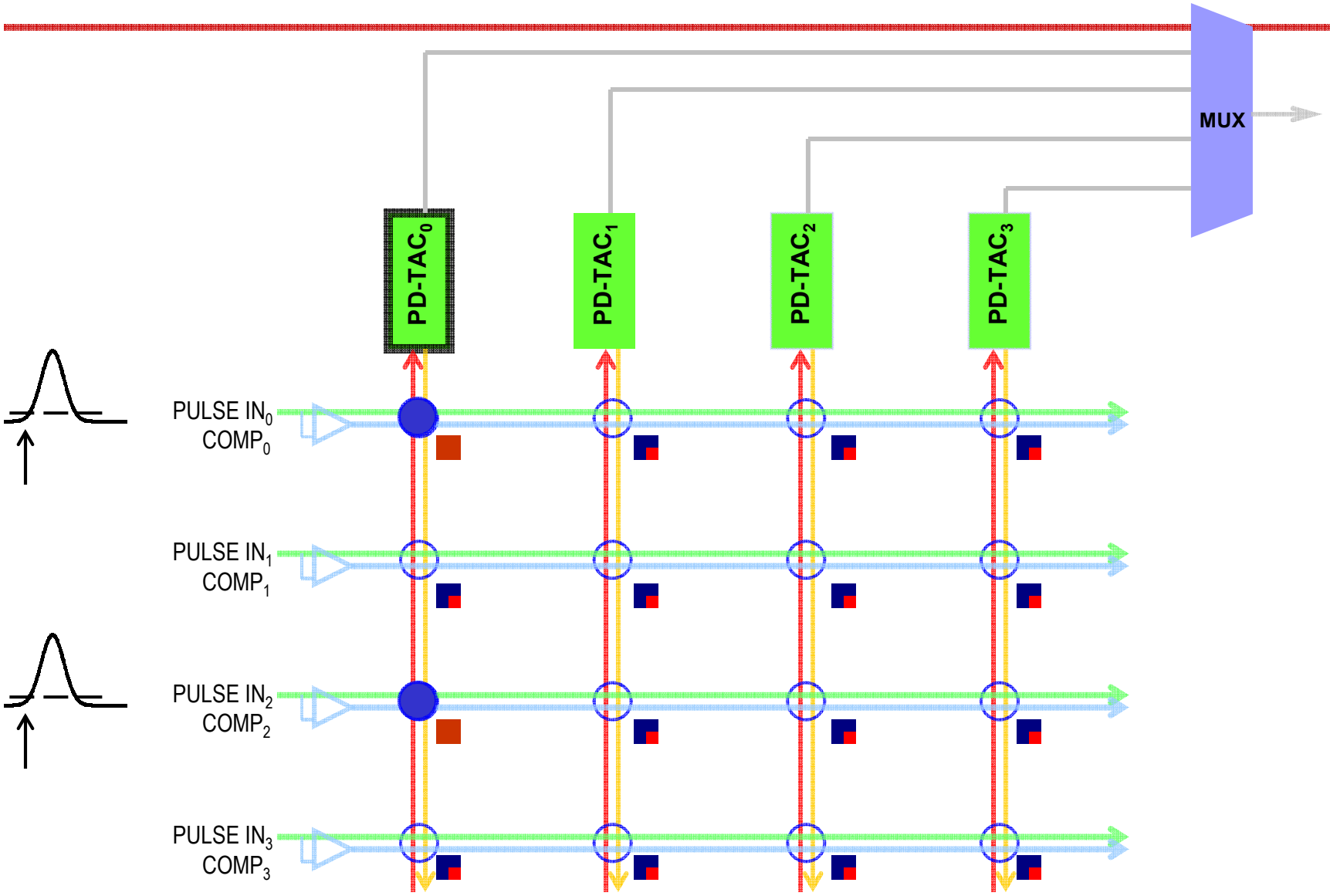
The Switch matrix



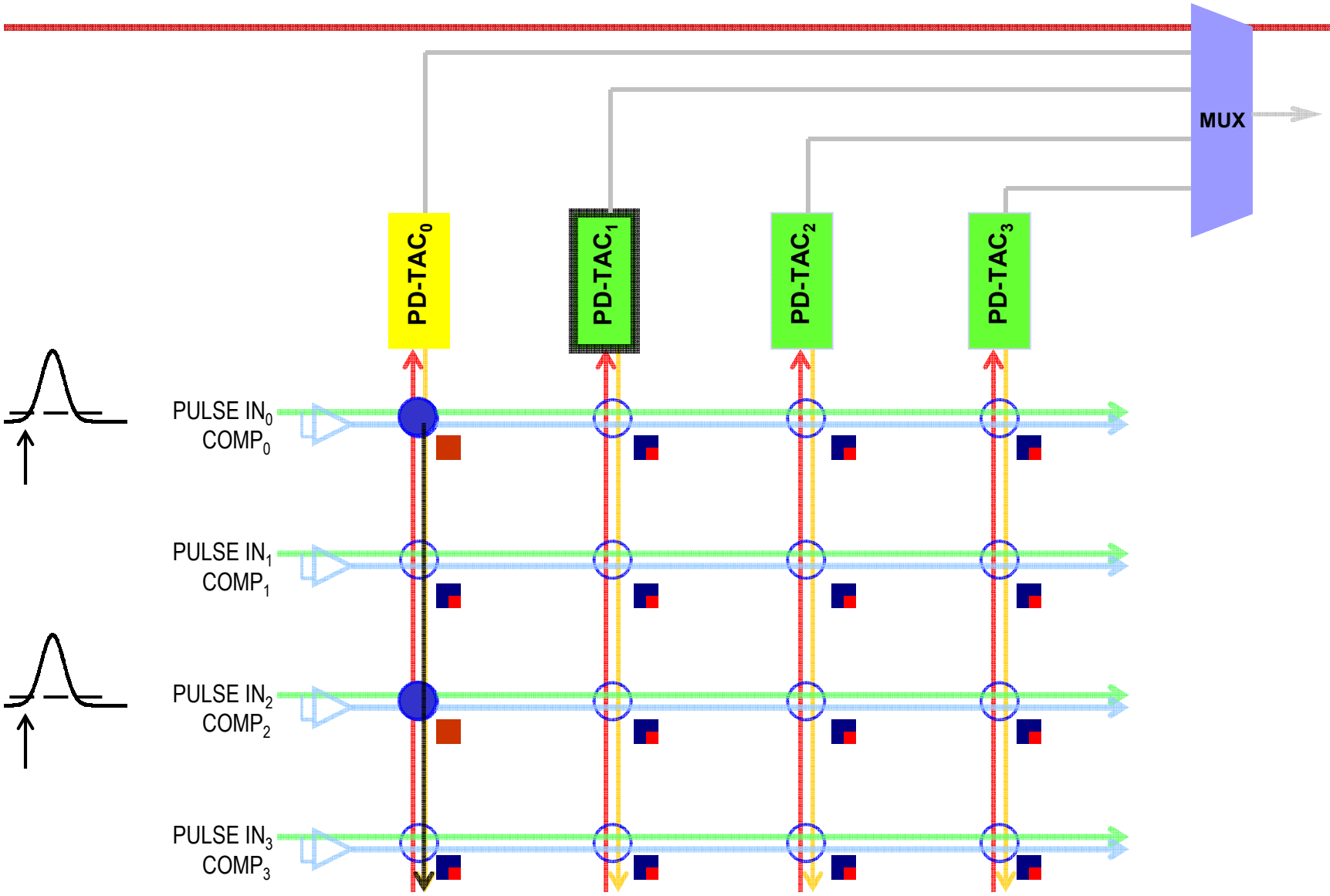
The Switch matrix



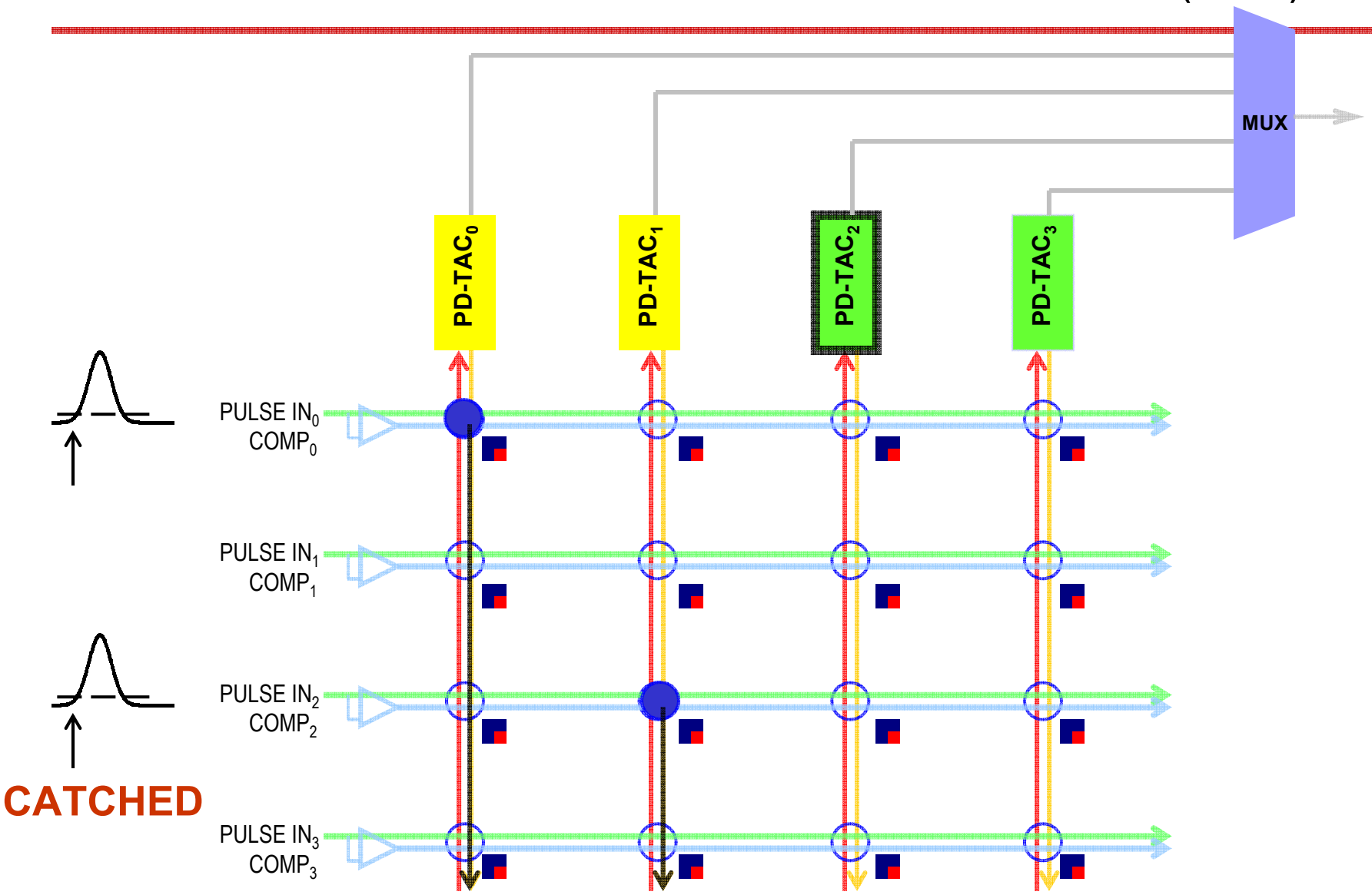
The Switch matrix + Simultaneous Events Catcher (SEC)



The Switch matrix + Simultaneous Events Catcher (SEC)



The Switch matrix + Simultaneous Events Catcher (SEC)

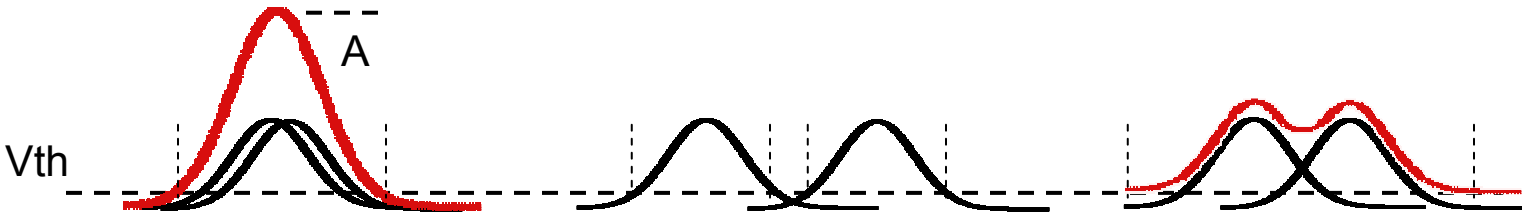


The PDD for High Rate

At High Rate the probability of piled up events increases

Is it possible to extract an information from the signals to properly identify and reject corrupted data?

Time-Over-Threshold

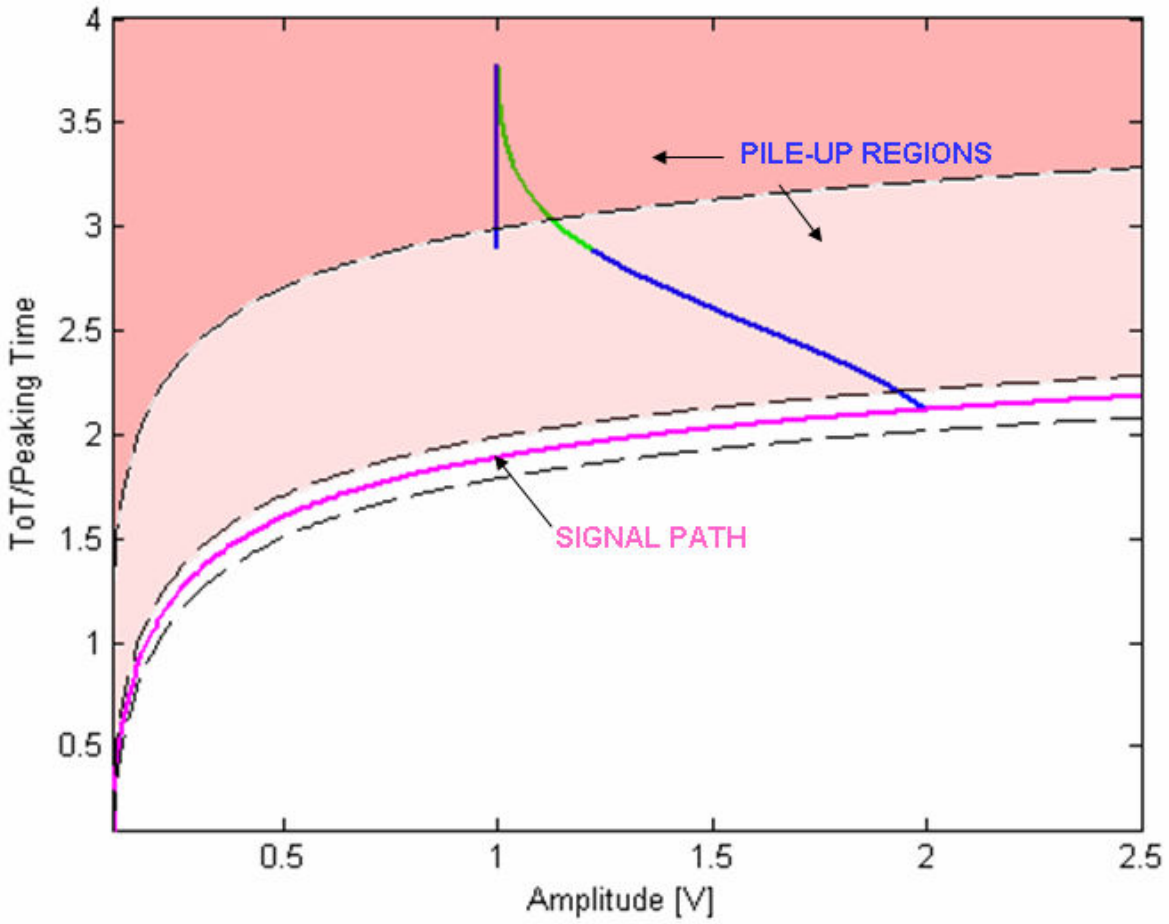


TOT > TOT(A) expected	TOT = TOT(A) expected	TOT > TOT(A) expected
Pulse to be rejected	Pulses acceptable	Pulses acceptable peaks are separate

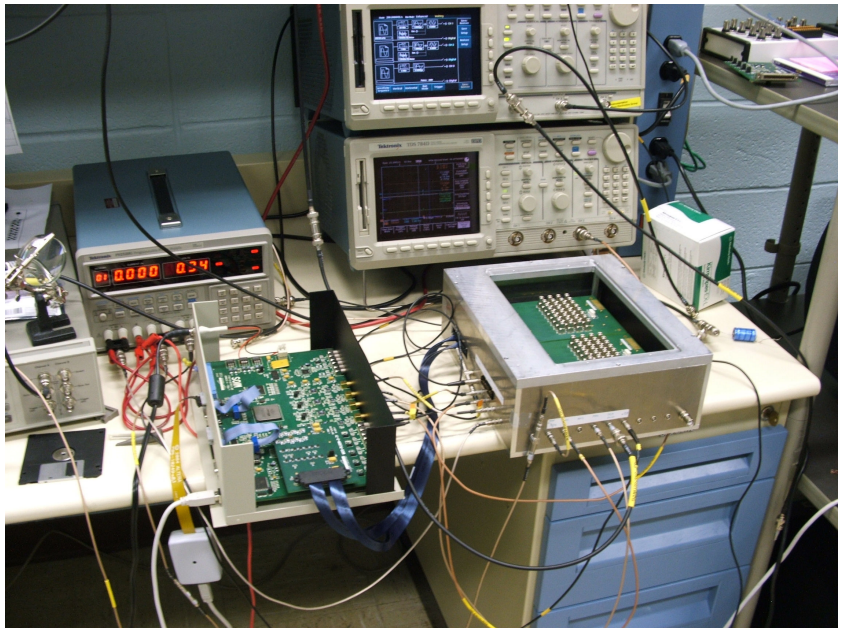
Time-Over-Threshold Measurement for pile-up rejection

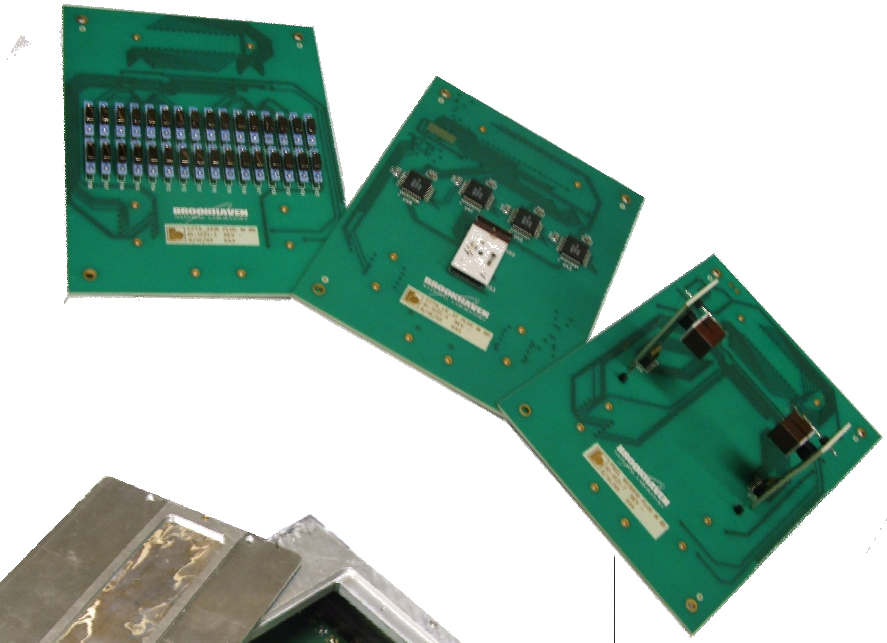
ToT vs. Peak Amplitude Characteristic

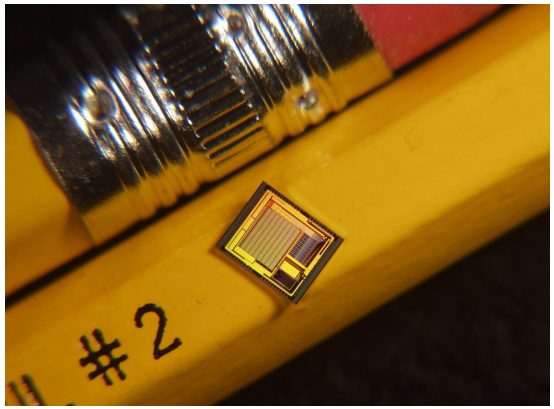
for a pulse from a 5th order complex poles semi-Gaussian shaper

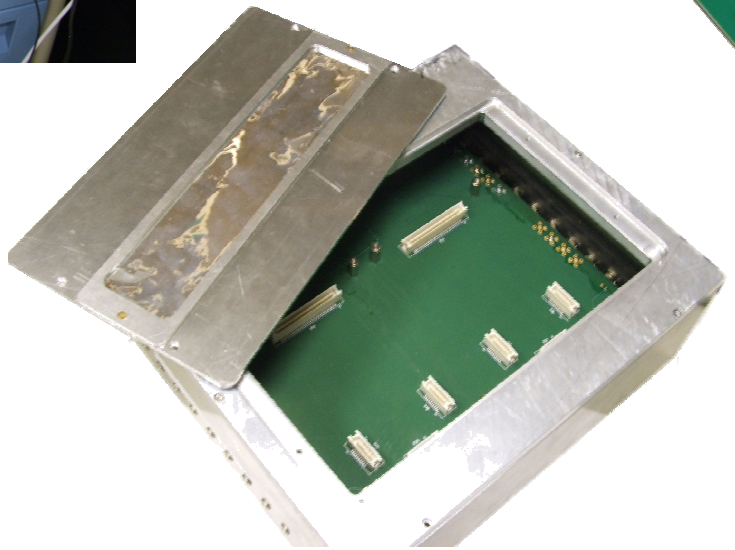


Test setup





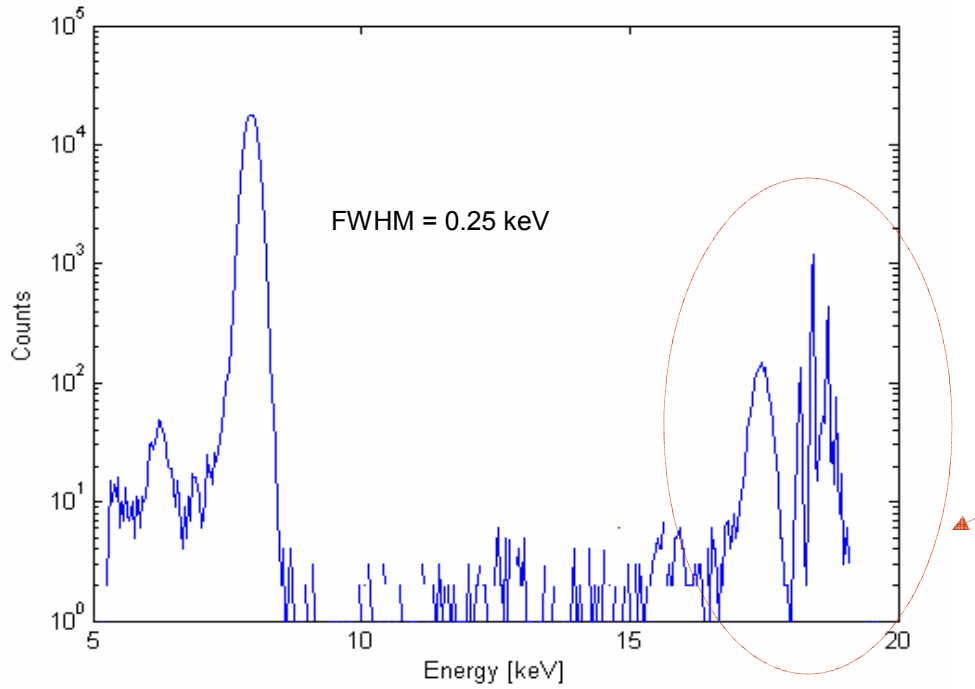




Time-Over-Threshold Measurement for pile-up rejection

Experiment Setup

- Array of 1mm x 1mm silicon diodes, built on a fully-depleted 400um high-resistivity wafer and cooled at ~ -54 ˚C
- 8keV X-ray monochromatic collimated 10umx10um beam from NSLS focused on the center of one pixel
- FE with 2us peaking time

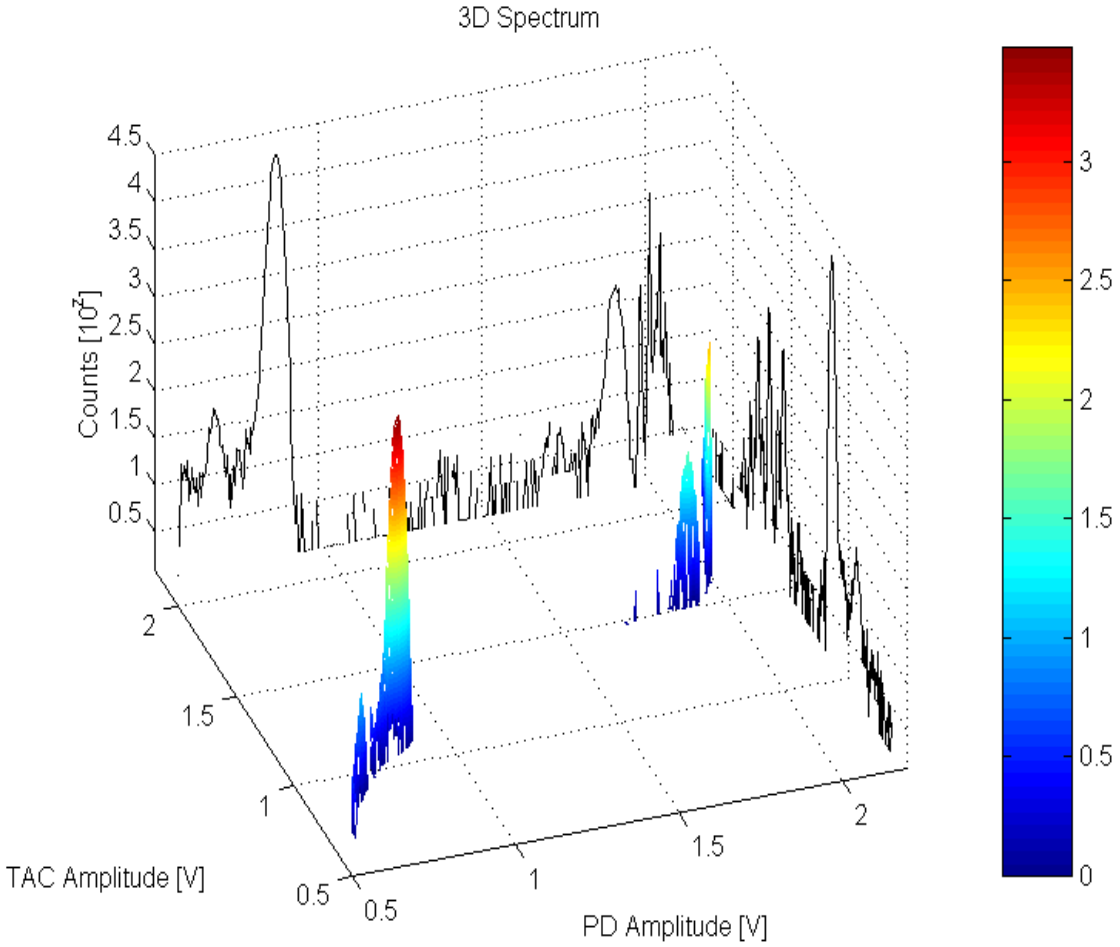


Pulse Height Spectrum when the events rate is equal to 400 Counts/s

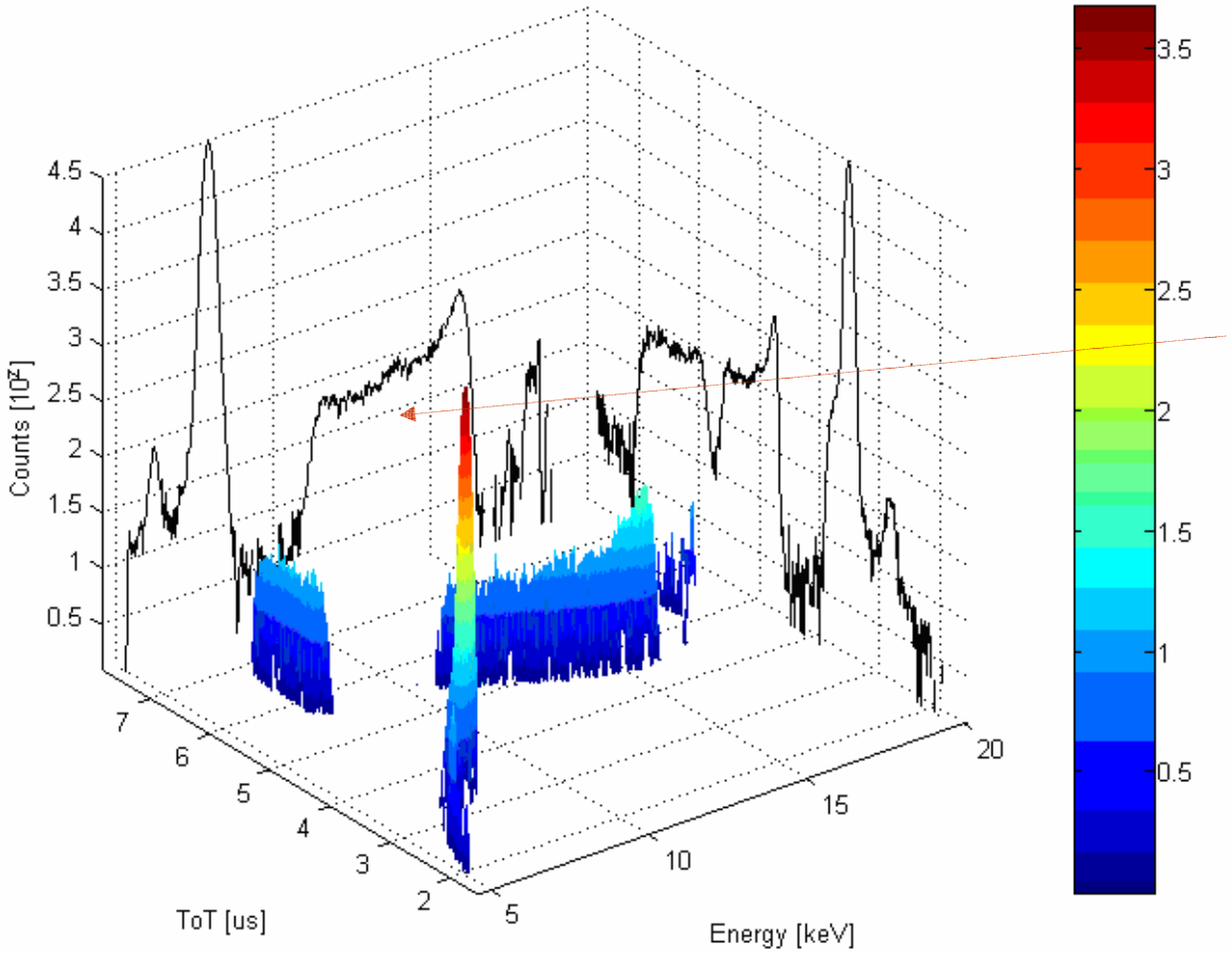
No pile up effects are visible

A 3rd order harmonic from the monochromator is present and saturates the FE

3D Pulse Height Spectrum as a function of the ToT



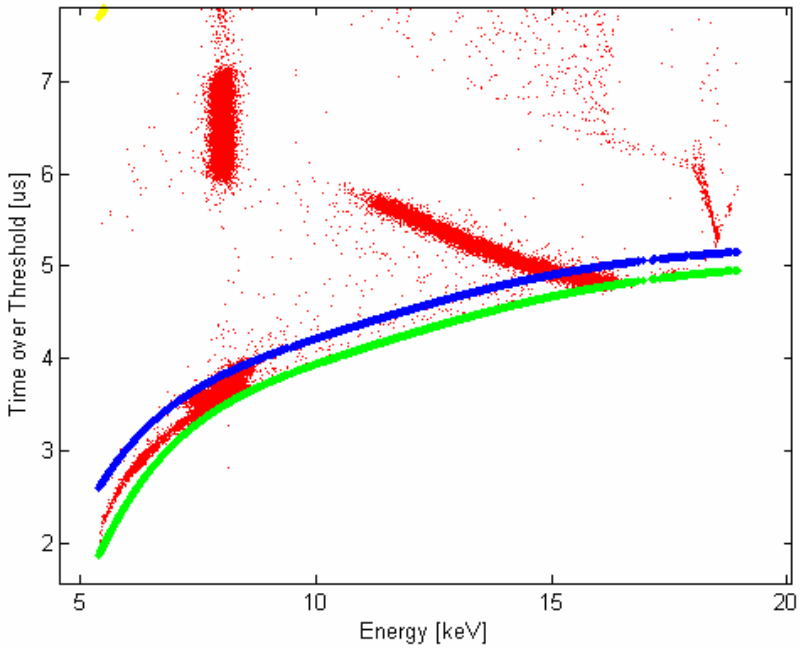
3D Pulse Height Spectrum as a function of the ToT



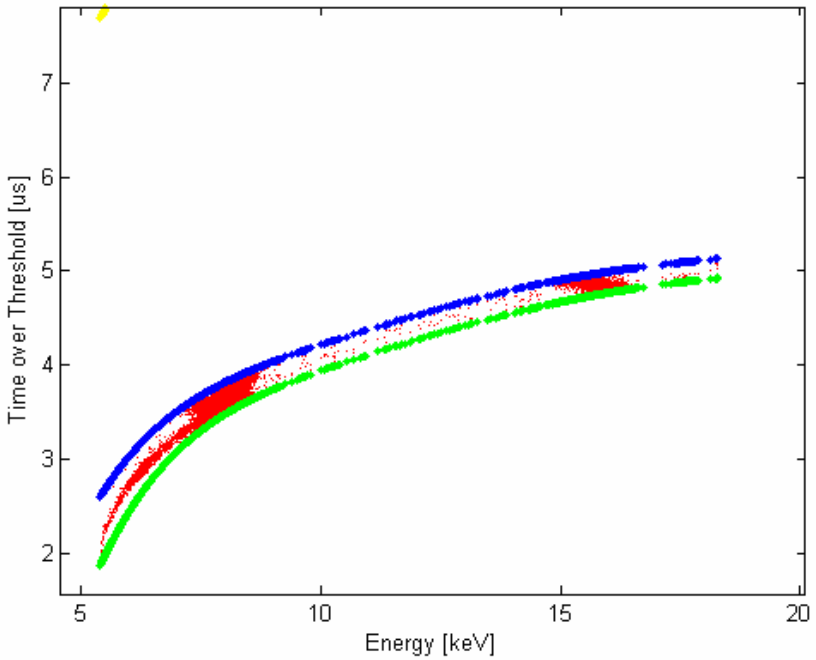
Pulse Height Spectrum when the events rate is equal to 22 kCounts/s

Pile up effects are visible

The Pile-Up Rejection Algorithm

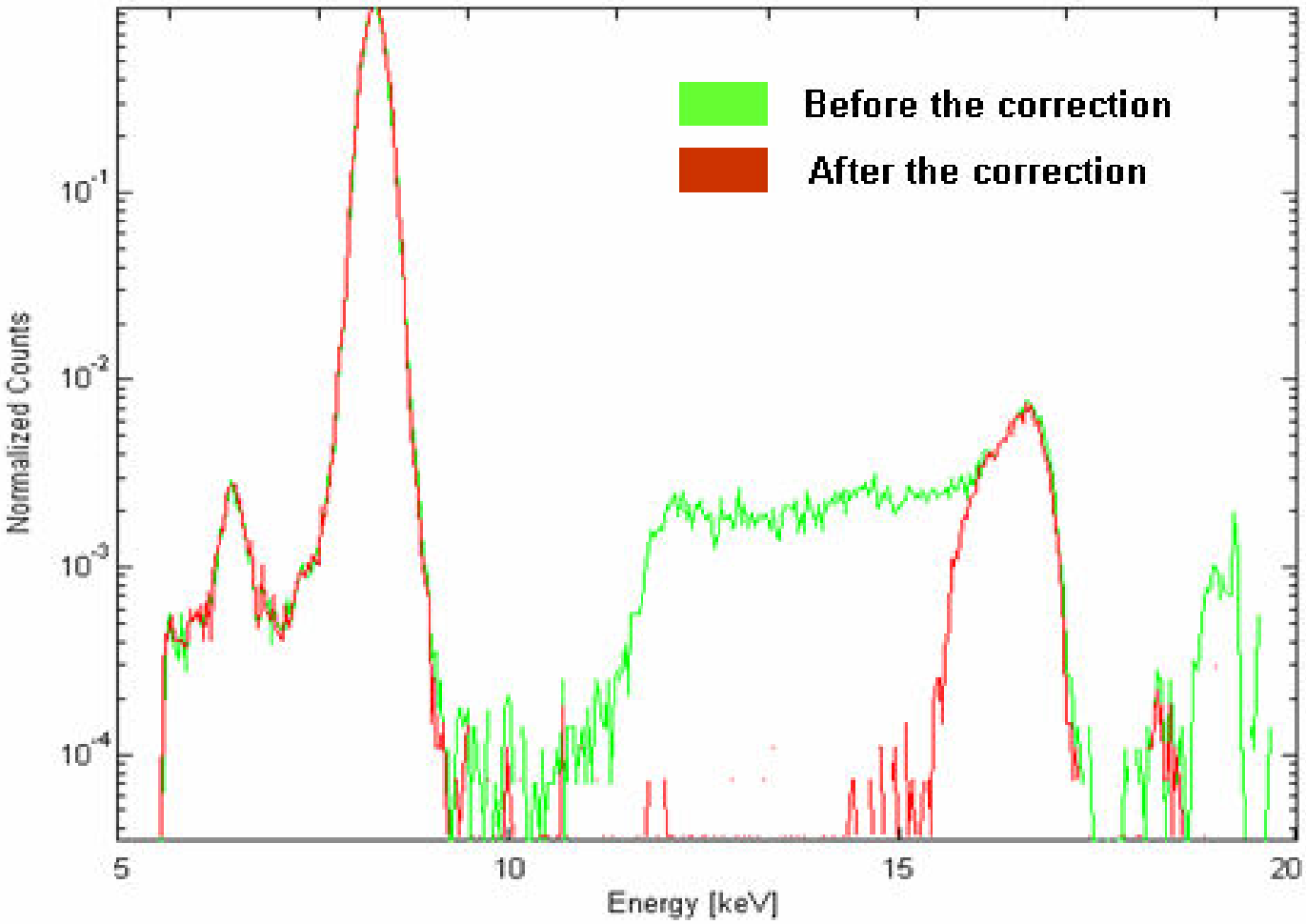


Before The Correction



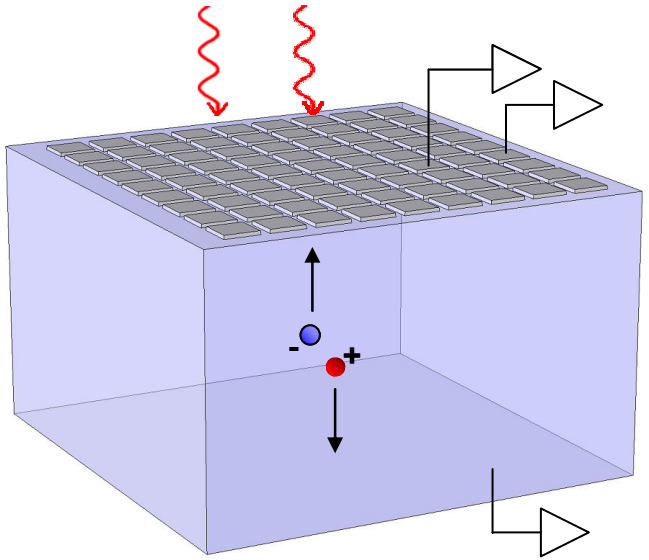
After The Correction

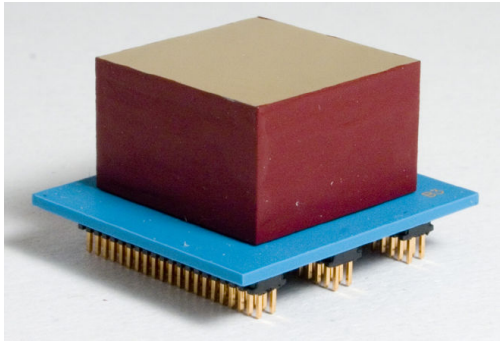
Pulse Height Spectra Comparison



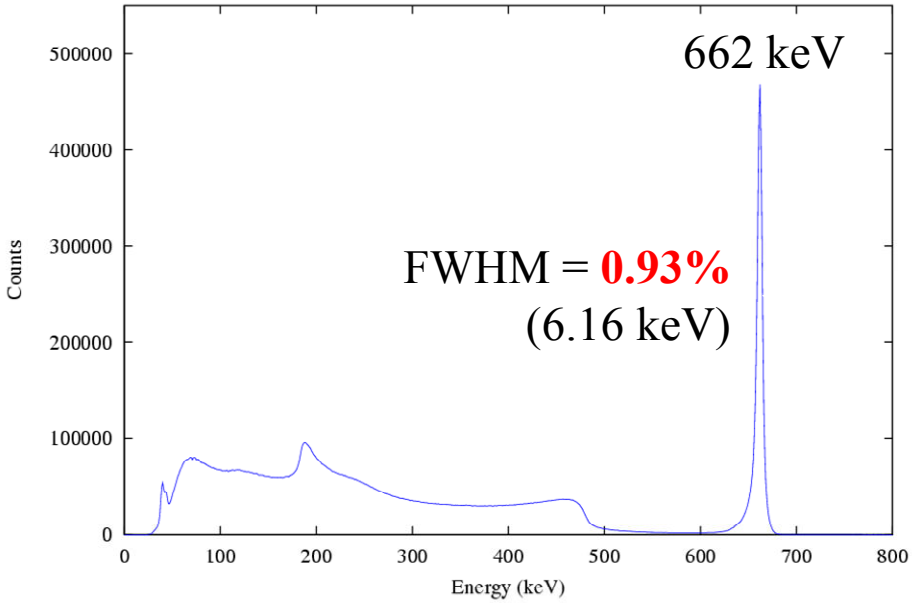
Z reconstruction in 3D CZT and material non uniformities compensation

3D Position Sensitive Detector (3DPSD)
Prof. Zhong He (University of Michigan)





Spectrum: 1,2, and 3-pixel events



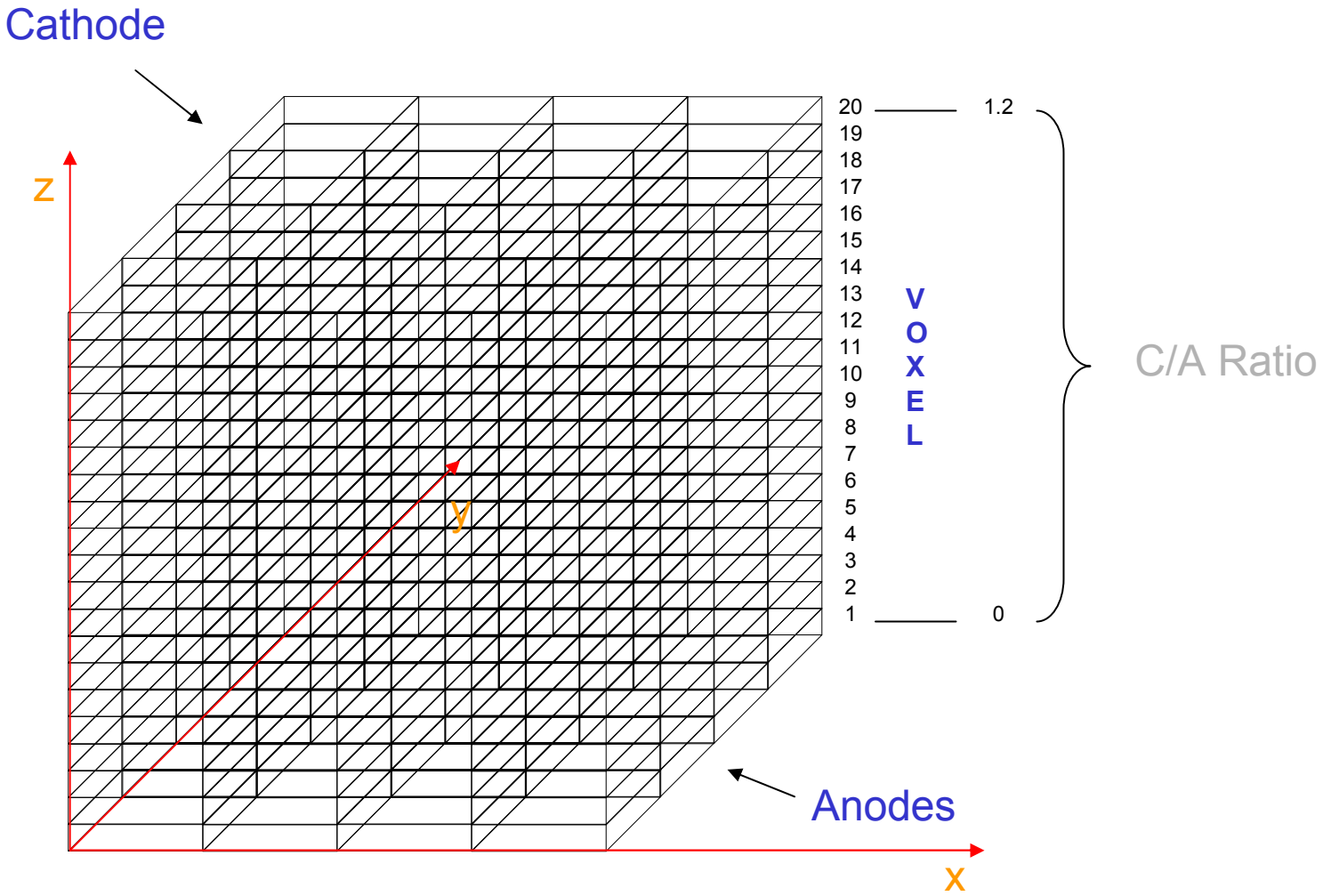
- **Combines:**
  - **small-pixel effect**
  - **depth sensing**
- **Multiple signals per event:**
  - **cathode (energy and timing)**
  - **anodes (energy and timing)**
- **Correction:**
  - **on voxel-by-voxel basis (volumetric pixel)**

Individual correction for each of 4800 voxels in 1.5 x 1.5 x 1cm3 crystal

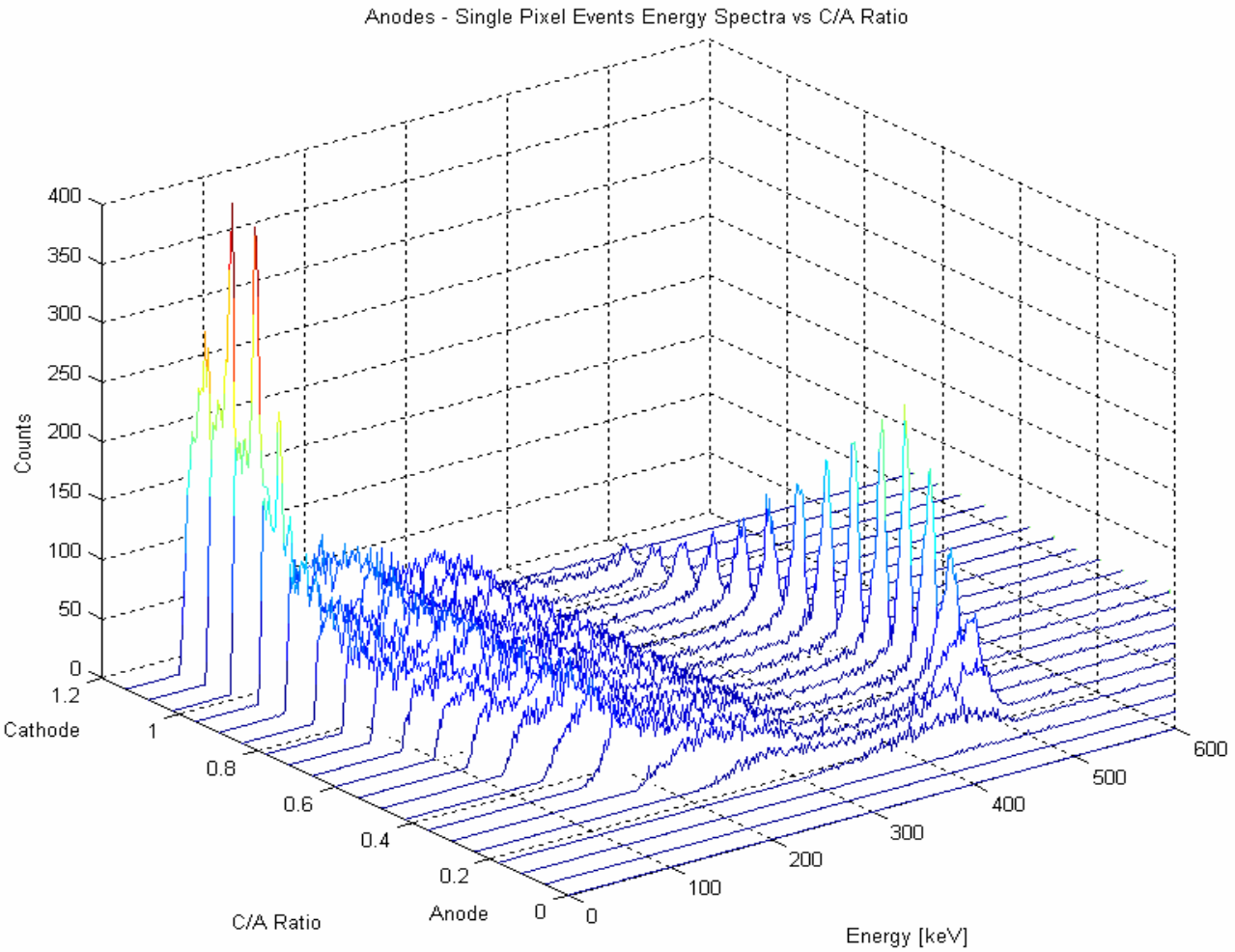
F. Zhang et al., 2005

Z reconstruction in 3D CZT and material non uniformities compensation

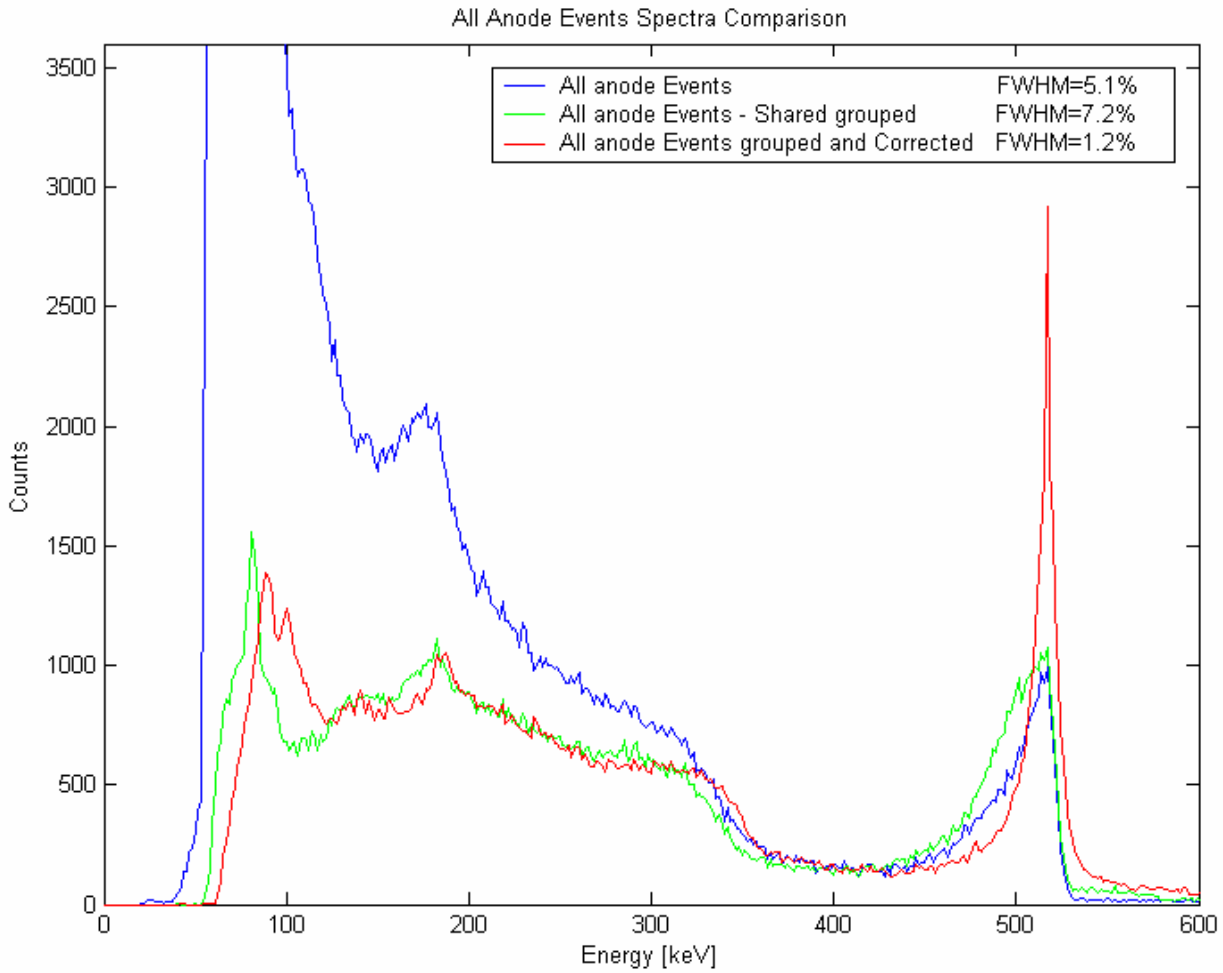
320 Voxel has been defined each level along z has an associated C/A ratio value. Single event position has been identified using the C/A ratio.
Gain correction factors, has been calculated from the Single events spectra along Z compensating for every single Pixel column.
Multiple events z position has been identified calculating an equivalent c/a ratio from the electron drift time of the first anode event that identifies the first interaction point.



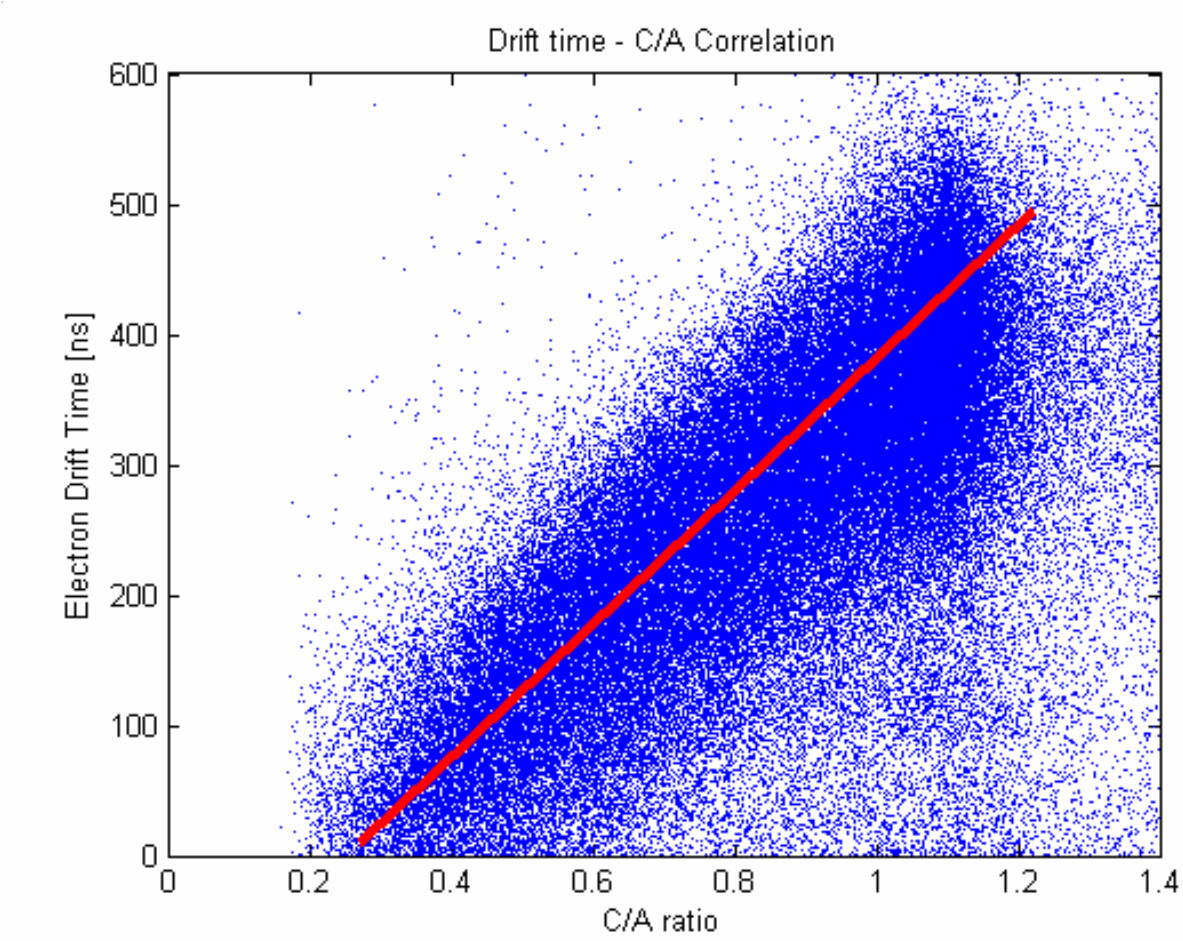
Z reconstruction in 3D CZT and material non uniformities compensation



Z reconstruction in 3D CZT and material non uniformities compensation



Z reconstruction in 3D CZT and material non uniformities compensation



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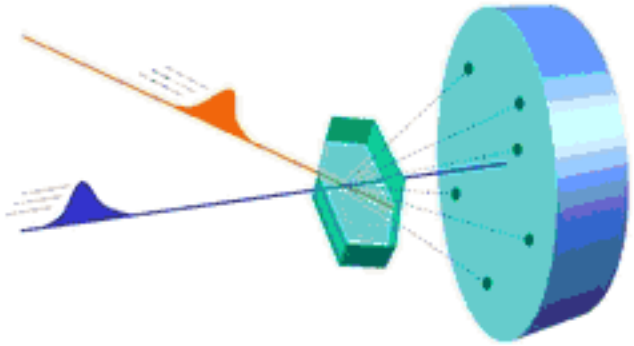
NSLS NATIONAL SYNCHROTRON LIGHT SOURCE

Front-End ASIC for the Readout of XAMPS detectors to be used in the LCLS XRPP instrument

A. Dragone, P. Rehak, J.F. Pratte, P. O'Connor, P. Siddons (PI)

The X-Ray Pump and Probe (XRPP) Instrument

A way to study of stimulated changes in the structures of molecules and condensed matter systems



Changes will typically be stimulated by a short pulse of optical laser light (orange), and observed using x-ray diffraction (blue).

Femtosecond-level synchronization between the optical laser and the LCLS x-ray pulse will allow sub-picosecond time resolution.

Examples of studies with this instrument:

•*Dynamics of photo-induced phase transitions:* Optical manipulation of solids can lead to photo-induced phase transitions on the ultra fast time scale. These materials possess potential technological importance as ultra fast optical signal processing materials.

•*Dynamics of photoactive proteins:* The variability and efficiency of proteins make them powerful molecular foundries. To understand how a protein functions at a mechanistic level of detail, it is necessary to measure in real time the nuclear motions that accompany its function.

•*Dynamics of photo-initiated electron transfer reactions:* Electron transfer reactions reside at the center of many important chemical, biological, and technological processes, including photosynthesis and the operation of photovoltaics for solar energy conversion.

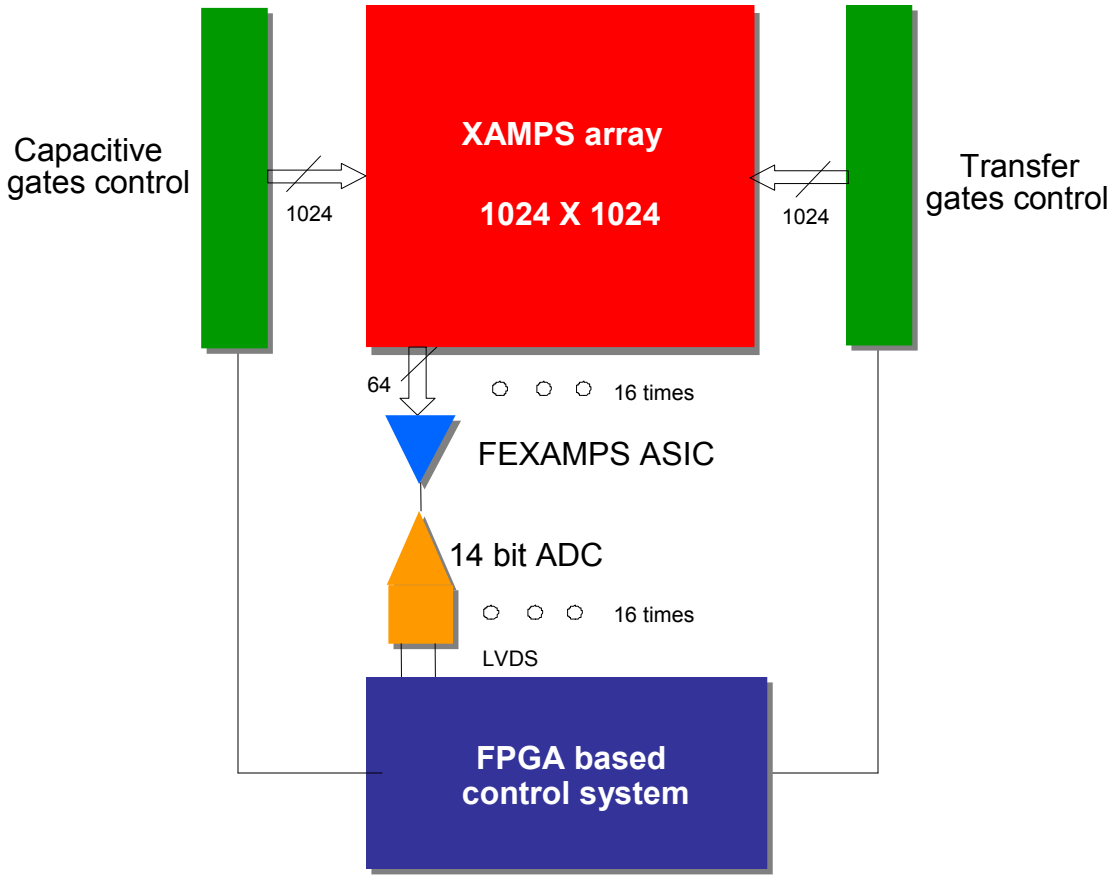
XRPP Specifications

Resolution (8 keV):	0.5 photons (FWHM) $\rightarrow$ 500 e- rms
Dynamic range :	10^4 photons $\rightarrow 2.2 \times 10^7$ e- (3.5 pC)
Dissipated power :	< 2 mW / channel
Pixel + line capacitance :	2-20 pF including the line (depend on the capacitive gate control) – optimized for 15pF
Processing time :	< 8 µs (1µs-8µs to be synchronized with the LCLS beam period of 120Hz)

Statistical fluctuations in e- h+ pair generation in Si

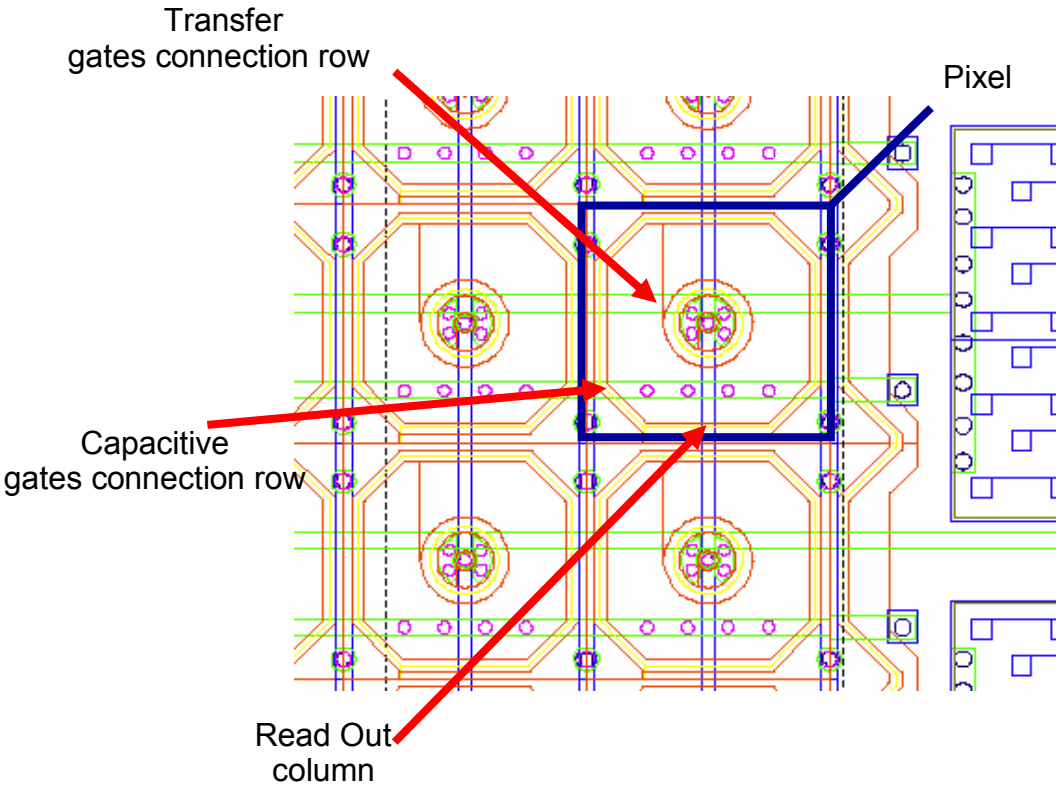
N photons	ENC e- rms	Photon Resolution FWHM
0.1	5	0.005
1	15	0.015
10	50	0.05
100	160	0.15
1000	520	0.5
10000	1630	1.7

System Architecture

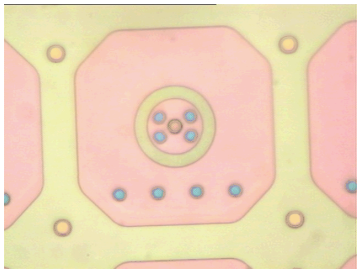


X-rays Active Matrix Pixel Sensor (XAMPS)

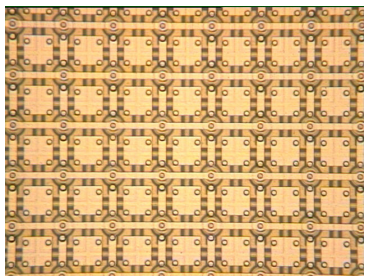
- Monolithic devices built on fully-depleted high-resistivity silicon provide simplest structure
  - Switching mechanism integrated with sensor
  - Small pixels in principle possible (no on-pixel amps or small 3T design)
  - row-by-row parallel readout by off-sensor amplifiers
  - N readout channels instead of N x N, modular readout from edge of detector by a few (~16) small ASICs



IBM version

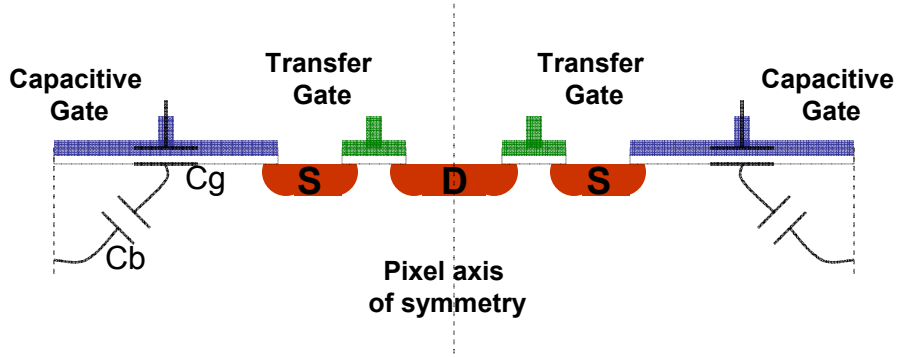


BNL version

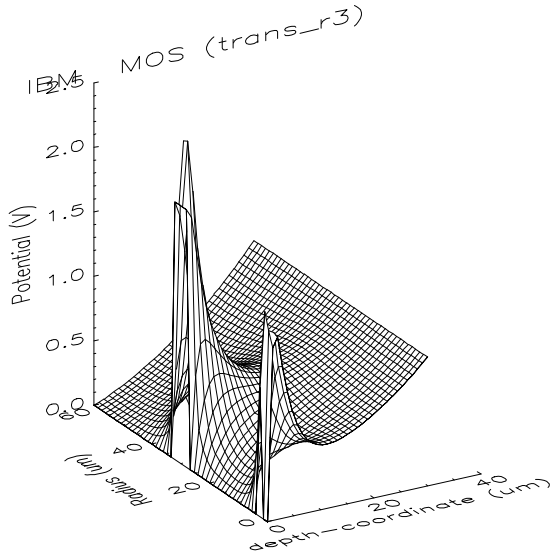


XAMPS charge storing: Potentials

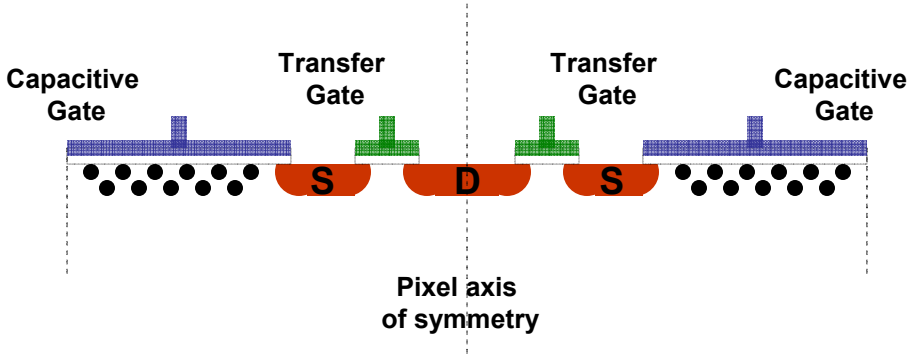
Pixel with no charge



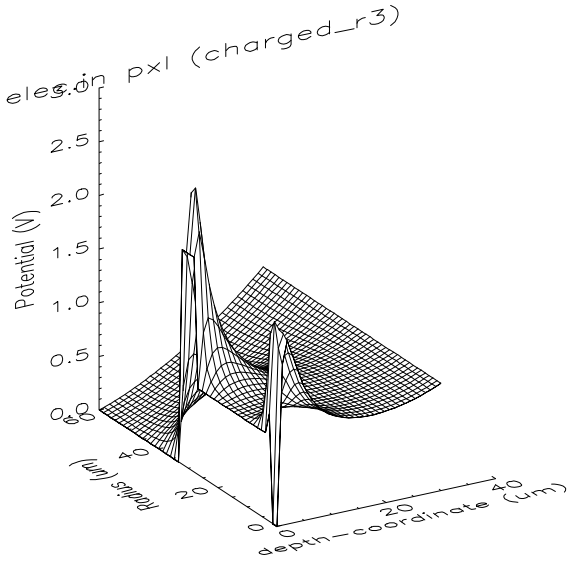
Substrate at 1200V



Pixel with full charge 3.5pC



Substrate at 1200V



To store the charge Cg must be big! Cg=7.5pF

XAMPS charge transferring and the KTC noise

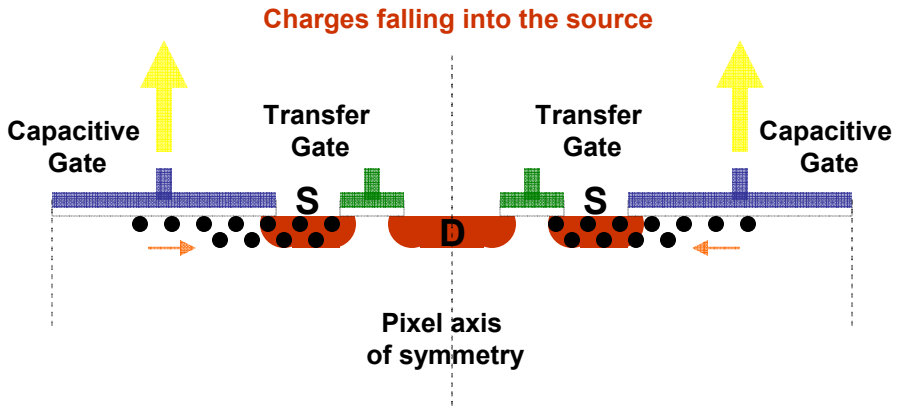
If Cpixel is big its kTC noise has to be considered.

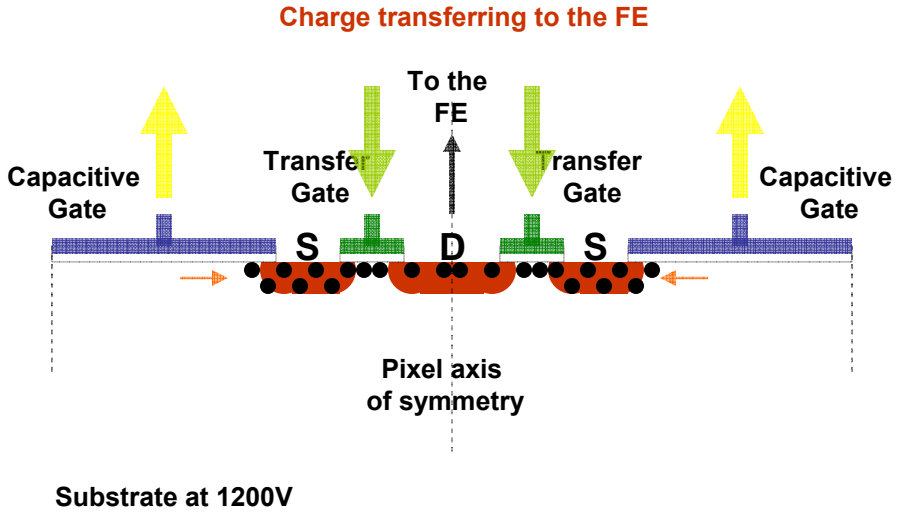
For a:
Cpixel ≈ 7.5 pF → √kTCpixel ≈ 1060 e-
If instead:
Cpixel ≈ 1 pF → √kTCpixel ≈ 400 e-

Capacitive Gates Control is fundamental

If the transfer gate is closed when the charge fall into the diffusion region since there is no more charge in the Cg the KTC will be due to an equivalent much smaller capacitance.

Note: the Cg sees in series a Cb of about 100fF to the boundary regions, thus to move the capacitive gates of a row (1024 connected together) we don't need huge drivers.

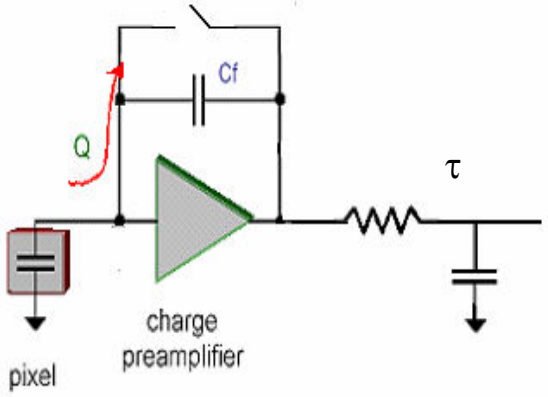


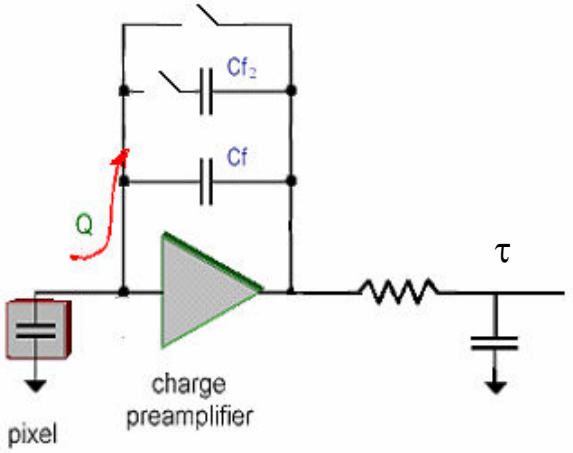


ASIC Architecture

The natural approach for the a fast readout of a detector in witch the charge is collected in synchronous with an external signal would be a classic:

Time Variant Gated Integrator System





DR= 10000 ph. @ 8keV

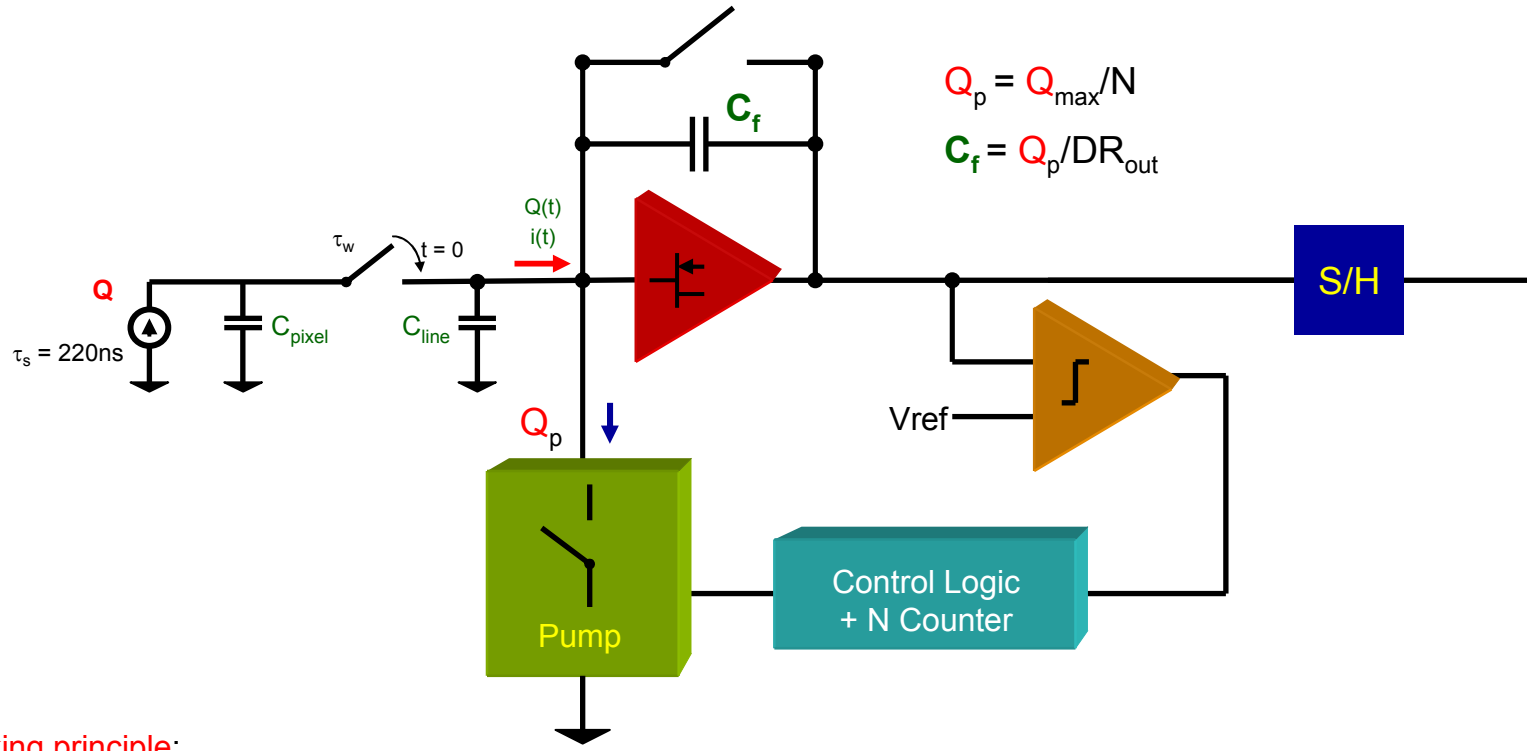
C_{pixel} ~ 15Pf → →

DRout=1.5V Cf=4.5pF KTC_{noise} = 850e^-

14bit ADC required so that 1LSB = 1.2 ph

The requested Input Dynamic Range is to large!

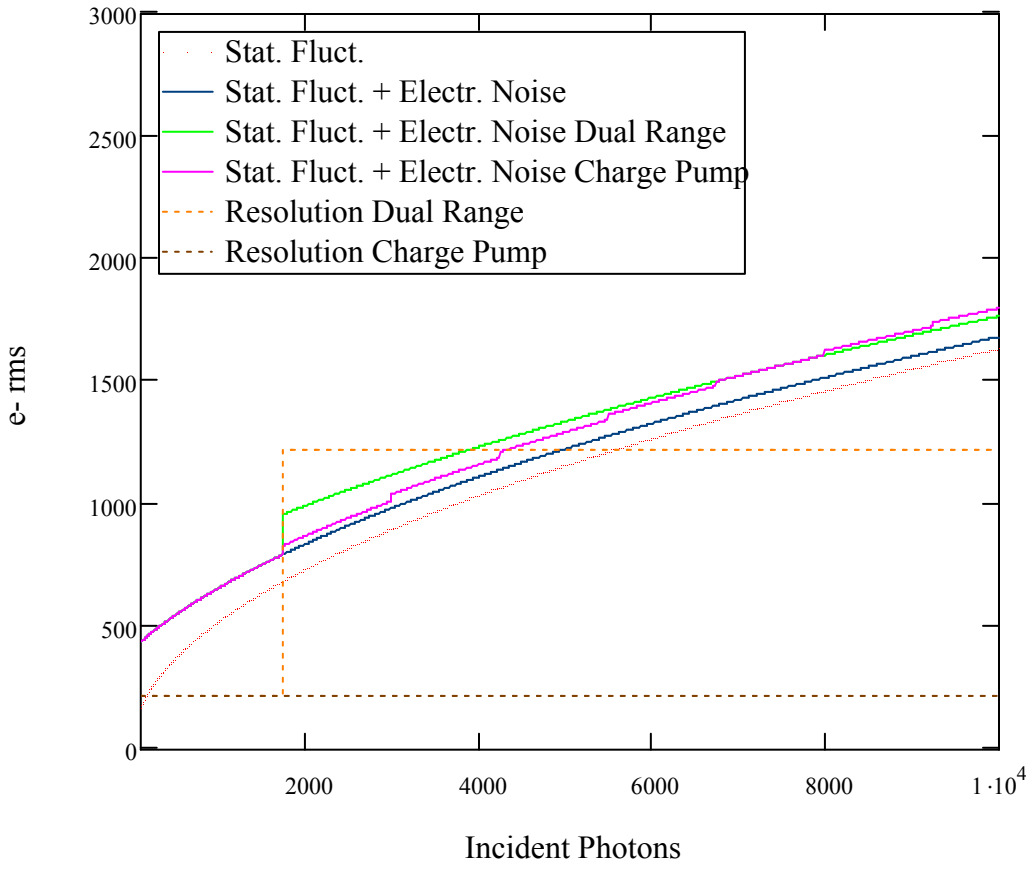
Charge Pump or 0 Balance Method



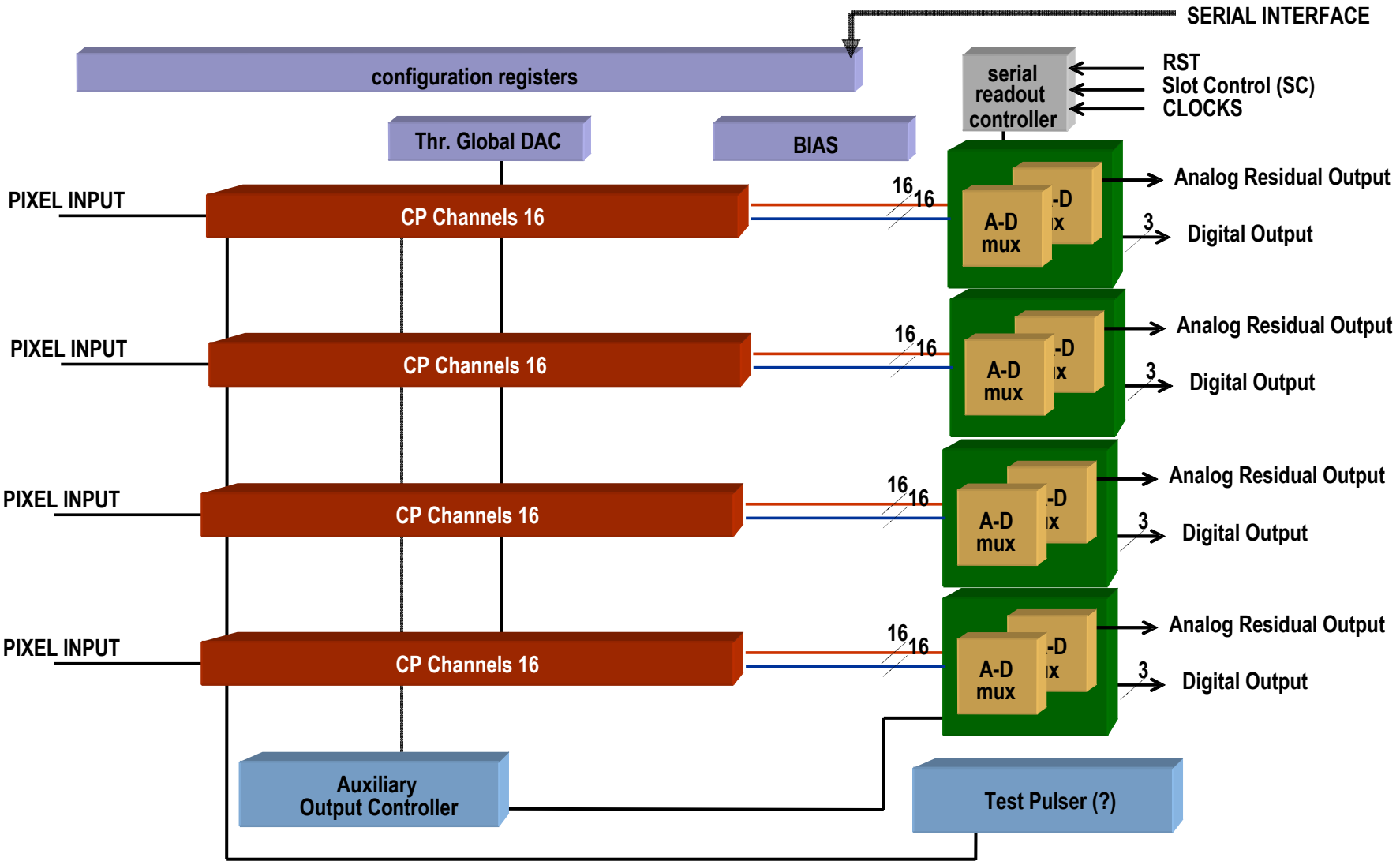
Working principle:

To meet the required resolution over the entire dynamic range a 0 balance method is applied: the dynamic range is divided in N ranges each one corresponding to a charge Qp=Qmax/N. When a charge larger than Qp is presented to the input a charge pump is activated to remove fixed amount of charge equal to Qp until a residual smaller than Qp remains stored in the feedback capacitor Cf. The number of charge quanta Qp removed by the pump are counted and the corresponding digital value is presented at the output representing the most significant bits of the final A/D conversion (for N=8 we have 3 bit).
The residual charge in the feedback capacitor is then sampled according to a CDS scheme, presented at the output and converted with a 14bit ADC (total of 14+3=16bit).

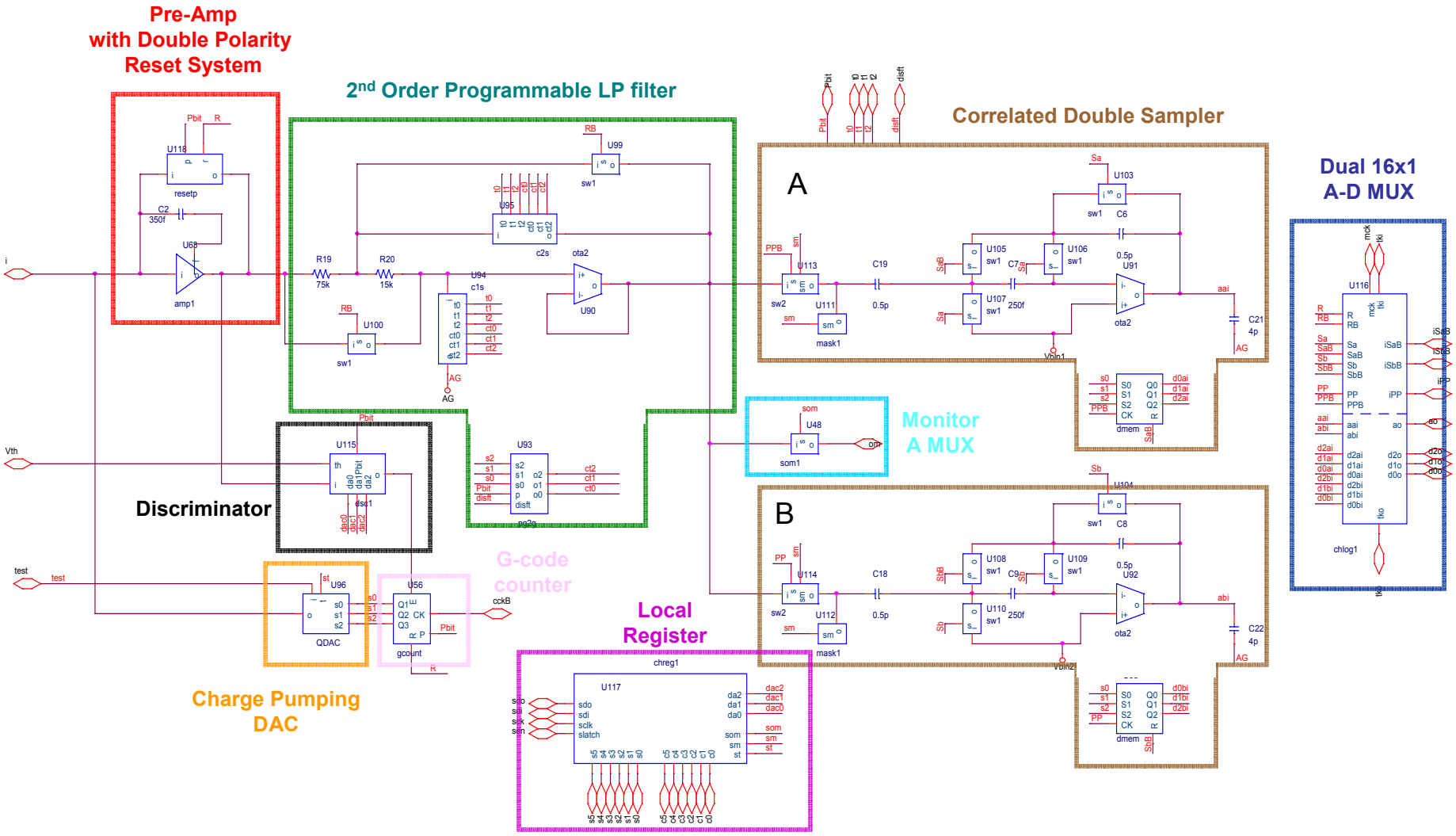
Comparison


Stat. Fluct.
Stat. Fluct. + Electr. Noise
Stat. Fluct. + Electr. Noise Dual Range
Stat. Fluct. + Electr. Noise Charge Pump
Resolution Dual Range
Resolution Charge Pump
e- rms
Incident Photons
3000
2500
2000
1500
1000
500
0
2000
4000
6000
8000
1·10^4

ASIC Architecture

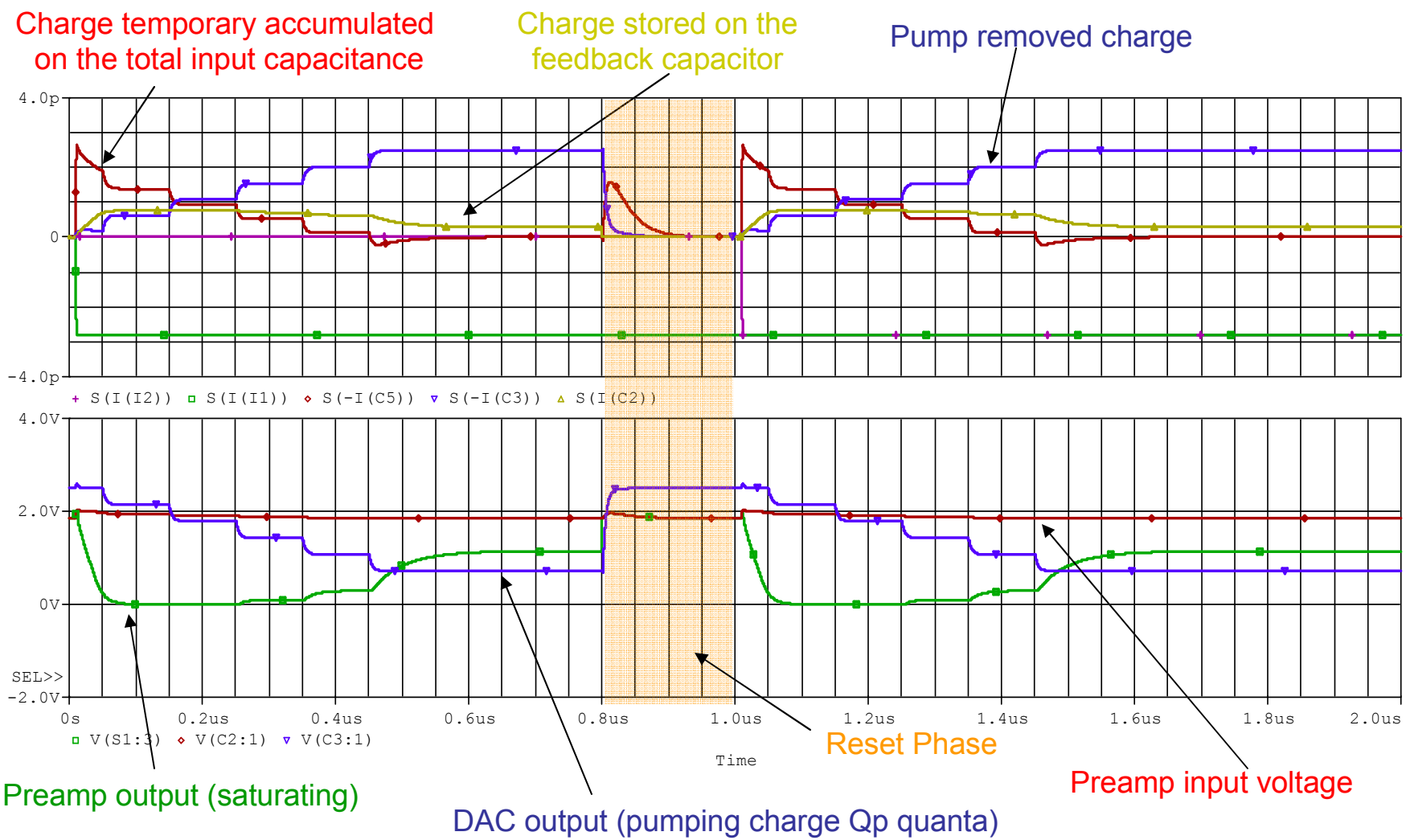


Charge Pump Channel



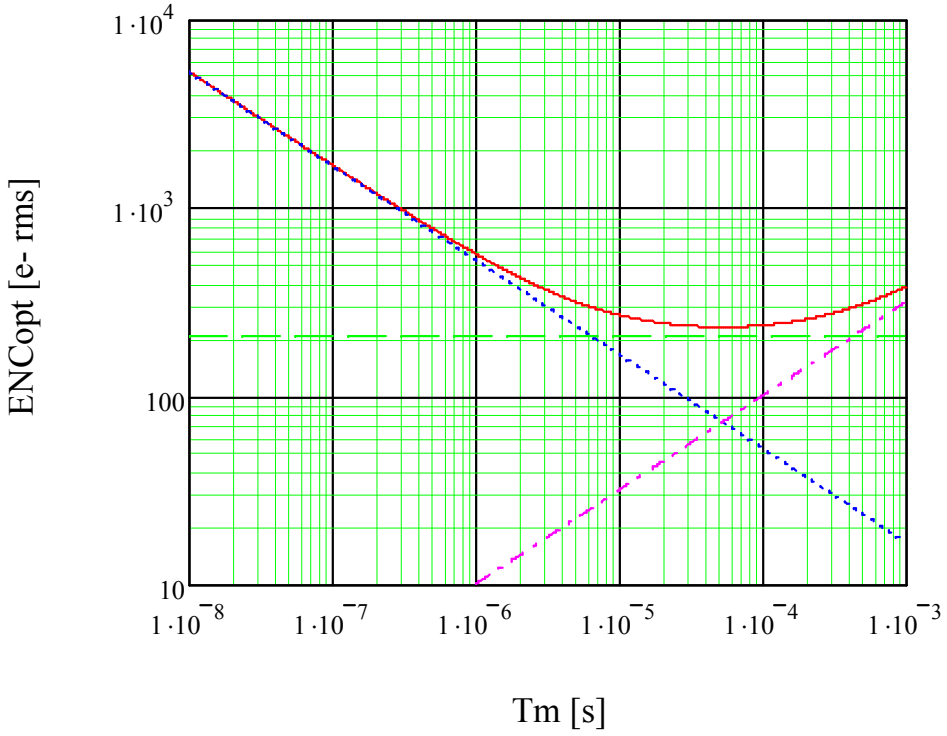
Simulation Result

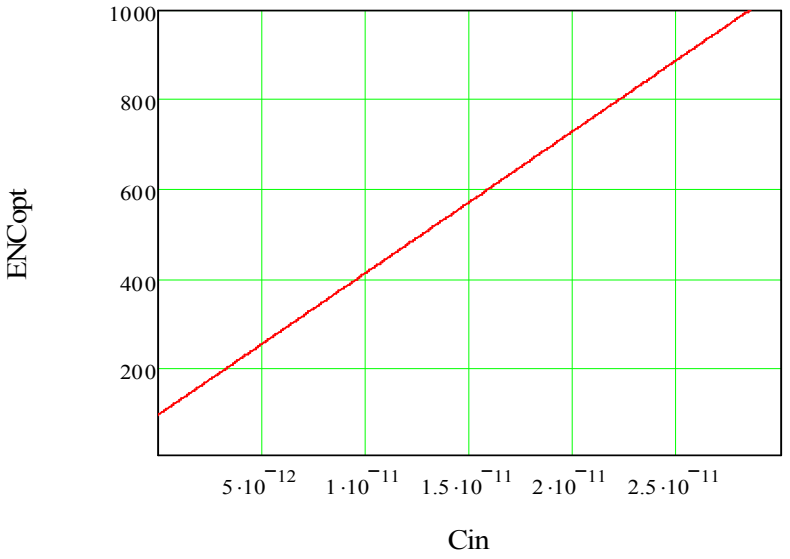
Example of the circuit behavior in response to 2 subsequent full dynamic impulse of charge (worst case) saturating the preamplifier



Noise Analysis Results

An estimate of the ENCopt considering the series noise and the parallel components common to the proposed solutions: Optimized for fixed power of 0.5mW, Cin of 15pF and assuming a 2nd order low pass filtering and CDS (Wopt=1.5mm).



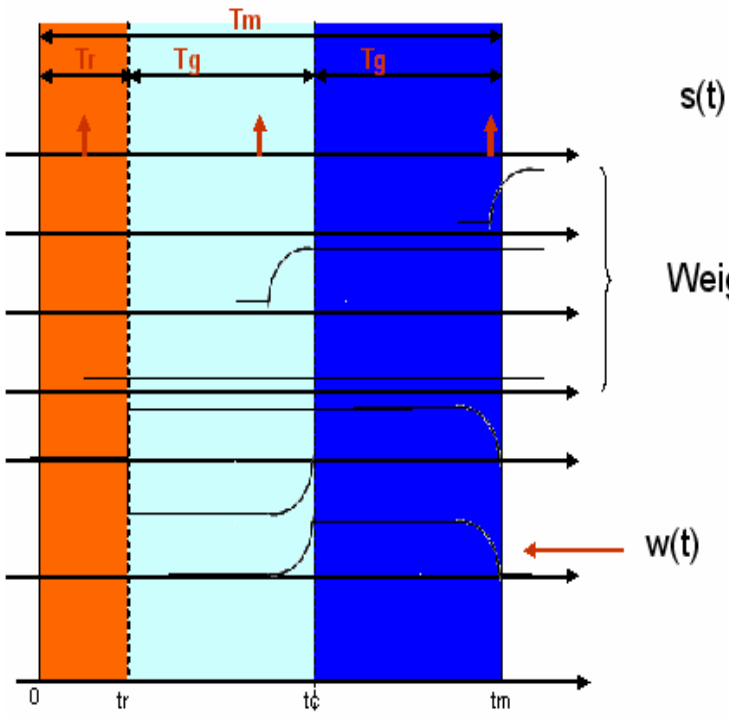


$$ENC^2 = (C_{in} + C_g)^2 \left[\frac{S_w}{\tau_p} a_w + A_f 2\pi a_f \right] + S_p \tau_p a_p$$

$$a_w = \frac{\int_0^\infty |H(x)|^2 x^2 dx}{2\pi \cdot h(t/\tau)|^2_{max}}, \quad a_f = \frac{\int_0^\infty |H(x)|^2 x dx}{2\pi \cdot h(t/\tau)|^2_{max}}, \quad a_p = \frac{\int_0^\infty |H(x)|^2 dx}{2\pi \cdot h(t/\tau)|^2_{max}}$$

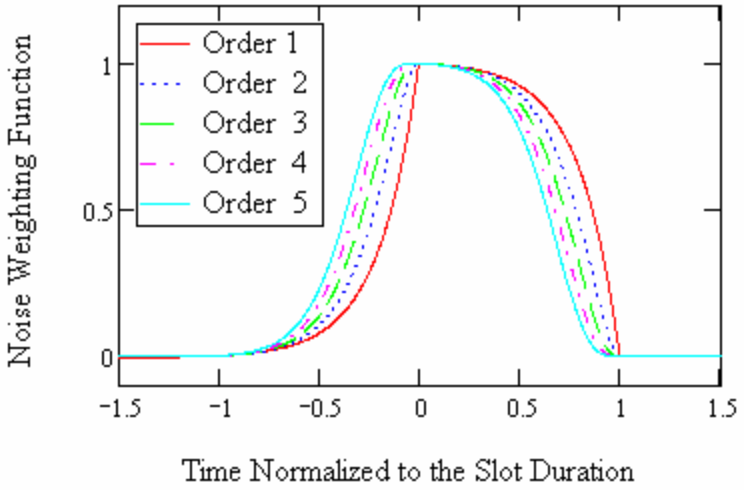
S_w and S_p are the series and parallel unilateral noise spectral densities respectively

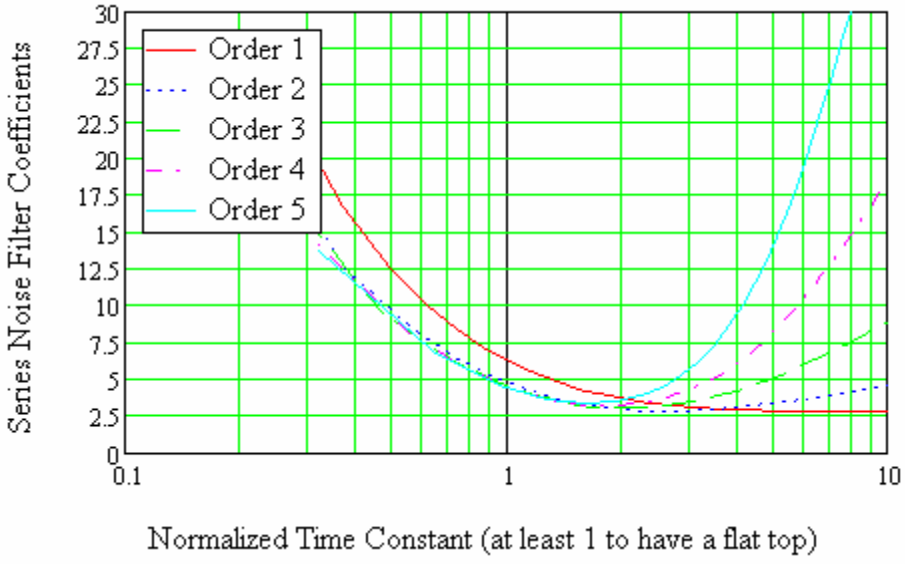
Time Domain Noise Analysis Results: System with CDS



Weighting function evaluation

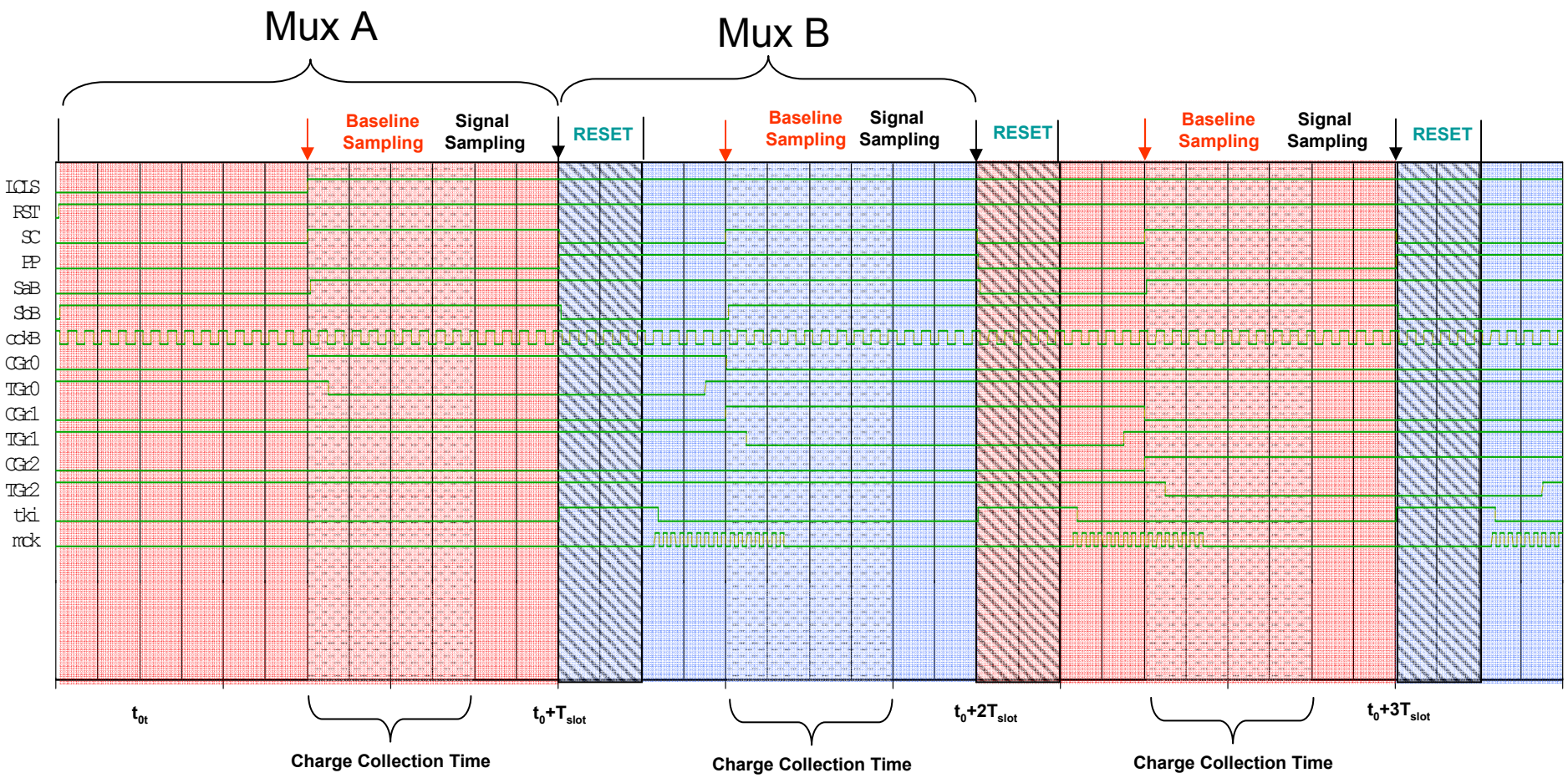
w(t)



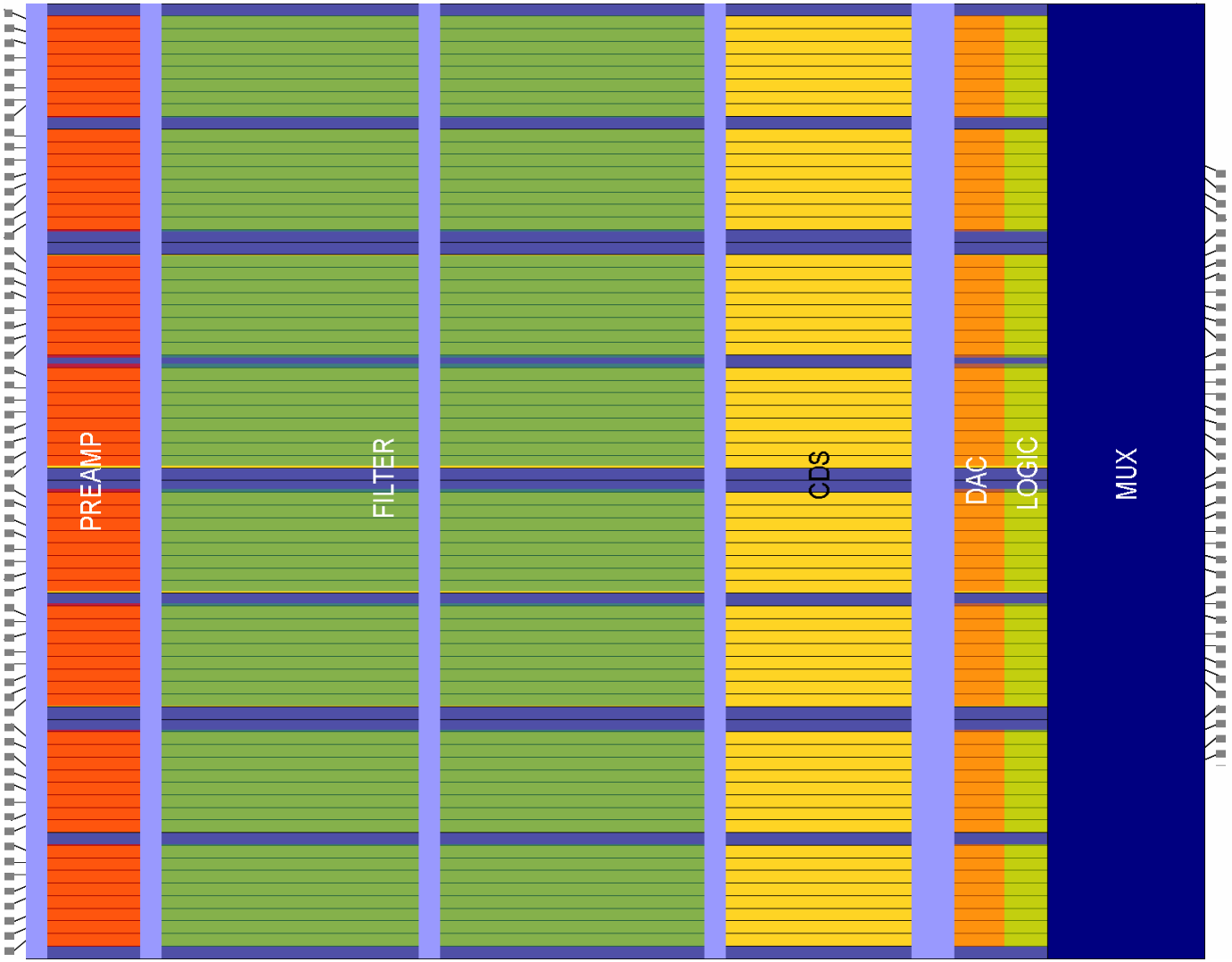


Tm = Measurement Time
Tg = Acquisition Time Slot
Tr = Reset Time

ASIC Timing Diagram



Floor plan



Thank you very much for your attention.