Advanced Pulse Processing Techniques for Synchrotron and Other High Rate Applications

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Southern Innovation

IFDEPS 2018

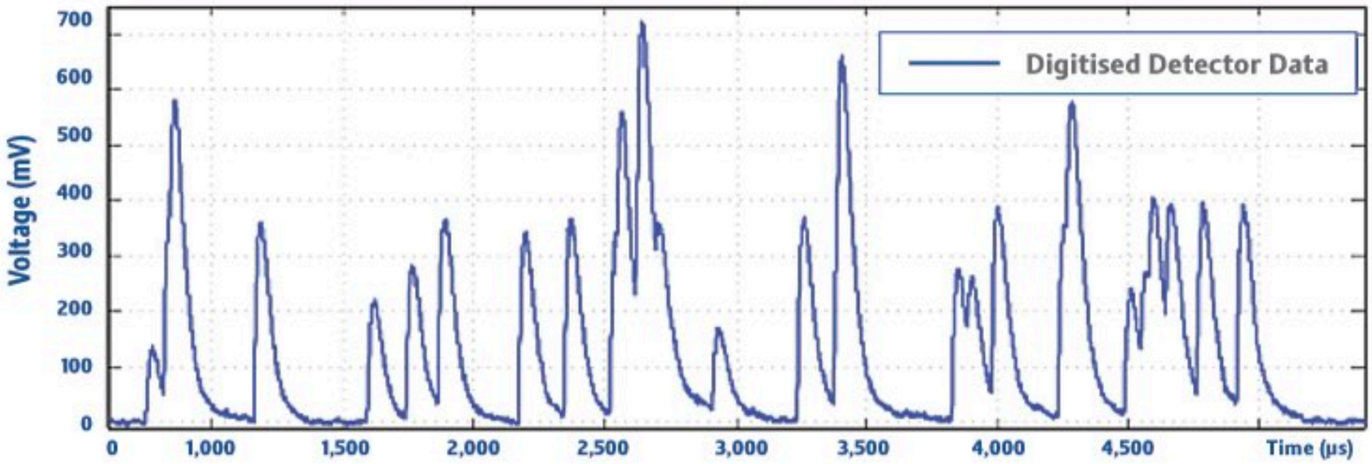
Presentation Outline

- Problem Definition
- Analogue Pulse Processing
- Linear Digital Filtering
- Model Based Signal Processing
- Model Based Pulse Processing
- Productisation, Testing and Results
- Industrial Uses for High Flux
- Next Generation

Problem Definition

Pulse Pile-up

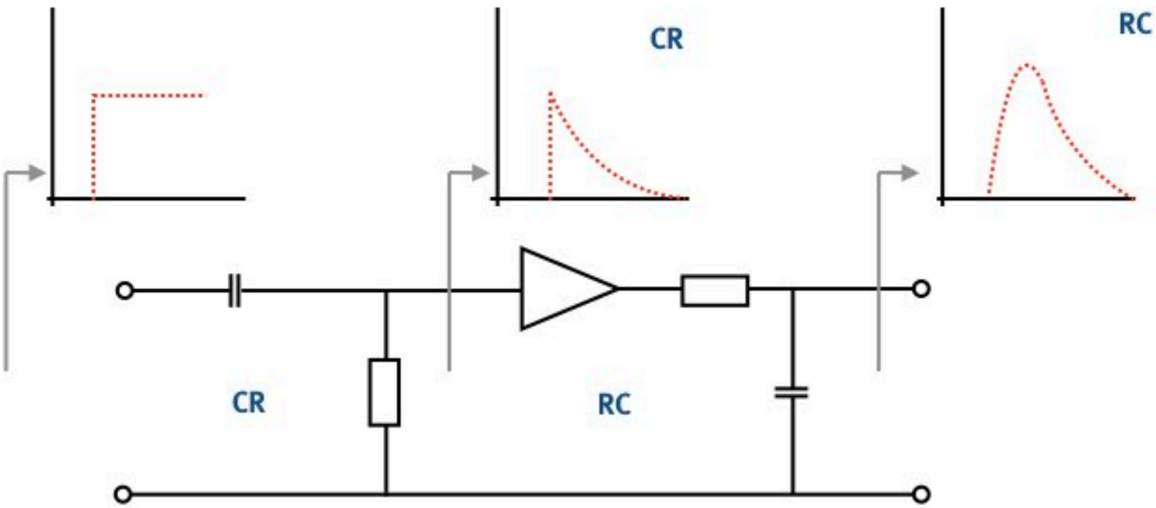
- A burst of radiation ‘arrives’ within the detector response time
- Reduces energy resolution and increases dead-time
- Extending the time required for accurate classification
- Current solution to the problem is to reject piled-up pulses



Analogue Pulse Processing

Pulse Shaping Networks

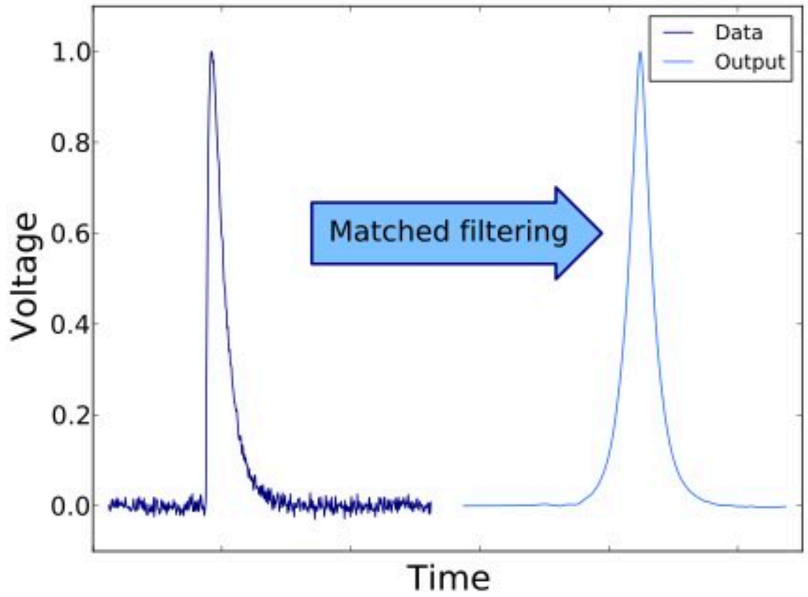
- Passive circuit components used to create CR and RC networks
- Various levels of complexity to control pulse shape and peaking time
- ADCs can be used at the end to read of the peak value of an event
- Challenges include noise, stability, ageing and throughput (‹20 kc/s)

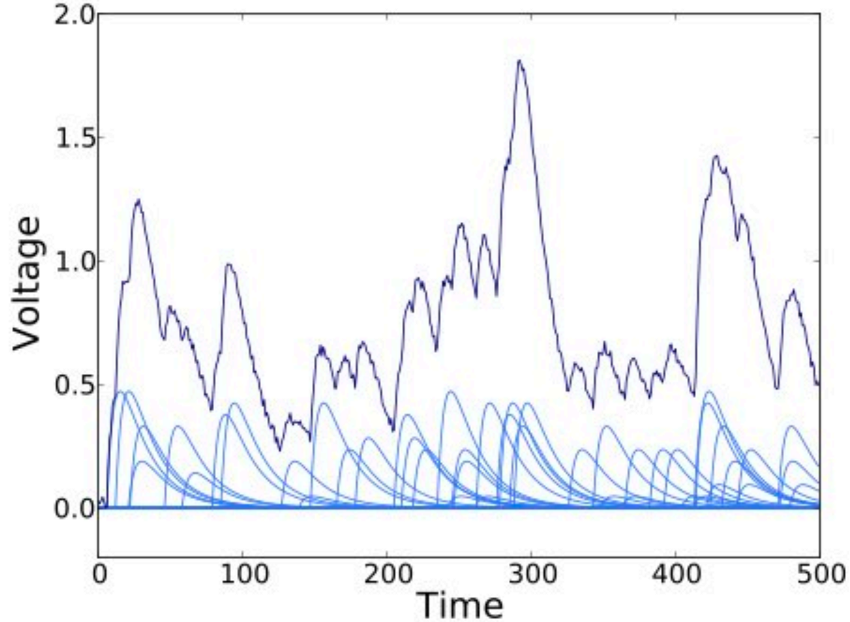


Digital Pulse Processing

Matched Filtering

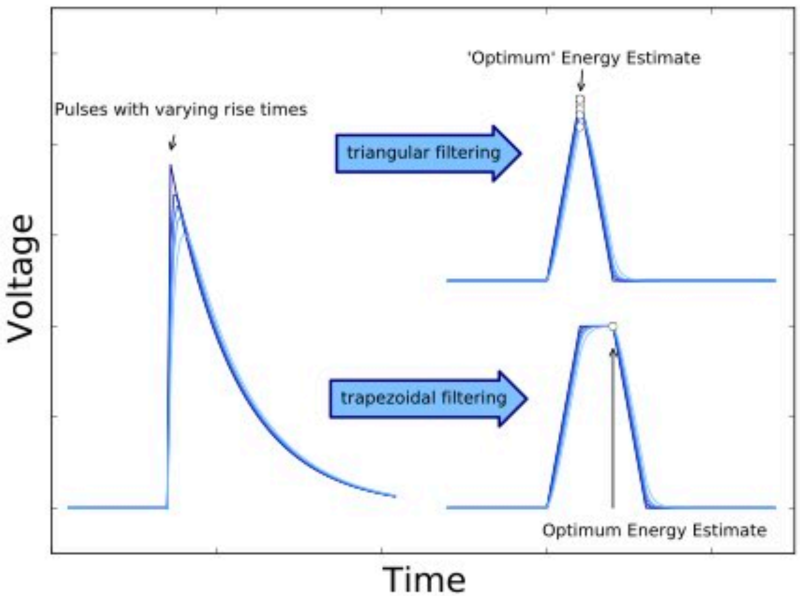
- Assuming the count rate is low enough so pulses are isolated
- The match filter gives optimal SNR use a simple threshold detection
- Low throughput, very susceptible to pile-up i.e. <20kc/s

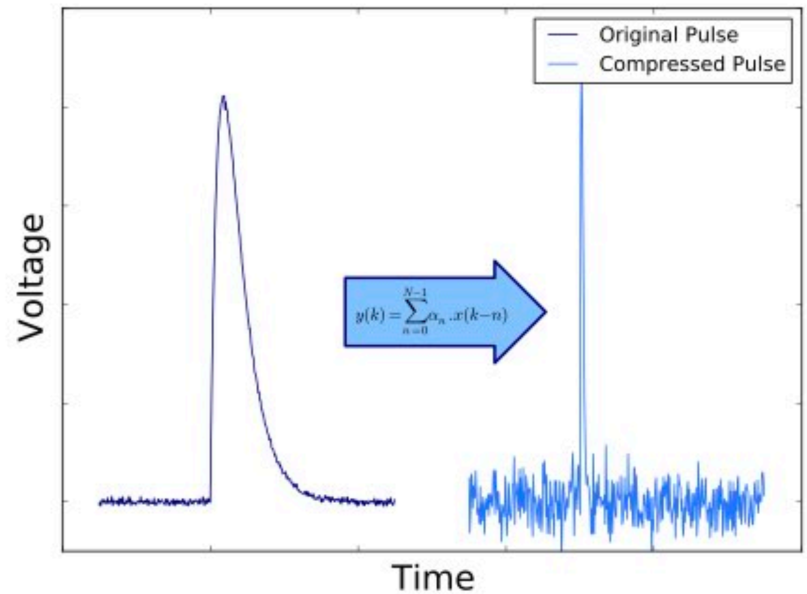




Triangular and Trapezoidal Filters

- Reduce pulse width by filtering pulse into a trapezoidal shape
- Much narrower response time than a matched filter
- Can mitigate the effects of ballistic deficit due to charge collection
- Trading off desired throughput Vs energy resolution (SNR)





Linear Filtering

Trapezoidal Filtering

- Analogue R/C filtering of the step reset preamplifier signal
- Fast digitisation and convolution with a time-invariant linear filter
- How do we optimally design that linear filter

Filter Design

- Long rise-time & flat-top time = good resolution & low throughput
- Short rise-time & flat-top time = poor resolution & high throughput
- Optimal SNR delivered by a matched filter (some assumptions)
- Shorter filters reduce signal power and increase noise
- Throughput limited <200 kc/s

Linear Filtering

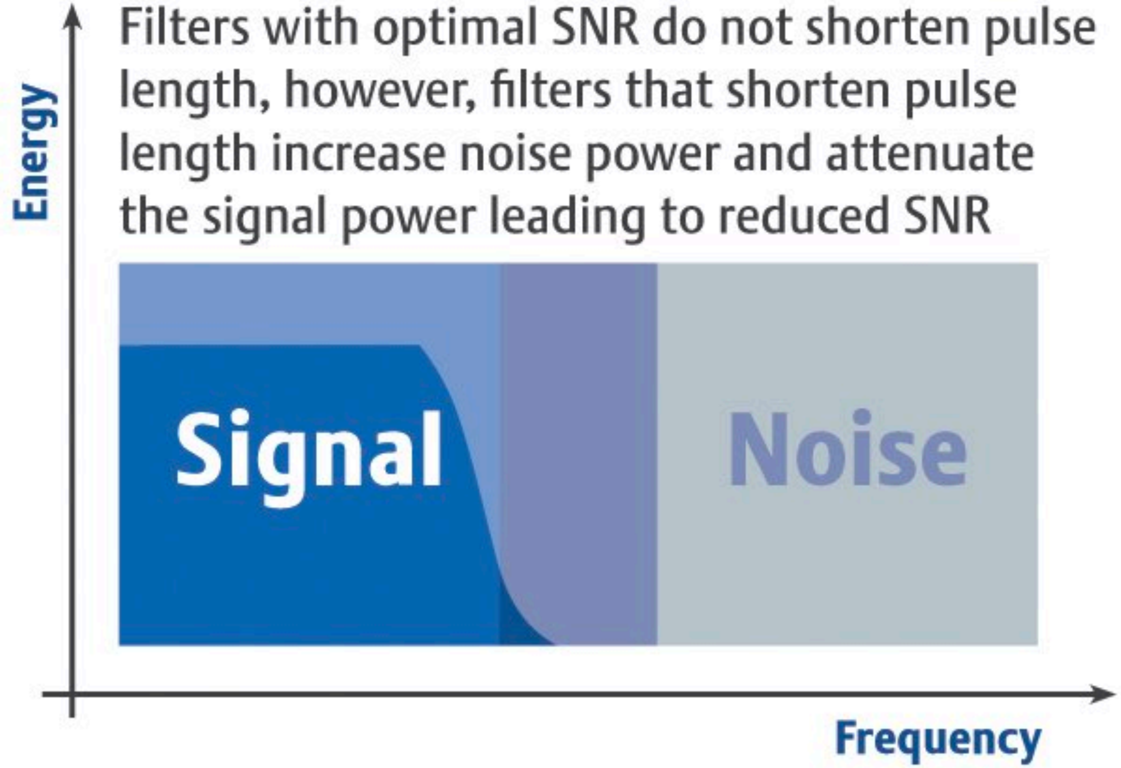
Trapezoidal Filtering

- Analog
- Fast d … ter
- How d

Filter I

- Long r … hput
- Short … ghput
- Optim
- Shorte
- Throu

Filters with optimal SNR do not shorten pulse length, however, filters that shorten pulse length increase noise power and attenuate the signal power leading to reduced SNR



Linear Filtering

Trapezoidal Filtering

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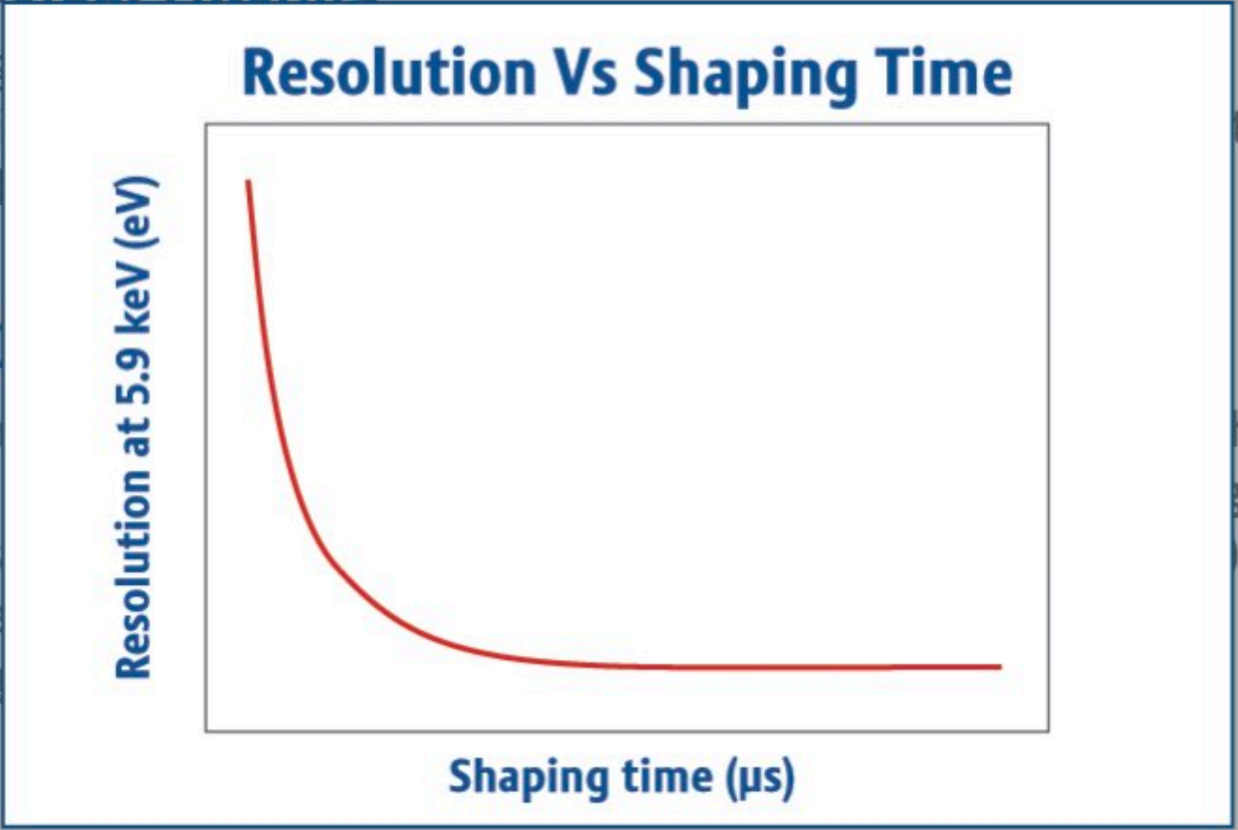
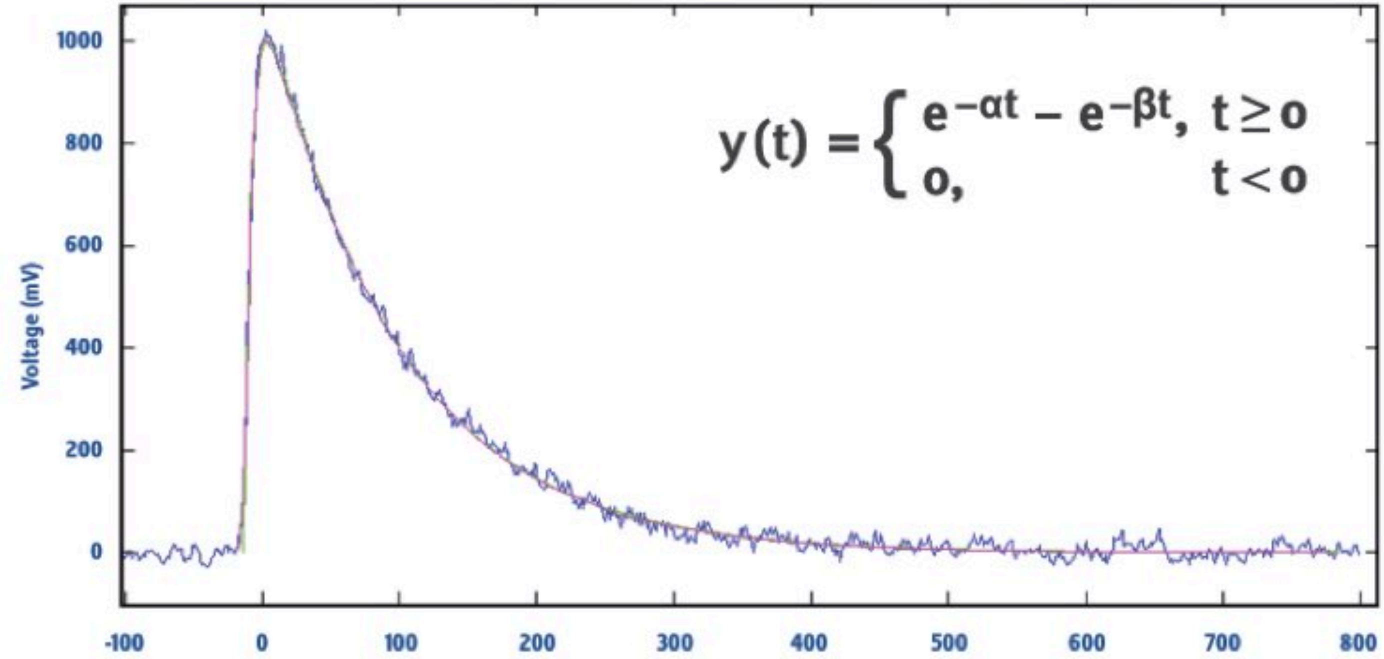


Model Based Signal Processing

Parameter Estimation

- Forming a mathematical relationship to model data
- Parameters describe an underlying physical dynamics
- Estimating the values of parameters based on measured data

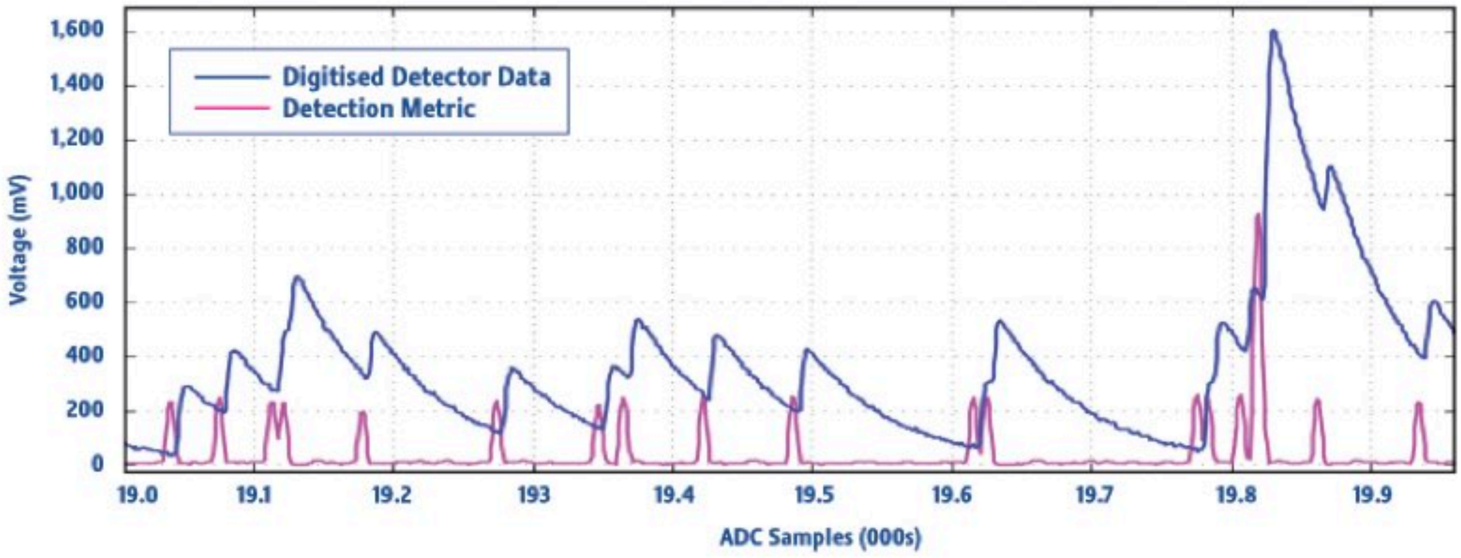
$$y(t) = \begin{cases} e^{-\alpha t} - e^{-\beta t}, & t \geq 0 \\ 0, & t < 0 \end{cases}$$



Model Based Signal Processing

Exponential Curve Fitting

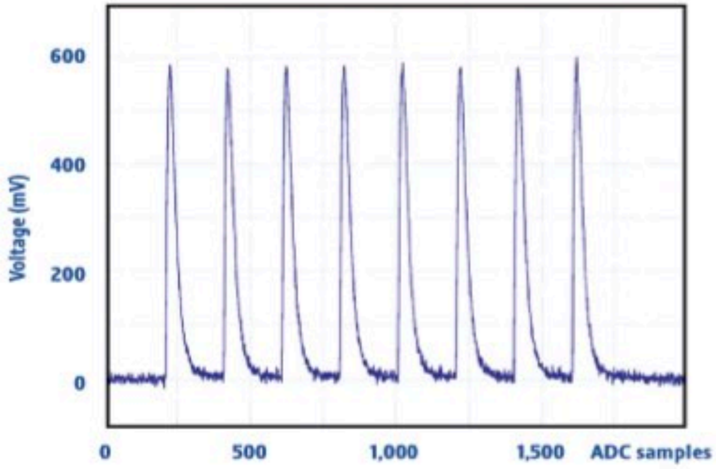
- Fit an exponential model across a fixed window length i.e. 16 samples
- Sum the square of the 'fit error', this is the detection metric
- Very sensitive to non-linearity in the data set i.e. a photon arrival
- Separate events within 30 ns of each other TOA estimate to 1 ns



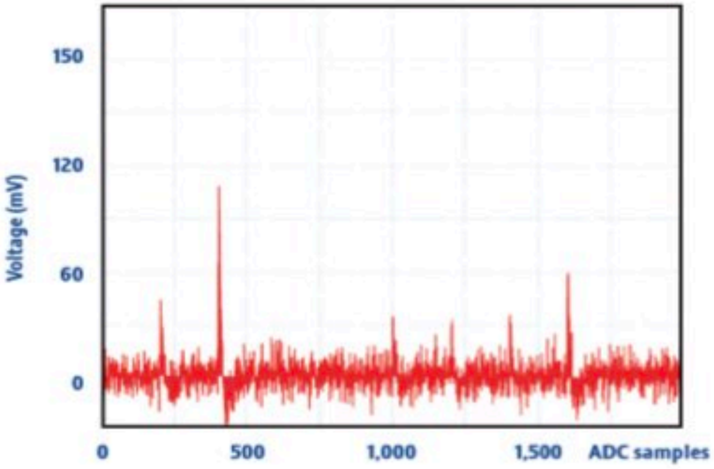
Model Based Signal Processing

Time of Arrival Estimation

- Exponential curve fitting based on a priori knowledge of pulse shape
- The real world complicates things as photons arrival randomly
- Asynchronous timing between sampling and photon arrival
- The majority of pulses have 'intra-sample' arrival times



Scanning sub-sample across 2 ADC samples

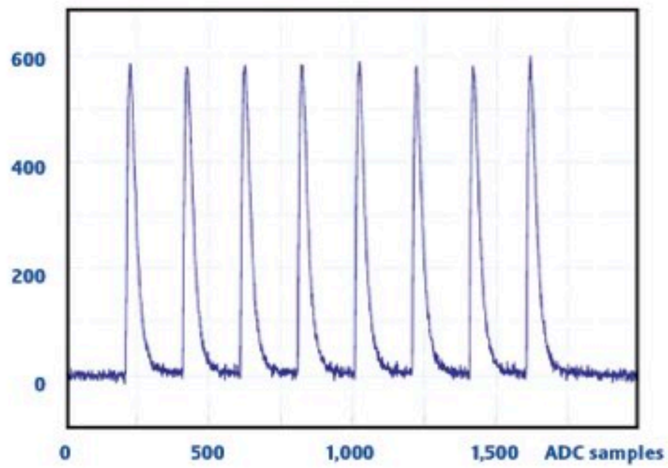


Effect of sub-sample arrival on residuals

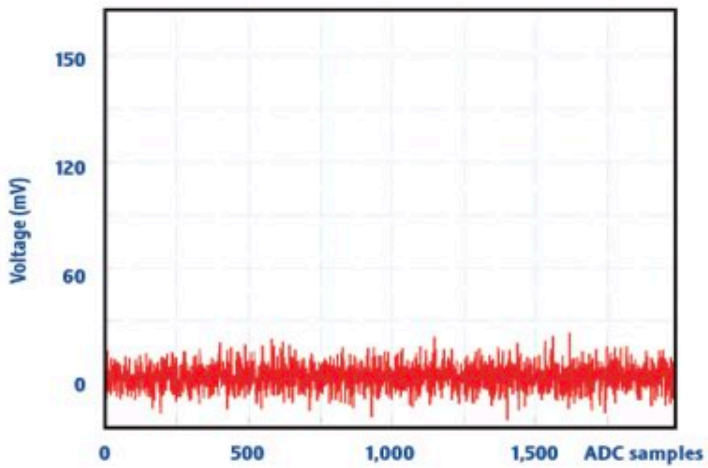
Model Based Signal Processing

Interpolation of Photon Arrival

- High resolution functional interpolation of the detection metric
- Enables time-of-arrival estimation to be limited by system SNR
- Less power in the residual signal leads to better overall performance
- Sub sample timing resolution circa 8:1 delivers <1ns timing resolution



Interpolation of the expected pulse shape

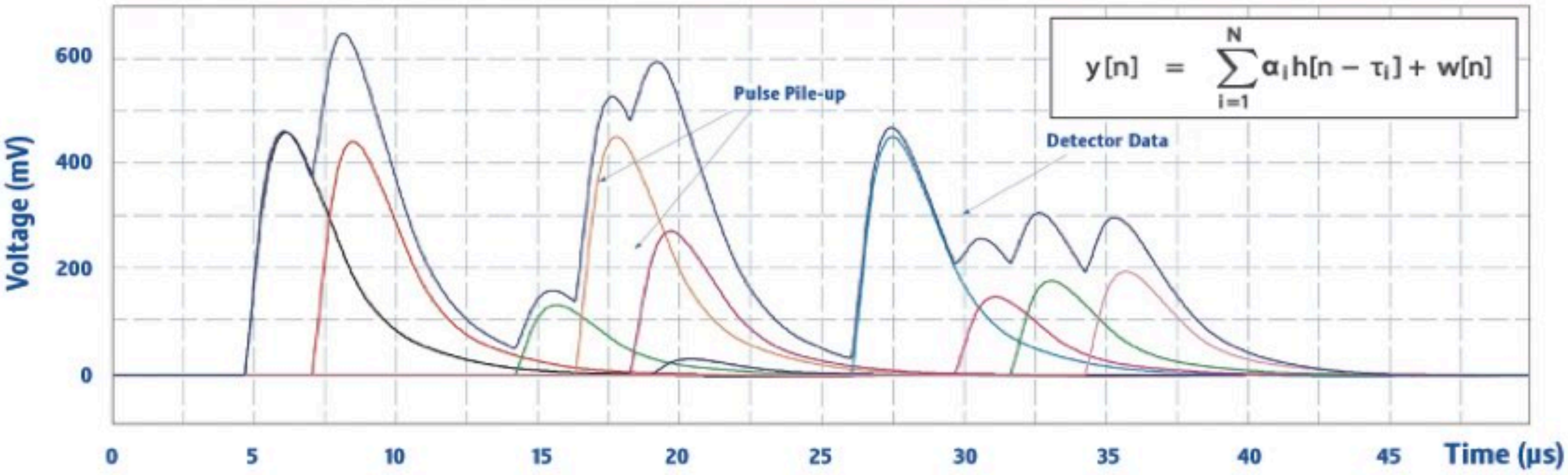


Dramatically reduced power in the residuals

Model Based Pulse Processing

We Need to Determine The Model Parameters

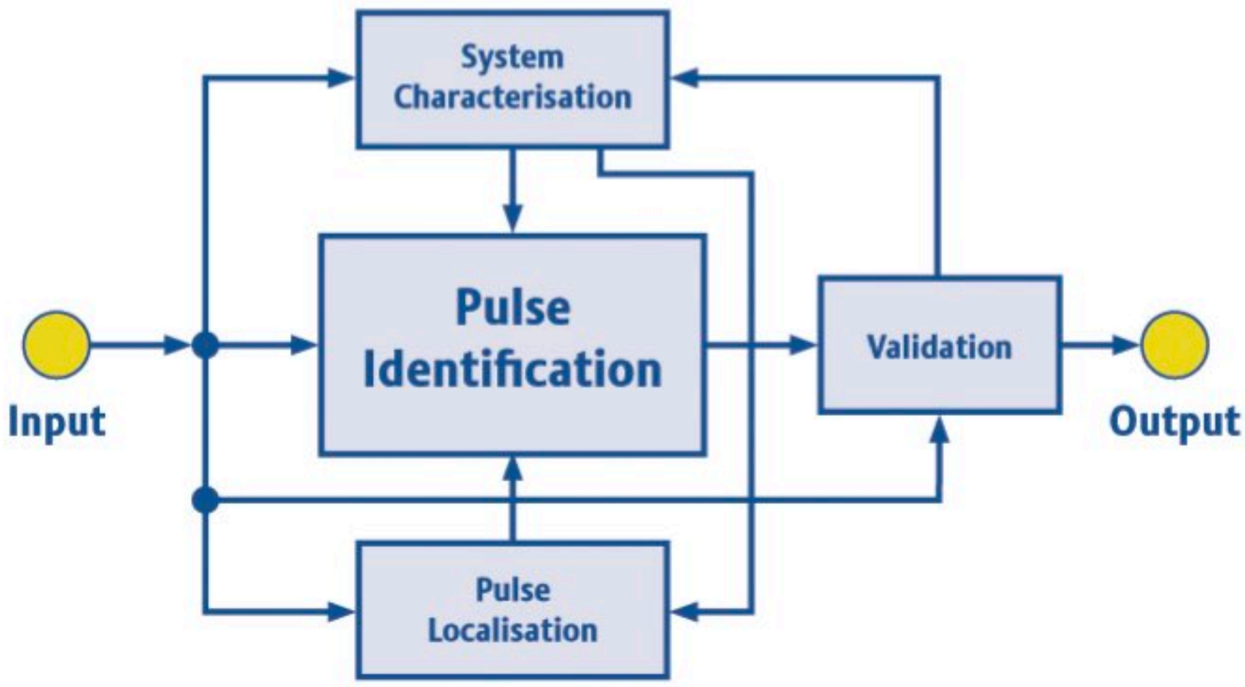
- The characteristic pulse shape produced in the detector by an X-ray;
- The number of radiation events present in the digital data;
- The relative time of arrival of each of these events; and
- Finally the energy of each of the X-ray events.



Model Based Pulse Processing

Maximum Likelihood Estimation

- Characterise the time-domain system ‘Impulse Response’
- Estimate the number and time-of-arrival of all photon events
- Solve for the energies of each photon, validate results



Model Based Pulse Processing

Maximum Likelihood Estimation of Photon Energy

- The detector data model may be written in matrix notation as

$$\mathbf{y} = \mathbf{A}\boldsymbol{\alpha} + \mathbf{w},$$

- Where the output data **y** is represented via the multiplication of a system matrix **A** by a vector of event energies **α** and additive noise **w**

- Where **A** is an m x n matrix with entries given by:

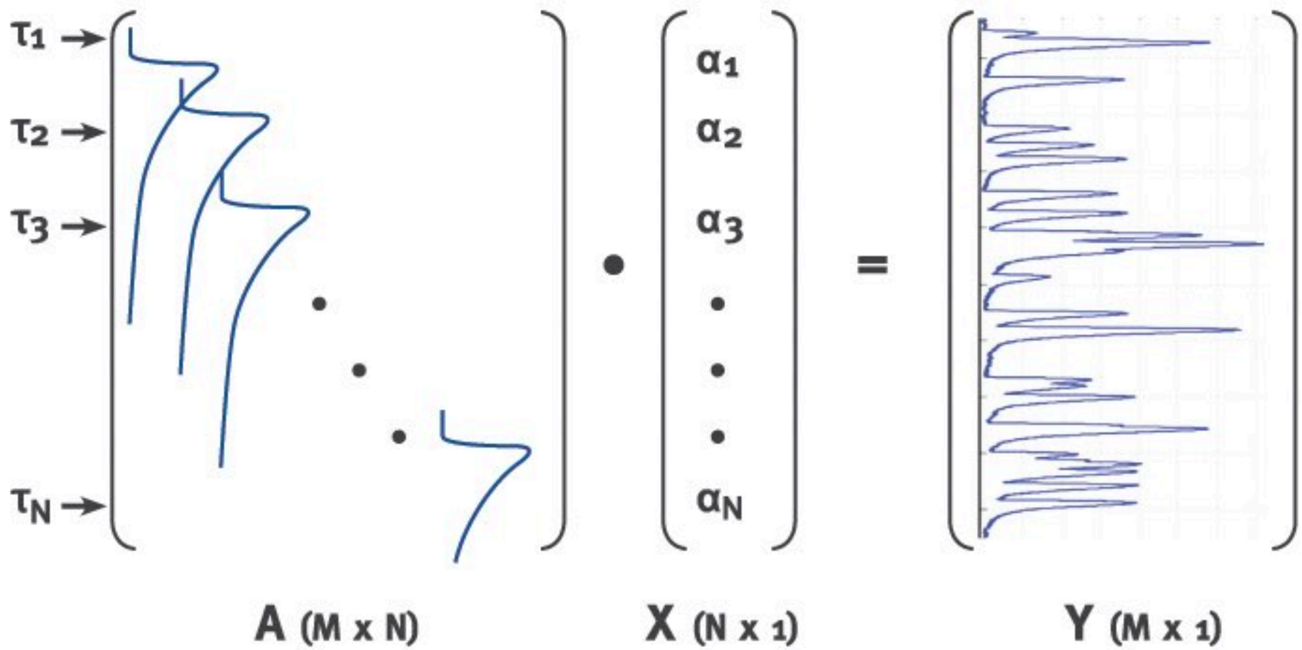
$$A(n,j) = \begin{cases} h(n - \delta_j) & \delta_j \leq n < \min(m, \delta_j + T - 1) \\ 0 & \text{otherwise} \end{cases}$$

- Create the System matrix from pulse shape h(n) and time of arrival
- Solve for all the event energies $\alpha_1, \alpha_2, \ldots, \alpha_N$
- $\alpha = (A^T A)^{-1} A^T . y$ gives the energies of all events

Model Based Pulse Processing

Estimation of Photon Energy

- Construct a system of equations using (τ, n, α) and the pulse shape
- Solve $\alpha = (A^T A)^{-1} A^T . y$ to determine the energy of all detected events



Model Based Pulse Processing

Signal Reconstruction

- Recombine the parameter estimates of shape, number, TOA & energy
- Produce a noise-free reconstruction of the detector data
- Validate the accuracy of the initial parameter estimation

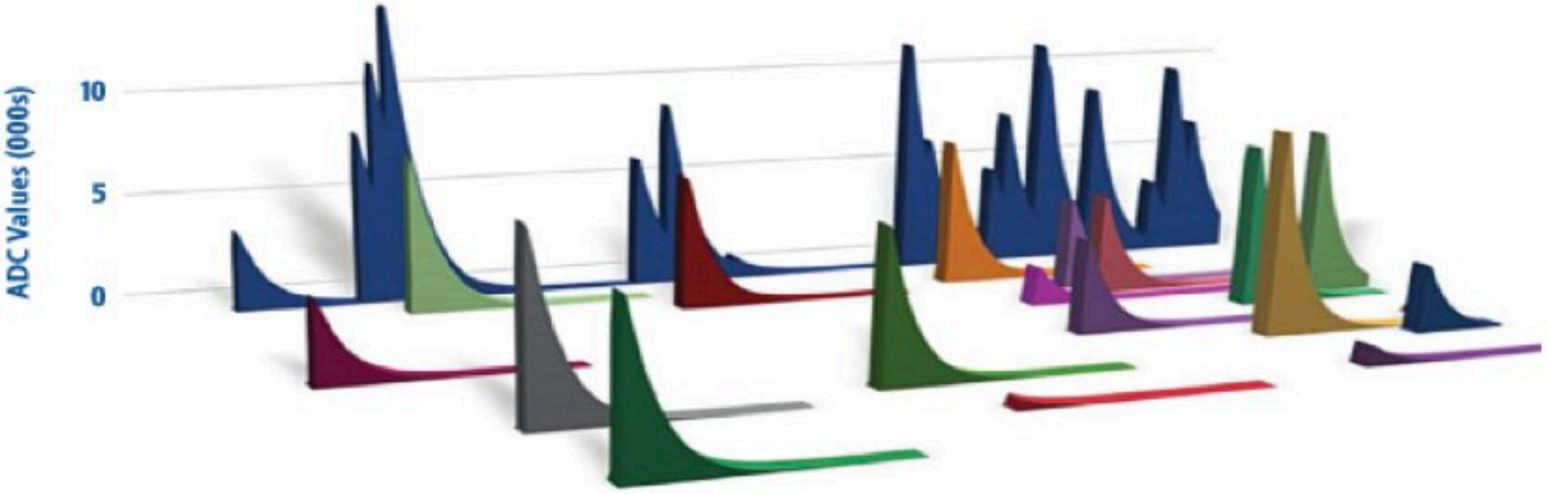
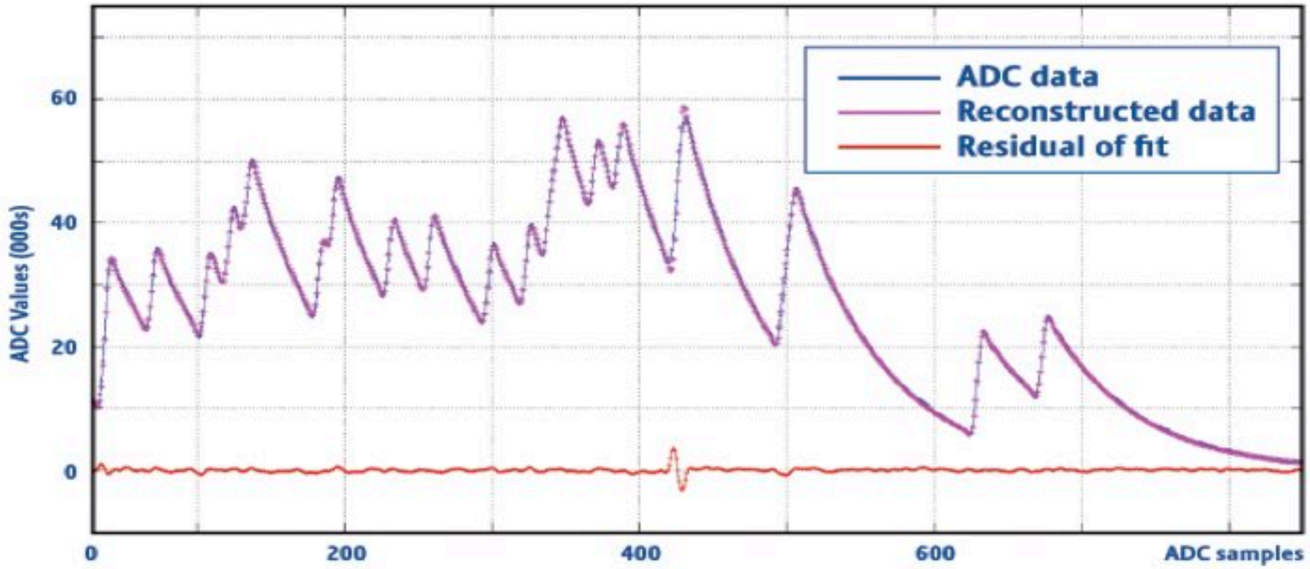


Figure depicting the reconstructed noise-free model of the digitised detector data stream

Model Based Pulse Processing

Validation of Results

- Validate the accuracy of the parameter estimation
- Reconstruct a 'noise-free' model of detector data
- Analysis of residual error reveals poor parameter estimation



A comparison of the reconstructed data with the original data reveals poor parameter estimation

Testing and Performance

Productisation Challenges

- Regular software release schedule to support customers & features
- Extensive release regression analysis & continuous integration
- Support for a range of user software environments
- Extensive 'burn-in' testing of units before shipping to customers

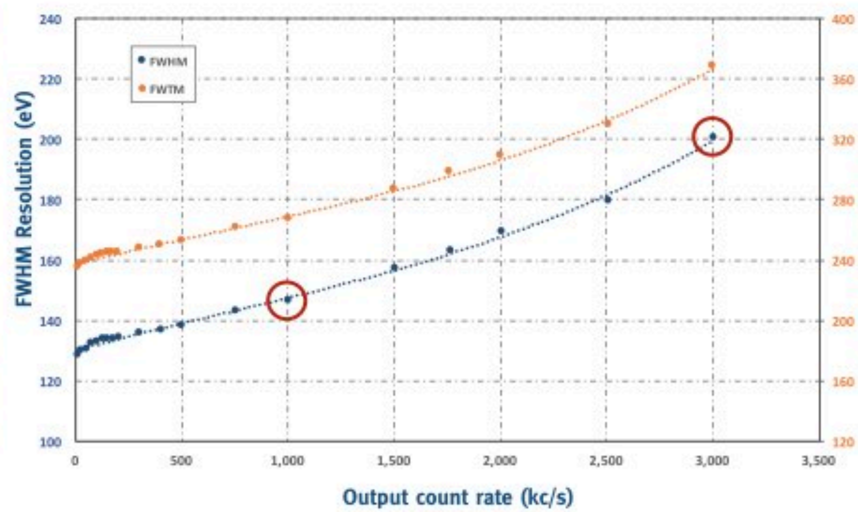
Hardware testing harness for FalconX hardware

Range of stand alone FalconX processors

Current Performance

- Resolution of circa 150 eV FWHM at output count rates › 1Mc/s
- Throughput in excess of 3 million counts per second per channel
- Full spectrum transfer rates ‹1 usec across all detector channels
- Transfer of list mode data at event rates › 2Mc/sec per channel
- Circa 150 eV at output count rates of 1 Mc/s and 200 eV at 3 Mc/s

Kv	uA	ICR	OCR	DT	FWHM	FWTM
10.0	5.0	12.2	11.5	5.7	128.4	234.7
10.0	10.0	24.0	21.5	10.5	130.0	237.0
10.0	23.0	54.4	50.1	8.0	130.5	238.6
10.0	36.0	82.8	75.6	8.7	132.2	240.4
10.0	47.0	110.9	100.1	9.7	132.6	242.7
10.0	59.0	139.3	125.5	9.9	133.7	243.2
10.0	71.0	167.6	150.9	10.0	133.9	244.0
10.0	100.0	198.5	175.4	11.6	133.6	244.1
11.0	59.0	225.6	200.2	11.2	134.5	244.8
20.0	10.0	339.5	300.2	11.6	135.7	247.3
20.0	14.0	473.1	400.3	15.4	136.5	249.4
20.0	18.0	606.9	500.7	17.5	138.3	252.0
20.0	28.0	948.5	753.8	20.6	143.0	260.7
20.0	40.0	1,365.0	1,004.0	26.4	146.4	267.2
20.0	70.0	2,429.0	1,500.0	38.2	157.0	286.0
25.0	52.0	3,151.0	1,762.0	44.1	162.9	297.5
25.0	61.0	3,713.0	2,005.0	46.0	169.2	308.7
40.0	35.0	4,748.0	2,508.0	47.2	179.3	328.6
40.0	45.0	6,064.0	3,000.0	50.5	200.3	368.0



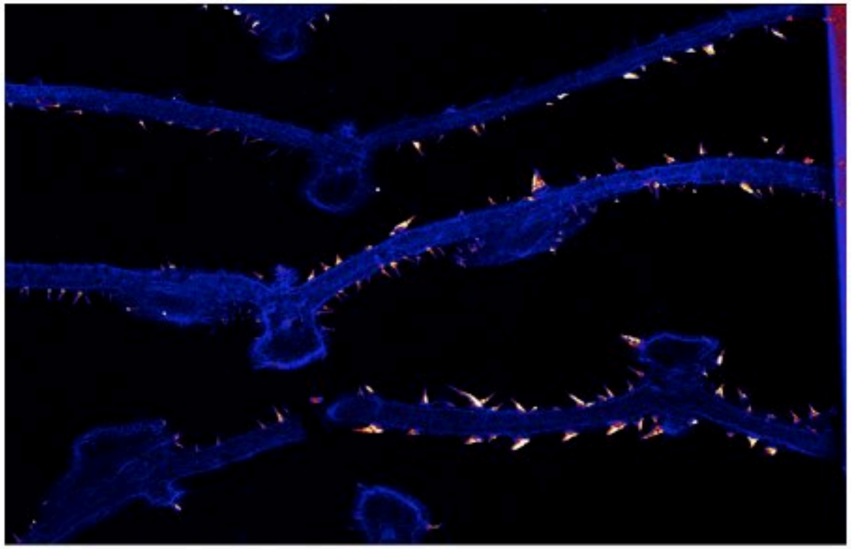
Various performance metrics of the FalconX digital pulse processor across a range of input count rates.

Applications

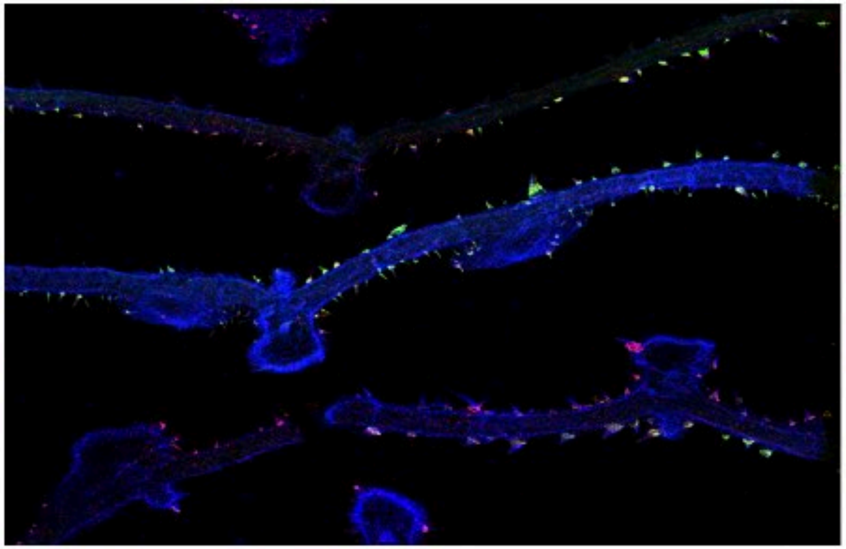
Photon Instrumentation

Use at the Australian Synchrotron

- Single element vortex detector at the XFM beamline of the Aus. Sync.
- Measurement time approximately 4 hours, raw data volume ~5.6 GB
- Resolution of 5 x 5 μm^2 pixels over 7.7 x 6.3 mm^2 ~1.94 Mega pixels



Freeze dried leaves with Ni, Ca & K in the trichomes

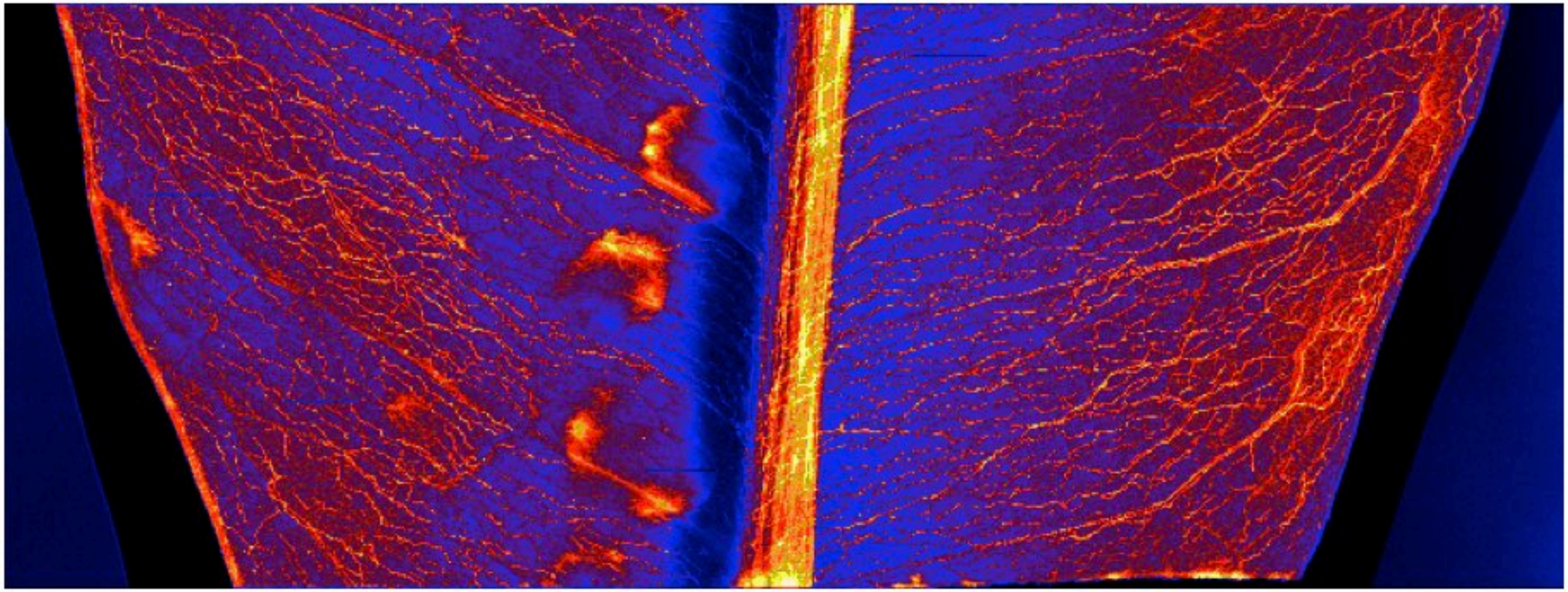


Freeze dried leaves with Mn, Zn & K in the trichomes

Photon Instrumentation

Use at the Australian Synchrotron

- Freeze dried whole leaf 25 µm pixels, 36.5 x 36 mm 2.1 Mega pixels
- Measurement time 2 hrs 50 mins using a pixel dwell time < 5us
- Analysis performed using GeoPIXE fed list mode data from FalconX



Energy dispersive X-ray analysis of a freeze dried leaf highlighting the distribution of Ni, Ca and K

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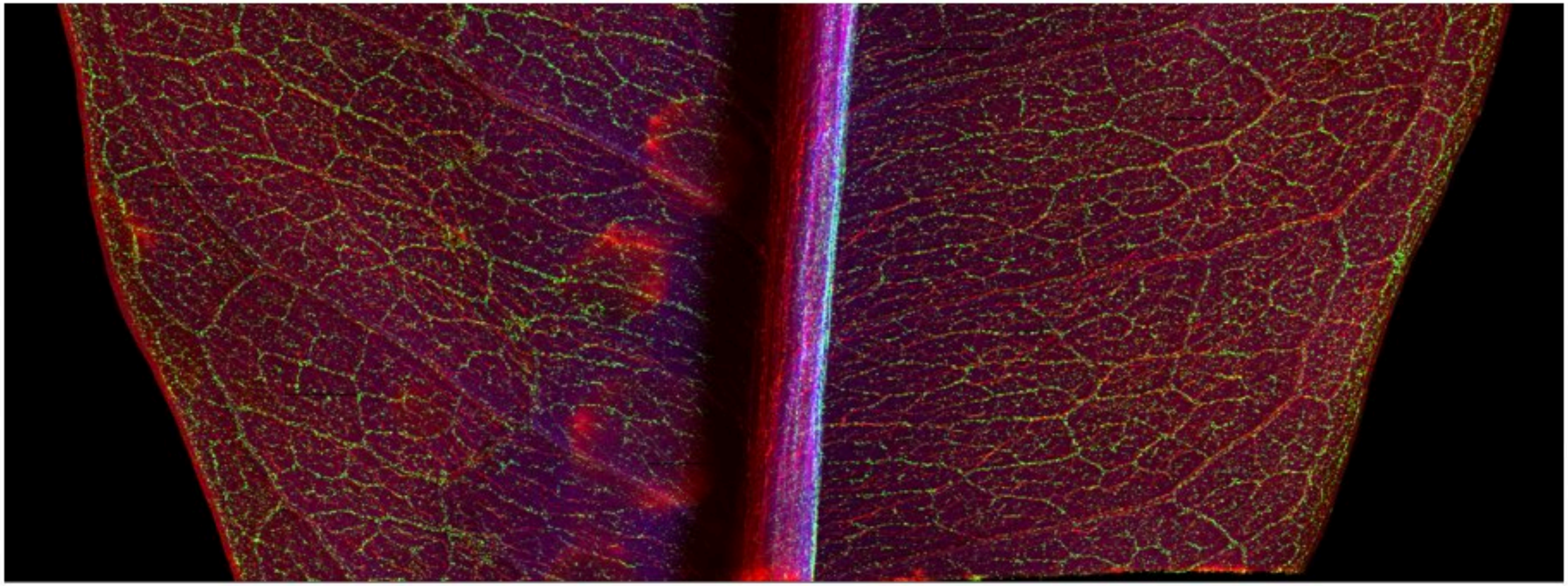
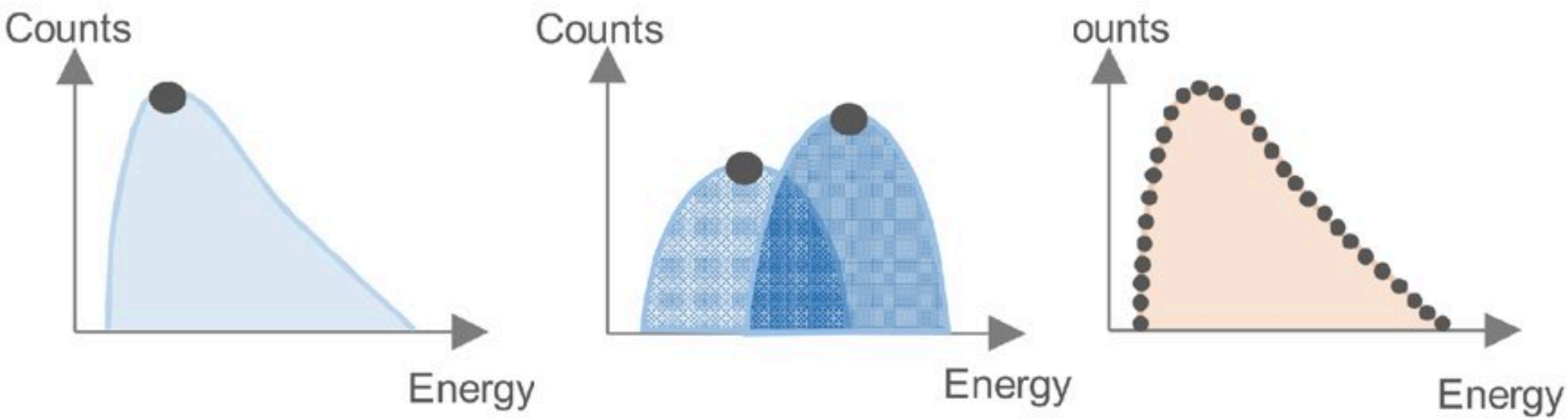


Energy dispersive X-ray analysis of a freeze dried leaf highlighting the distribution of Mn, Zn and K

Industrial Applications

X-ray Transmission

Multi Energy X-ray Transmission Spectroscopy

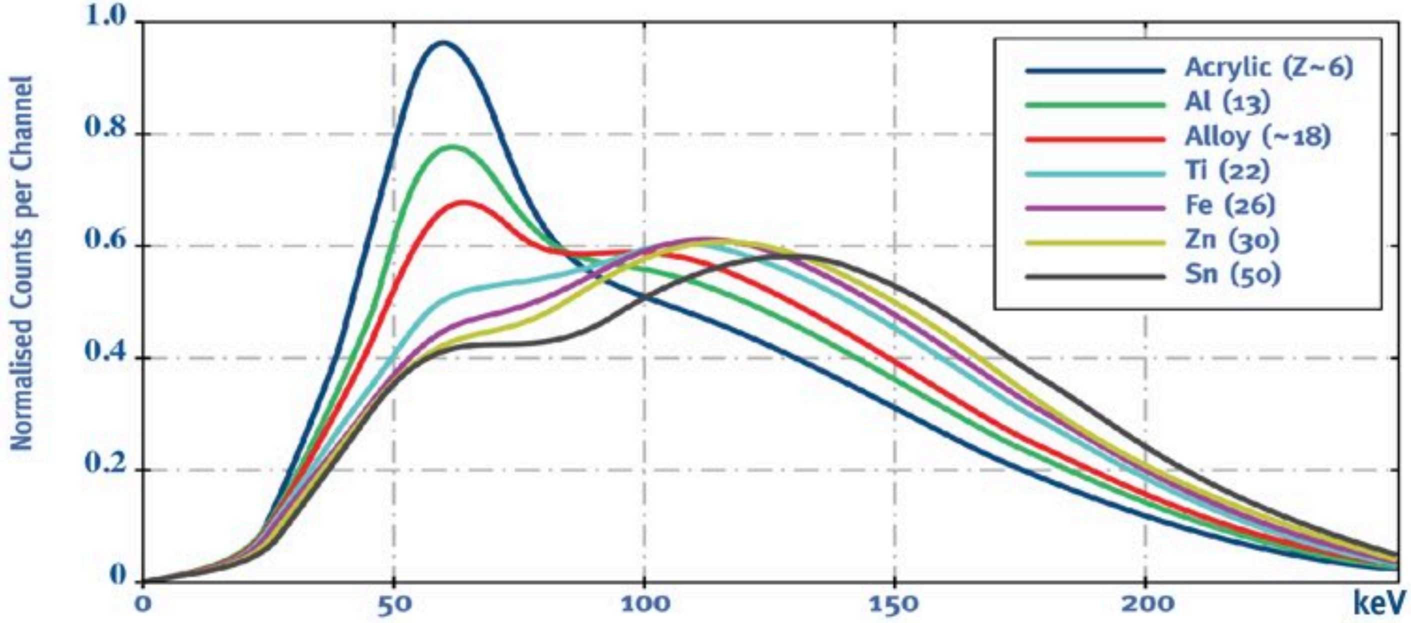


1. Single estimate of X-ray photon flux = grey scale image of structure
2. Dual energy estimates of photon flux = discrimination of organics / metals
3. Energy resolved photon counting = very accurate material discrimination

Full Spectrum Effective-Z

Absorption Spectra for a number of Materials

- X-rays transmitted from a 300 keV polychromatic X-ray generator
- The absorption of X-ray varies with material of different effective-Z
- Accurate characterisation of materials to ±0.1 effective-Z

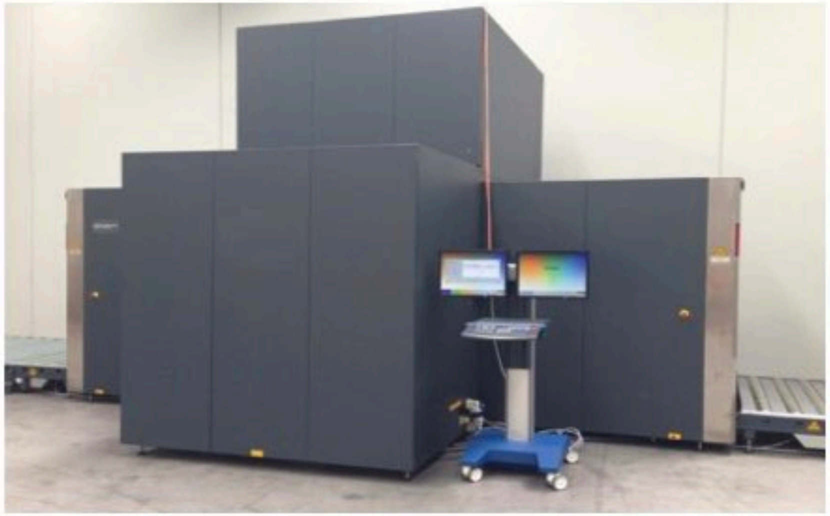


Absorption energy spectra of a range of materials across a broad range of Effective-Z

Freight and Logistics

Aviation Security

- Retrofit detectors and processing to a 1.8 x 1.8 meter air cargo scanner
- Two L-shaped detector arrays for a top-view and side-view of cargo
- X-ray generators produce a 'fan-beam' of photons up to 300 keV



Smiths air cargo scanner X-ray scanner 300 keV

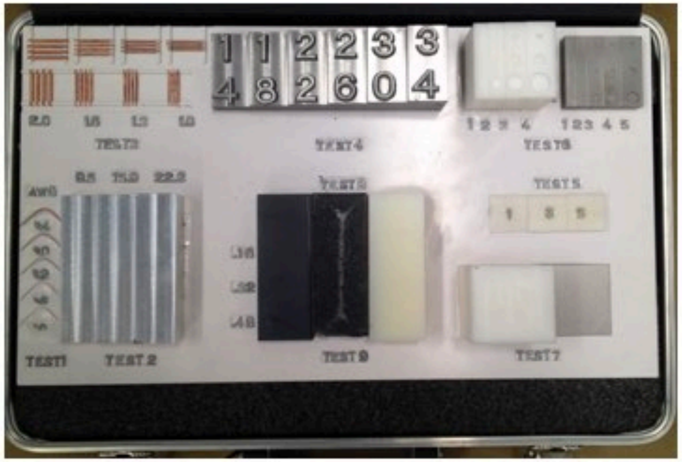
Retrofitting of energy dispersive X-ray detectors

Freight and Logistics

Aviation Security Standards

- ATSM standard for evaluating the performance of X-ray scanners
- Tests for steel penetration, spatial resolution & wire detection
- Material discrimination of organics Vs inorganic and contrast

Conventional X-ray scanner test briefcase

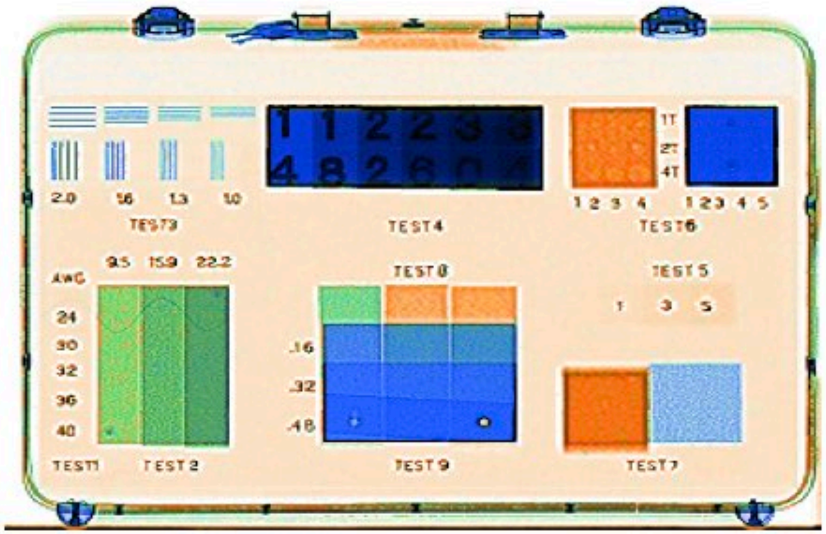


Photograph of the various ATSM test objects

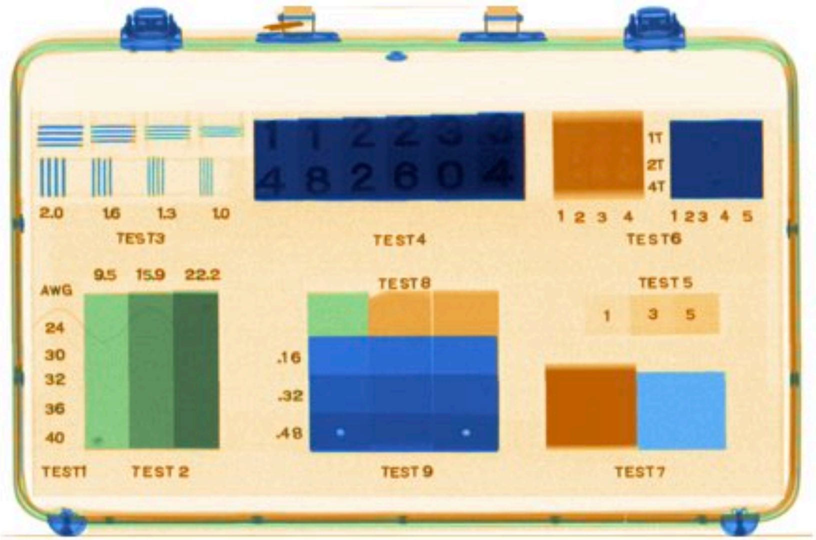
Freight and Logistics

Multi Energy Vs Dual Energy

State-of-the-art air cargo image of ATSM briefcase



Southern Innovation's image of the ATSM briefcase

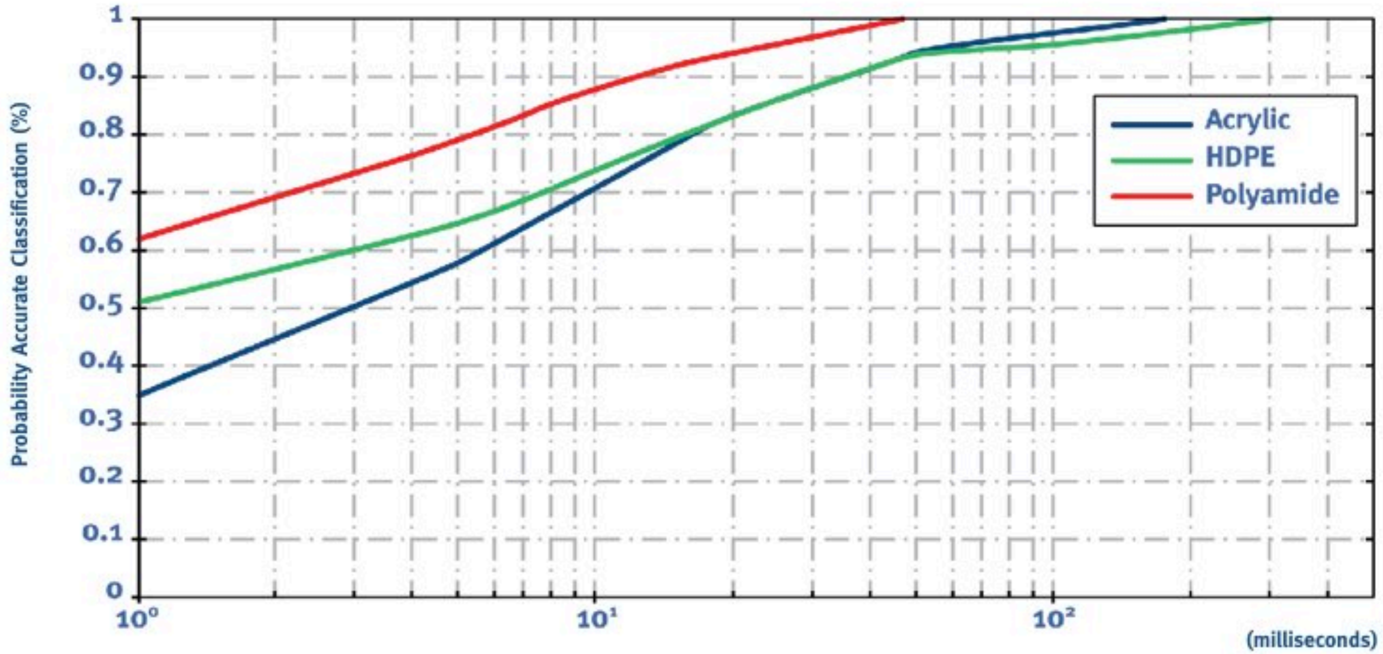


- Poor resolution of text & wire
- Steel penetration circa 30 mm
- Patchy colours, heavy processing

- Superior resolution of text & wire
- High steel penetration › 50 mm
- Crisp image with consistent colour

Discrimination of Organic Material

- May contraband material are classified organic i.e. drugs & explosive
- Utilising differential absorption across the full spectrum of X-ray energy
- Rapid discrimination of material even when Z^{eff} separation is small $\pm$ 0.1

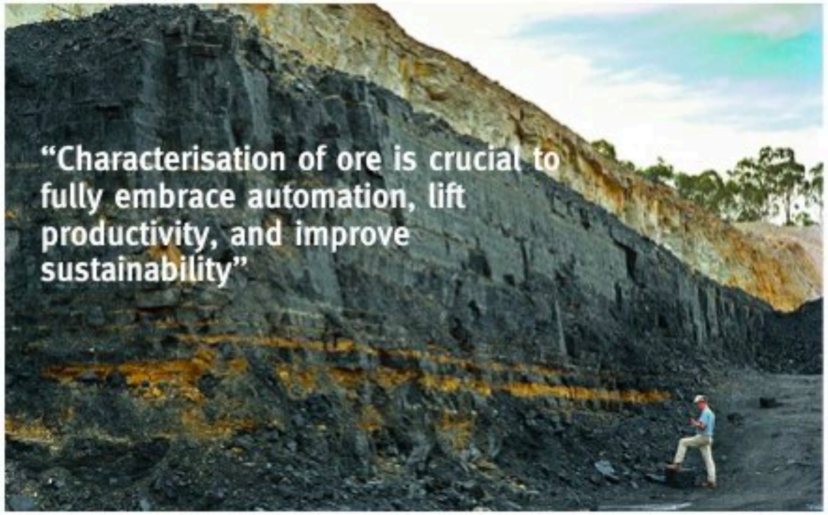


Industrial Applications

Mining Coal

Coal Handling and Processing Plant

- Caval Ridge is $2 billion CHPP, throughput ~10 Mt/a hard coking coal
- Run-of-mine coal at 2,390 t/hr, speed 3 m/s and bed depth 390 mm
- Feedback control to improve plant efficiency currently around 50%



Strip mining a coal seam, contamination evident

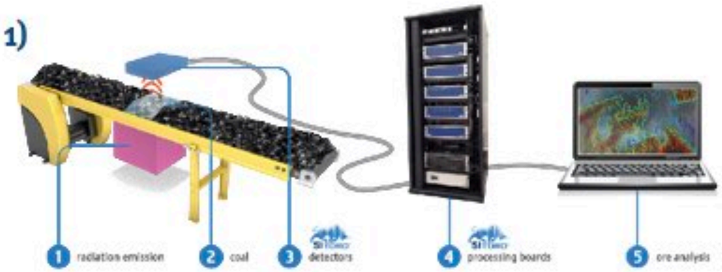
The Caval Ridge coal handling and preparation plant

Mining Coal

Real-time Monitoring and Feedback

- Sulphides in coal (Cu & Fe) dramatically increase the Z^{eff} of waste
- Real-time feedback control monitoring the ‘reject’ coal belt
- Potential for grade engineering via real-time diversion of high grade ore

1)



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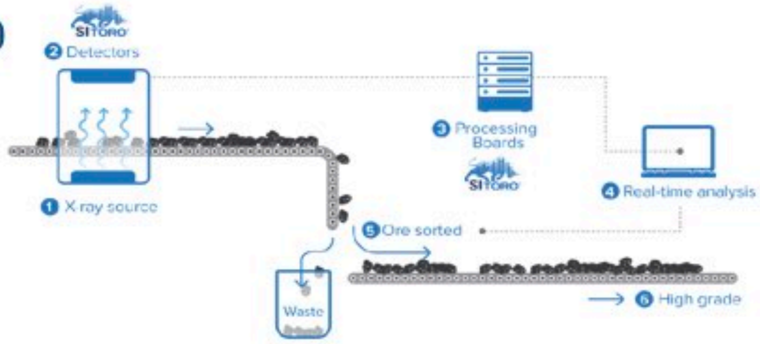


Transmission of X-rays through coal & processing

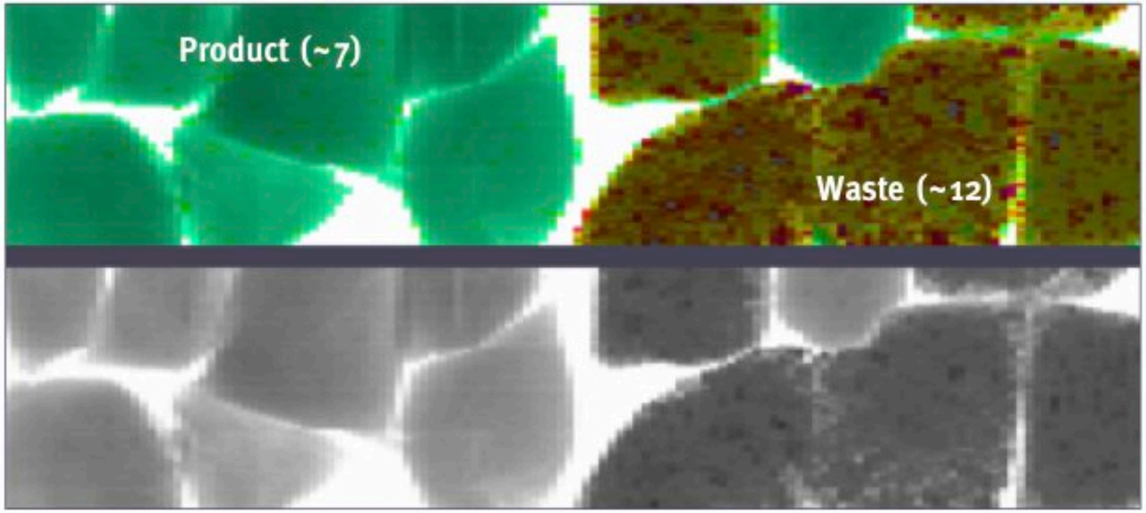
Monitoring of waste belt or diversion of high grade ore

Mining Coal

GradeScan On-Belt Analyser

- Polychromatic X-ray generator 300 keV and 500 uA
- Linear array of 239 scintillation/SiPM detectors 2.5 x 2.5 mm resolution
- Photon flux greater than 2 Mc/s per detector, system total >500 Mc/s

GradeScan Analyser

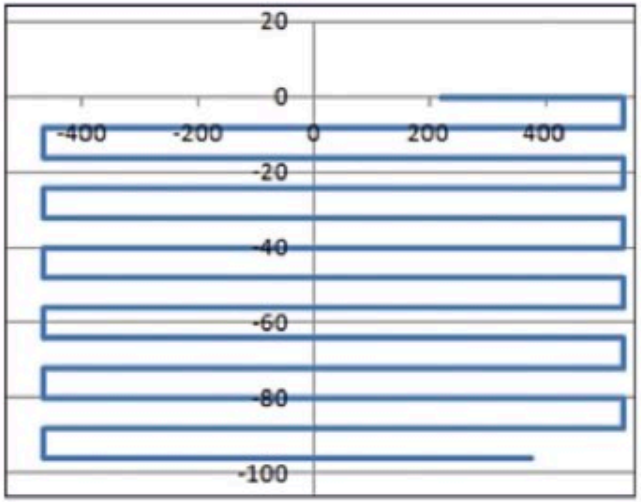


Real-time (50ms) imaging of the effective-Z and structure of coal

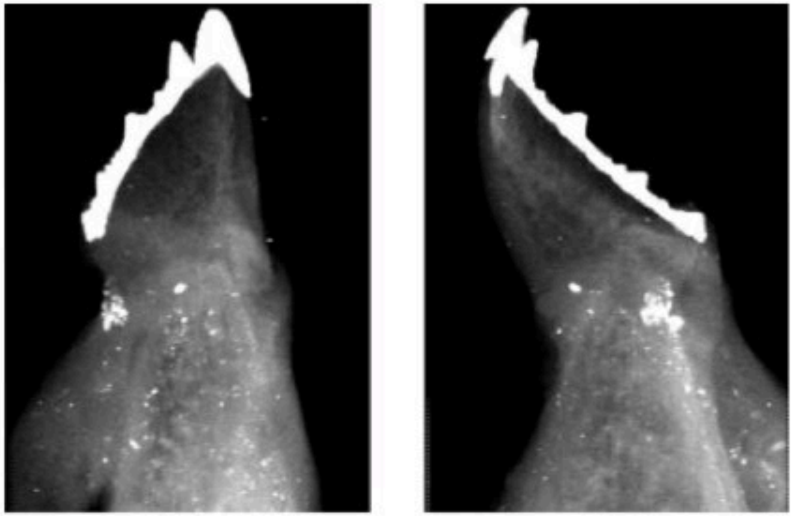
Status Quo - State of the Art

DPP for Energy Dispersive X-ray Instrumentation

- The 'step & collect' approach enabled dwell periods < 1 sec
- New 'on the fly' approaches to scanning enable dwell < 10 ms
- High rate digital pulse processing enables circa 2-3 mc/s throughput
- 5,000 - 20,000 photons per pixel depending on desired SNR



Continuous 'on the fly' mapping in the X & Y axis



Pixel movement & rotation encoded into list mode data

What Next

Incremental Improvements

- Tighter integration into the beam-line environment
- List-mode or Spectral data files with embedded data
- Continuing trend towards multi-element detectors
- Further improvement in ICR and throughput performance
- Is there potential for 180 eV at 3 Mc/s or 200 eV at 4 Mc/s
  - Analogue pulse processing ~ 10 kc/s
  - Digital pulse processing ~ 100 kc/s
  - Model based pulse processing ~ 1,000 kc/s
  - Stochastic pulse processing ??? ~ 10,0000 kc/s

Thank you

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