Design and performance of the X-123 compact X-ray and Gamma-ray spectroscopy system

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This Web presentation is an extended version of the paper presented at the 2006 Room Temperature Semiconductor Detector Workshop, at the IEEE Nuclear Science Symposium

Outline

Design

- System
- Detector and preamp
- Digital processor
- Power supplies & packaging

Performance

- Resolution
- High Count Rates
- Stability
- Spectroscopy

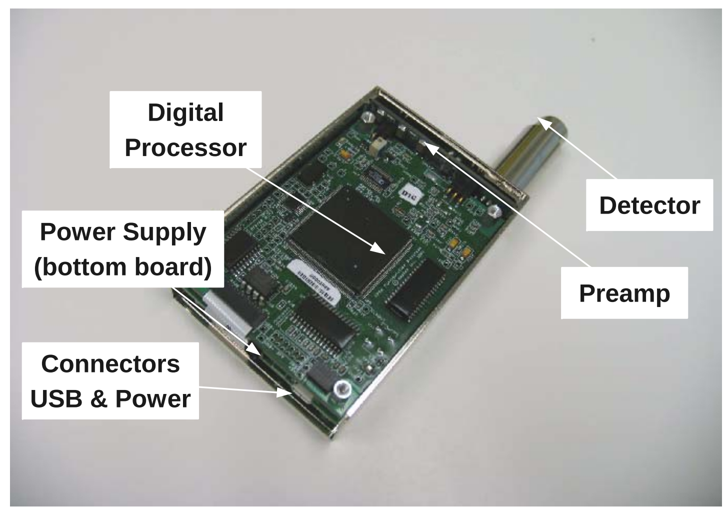
Applications

X123 Design

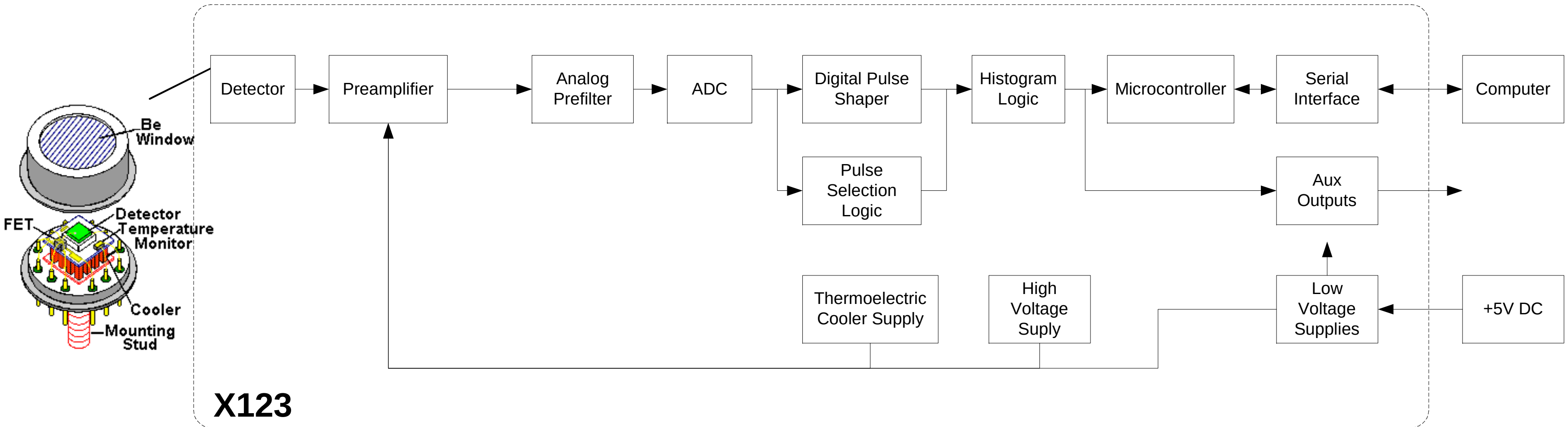
Compact integrated system

- Detector and preamplifier
  - Detector thermoelectrically cooled
- Digital pulse processor with shaping amplifier and MCA
- All power supplies

- Small size
  - 7 x 10 x 2.5 cm^3 (2.7 x 3.9 x 1 in^3)
- Low power (1.2W)
- Light weight (180 g or 6.3 oz)
- Simple to operate
  - USB communications
  - +5VDC



X123 Design



Block diagram of X123 (and related systems)

- Complete spectroscopy system: detector, preamp, digital processor (with shaping, MCA, and logic), comm ports, power supplies, packaging
- Same building blocks as Amptek's DP4 and PX4

  Animation shows relationship between Amptek's digital processing products
- Detector options include Si-PIN, CdTe, and CdTe-stack

X123 Design

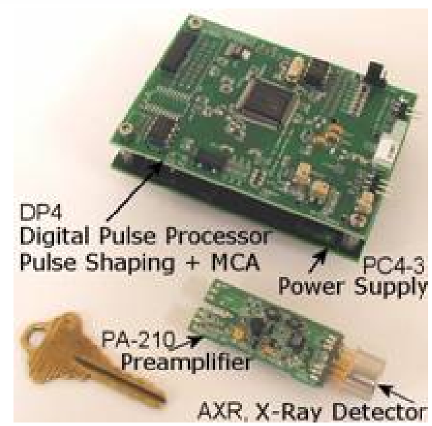
X123, PX4, DP4

- All are complete spectroscopy systems
- All share detectors, digital processing, other core technologies
- Targeted at different applications

X123 for compact, packaged system

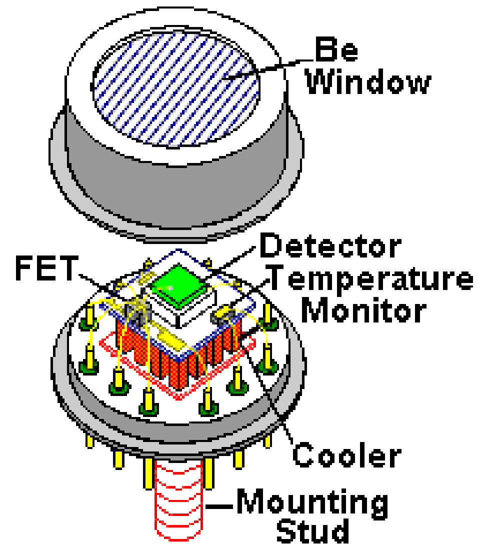
PX4 and XR100 for benchtop & laboratory

DP4 and PA210 for embedding in instruments



X123 Detectors

Thermoelectrically Cooled Solid State Detector

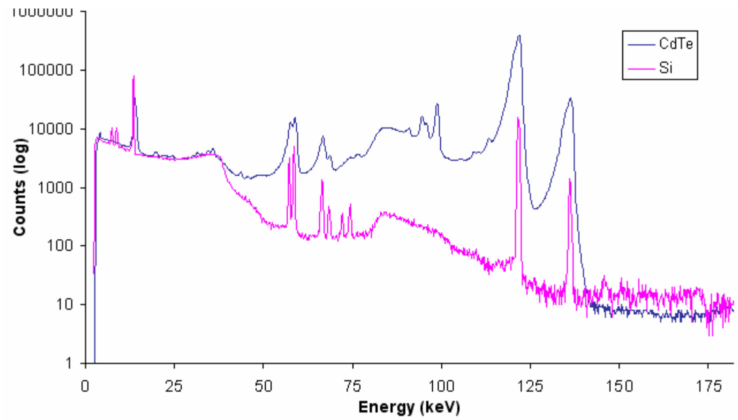


- Reasons for thermoelectric cooling
  - Reduces shot noise and thermal noise
  - For CdTe, allows higher bias
  - Cooling invisible to user
- Cooler achieves >80˚C differential
  - Now using 2 stage coolers in all products
  - 215K for lab use
  - 240K for field use (at ambient of 45˚C)
- FET and feedback components on cooler
  - Leakage currents as low as 5 fA
  - Low stray capacitance, reduced EMI pickup

X123 Detectors

Three detectors for different energy ranges

- Low energies (X-rays)
  - Si-PIN detector
  - Recommended from 1.5 to 25-40 keV
  - Resolution: 150 eV FWHM at 5.9 keV
- Medium energies
  - CdTe diode
  - Recommended from 25-40 to 100 keV
  - Resolution: 600 eV FWHM at 59.5 keV
- Gamma-Rays
  - CdTe diode stack
  - Recommended from 100 to 600 keV
  - Resolution: 6 keV at 662 keV
- All based on thermoelectric cooling
- All are compatible with X123



Plot compares a ^{57}Co spectrum from Si-PIN and CdTe detectors: the Si-PIN has much better resolution but above 30 keV much lower sensitivity.

X123 Detectors

Low energy X-rays

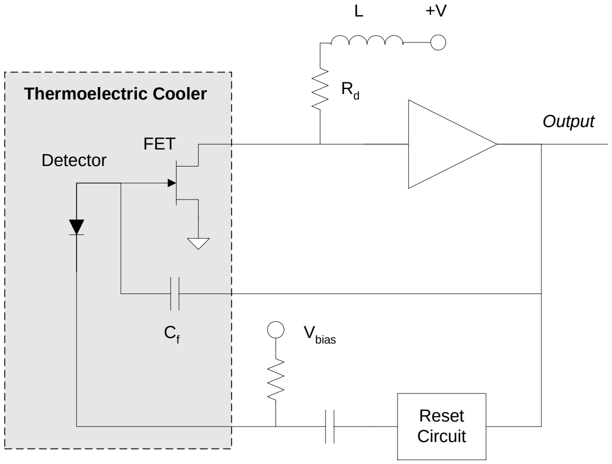
- Detector : Si-PIN
- Thickness: 200 to 1000 μm
- Area: 5 to 25 mm^2
- Feedback: Capacitive reset into the HV node
- Be window: 0.5 to 4 mil
- Internal multilayer collimator

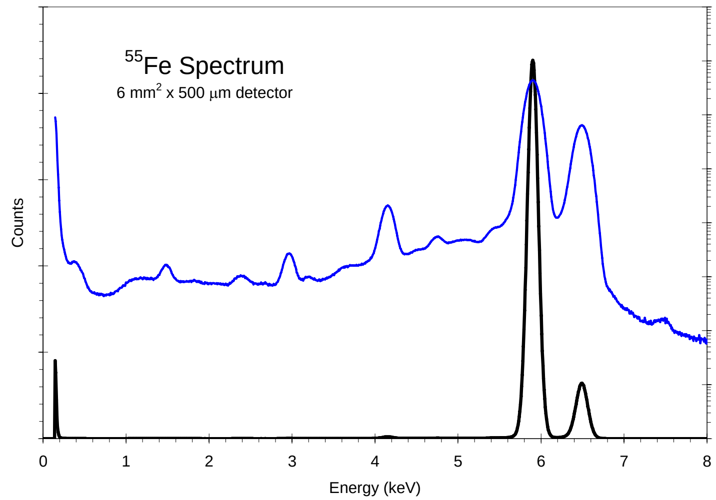
  Prevents interactions near guard rings

- Best resolution 149 eV FWHM

  ENC = 100 eV FWHM ⇒ 12 electron rms

  Measured with 6 mm^2 x 500 μm detector at 215K and 20 μsec shaping time

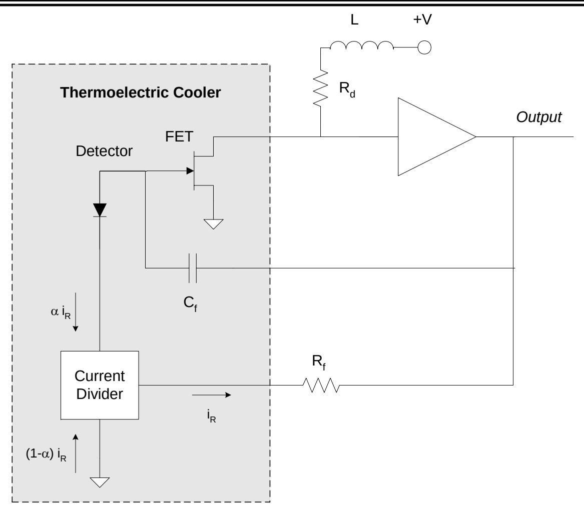




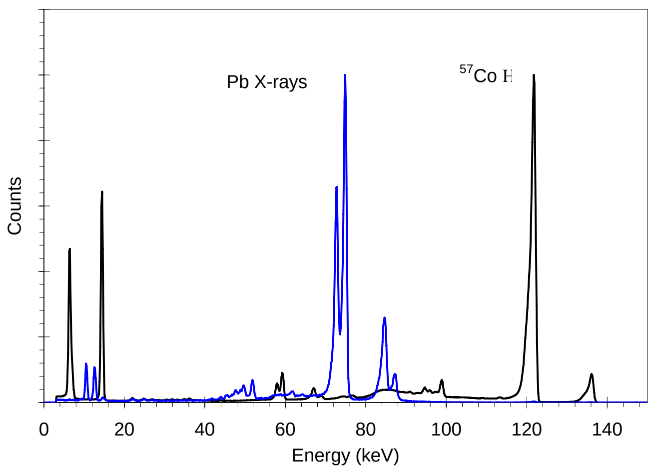
X123 Detectors

Med energy X-rays

- Detector : CdTe Schottky diode
- Thickness: 750 to 1000 μm
- Area: 9 to 25 mm^2
- Feedback: Current divider
- Bias: 300 to 1000V



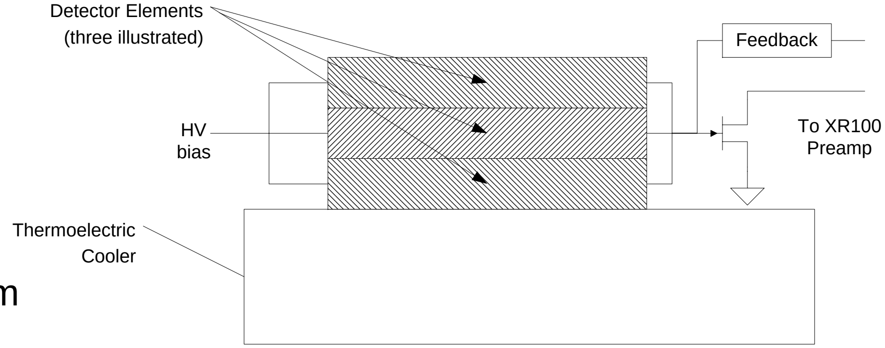
- Photofraction >90% to 80 keV
- Resolution
  - ENC as low as 500 eV FWHM
  - 750 ev FWHM at 59.5 keV
  - 1200 eV FWHM at 122 keV



X123 Detectors

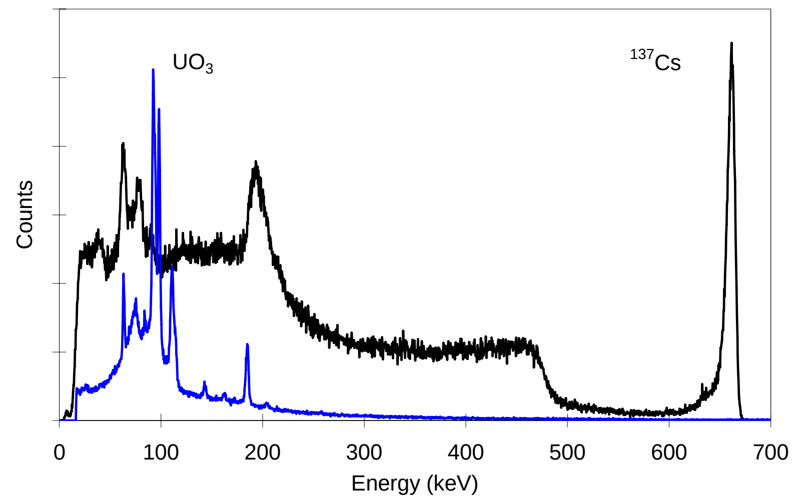
Gamma-rays

- Detector : CdTe stack
  - Multiple planar elements
  - Summed into single preamp
  - Sensitivity arises from entire volume
  - Max charge transport length 0.75 mm
  - Operates like single detector

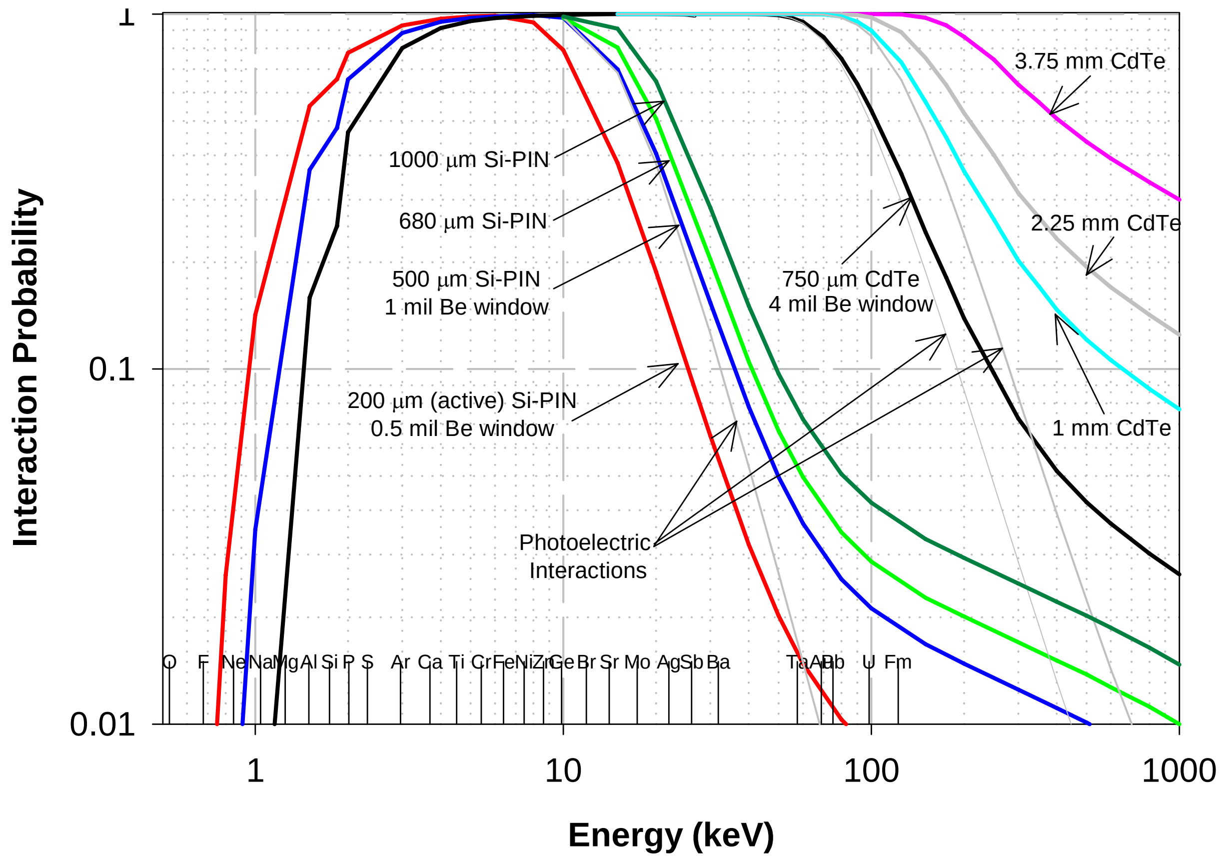


- Thickness: 2.25 or 3.75 mm
- Area: 25 mm^2
- Feedback: Resistive
- Bias: 1 to 1.4 kV

<1% FWHM at 662 keV



X123 Detectors



Plot compares intrinsic efficiency of the detectors. At low energies, the Be window limits sensitivy. The Si-PIN have good efficiency to 30 keV, CdTe to 100 keV, and the CdTe-stack to 500 keV.

X123 Detectors

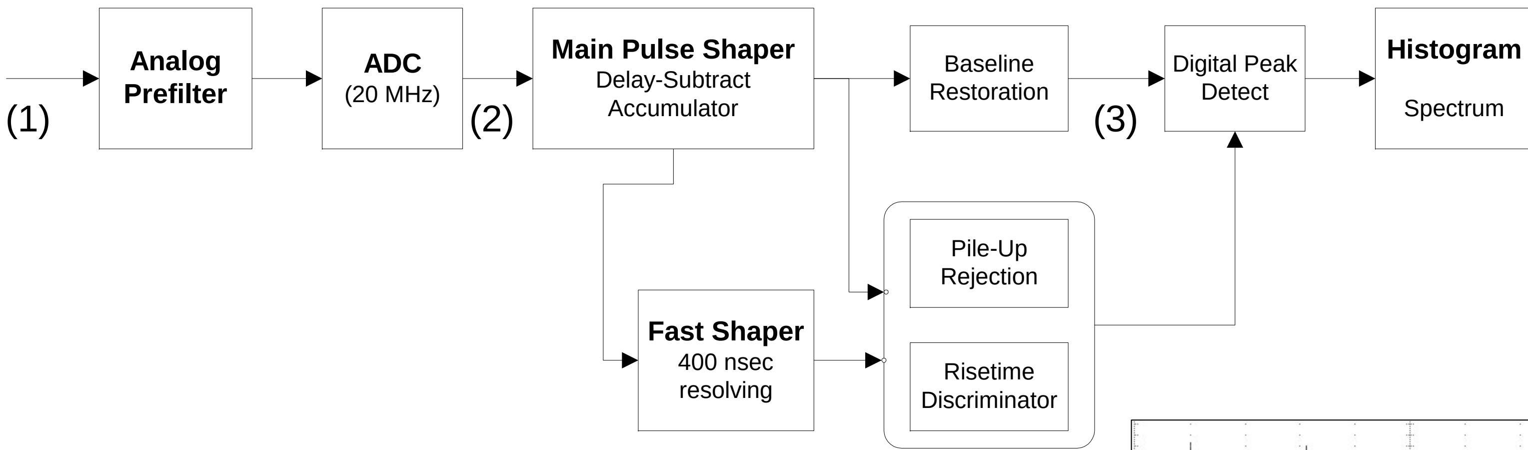
Recent Detector Developments

- Cooler achieves >80˚C differential
  - 2 stage coolers in all products
  - 215K for lab use, 240K for field use (at ambient of 45˚C)
- Thicker active depth for Si-PIN
  - 1000 μm, fully depleted, with areas of 7 and 25 mm^2
  - Resolution 185 eV FWHM
- Si-PIN with internal multilayer collimator
  - Collimator prevents interactions near guard rings and outer edge
  - Multilayer design prevents characteristic X-rays contaminating signal

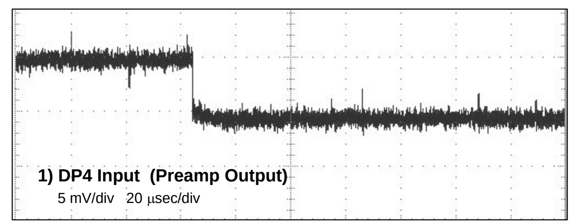
Work in Progress

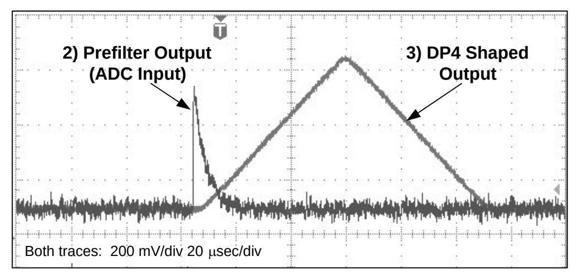
- Si drift diodes
  - Will increase count rates to reduce measurement time
- Reset preamp for CdTe
  - Will combine lowest noise with good count rate stability

Digital Pulse Processor



- Preamp output digitized
  12 bit, 20 MHz ADC
- Pulse shaped digitally
  FPGA pipeline logic
- Integrated MCA & pulse selection logic
- Same core on DP4, PX4, and X123





Digital Pulse Processor

Advantages of digital processing

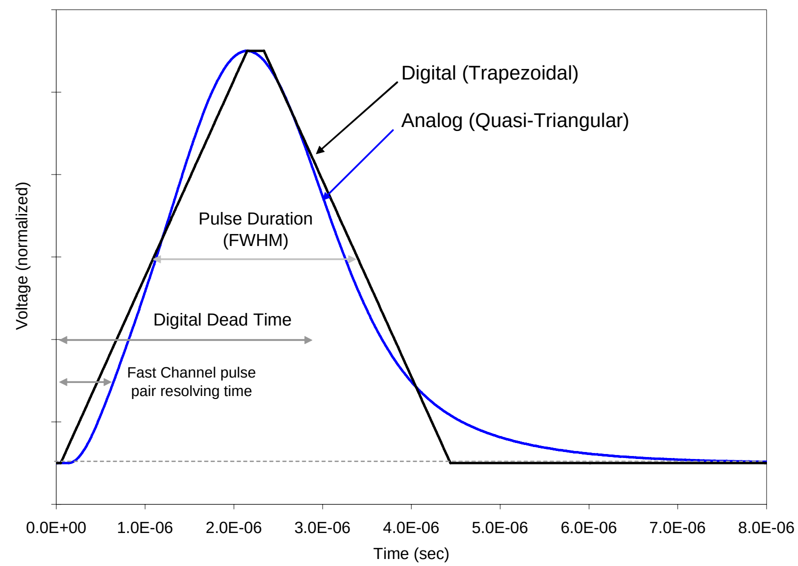
- Flexible
  - Many shaping times: 24 log steps from 0.8 to 102 μsec peaking
  - Adjustable settings for BLR, RTD, etc
  - All adjustments are in s/w, via serial connection
- Faster than analog
  - No dead time for pulse digitization
  - Finite Impulse Response improves baseline stability
  - Symmetric shape enhances throughput
- Pulse shape closer to optimum for signal to noise
- Improved stability and reproducibility

Digital Pulse Processor

Trapezoidal Pulse Shape

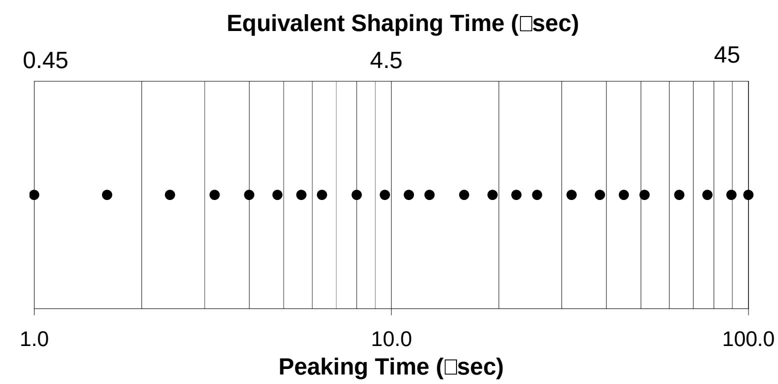
- No long tail so reduced pile-up
- Finite impulse response reduces baseline shifts
- Symmetry reduces PUR interval

  Dead time 1.25 $\tau_{peak}+\tau_{flat}$
- Improved ENC for same pulse duration (FWHM)



Fast Channel

- 600 nsec resolving time
- Used for
  - Pile-up rejection,
  - Risetime discrimination
  - Measurement of incoming count rate



Digital Pulse Processor

Digital processing features

- Gain
  - Coarse gain range x11 to x110 (4 ranges)
    PX4 has larger coarse gain range, fully overlapping
  - Fine gain range 0.75 to 1.25, 10 bit resolution
  - All gain changes software selectable over serial bus
- System Conversion Gain
  - For Si-PIN at 1k channels, 7 to 110 eV/channel $\Rightarrow$ 7 to 110 keV full scale
  - For CdTe, 20 to 310 eV/channel $\Rightarrow$ 20 to 310 keV full scale
  - For CdTe stack, 50 to 3100 eV/channel $\Rightarrow$ 50 to 3100 keV full scale
- Baseline Restoration
  - Asymmetric algorithm stabilizes negative noise peaks
  - Software selectable parameters (64 settings) to tune for application

Digital Pulse Processor

MultiChannel Analyzer Features

– MCA Performance

- Commandable to 256, 512, 1024, 2048, 4096k, 8192 channels.
- 3 bytes (24 bits) per channel - 16.7M counts
- Minimum Acquisition Time < 10 msec
- Data transfer time for 1k channels in 10 msec (USB) or 500 msec (RS-232)
- Conversion time: None, part of digital pipeline

– Acquisition Modes

- Standard MCA Mode: Integrated pulse height spectrum
- Delta Mode: Pulse height spectrum from most recent 1 sec acquisition
- Repetitive Mode: After each acquisition, saves data to file and then restarts.
- MCS Mode: Each channel has number of counts in a time bin, >10 msec per bin

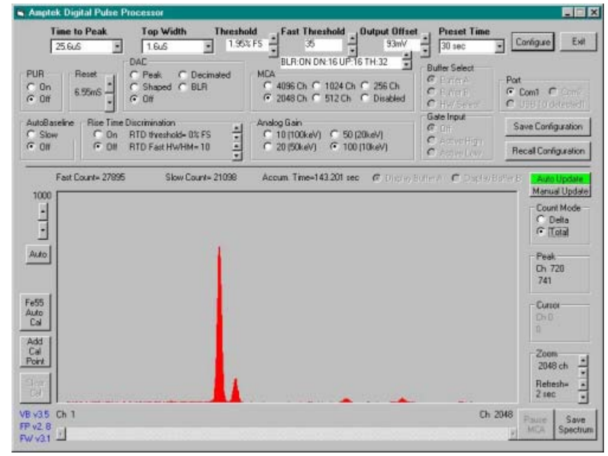
– Other features

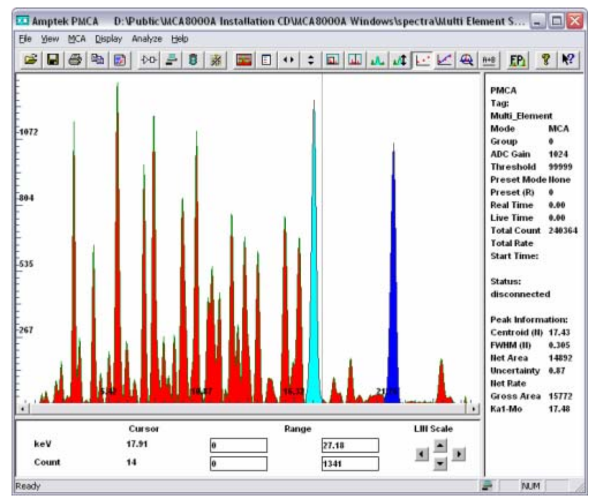
- Presets: Time, total counts, counts in an ROI, counts in a channel
- External controls: Gate and buffer select inputs

Digital Pulse Processor

Command and Control

- Software control over serial interfaces
  - Sends commands, starts and stops acquisition
  - Reads out and displays spectra and count rates
- Protocols supported
  - RS232 and USB standard
  - Can be tailored for Ethernet
  - I^2C and μP pins for direct h/w interfaces
- Software
  - Amptek's standard ADMCA software for data acquisition and control
  - Interface to with analysis packages (XRF-FP available from Amptek)
  - Library (DLL) of drivers for custom software





Digital Pulse Processor

X123 Outputs

- Primary output is the spectrum
  - Packet of spectral data
  - Typically 1k or 2k channels, updated 1 Hz
- Secondary output is oscilloscope display
  - Captured waveform sent over serial interface
  - Computer displays waveform, for setup and debugging
- Other outputs available on digital processor board
  - Standard outputs on DP4, PX4. X123 requires custom connector
  - Analog outputs: shaped pulse, ADC input, fast pulse, test pulser
  - Digital outputs: Timing trigger, reset flag, pile-up flag, peak flag, etc
  - Eight single channel analyzer outputs (LLD, ULD set in software)

X123 Power Design

Architecture

- **Multiple switching supplies**
- Low voltages: +3.3V digital, +/-5V analog, +/-8V preamp
  Standard, commercial PWM supplies
- High voltage: +100 to +1500VDC at microamps
  Switch mode supply with Cockroft-Walton
- Cooler supply: Closed loop regulation of temperature
  Commercial PWM supply with temperature feedback

Configurations

- X123: Output voltages set by internal jumpers and pots
- PX4: Voltages set by serial command

X123 Power Design

Input

- +5VDC nominal
- Actual range is 4V to 6V for battery operations
- Typical steady state 1.2W (240 mA at 5V)
- First minutes, 1.8W (360 mA) until detector is cooled

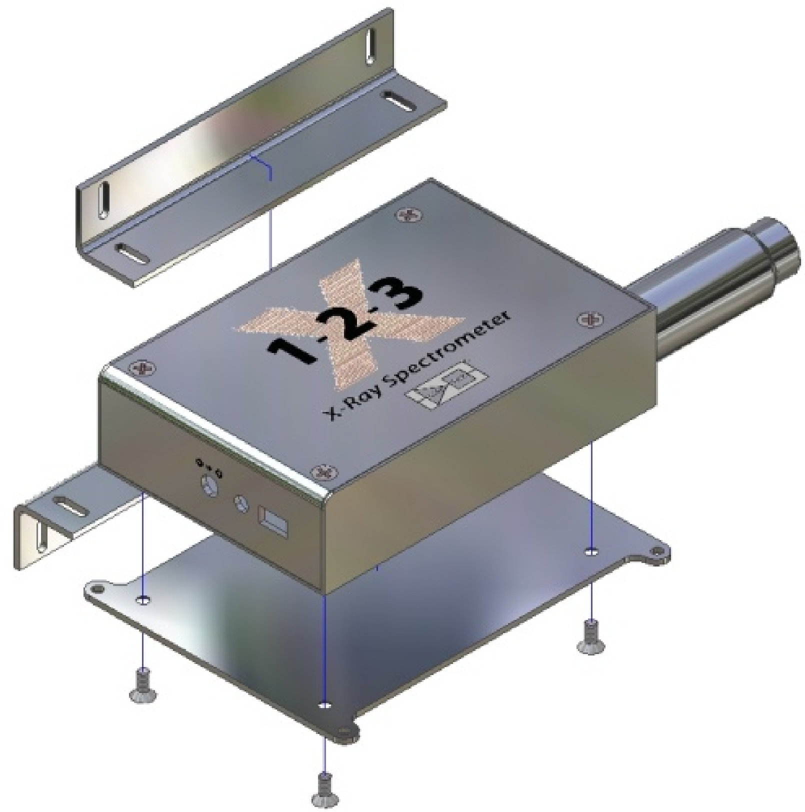
Power Budget

- 0.4W for Peltier cooler (typical steady state at 25˚C)
- 0.4W for digital processor
- 0.2W for analog circuits
- 0.2W for power supplies

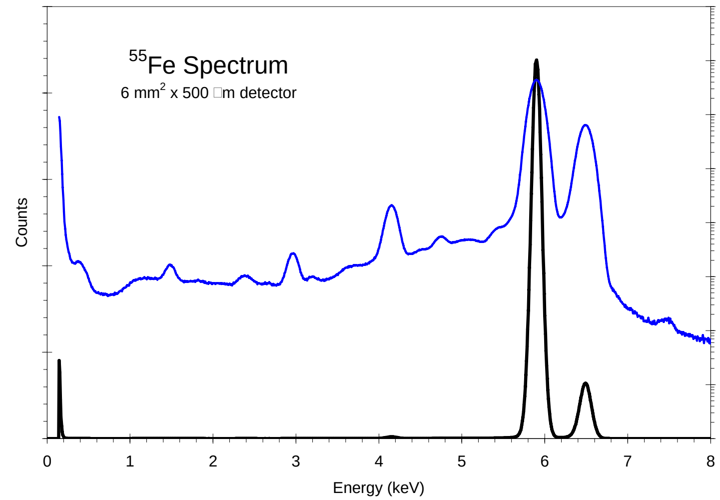
X123 Packaging

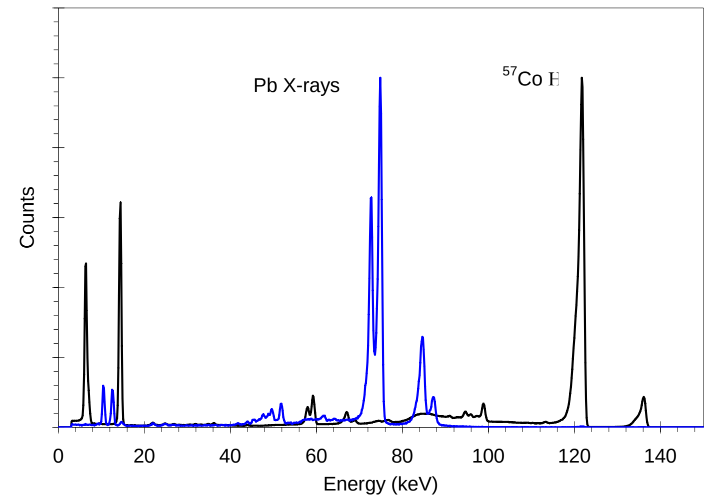
Packaging is critical!

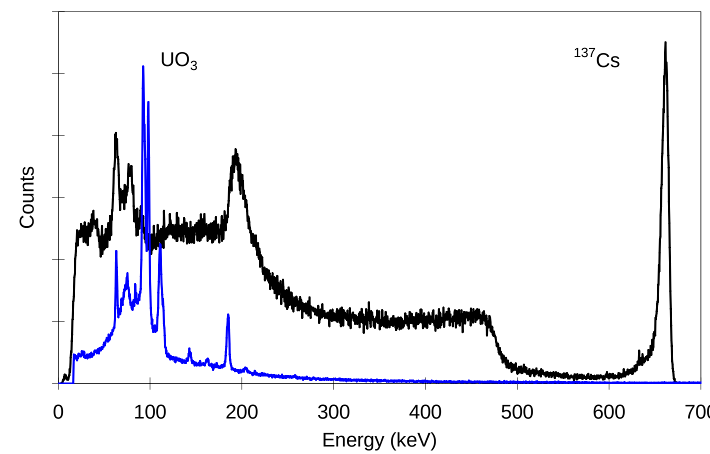
- Charge sensitive preamp, with noise of 12 e- rms, located with cm of 0.3A switching supply
- Must remove 0.5W from detector with minimal $\Delta T_{ambient}$
- Machined Al box for EMI, thermal
- Careful grounding, layout, and shielding
- Connections
  - USB, serial, power standard
  - Others available
- Mounting kit shown



X123 Resolution







Si-PIN ^{55}Fe spectra

- Best resolution 149 eV @ 5.9 keV

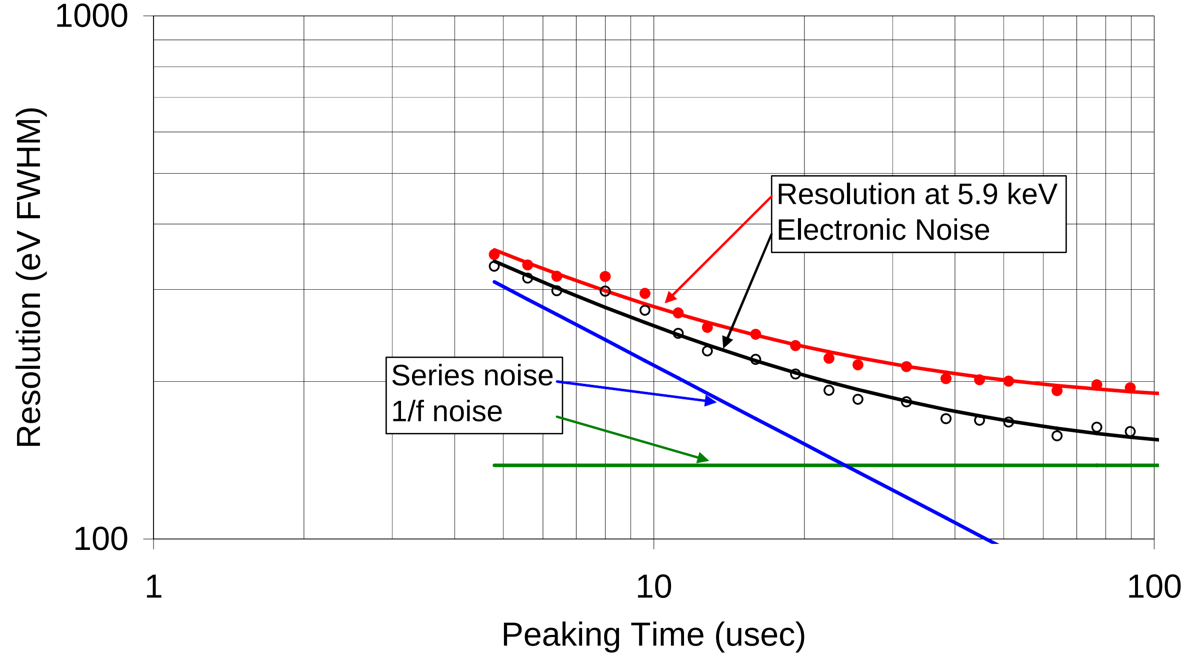
CdTe spectra

- Resolution 0.75 keV @ 59.5 keV

CdTe stack spectra

- Resolution 5 keV @ 662 keV

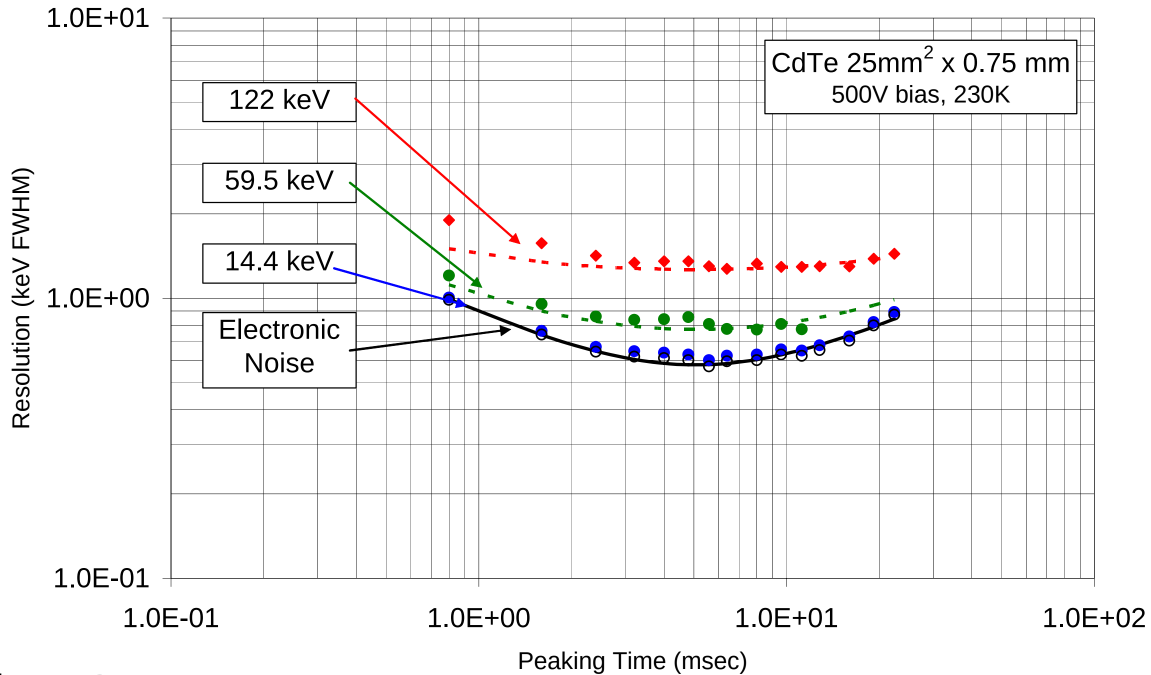
X123 Resolution



Si-PIN Noise Components

- Typical results with a 13mm^2 detector
- Series noise dominates below 25 μsec peaking time
- Parallel noise unimportant
- Fano broadening dominates >10 keV

X123 Resolution



CdTe Noise Components

- Typical results with a 25 mm^2 x0.75 mm detector
- Noise corner near 6.4 μsec peaking time
- Noise dominates below 30-50 keV
- Hole tailing dominates above this

X123 Resolution

What determines the energy resolution?

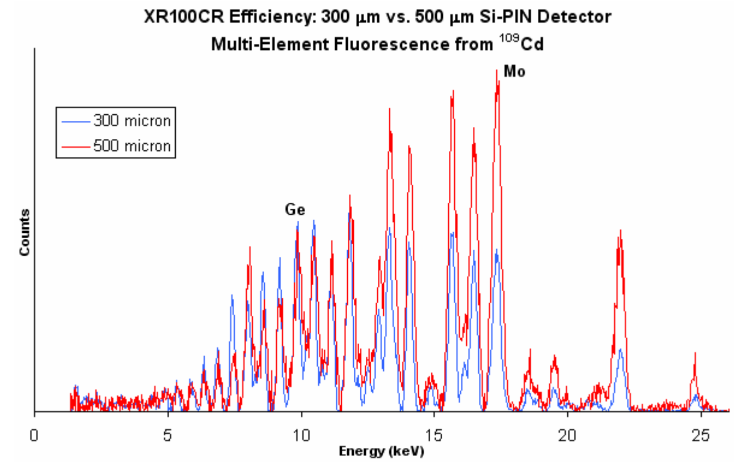
$$\Delta E^2 = F \bullet E + ENC^2 + F_{tail}(E) = \left(F \bullet E\right) + \left(\frac{n_{series}}{\tau} + n_{1/f} + n_{parallel}\tau\right) + F_{tail}(E)$$

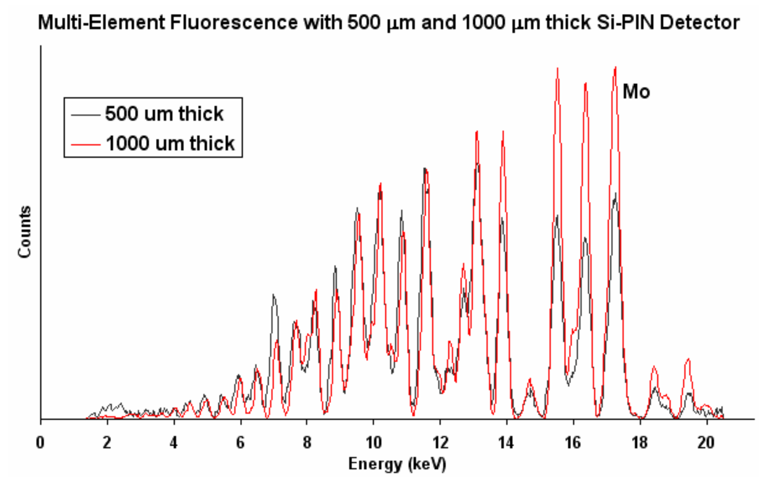
- Add in quadrature: ΔE is square root of sum of squares, not linear sum.
- Statistical fluctuations
  - Contribution scales as √FE, F is Fano factor, about 0.1
  - A function of energy only. Dominates at high energy for Si-PIN
- Electronic noise
  - Independent of energy so dominates at low energy
  - A function of the shaping time, with a minimum at the “noise corner” where the series and parallel terms are equal.
  - Series noise is proportional to total input capacitance and dominates at short shaping times.
  - Parallel noise arises from detector leakage current and dominates at long shaping times.
  - 1/f (pink) noise does not vary with shaping time.
- Hole tailing is important for CdTe only, not Si-PIN
  - Complicated function of energy and voltage and varies from one detector to next
  - Dominates at high energies. Improved with increased bias voltage

X123 Sensitivity

Si-PIN Sensitivity

- For Si-PIN detectors, sensitivity vs. resolution trade-off
- 6 mm^2 x 500 μm best resolution
- 25 mm^2 x 500 μm large area
- 13 mm^2 x 1000 μm has sensitivity to higher energies
- Must be matched to application





X123 High Count Rates

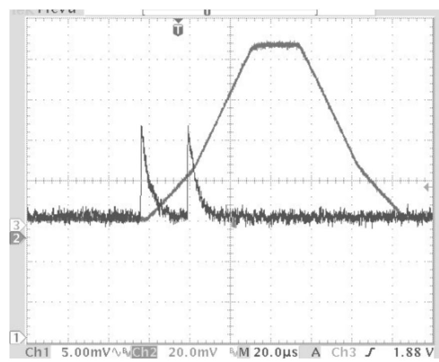
Dead Time and Throughput Different from Analog

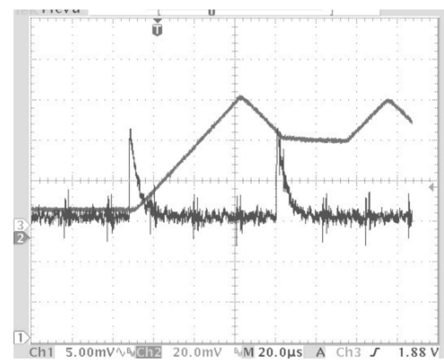
- In analog, “dead time” specified is for peak digitization.
- In digital, there is no dead time for this, only for pulse overlap $\Rightarrow$ much shorter dead time and so higher throughput
- In digital, pulse is symmetric and timing well defined $\Rightarrow$ shorter and better known dead time intervals.
- In analog, fast signal used to detect pile-up but fast rate not recorded. In digital, directly measure the fast rate $\Rightarrow$ more accurate correction.

Pulse dead time: τ_{peak}

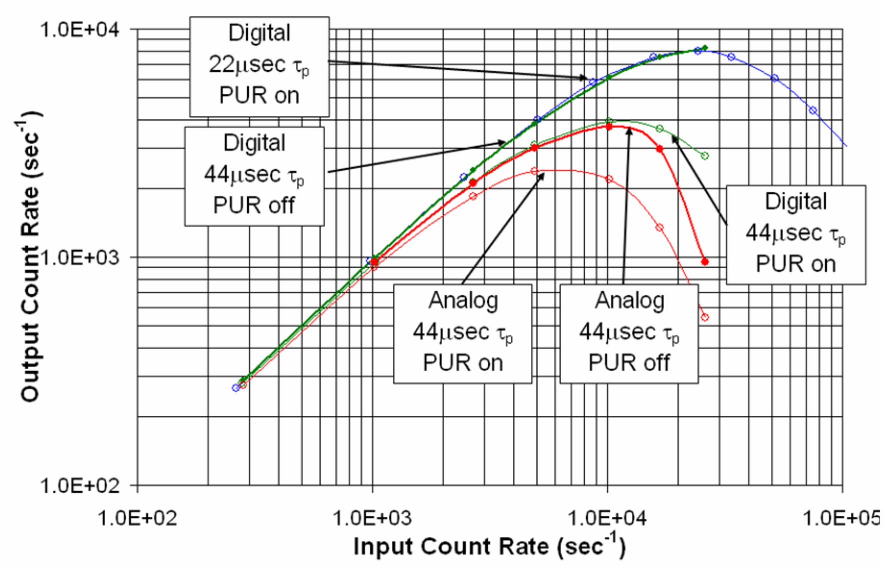
Pile-up reject interval: $2*(1+3/8)\tau_{peak}$

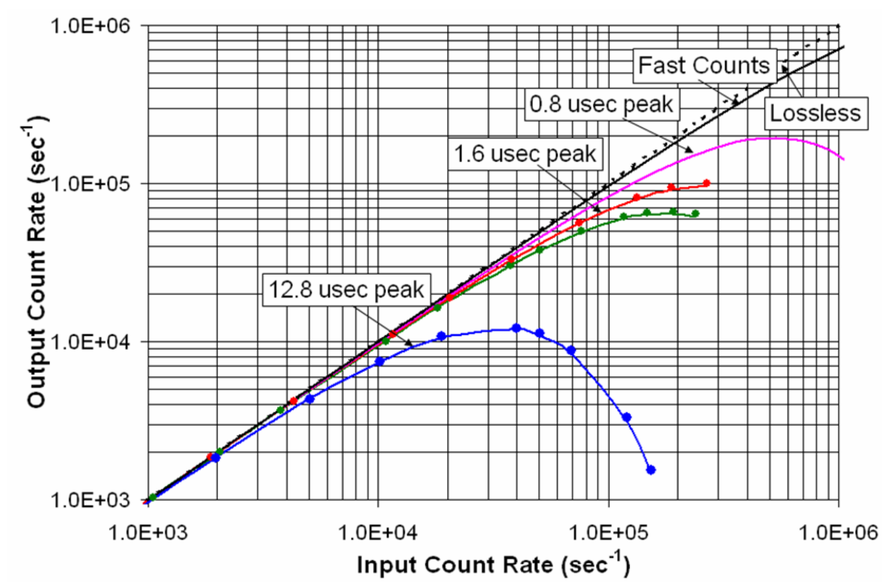
Fast channel resolving time: 400 nsec





X123 High Count Rates





Throughput

- Much better than analog system for same τ_{peak}
- Measured results matches equations very well
- Fast channel permits direct dead time correction

$$R_{Out} = R_{In}\left(e^{-R_{In}(\tau_{Peak}+\tau_{Flat})}\right) \qquad \text{PUR Off}$$

$$R_{Out} = R_{In}\left(e^{-(2.375)(R_{In})(\tau_{Peak}+\tau_{Flat})}\right) \qquad \text{PUR On}$$

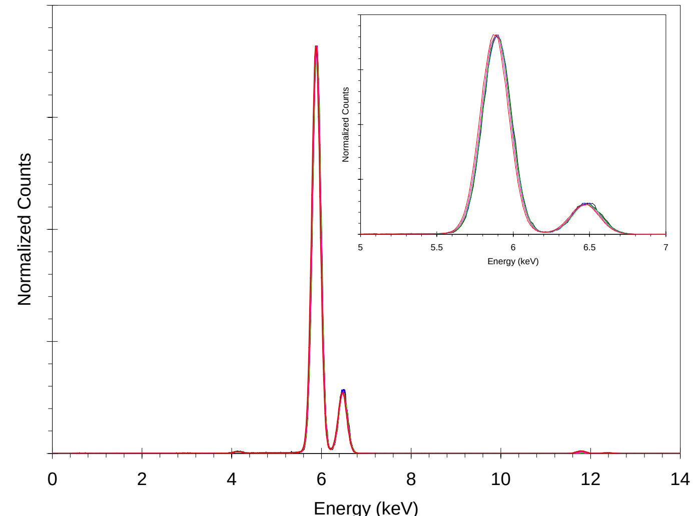
$$R_{In} = \frac{R_{FAST}}{1 - R_{Fast}\tau_{Fast}} \qquad \text{Dead Time Correction}$$

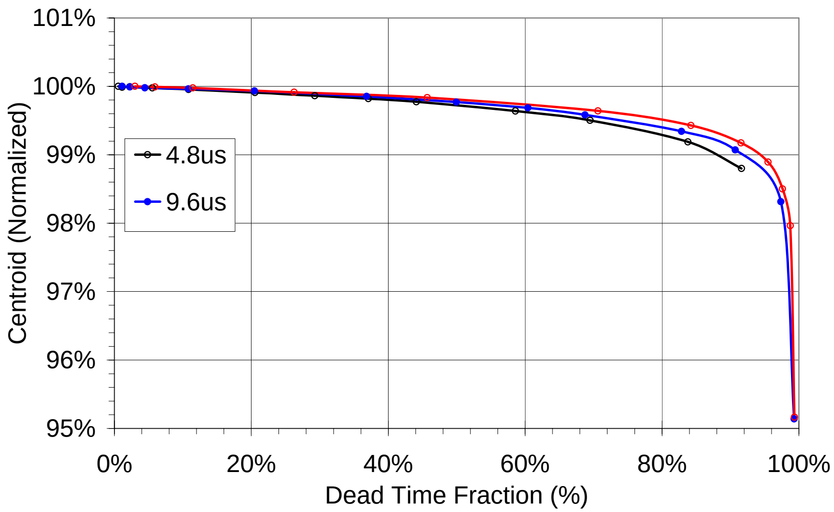
X123 High Count Rates

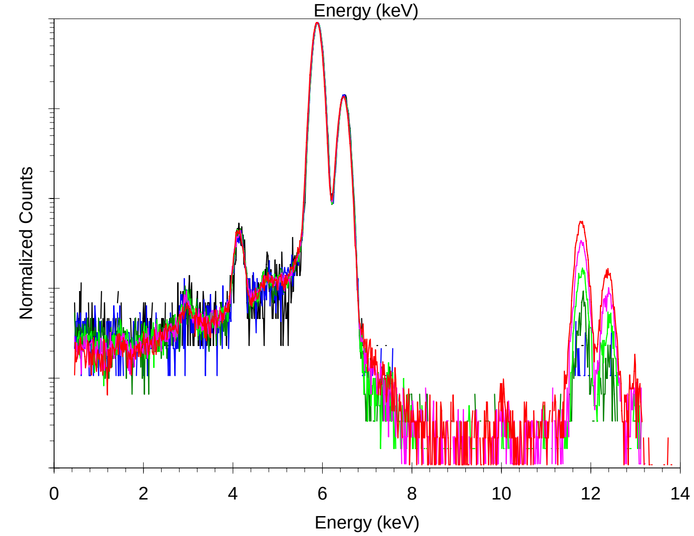
Spectral performance at high rates

- We recommend operation <50% dead time
- Baseline shifts <0.2% to 50% dead time
- Resolution changes similarly

- Spectra here are up to 70% dead time
- Double peaks visible to 95% dead time





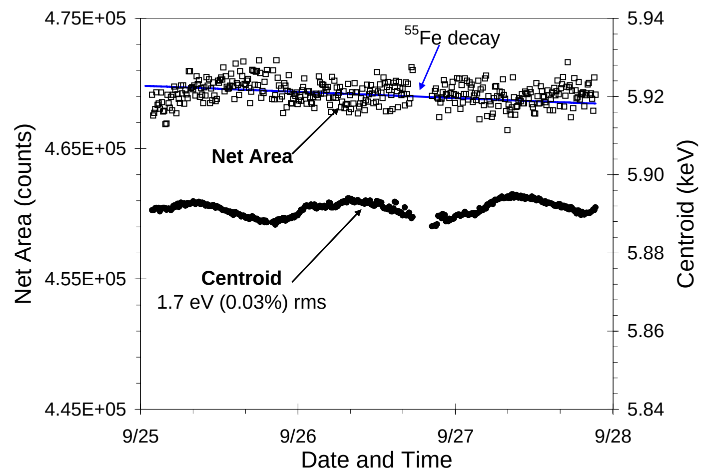


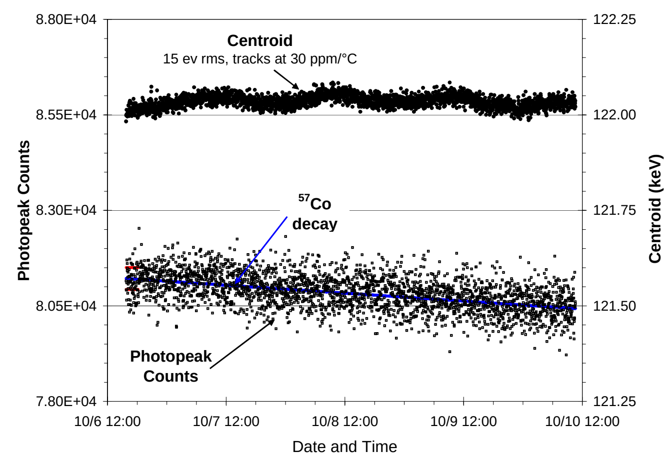
X123 Stability

Drift over time

- Top plot shows X123-Si data
- Bottom plot shows X123-CdTe
- Gain fluctuations consistent with temperature coefficient
  - 60 ppm/°C for Si-PIN
  - 30 ppm/°C for CdTe
- Count rate follows decay

- PX4 data taken for 1 month
- No long term drift observed
- Slope within std dev of zero





X123 Applications

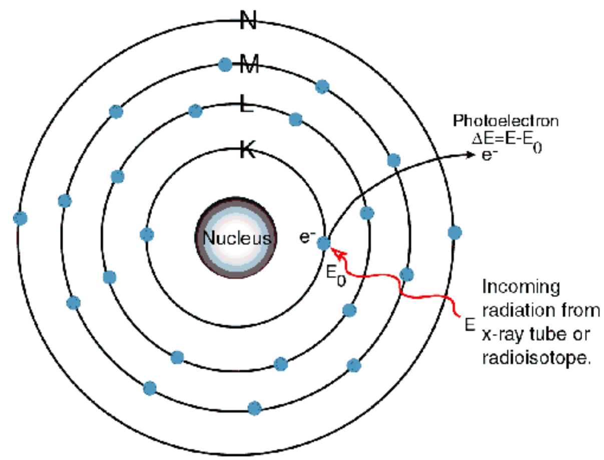
X-Ray Fluorescence

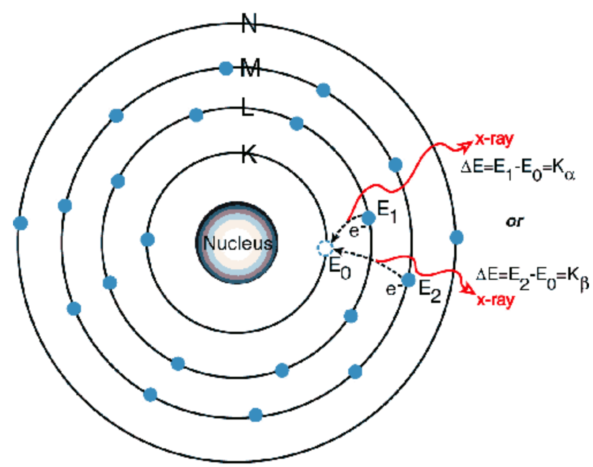
- Method used to non-destructively identify and measure which elements are in a sample
- Physics:
  - Incoming X-ray or γ-ray ejects inner shell electron from an atom
  - Excited atom decays to ground state
  - During decay, atom emits characteristic X-ray with energy equal to difference in shells
  - Each element has a unique pattern of transitions so a unique, characteristic set of X-rays
- Presence of X-rays $\Rightarrow$ presence of element

  Need sufficient energy resolution to separate peaks
- Rate of X-rays $\Rightarrow$ quantity of sample

  Need accurate measurement of counts

  Need to correct for attenuation, scattering, etc

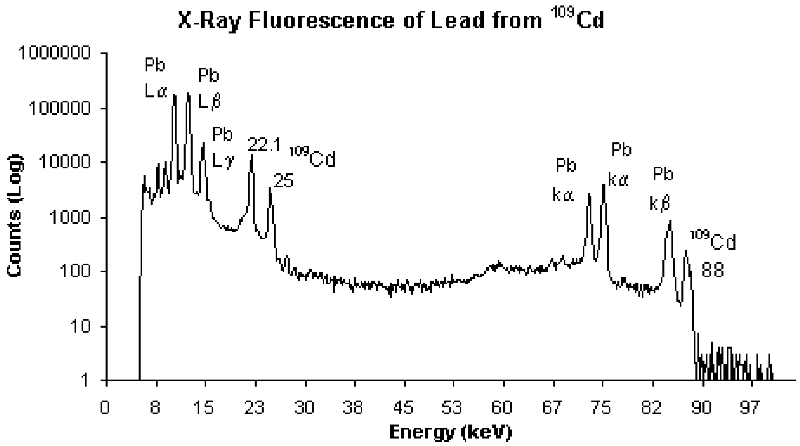




X123 Applications

X-Ray Fluorescence: Sample Spectra

- Typical result for lead
- 88 keV incident photons excite sample
  - Some scattered photons reach the detector
  - Lead K-shall has 88 keV binding energy, so photoelectrons are ejected
  - Decays from L shells (13-15 keV) lead to characteristic X-ray emissions at 72, 75, and 85 keV
  - Vacancies in L shells are filled by transitions from M shells
  - Generates characteristic X-rays at 10, 12, and 15 keV
- No damage to sample
- Penetrates beyond surface layers
- Rapid and accurate

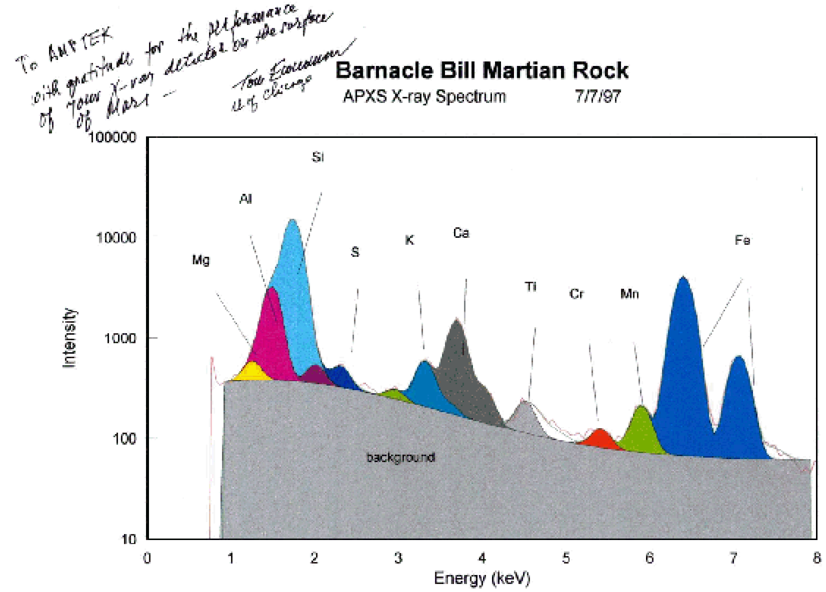


X123 Applications

Sample Spectrum

- Used Amptek XR100, not X123
- Taken by Mars Pathfinder

- Spectrum shows peaks present in sample and relative areas
- Yields elemental composition of Martian rocks

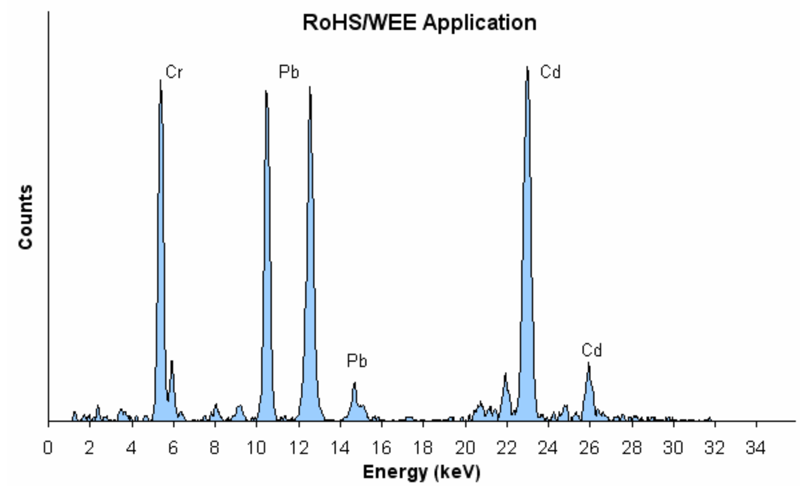


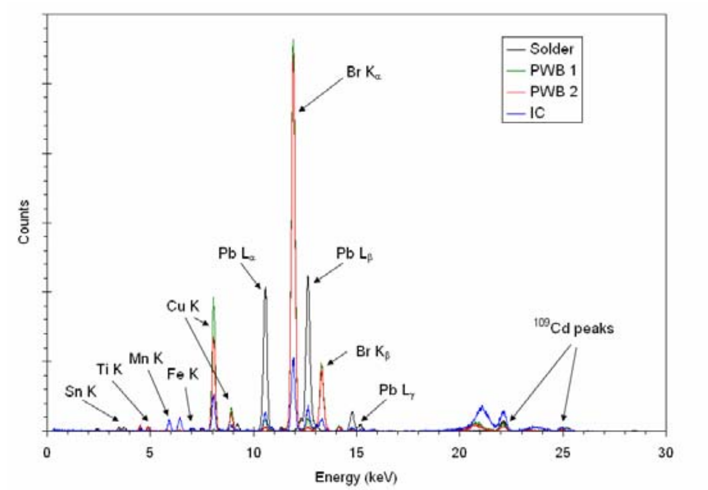
X123 Applications

ROHS Verification

(Reduction of Hazardous Substances)

- EU requires commercial electronics to be free of lead, cadmium, mercury, etc. as of 7/06
- OEMs need to verify compliance of vendors and suppliers
- X123 Si-PIN can reliably quantify the critical elements
- Compact packaging, easy connections provide simple, COTS solution for end users



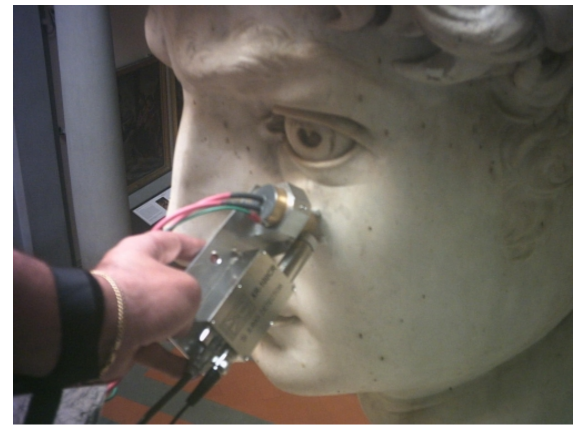


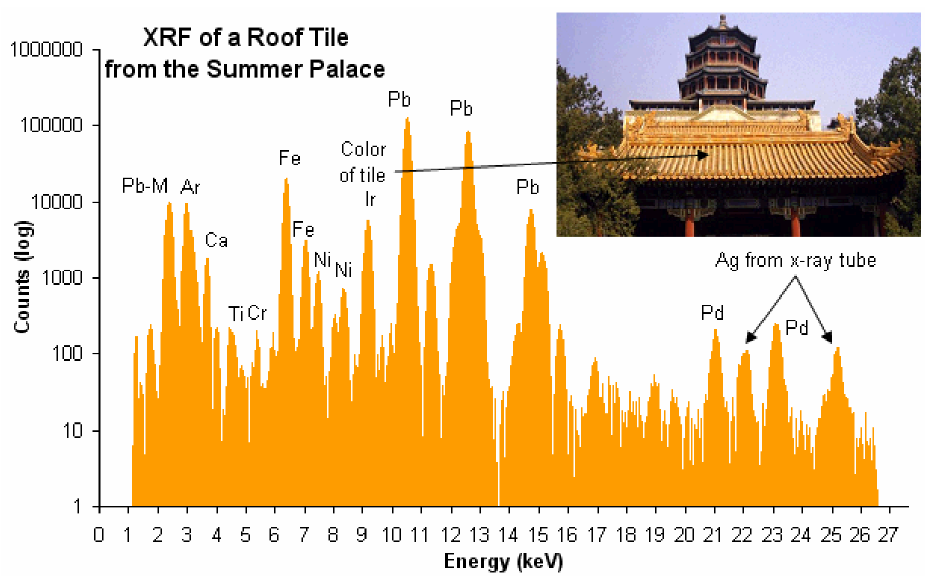
X123 Applications

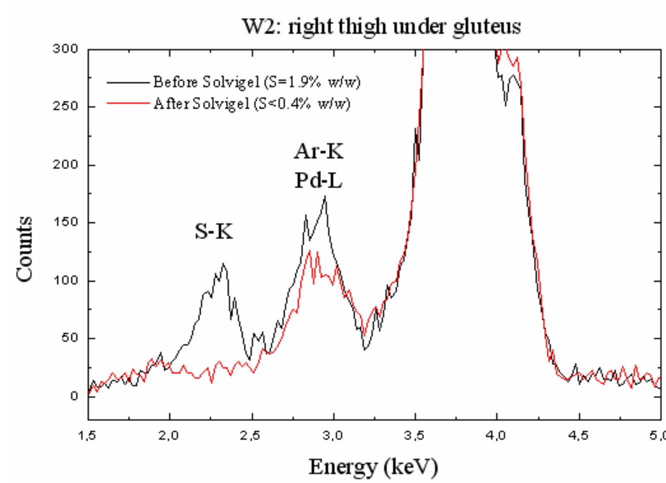
Art and Archeology

- XR100 currently used for XRF analysis
- X123 provides same performance in much more compact form

XRF of Michelangelo's David



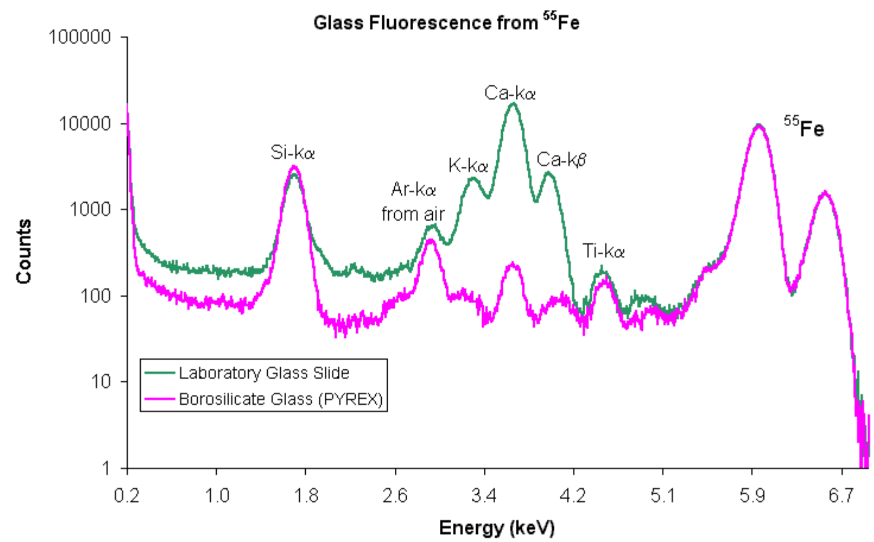


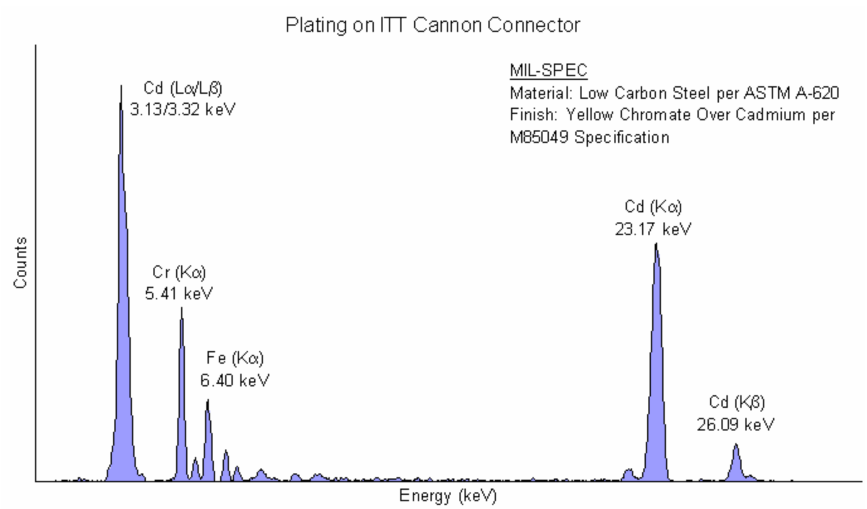


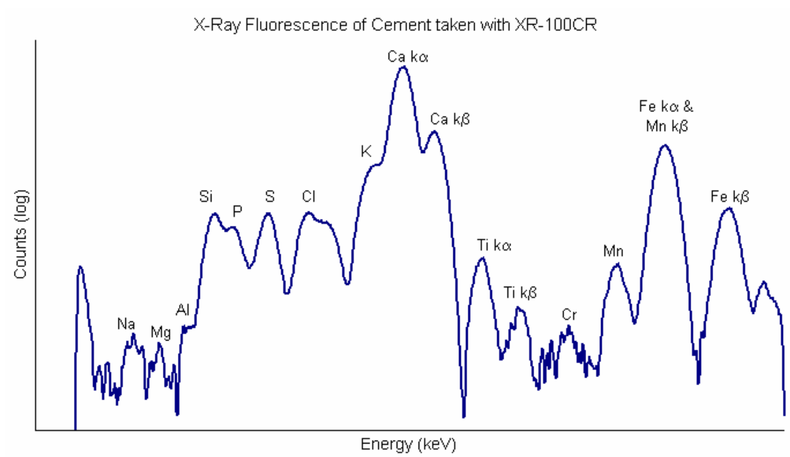
X123 Applications

Industrial process control

- XRF provides key quality measurements
- X123 permits simple, integrated solution for end users





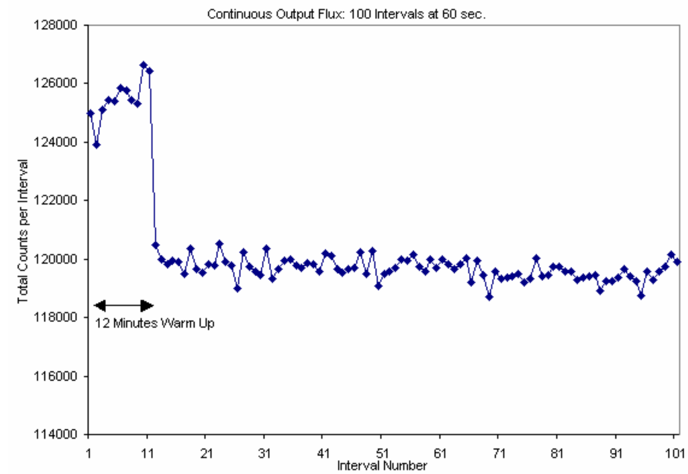


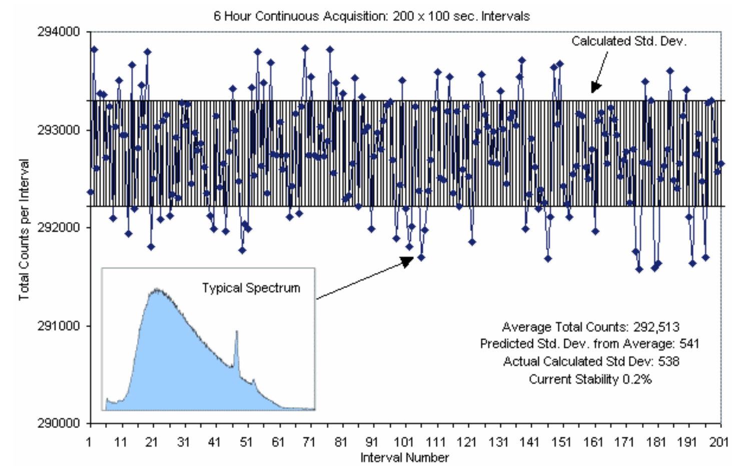
X123 Applications

X-Ray Tube Quality Assurance

- Stable tube output is very important for many applications
- Mammography particular demanding
- X123 CdTe provides high sensitivity over the energy range of most tubes
- Validate beam at start of day
- Track beam flux over time
- Track spectral stability over time

- Compact, integrated X123 makes integration into system easy

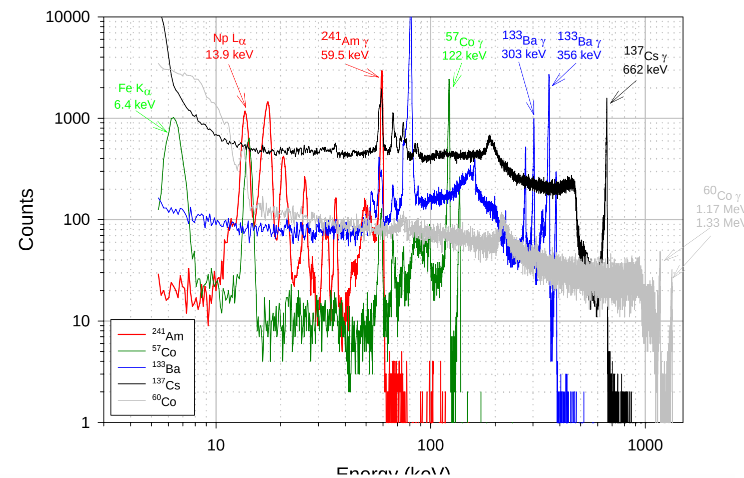


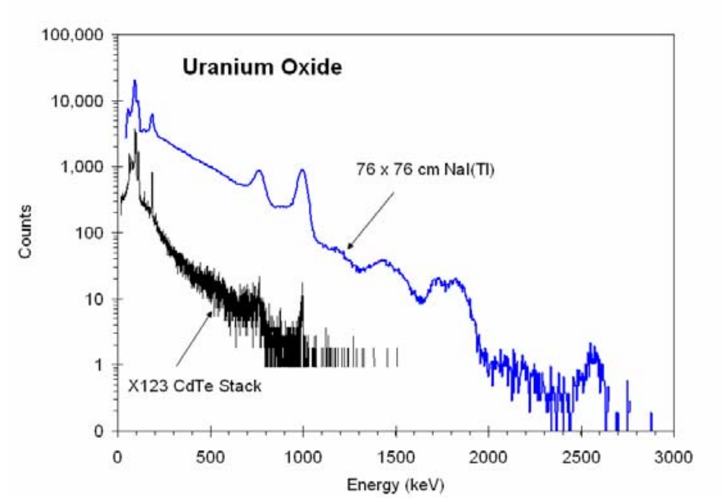


X123 Applications

Radioistope identification

- X123 CdTe-Stack
- Good energy resolution to 750 keV
- Complements higher sensitivity detectors such as NaI(Tl)
- Small size, low power, simple interface simplify system integration





X123

Conclusions

– Successfully integrated Peltier cooled detectors, digital pulse processing, and power supplies into a compact package
– Works well for Si-PIN, and for 1 mm CdTe, and for CdTe stacks to cover a wide energy range
– Provides high resolution of analog benchtop systems
– Digital processor provides much higher throughput and stability than analog benchtop system
– Compact size, low power, and simple interface simplify system integration for the end user

– For more information, go to www.amptek.com