Digital Pulse Processing for Isotope Identification

Joint ICTP-IAEA School on Detector Signal Processing and Machine Learning for Scientific Instrumentation and Reconfigurable Computing

Trieste – Italy
27 October – 7 November 2025

M. Bogovac
IAEA, Vienna

IAEA
International Atomic Energy Agency

Overview

- About IAEA and NSIL Laboratory
- Principles of Nuclear Radiation Spectroscopy
- Nuclear Radiation Spectroscopy with PMOD kit (School Project)
- Possible Applications of the Project and Platforms for a Custom Design
- Interaction of Radiation with Matter and Radiation Spectra
- Radiation Spectroscopy with Scintillators coupled to PMT and SiPM

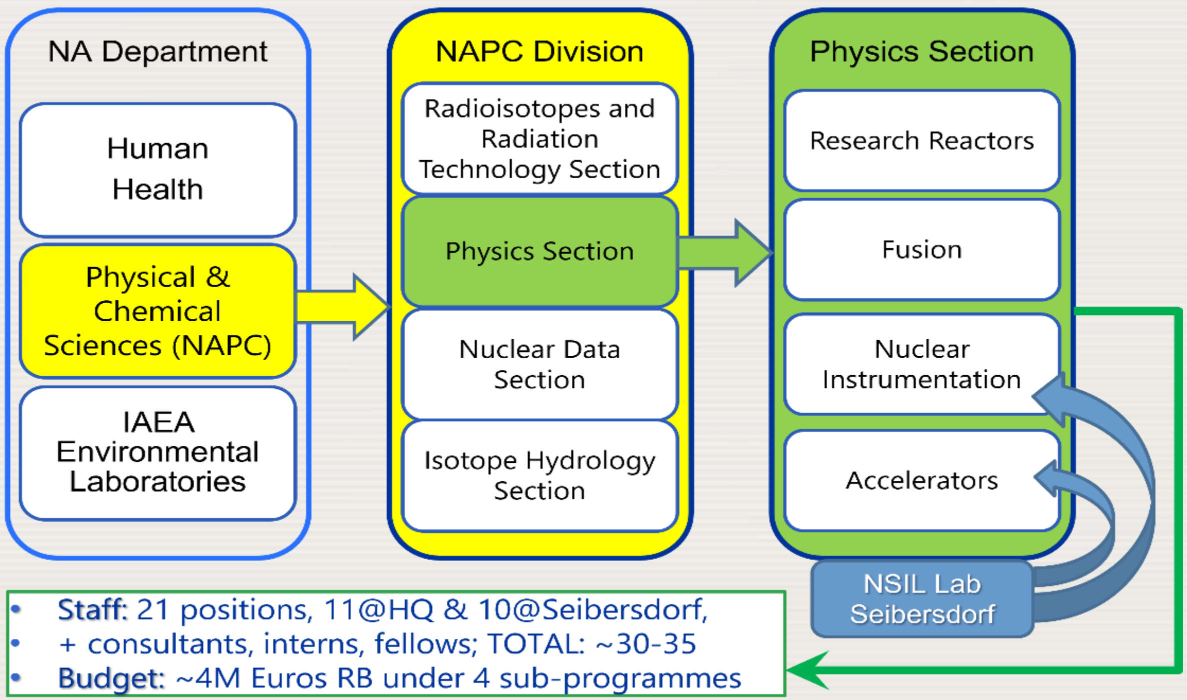
About IAEA

An autonomous international organization within the United Nations system

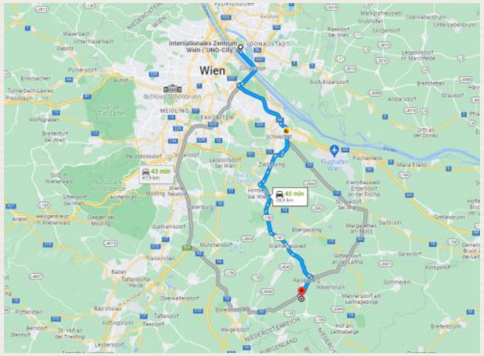
173 Member States; 2500+ staff from over 100 Member States; HQ in Vienna

- Labs in Seibersdorf, Vienna and Monaco
- Regional offices in Toronto and Tokyo; Liaison offices in New York and Geneva

The Department of Nuclear Science and Applications (NA)



About NAPC
Laboratories at Seibersdorf



- Vienna
  - Isotope hydrology
- Monaco
  - Radioecology
  - Radiometrics
  - Marine Environmental Studies
- Seibersdorf
  - Plant Breeding and Genetics
  - Soil and Water Management & Crop Nutrition
  - Animal Production and Health
  - Insect Pest Control
  - Terrestrial Environmental Radiochemistry
  - Dosimetry
  - Food Safety and Control
  - **Nuclear Science and Instrumentation**

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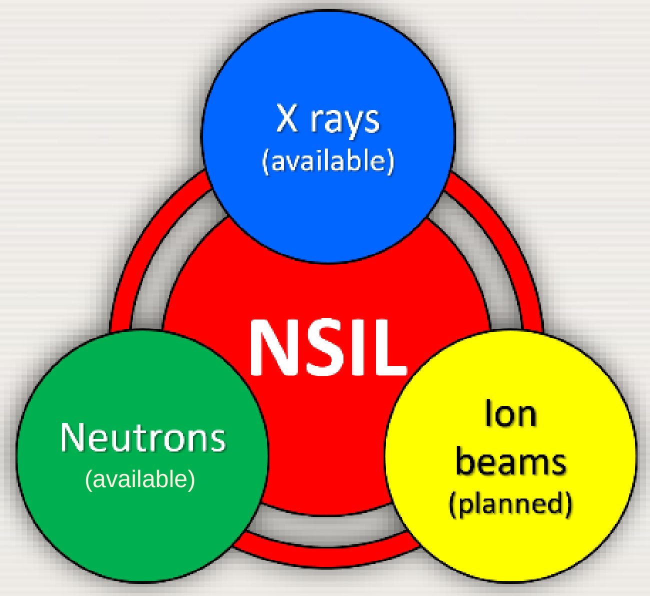
Nuclear Science and Instrumentation Laboratory (NSIL)

- To assist the IAEA member states in introducing and extending the use of nuclear instrumentation and radiation measurement techniques, including related capacity building
- Achieved via dedicated trainings, fellowships, internships, scientific visits (duration 1 week – 1 year), expert missions, services, R&D projects

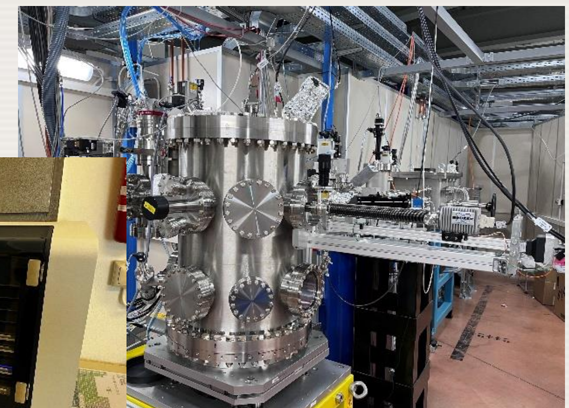


Nuclear Science and Instrumentation Portal

X-ray Instrumentation at NSIL

- Secondary Target – Energy Dispersive XRF
- Wavelength Dispersive XRF
- Total reflection XRF
- µ and confocal XRF
- Full Field XRF
- SEM-EDS
- XRF 2D scanner (under development in cooperation with ICTP-MLAB)
- Handheld XRF
- Transportable XRD
- Sample preparation for solids and liquids

Elettra Sincrotrone, Trieste
XRF beamline:



Neutron Source at NSIL

Sealed tube neutron generators

- DD (Thermo Fisher): 2.45 MeV neutrons, emission rate up to 5e6 n/s
- DT (Sodern, donated by CSIRO, Australia): 14.1 MeV neutrons, emission rate up to 2e8 n/s

Training topics with neutrons

- Operation & maintenance of neutron facility based on DD/DT generators
- Radiation protection with neutron and gamma fields
- Neutron instrumentation
- Neutron detection
- Neutron spectrometry
- Neutron imaging
- Neutron activation analysis (NAA)
- Prompt and delayed gamma analysis
- Delayed neutron counting
- Demonstration of radiotracer production and usage

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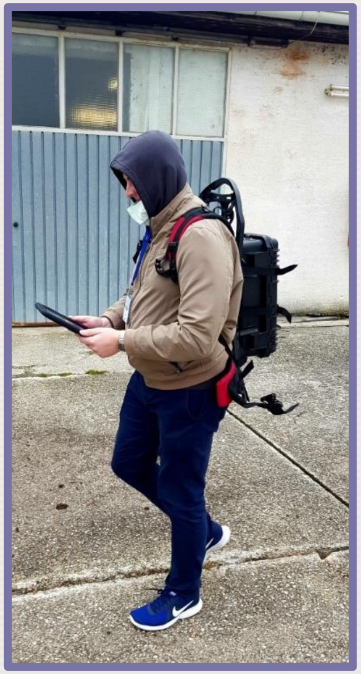
Radiological Mapping at NSIL

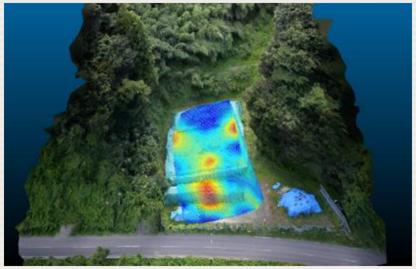
RSS-131
High Pressure Ionization Chamber

μ-DETECTIVE
HPGe In-Situ Gamma Spectroscopy System

AEGIS
HPGe In-Situ Gamma Spectroscopy System



PGIS (Upgrade)
Backpack Gamma Spectrometer



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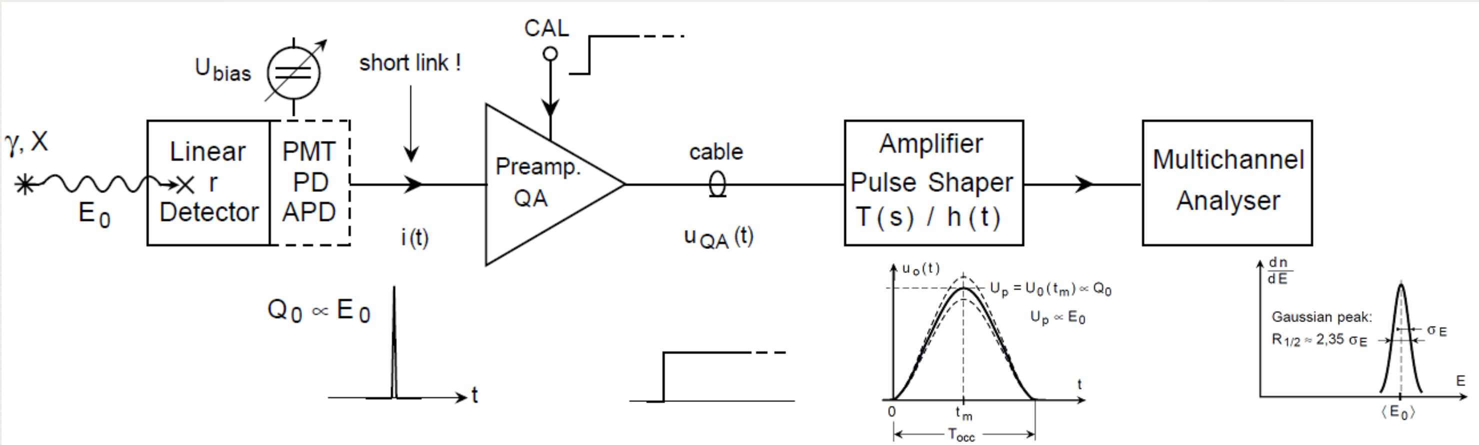
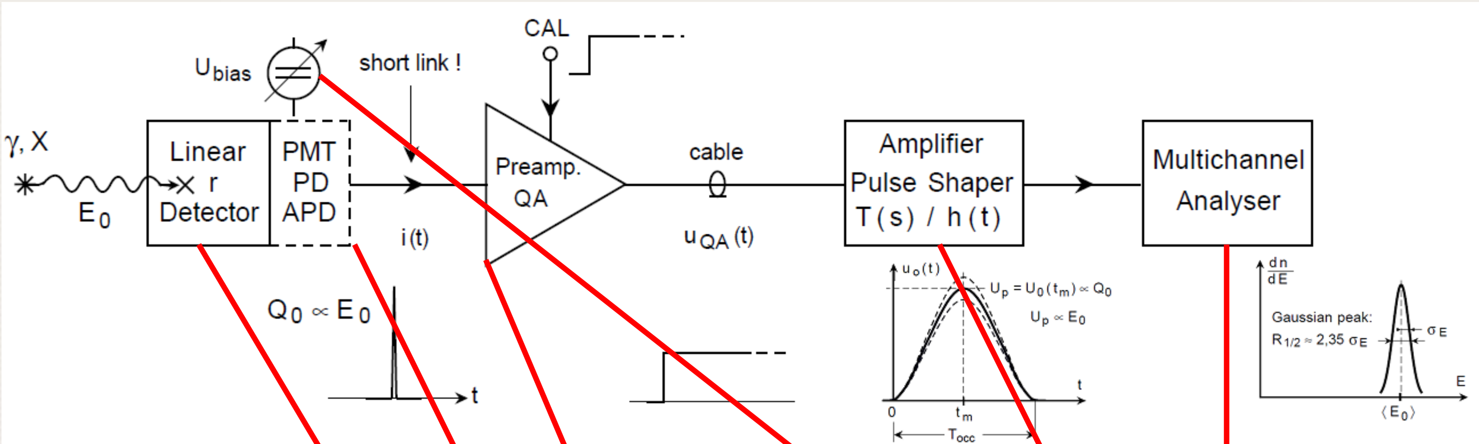
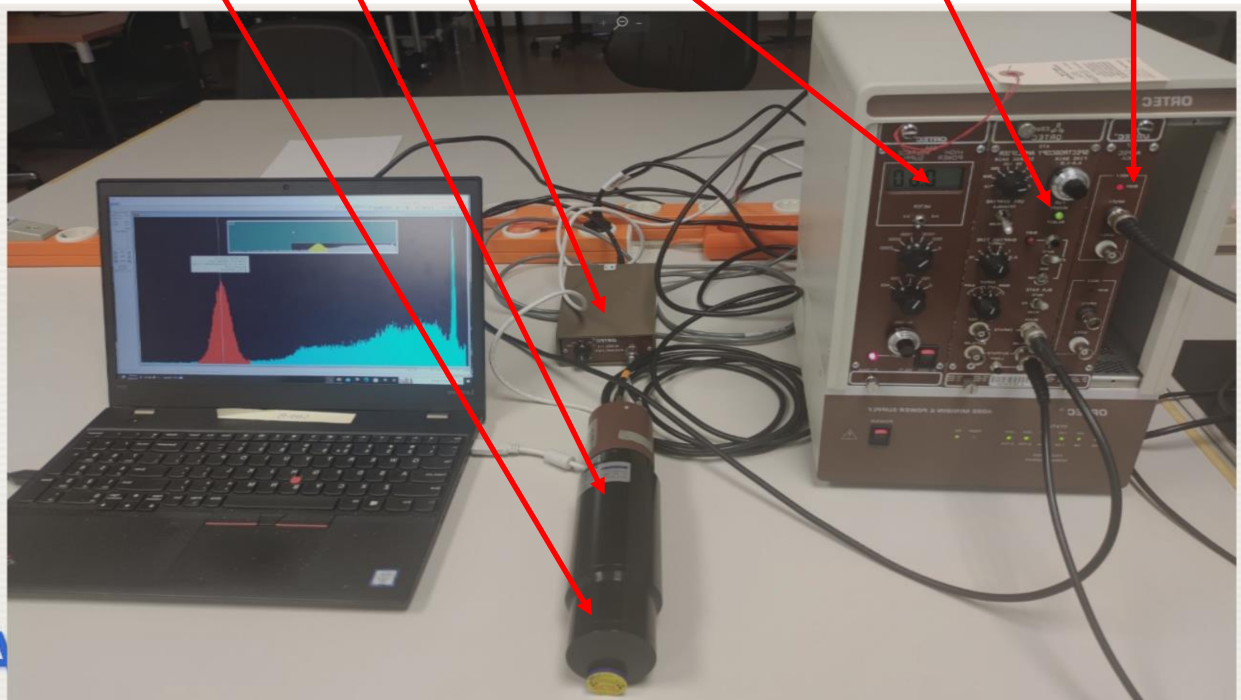
Principle of Nuclear Radiation Spectroscopy



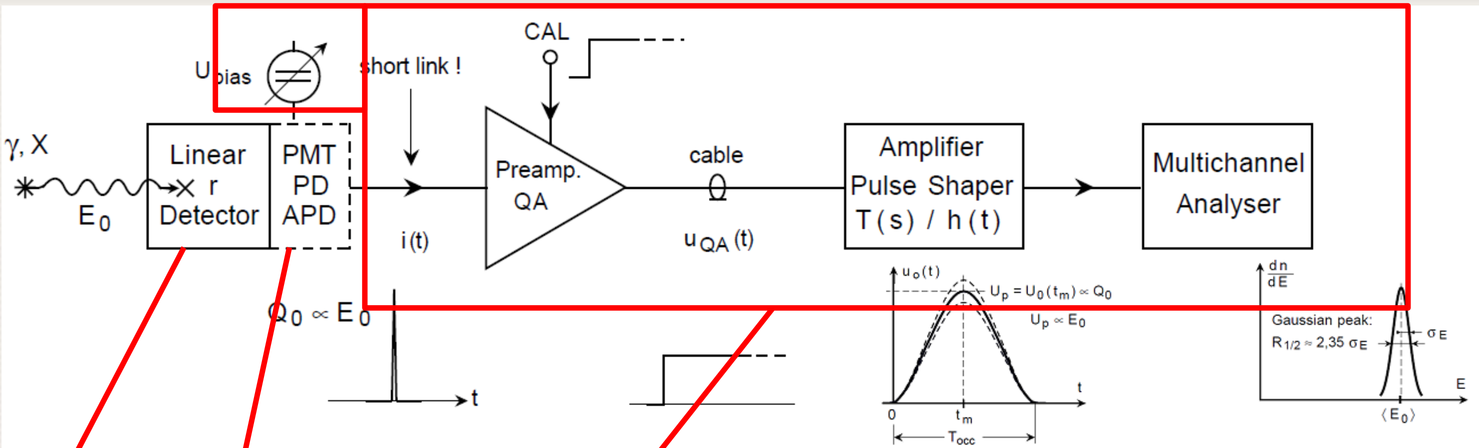
- The energy E_0 of each particle or photon is converted, in one or two steps, in a current pulse i(t) carrying an electric charge Q_0
- The collected charge is proportional to the energy lost by the particle or photon
- After peamplification, amplification and shaping, we obtain voltage pulses the peak amplitude of which is a measure of particle or photon energy
- The peak amplitude fluctuates around its mean value
- In the Multichannel Analyzer (MCA), the pulses are classified according to their amplitude
- The MCA screen displays the resulting histogram the radiation spectrum with the energy E in abscissa and the number of pulses by energy bin in ordinate.
- Despite the complexity of photons or particles interactions, these radiations produce a spectrum with well-defined peaks characteristic of the emitting atom or nucleus

Principle of Nuclear Radiation Spectroscopy





Principle of Nuclear Radiation Spectroscopy



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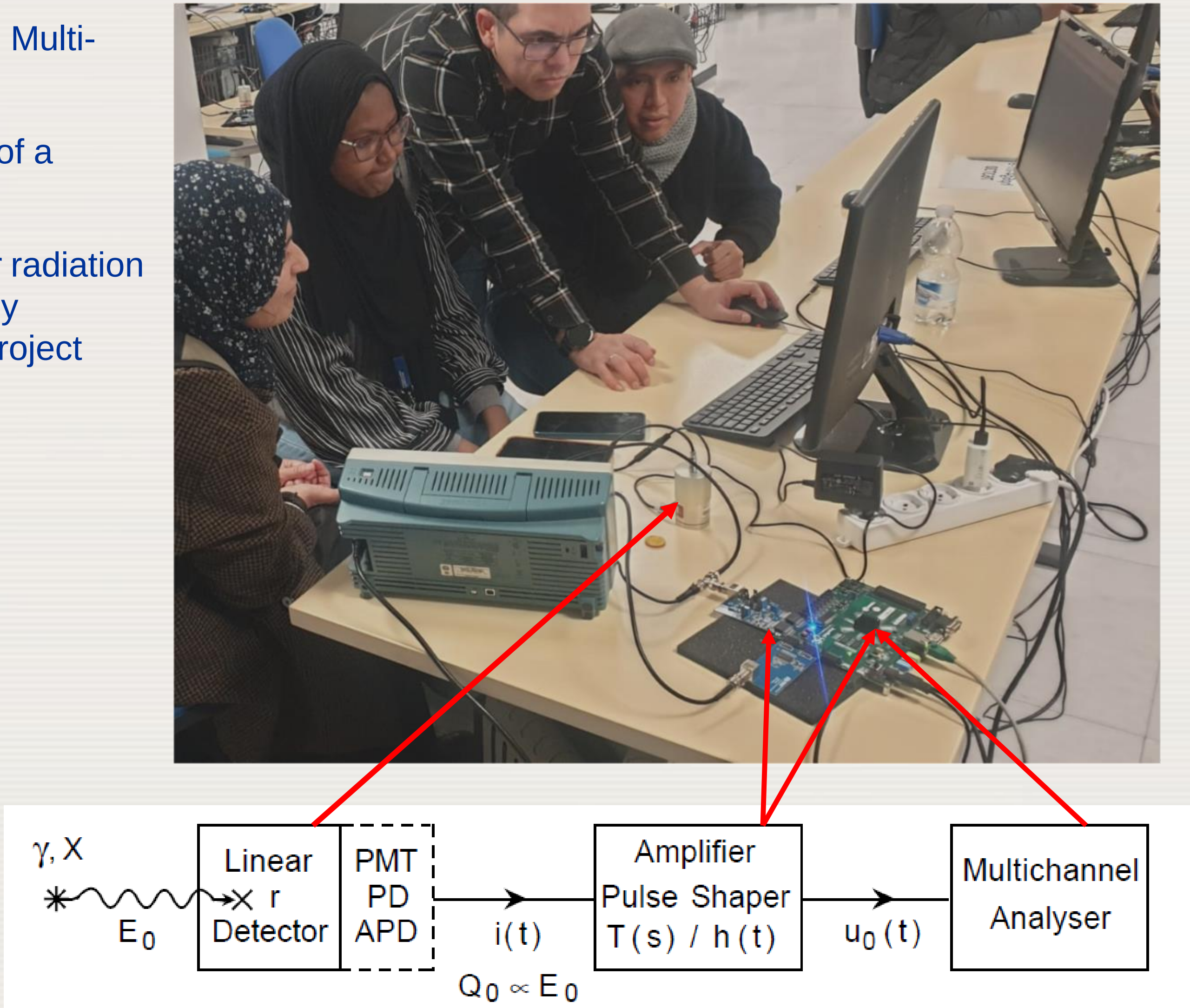
Spectroscopy with a PMOD kit

- Implement Pulse Shaper and Multi-Channel Analyzer in SoC
- Obtain Pulse Height spectra of a radiation source
- Get familiar with a Scintillator radiation detectors and be able to apply knowledge for your custom project



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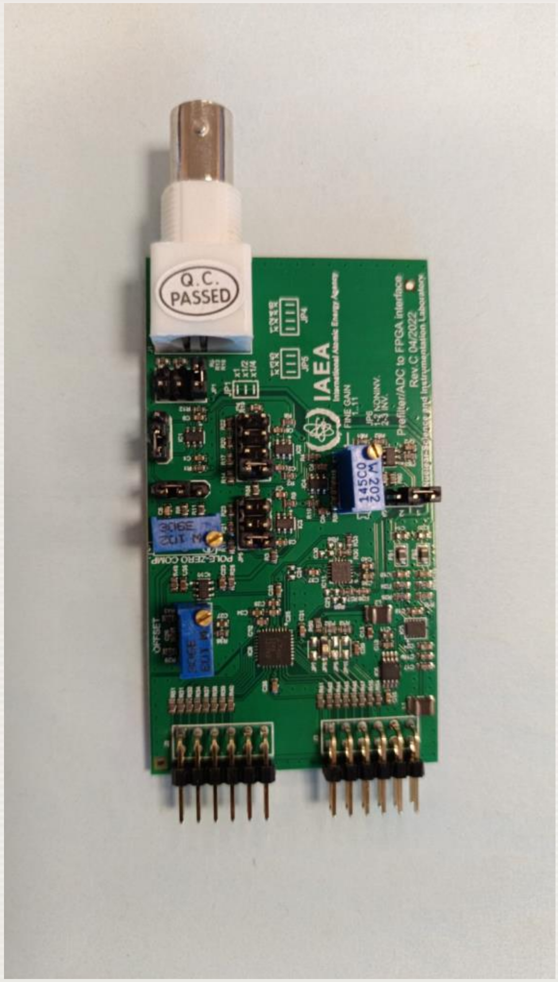
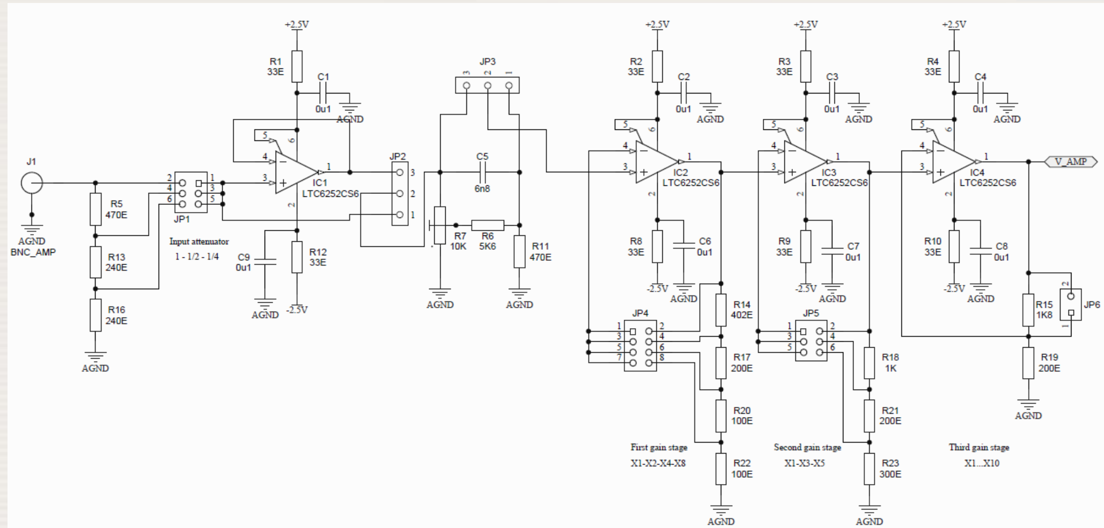
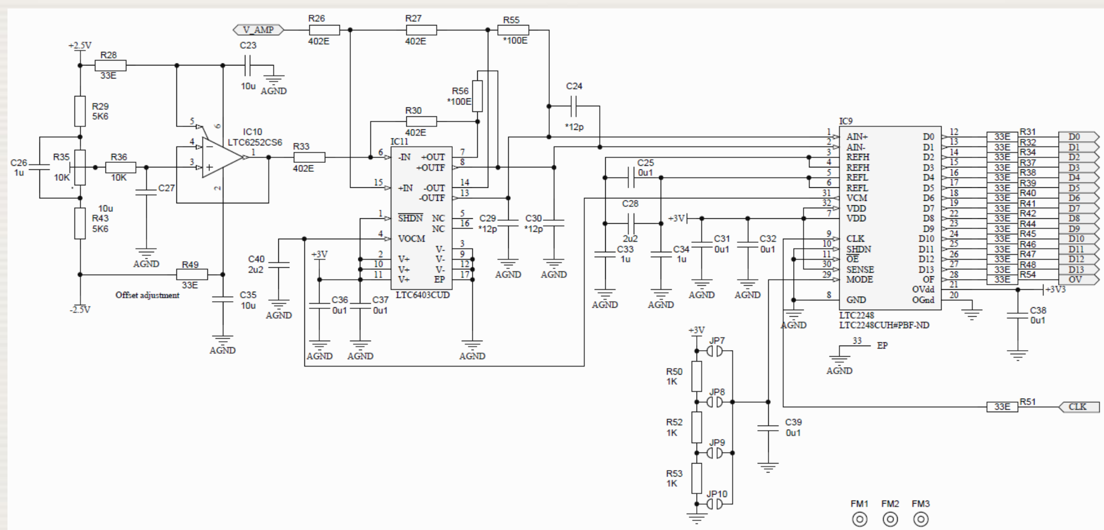
PMOD-ADC







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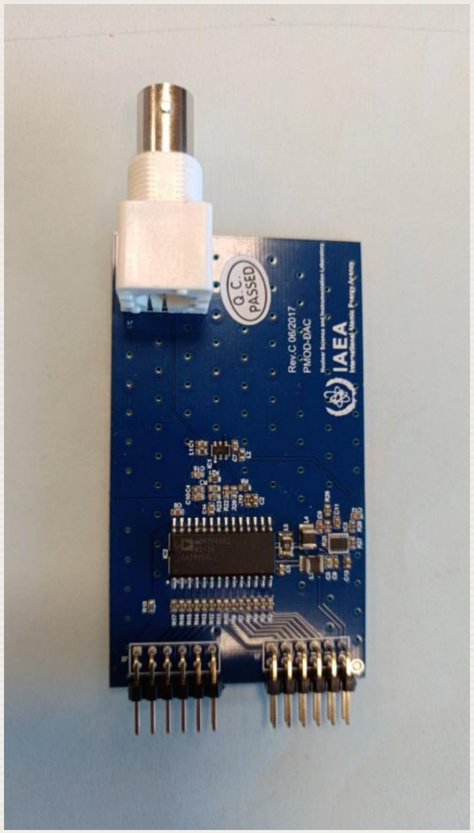
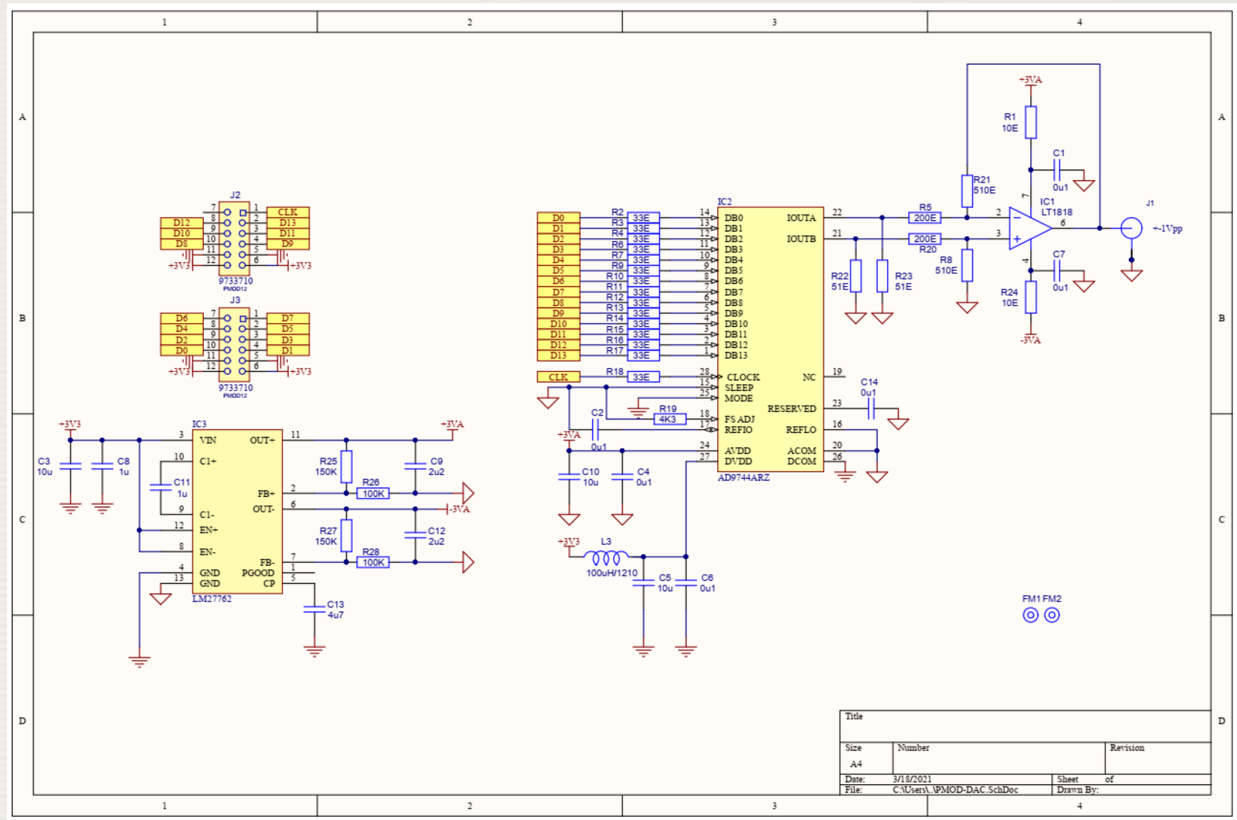
PMOD-DAC





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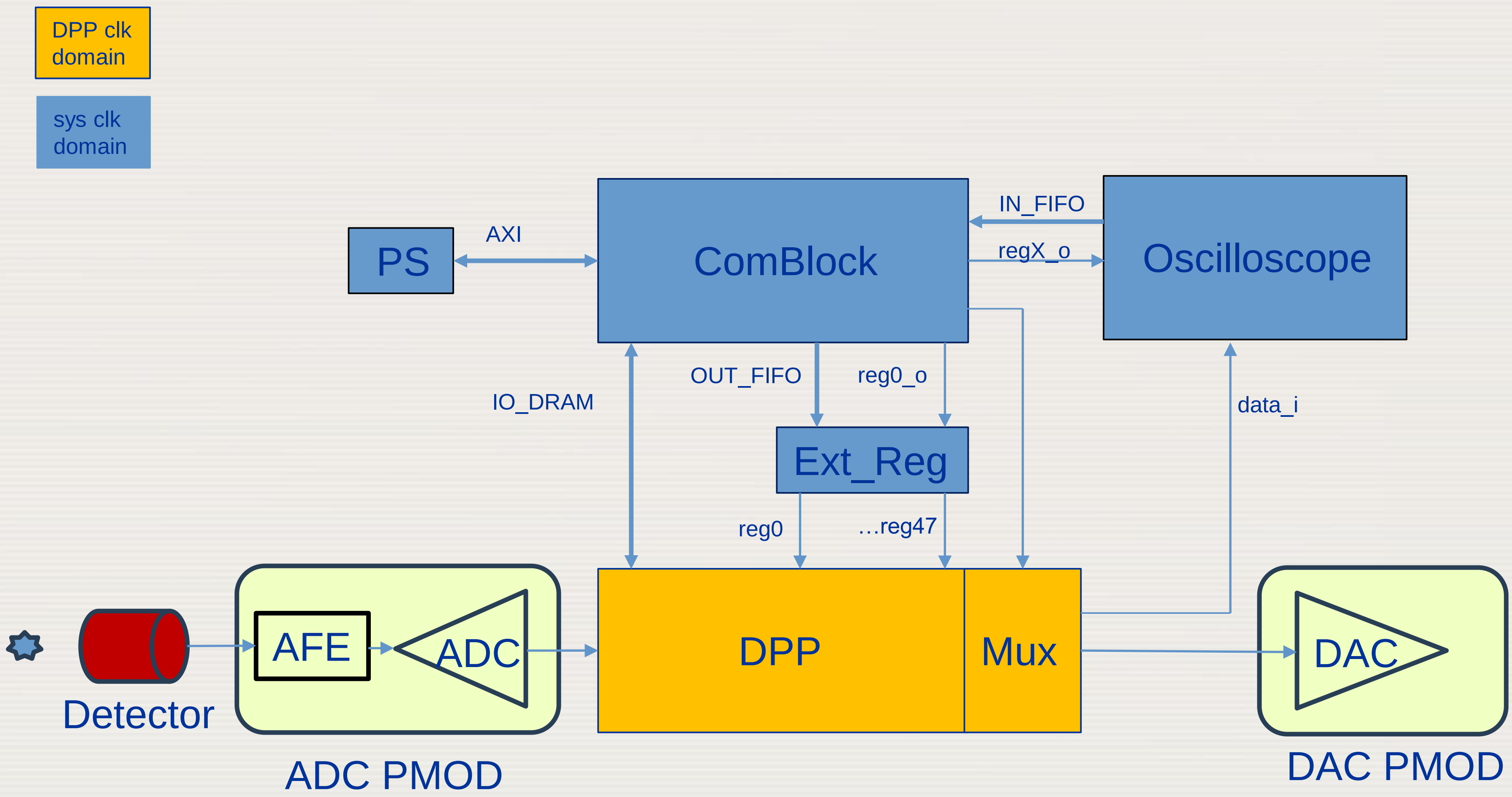
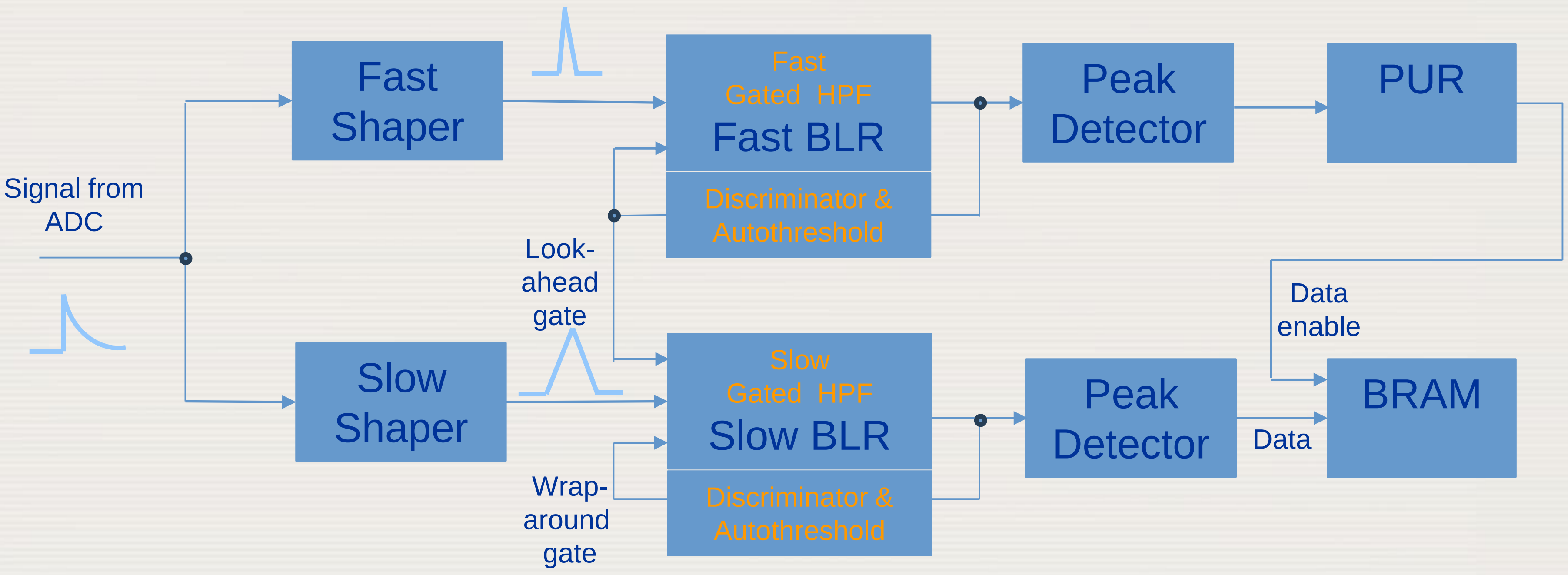
DPP Design – Top Level

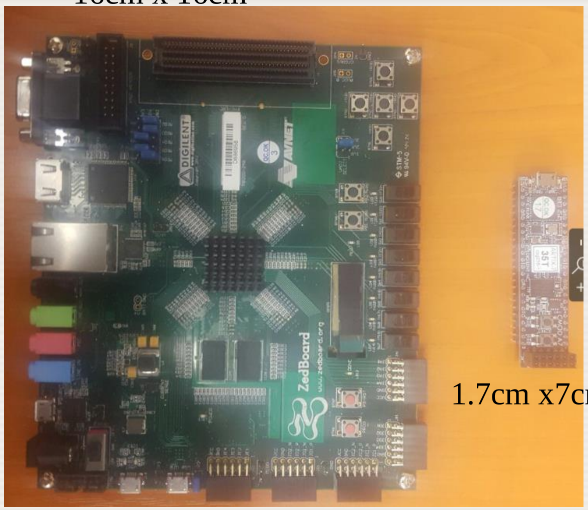


DPP Design – DPP block



Platforms for custom made systems CMOD-A7 vs Zedboard

16cm x 16cm



1.7cm x7cm

410-248	ZEDBOARD ZYNQ-7000	$449.00000
410-328-35	BOARD CMOD A7-35T FPGA 48DIP	$89.00000

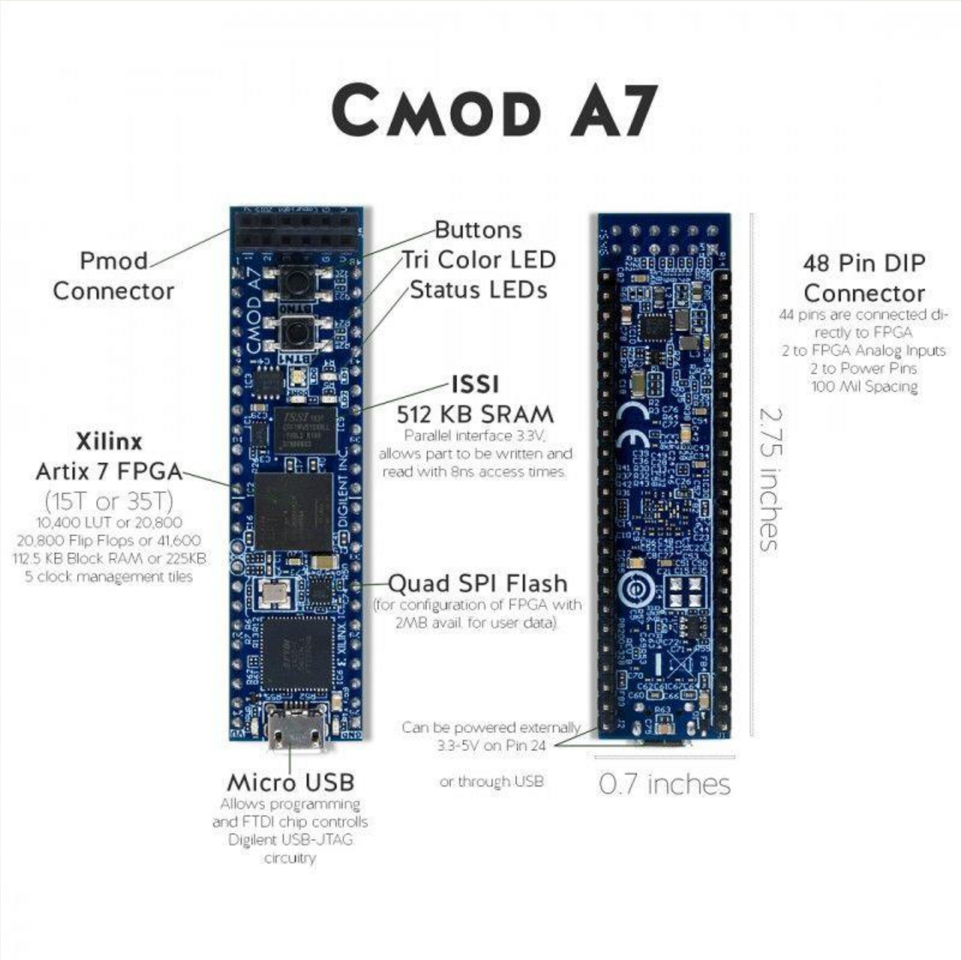
MicroBlaze Processor Device Utilization - Artix-7 FPGAs

Configuration	Device Resources (32-bit) LUTs	FFs	BRAMs (36K)	F_{max} (MHz)
Microcontroller Preset	1174	811	0	218
Real-time Preset	2467	2121	6	177
Application Preset	4326	3747	19	149
Minimum Area	625	227	0	267
Maximum Performance	4106	3208	19	153
Maximum Frequency	911	553	0	267
Linux with MMU	3515	3122	11	150
Low-end Linux with MMU	2987	2506	7	151
Typical	2014	1682	6	187
Frequency Optimized	5956	5787	14	166

	Device	Logic Cells	Configurable Logic Blocks (CLBs)				DSP48E1 Slices(2)	Block RAM Blocks(3)			CMTs(4)	PCIe(5)	GTPs	XADC Blocks	Total I/O Banks(6)	Max User I/O(7)
			Slices(1)	Flip-Flops	LUTs	Max Distributed RAM (Kb)		18 Kb	36 Kb	Max (Kb)						
Artix-7	XC7A35T	33,280	5,200	41,600	20,800	400	90	100	50	1,800	5	1	4	1	5	250
Zynq-7000	XC7Z020	85K	13,300	106,400	53,200		220		140	4.9 Mb	4	0	0	2		

Notes:
1. Each 7 series FPGA slice contains four LUTs and eight flip-flops; only some slices can use their LUTs as distributed RAM or SRLs.
2. Each DSP slice contains a pre-adder, a 25 x 18 multiplier, an adder, and an accumulator.
3. Block RAMs are fundamentally 36 Kb in size; each block can also be used as two independent 18 Kb blocks.
4. Each CMT contains one MMCM and one PLL.
5. Artix-7 FPGA Interface Blocks for PCI Express support up to x4 Gen 2.
6. Does not include configuration Bank 0.
7. This number does not include GTP transceivers.

Platforms for custom made systems
CMOD-A7



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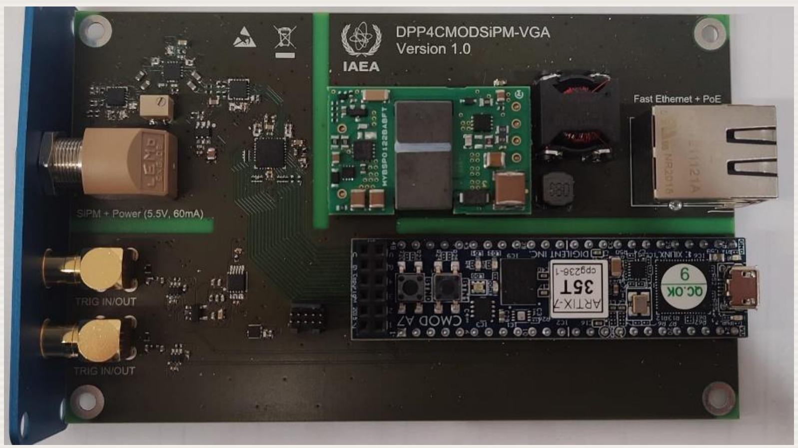
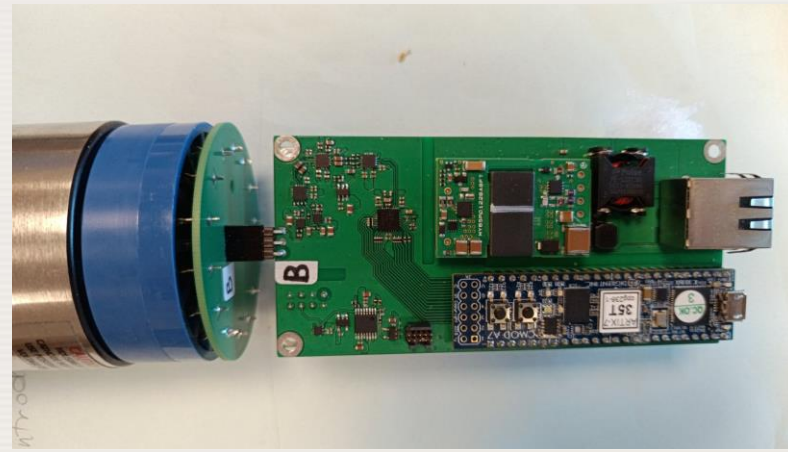
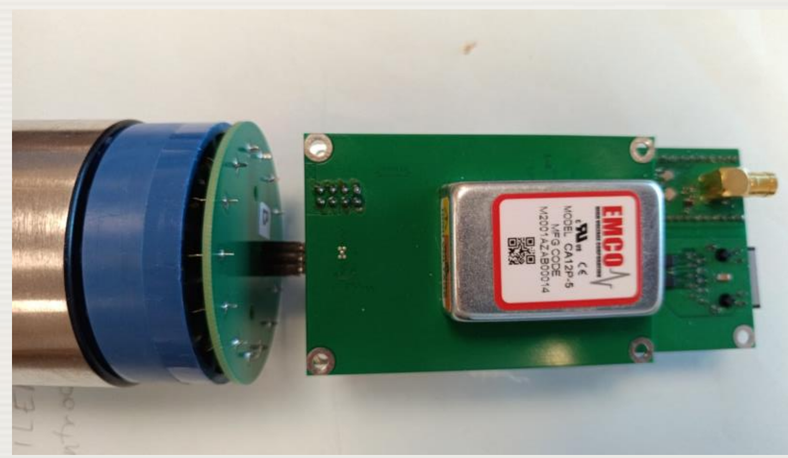
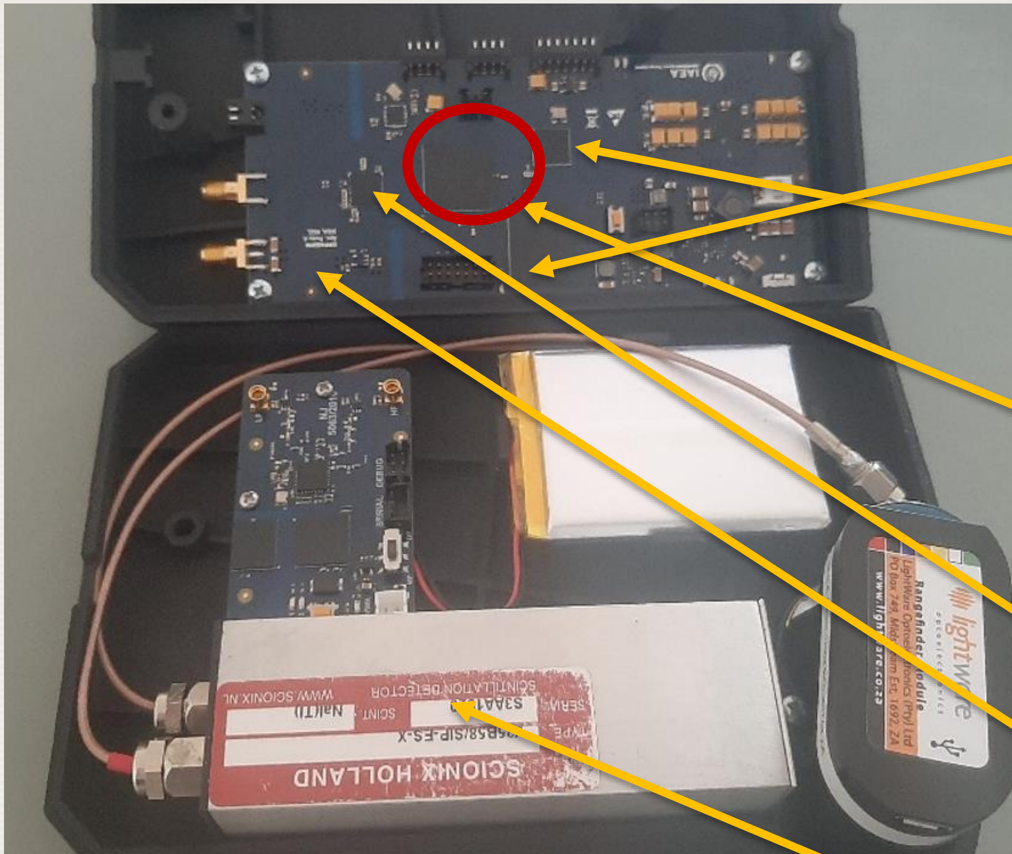
IAEA Platforms for custom made systems CMOD-A7







IAEA Custom made system DPP for UAV



eMMC

ARM uC

FPGA

FAST ADC

Preamplifier

Detector

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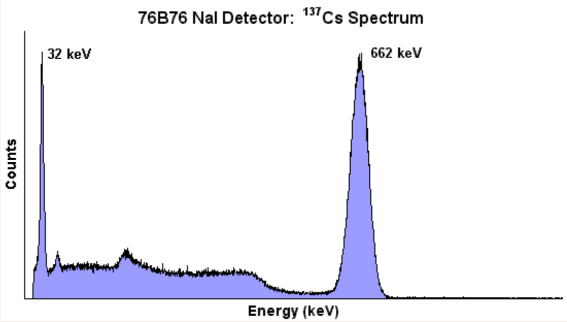
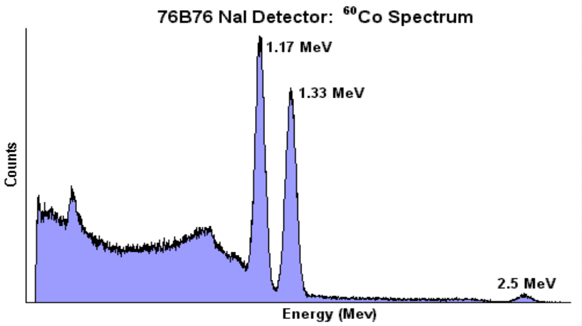
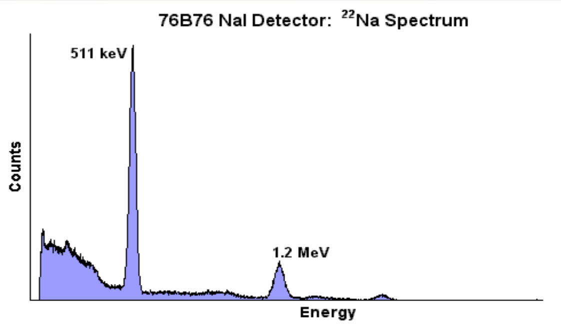
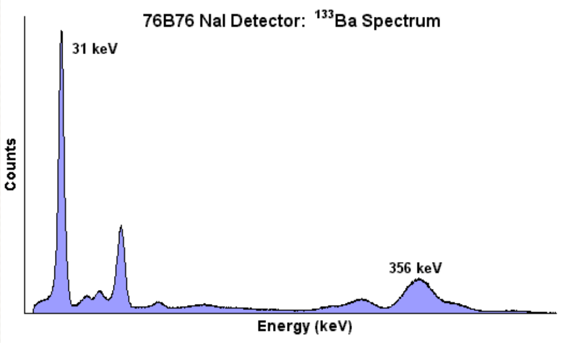
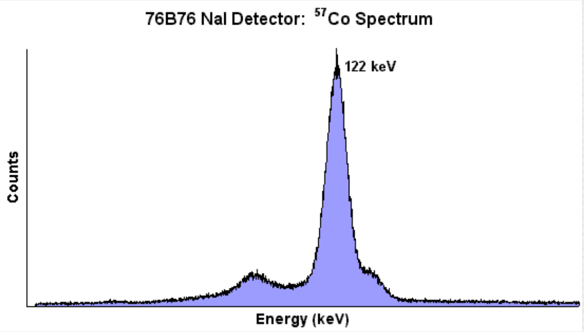
Shape of the Spectrum
Examples

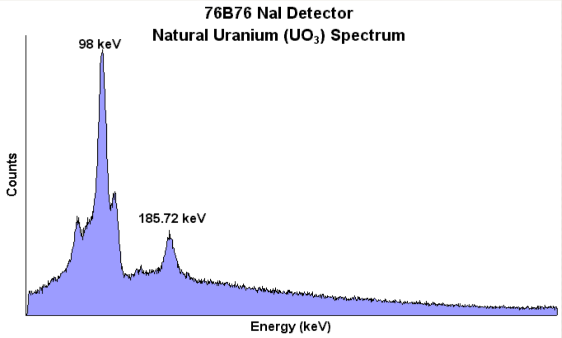












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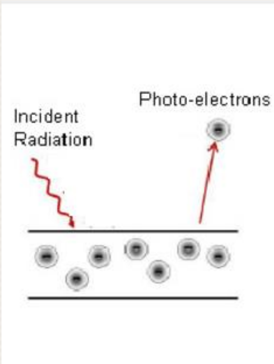
Interaction of γ Radiation with Matter

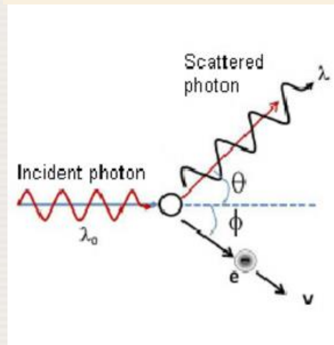
Photo effect



$$E_e = E_\gamma - E_b$$

$$\sigma_{phe} \approx \frac{Z^n}{E_\gamma^m}$$ n=3 to 5, m=3 to 4

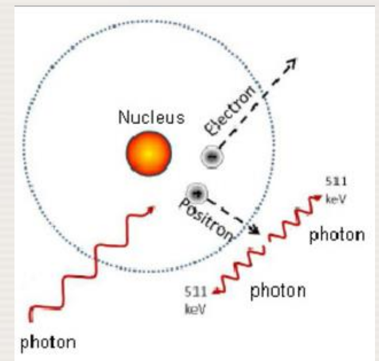
Compton scattering



$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - cos\theta)}$$

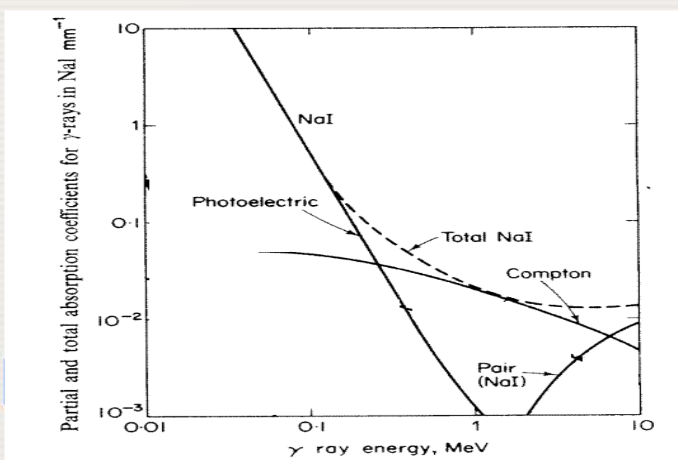
$\sigma_{cs} \approx$Z

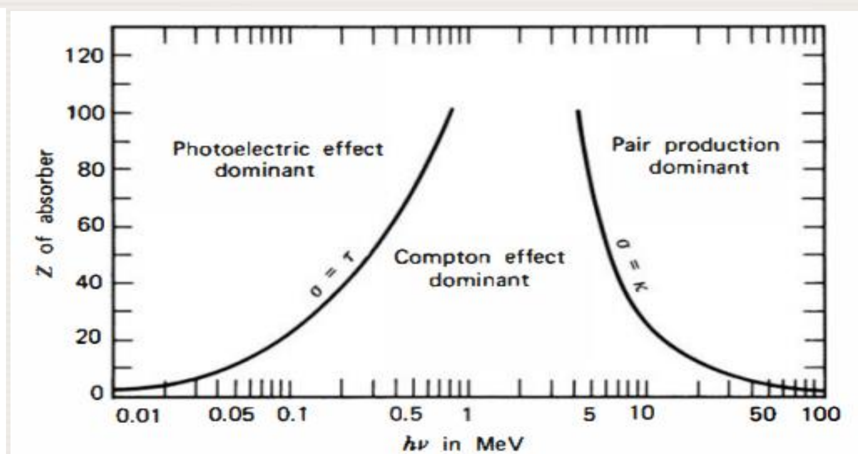
Pair production



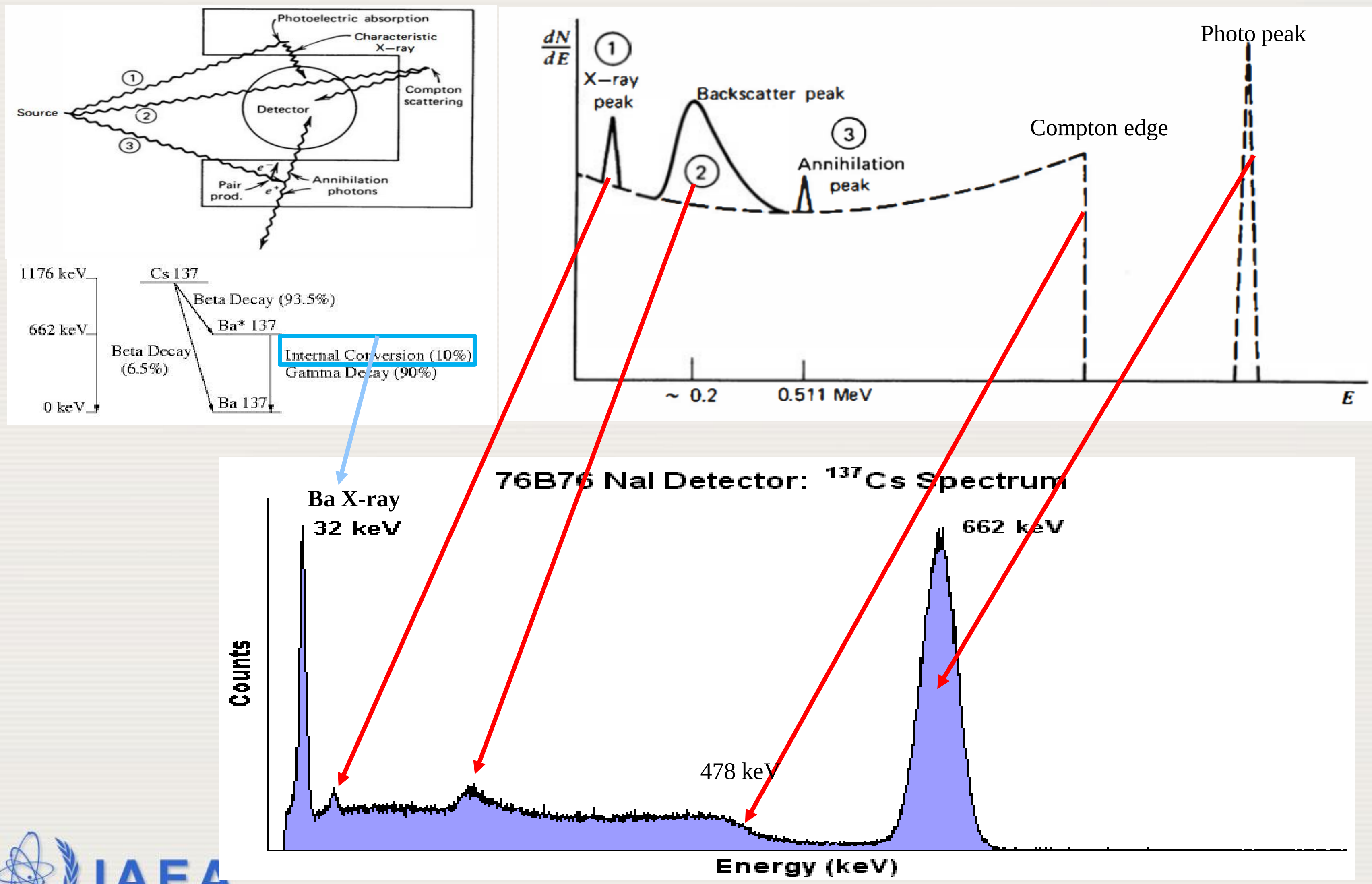
$Z + \gamma \longrightarrow e^- + e^+$

$\sigma_{cs} \approx Z^2$





Shape of the Spectrum Summary



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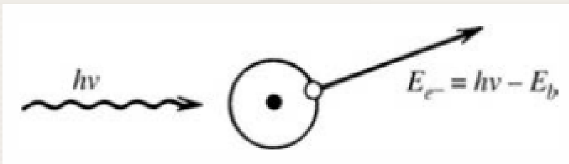
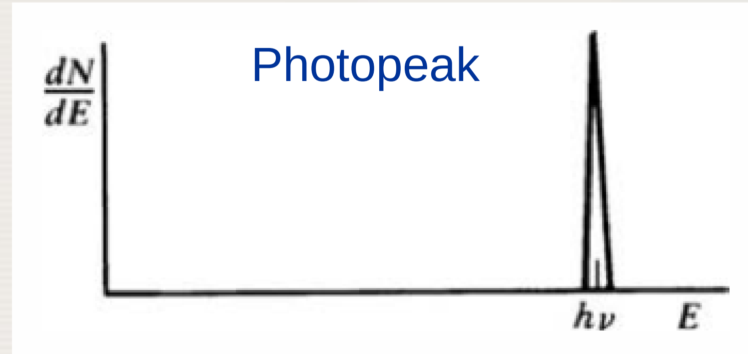
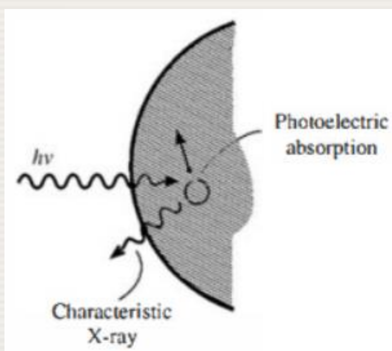
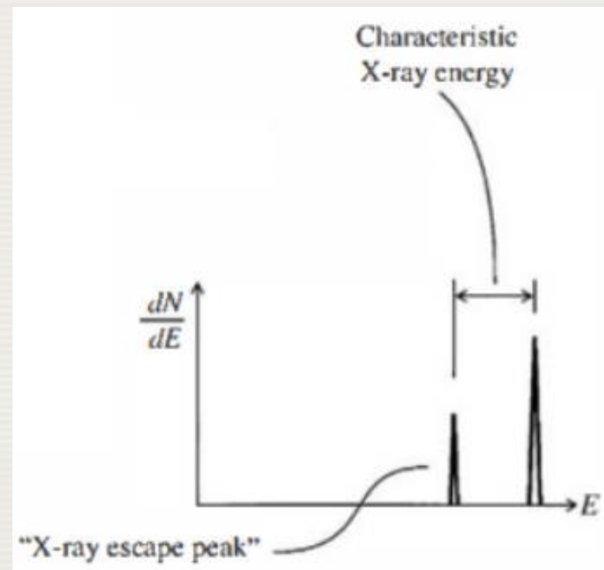
Shape of the Spectrum
Photo Absorption → Photopeak

Photoelectric absorption



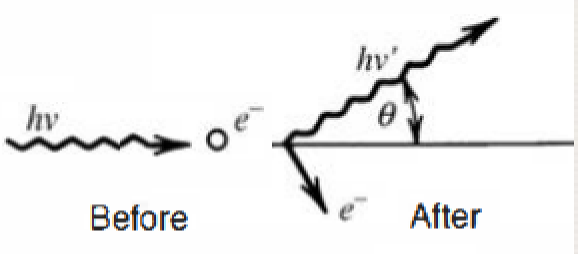




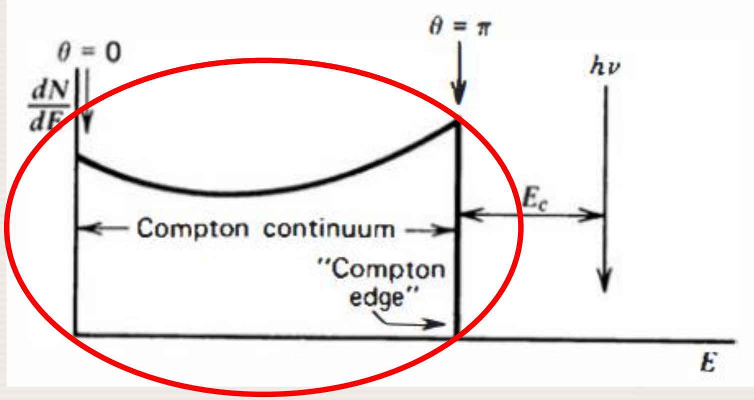


Shape of the Spectrum
Compton Scattering → Continuum

Compton Scattering



Compton continuum



$$E_{e^-} = h\nu - h\nu' = h\nu\left(\frac{(h\nu/m_0c^2)(1-\cos\theta)}{1+(h\nu/m_0c^2)(1-\cos\theta)}\right)$$

Grazing angle: $\theta \cong 0.$ → $E_{e^-} \cong 0$

Head-on collision: $\theta = \pi$ → $E_{e^-} = h\nu - E_C$ $\quad E_C = \dfrac{h\nu}{1+2h\nu/m_0c^2}$

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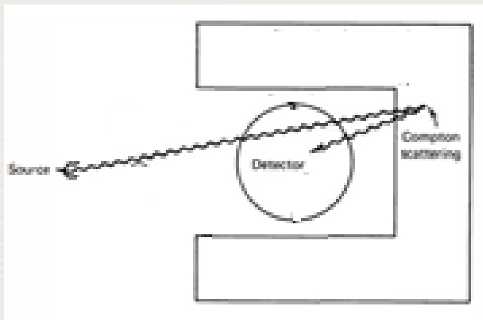
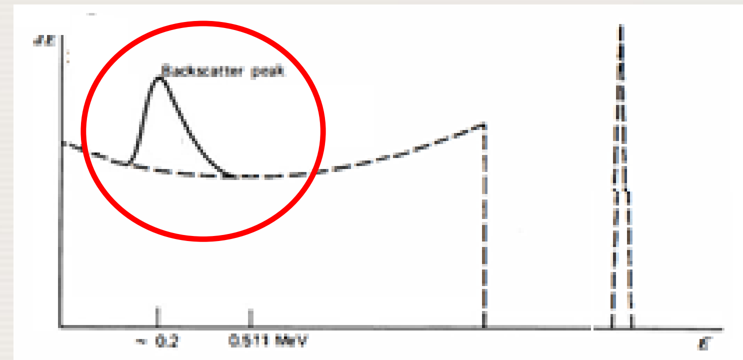
Shape of the Spectrum
Back-scattering → Backscatter peak





Back-scattering:

$$\theta = \pi.$$

$$E_C = \frac{h\nu}{1 + 2h\nu/m_0c^2}$$ $$h\nu \gg m_0c^2/2,$$ $$\Rightarrow$$ $$E_C \cong \frac{m_0c^2}{2}(= 0.256\,\mathrm{MeV})$$ $$E_{e^-} = E_C$$

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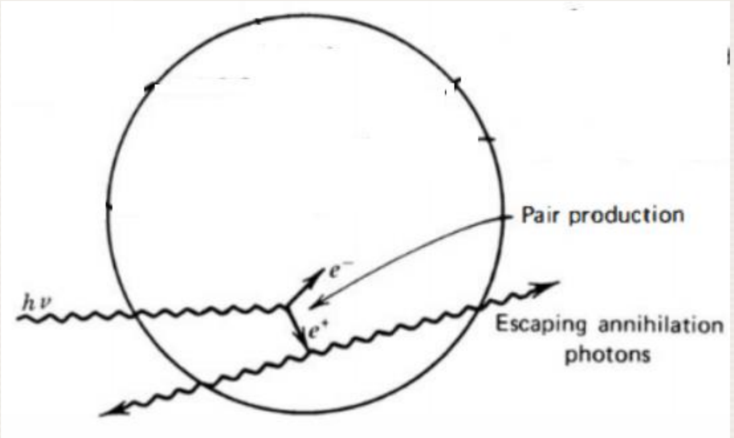
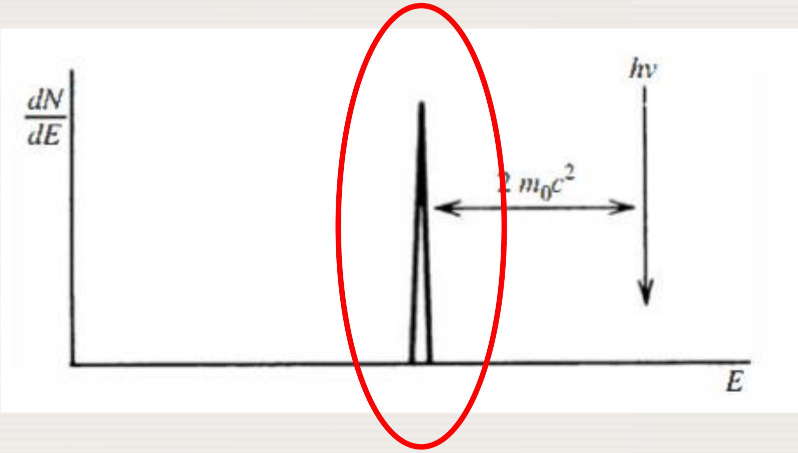
Shape of the Spectrum
Pair Production → Escape peaks



Pair production



Double escape peak

$$E_{e^-} + E_{e^+} = h\nu - 2m_0c^2$$

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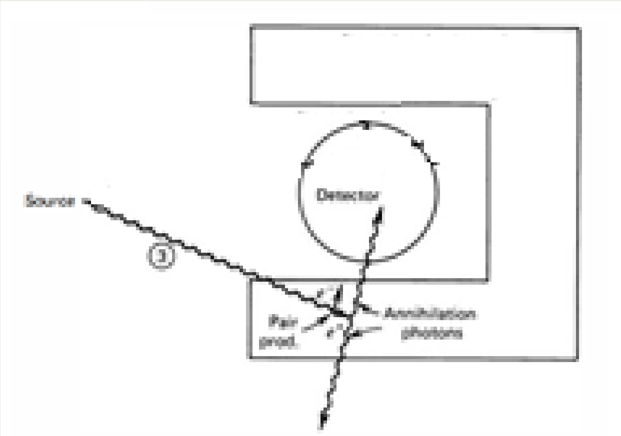
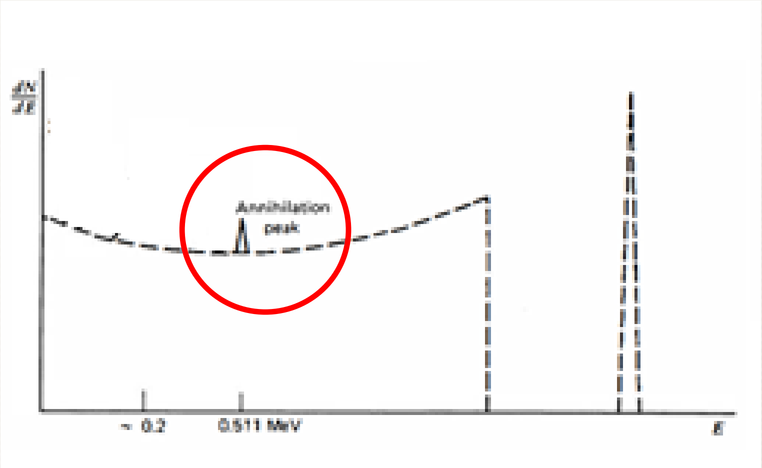
Shape of the Spectrum
Pair production → Annihilation peak





- pair production within high-Z surrounding materials can give a significant yield of annihilation radiation
- A peak (called annihilation) can therefore appear at 0.511 MeV in the spectrum from the detection of these secondary photons

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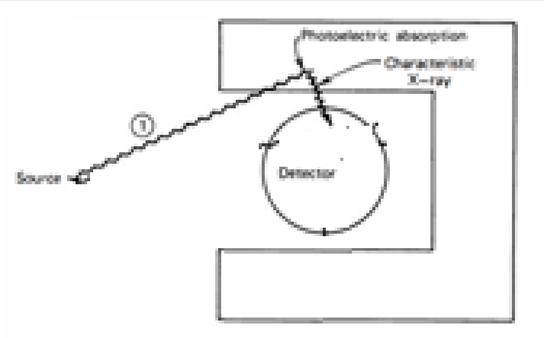
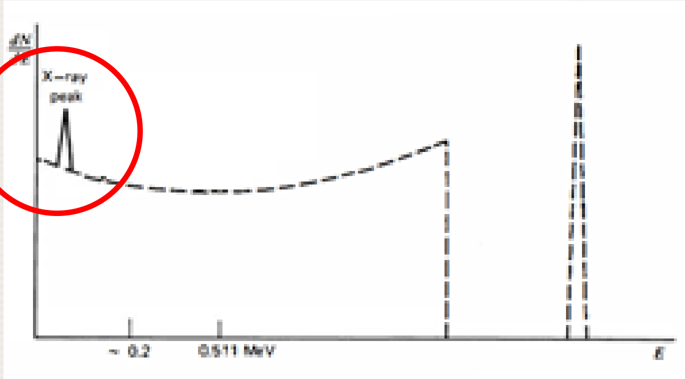
Shape of the Spectrum Characteristic X - Rays





- Photoelectric absorption in the materials immediately surrounding the detector can lead to generation of a characteristic X-ray that may reach the detector.

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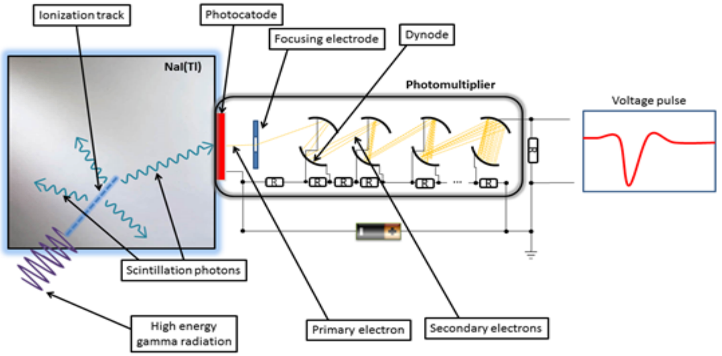
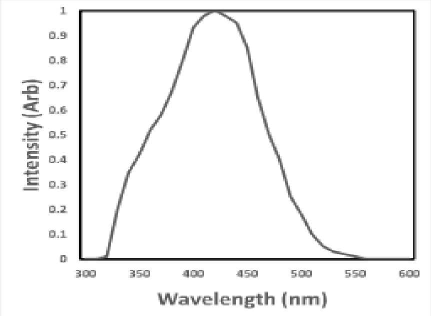
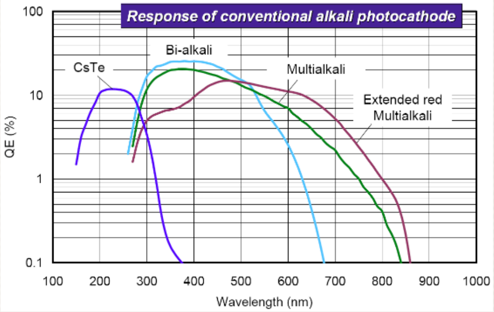
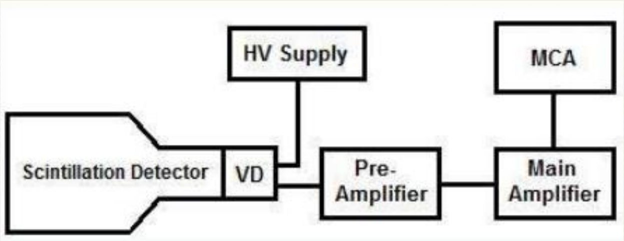
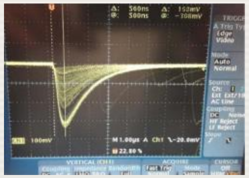
Scintillator Detectors with PMT

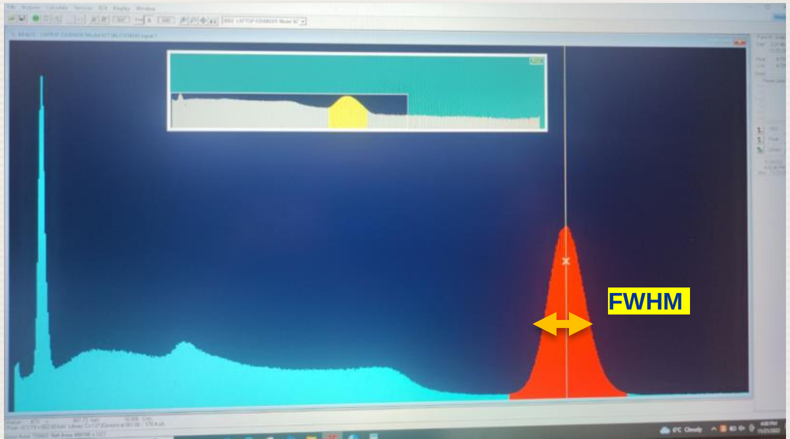










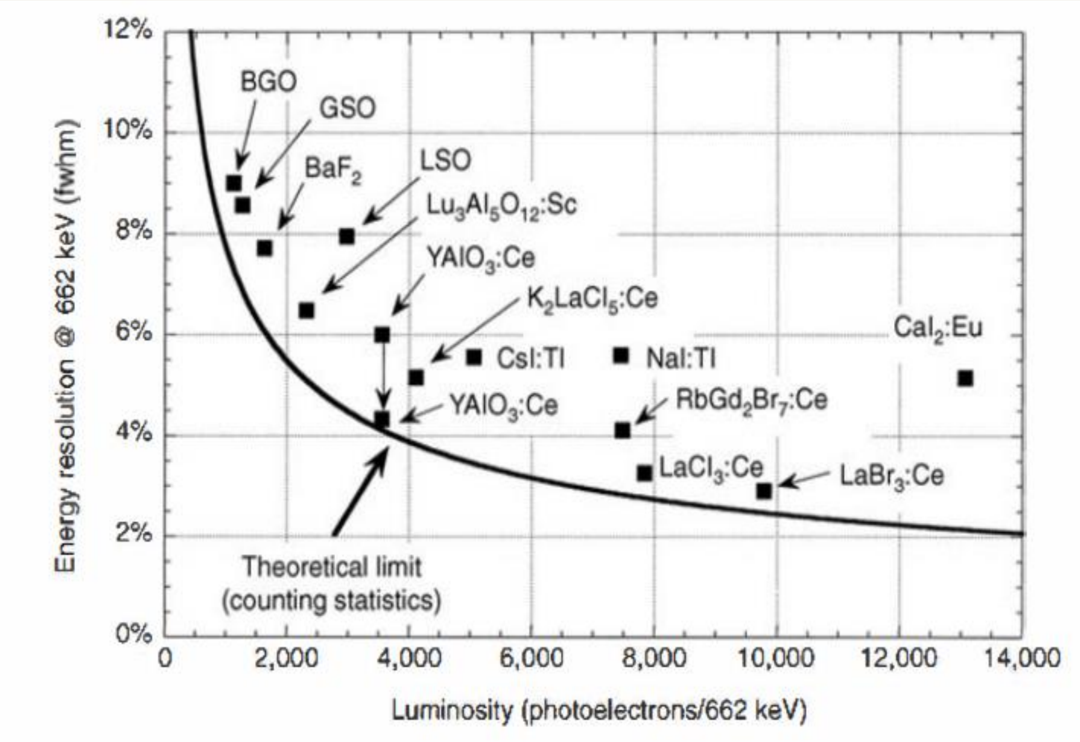


Scintillator detectors resolution

Theoretical Resolution $FWHM$ depends on variation of number of photo-electrons that are generated on the photo cathode (PMT, $counting$ $\boldsymbol{statistics}$)

$$\frac{FWHM(theoreticl\ limit)[keV]}{E} \cong 2.35 \frac{1}{\sqrt{N_{phe}}}$$

In practice resolution of a good NaI(Tl) detector at 662 keV Cs-137 photo peak is 6%-7%



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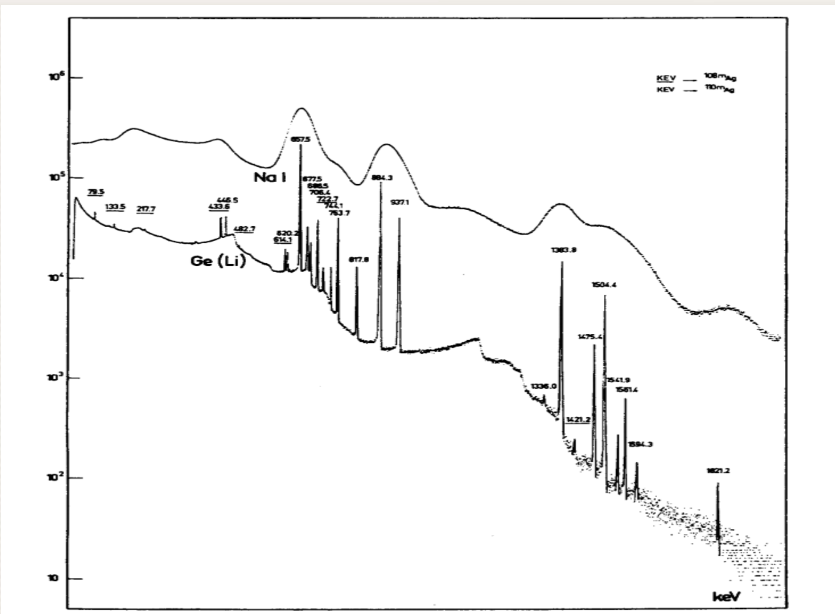
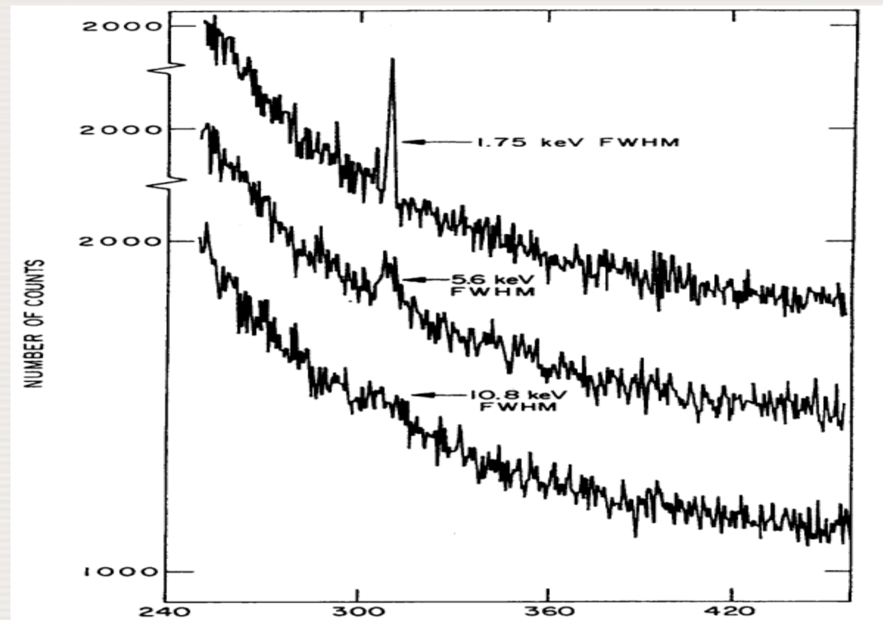
Why Detector Resolution is Important?



- To better recognize structure in spectra



- To improved sensitivity: signal counts in fewer channels compete with fewer background counts

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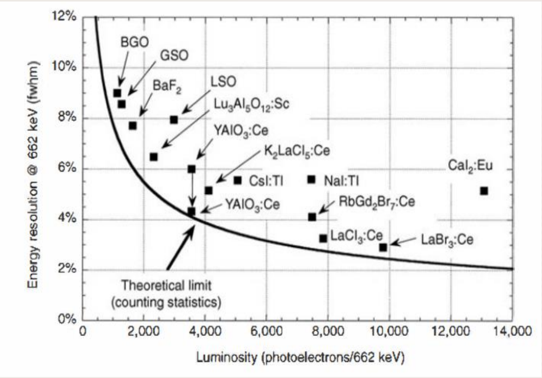
Resolution: Scintillators vs Germanium

Scintillators

- Electronic circuits noise (below keV)
- Statistical variation in production of photo electrons
- Intrinsic resolution od scintillator

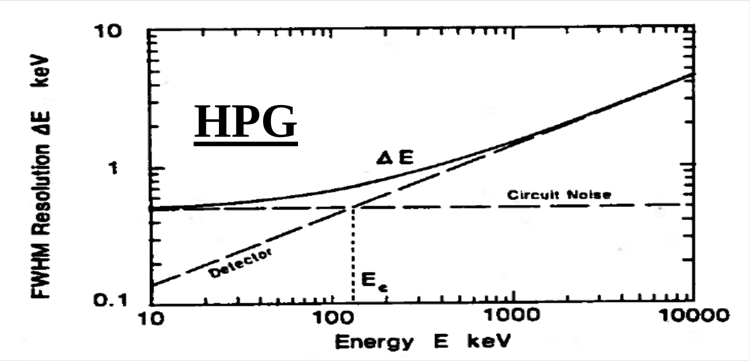


$$\frac{FWHM_{stat}\,[keV]}{E} = 2.35\frac{1+\vartheta_M}{\sqrt{N_{phe}}}$$

$$FWHM(662keV) > 2\%$$

Semiconductors

- Electronic circuits noise
- Statistical variation in production of charge carriers



$$FWHM = 2.35\sqrt{E\cdot F\cdot W + \left(W\cdot Q_n\right)^2}$$

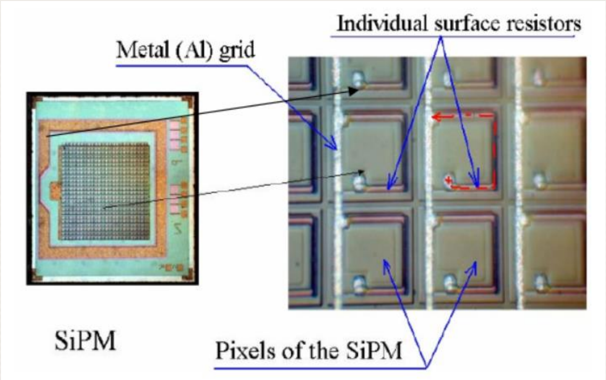
$$Q_n = electronic\ noise\ (ENC)$$

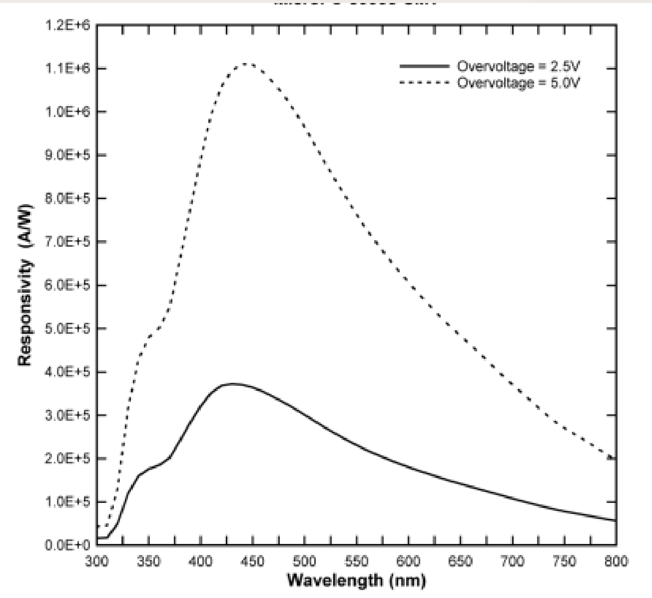
F=Fano factor 0.129 at 77K
W=average energy for e-h production 2.9eV

$$FWHM(662keV) = 1.3keV = 0.2\%$$

Scintillator Detectors with Silicon Photo Multipliers (SiPM)

- A SiPM is array of 1000s APD operating above breakdown voltage
- Total area < 1cm2 (6mm x 6mm contains ~22000 APDs, each 35umx35um)
- Individual APD are connected in parallel trough a decoupling resistor, which is used for quenching avalanches
- Each element is independent and gives the same signal when fired by single photon from scintillator (400 nm)





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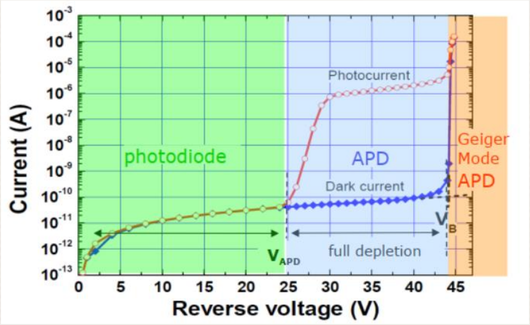
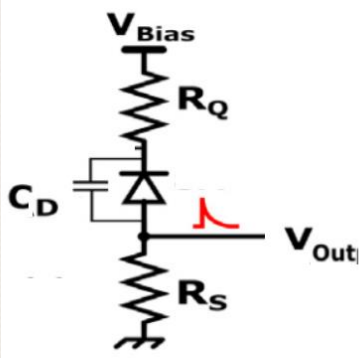
Scintillator Detectors with Silicon Photo Multipliers (SiPM)

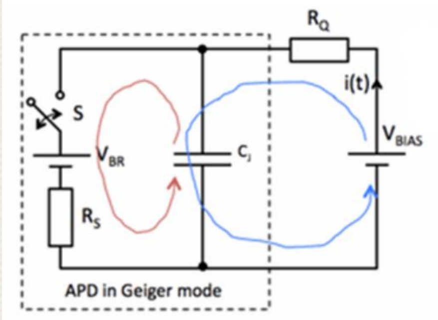
- Output charge is proportional to the number of incident photons, gain M=10^5 to 10^6

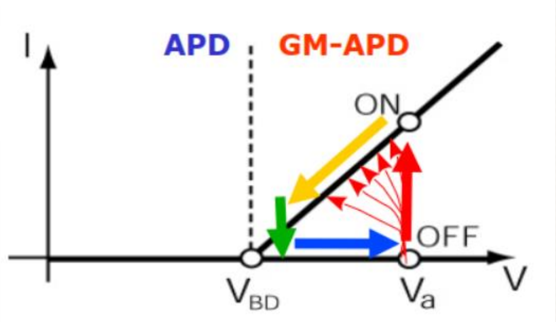


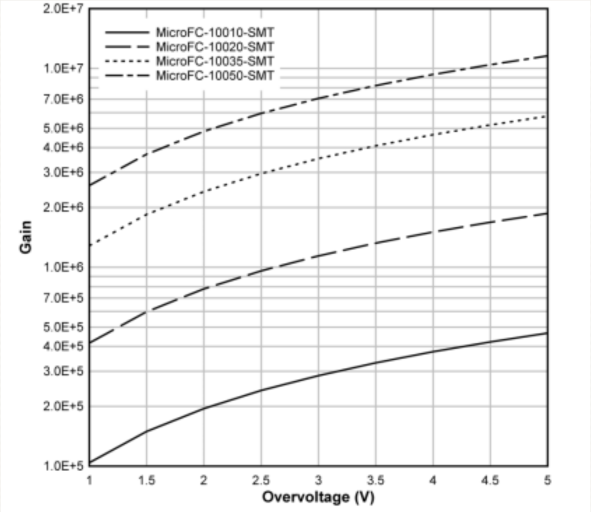


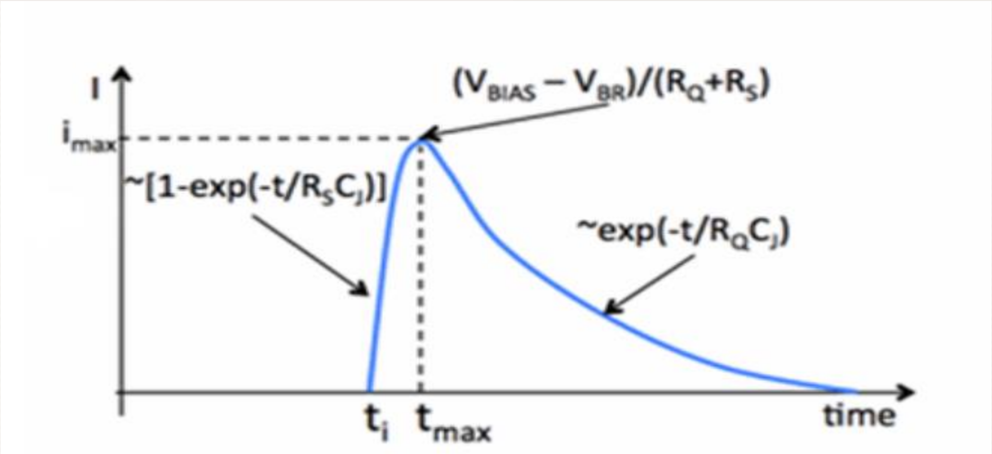
$$i_{max} \approx \frac{V_{BIAS} - V_{BD}}{R_Q + R_S} = \frac{\Delta V}{R_Q + R_S}$$

$$M = \frac{Q}{e} = \frac{\Delta V \cdot C_J}{e}$$









Scintillator Detectors with Silicon Photo Multipliers (SiPM)

Advantage

- Low voltage operation (25-30 V)
- Insensitive to magnetic fields
- High gains (10^6)
- Mechanically compact

Disadvantage

- Temperature dependent gain
- noise at higher temperatures
- cost per cm2

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