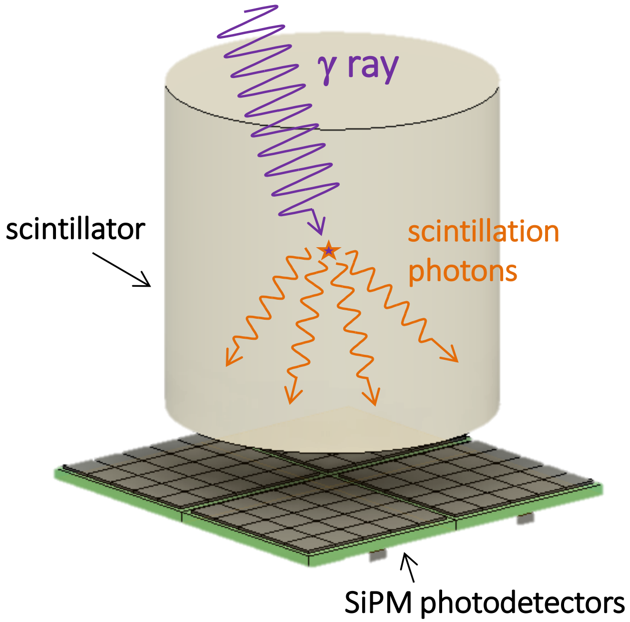

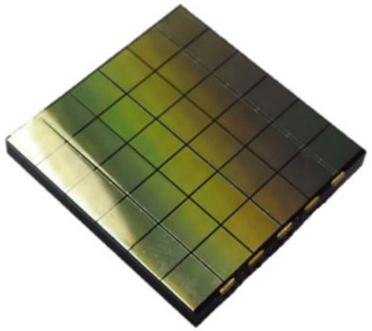

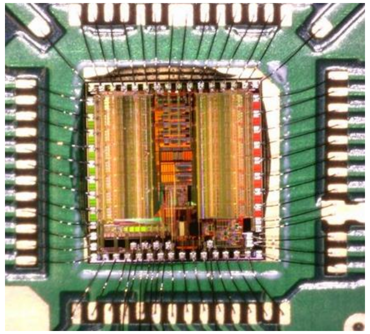

Readout of large scintillators by SiPMs and high-dynamic-range ASICs

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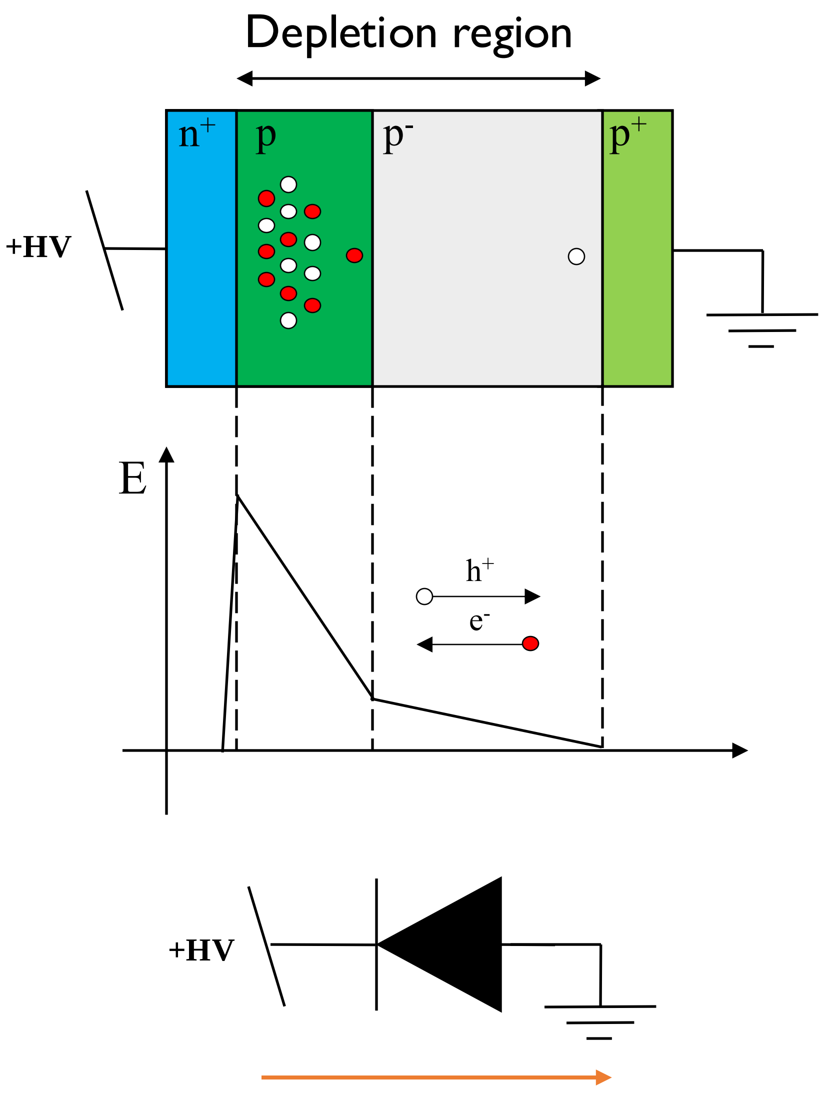
Istituto Nazionale di Fisica Nucleare (INFN) - Sezione di Milano, Milano, Italy

UniMI/INFN-MI Workshop – 17/10/2024

Impact Ionization in a *pn* diode

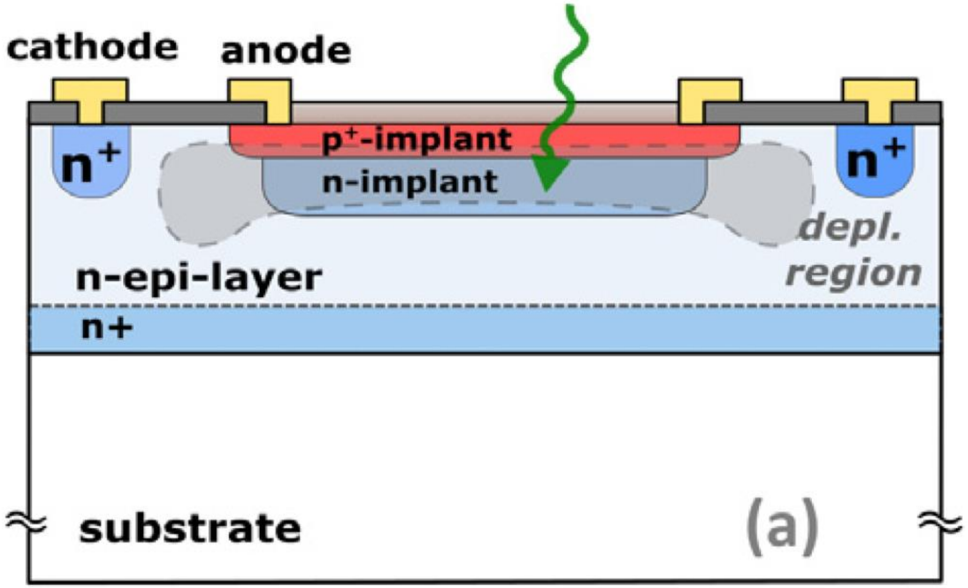


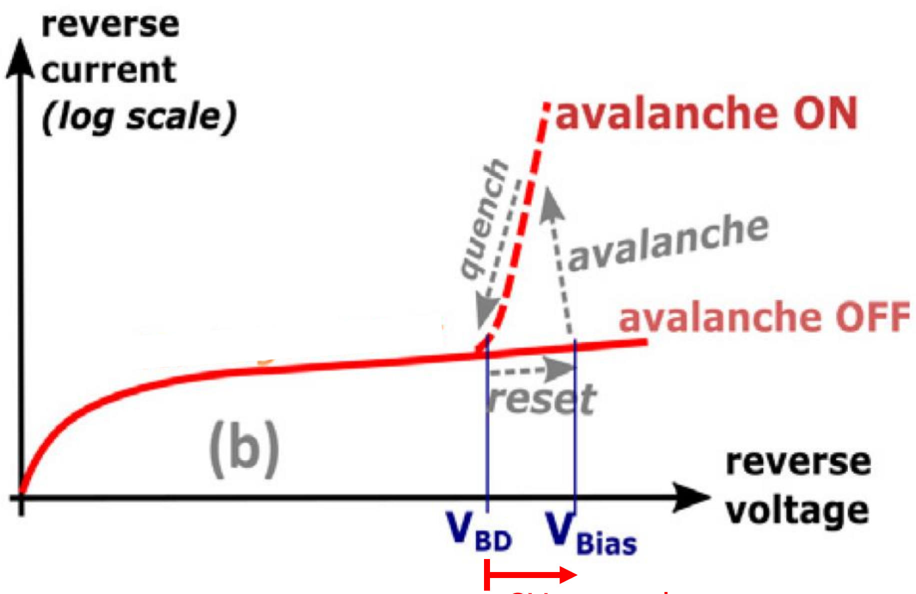
- **High electric field** (>5x10^5 V/cm) in the depletion region
- Charge carrier can be accelerated to create secondary charge pairs through **impact ionization.**

Two different working regimes, depending on the applied voltage to the reverse biased diode:

- APD (Avalanche photodiode): the output current is proportional to the input signal
- **SPAD** (Single Photon APD) or GM-APD (Geiger Mode APD): **the output current is independent from the input signal**

SPAD operation

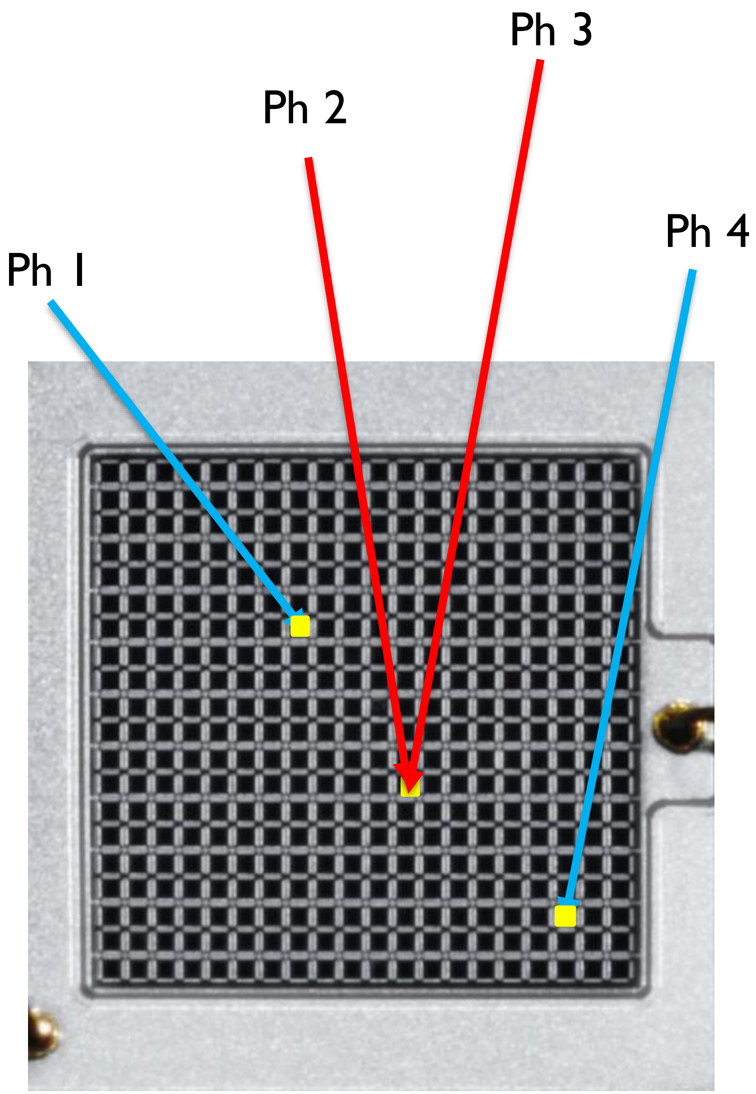




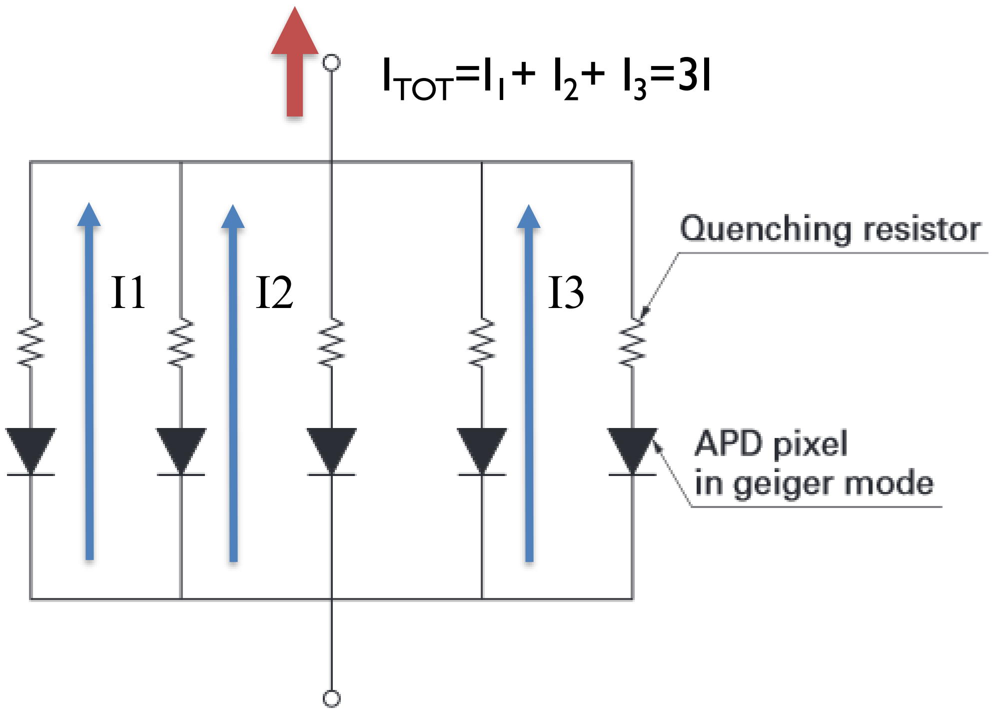
The SPAD <u>is biased above the breakdown voltage</u> (V_{BD}). In such conditions, the electric field is so high that a single carrier generated into the depletion layer (by an incoming photon or by thermal generation) can <u>trigger a self-sustaining avalanche process</u> and a rapid increase of the current to a macroscopic level.

The current theoretically would continue to flow <u>until the avalanche is quenched by lowering the bias voltage</u> to or below the breakdown voltage, by a so called “quenching circuit”. The bias voltage (V_{bias}) must then be restored in order to be able to detect another photon (reset phase).

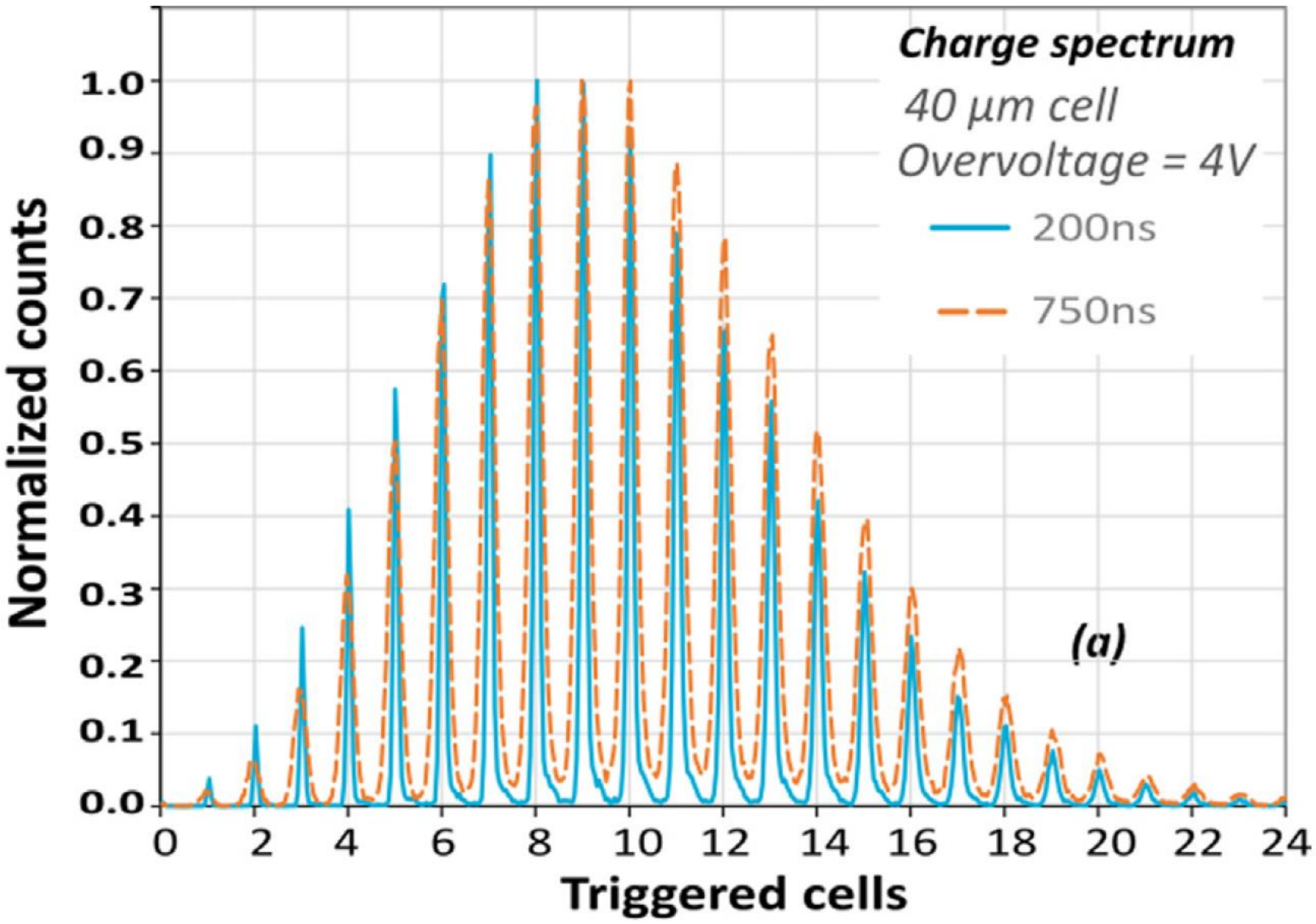
The Silicon Photomultiplier (SiPM) principle



- **Many SPAD cells in parallel** with quench resistors
- The total signal is proportional to the number of fired cells, i.e. to the number of detected photons
- Measuring the 'analog' information of I_{TOT} allows to retrieve the **number of photons absorbed**
- Multiple photons interacting on the same cell are counted as a single hit



Example of single photon detection capability

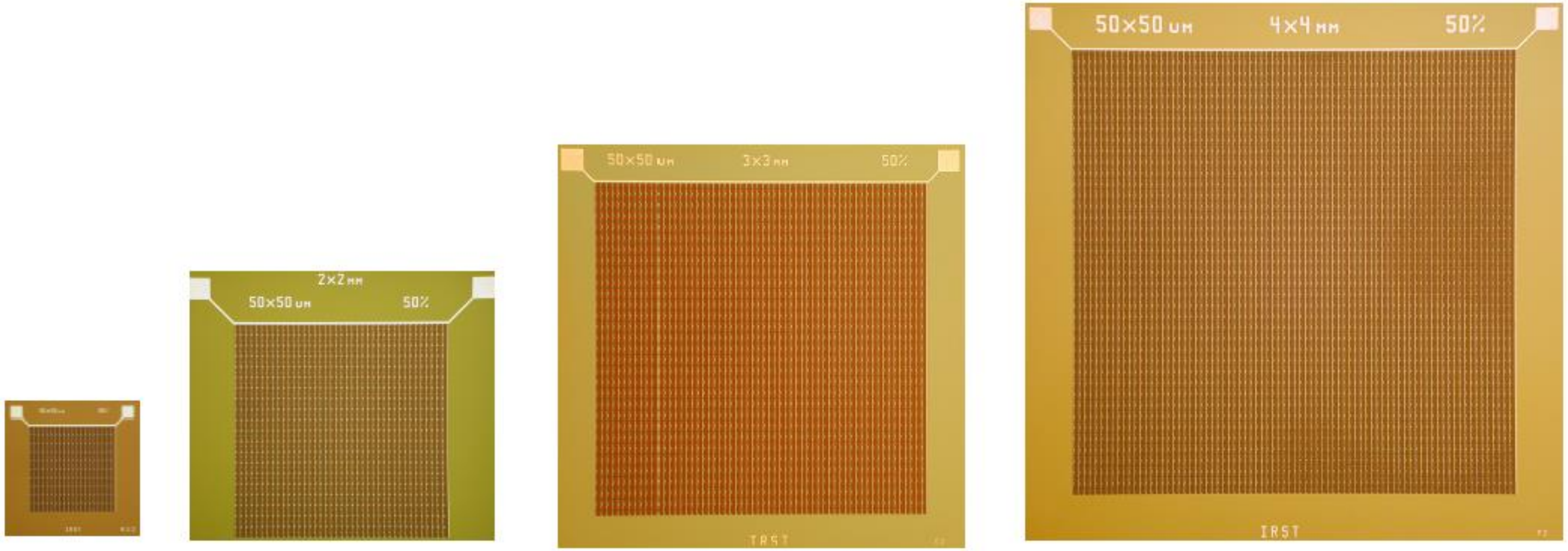


SiPMs (several producers: Hamamatsu, ON-Semi, FBK, ...)

These devices are called in different ways:
- **SiPM: Silicon Photo Multipliers**
- MPPC: Multi-Photon Pixel Counter
- Si-SSPMT: Silicon Solid State PMT

Typical SPAD cell size from 15 µm × 15 µm up to 100 µm × 100 µm

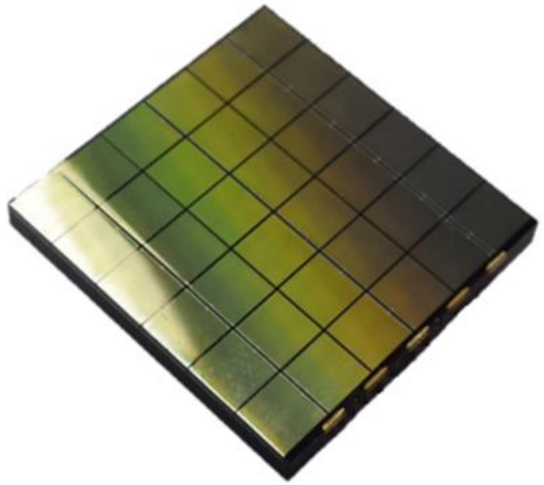
More and more alternative of Photo-Multiplier Tubes (SiPMs are more compact and MR compatible)



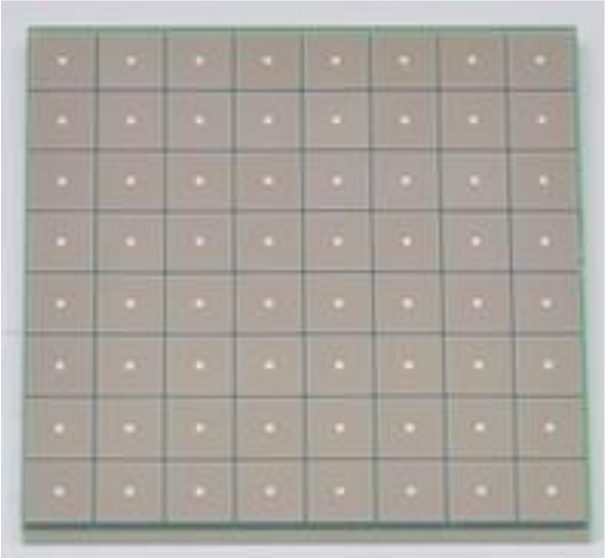
1x1mm 2x2mm 3x3mm (3600 cells) 4x4mm (6400 cells)

SiPM arrays

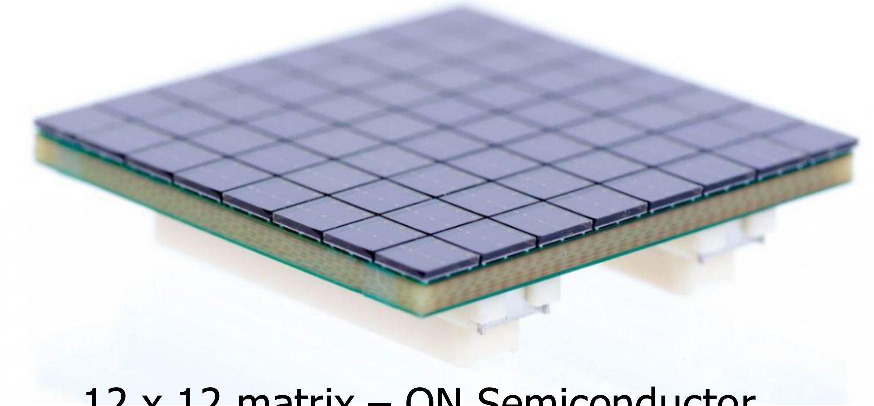
- Arrays of SiPM for Imaging applications
- Compact alignment of SiPMs
- Reduced dead area
- Common bias strategies
- Tilable on 4 sides (Possibility to create larger matrices by combining single units)
- TSV (Through Silicon Via) technology



6 x 6 matrix - FBK



8 x 8 matrix – Hamamatsu



12 x 12 matrix – ON Semiconductor

SiPMs in gamma-ray detection

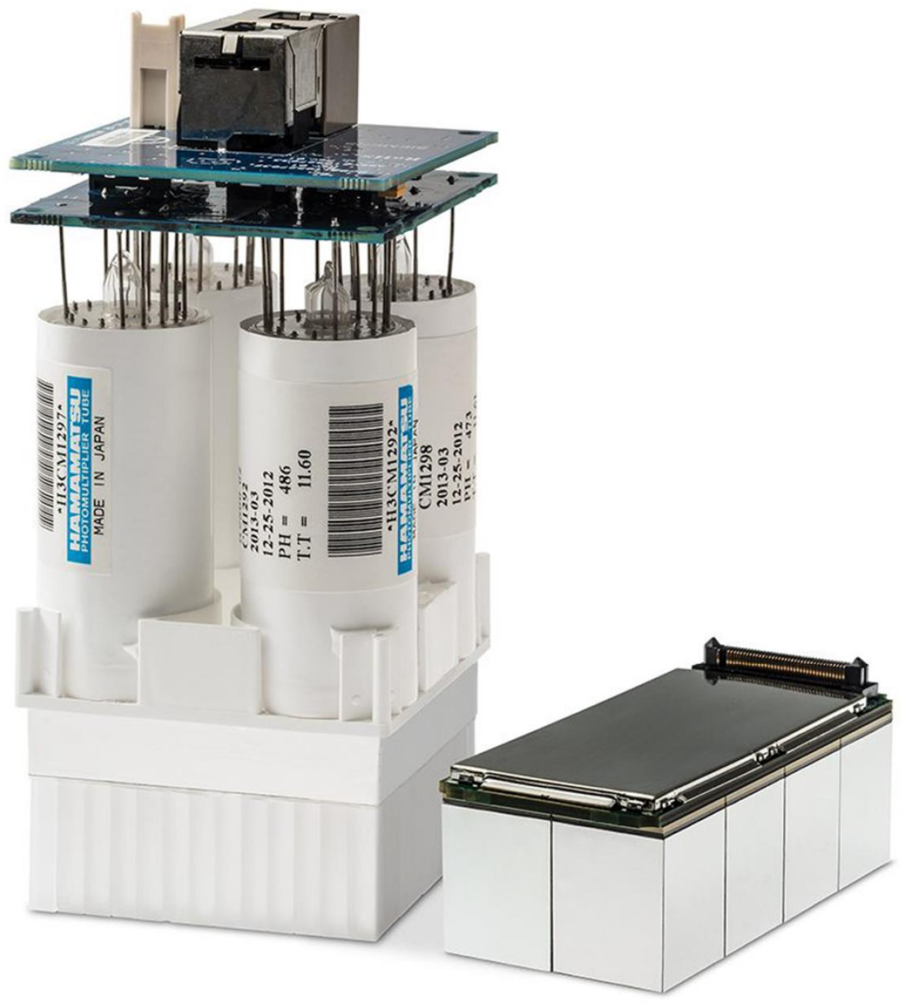
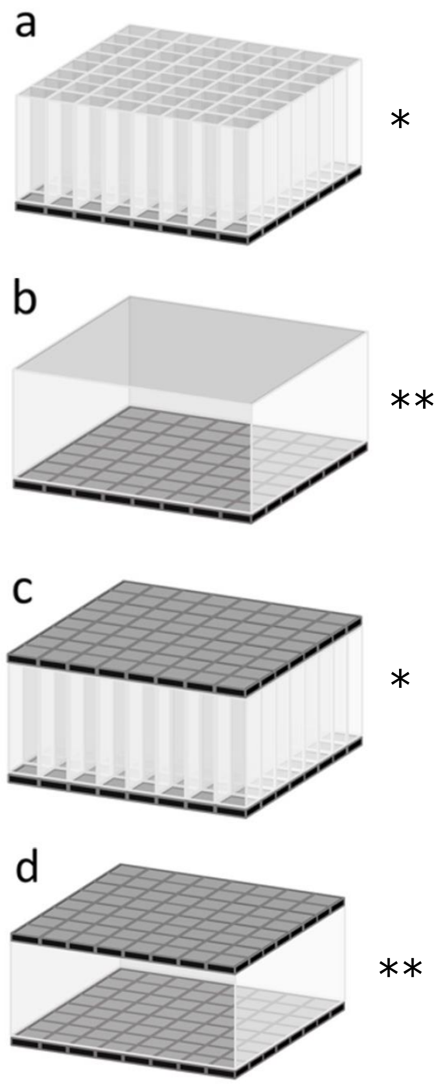


Fig. 2. Picture showing the comparison of PET detectors based on PMTs (left) and on SiPMs (right) in their implementation by Siemens Healthineers (picture from [34]).

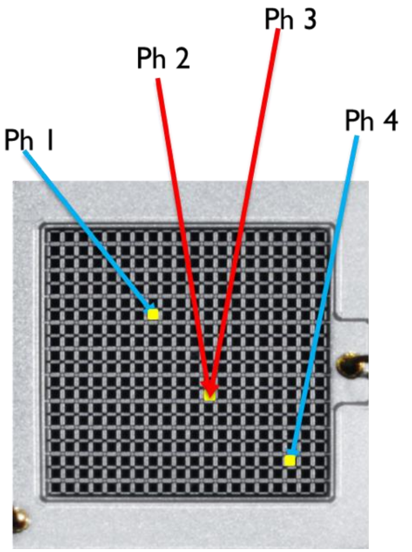
Different scintillator readout configurations:

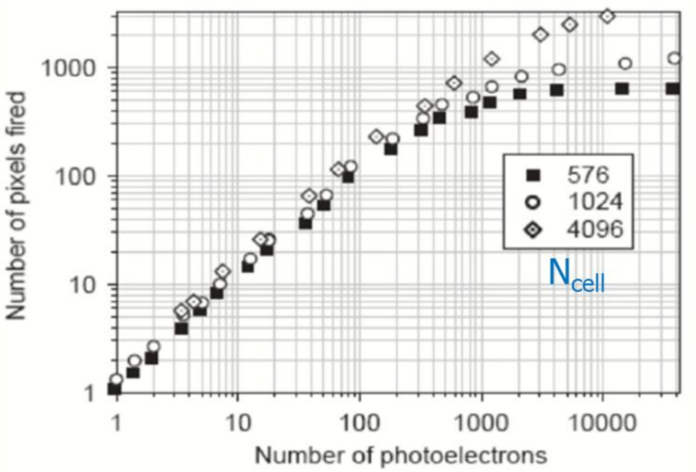


* Pixellated
** Monolithic

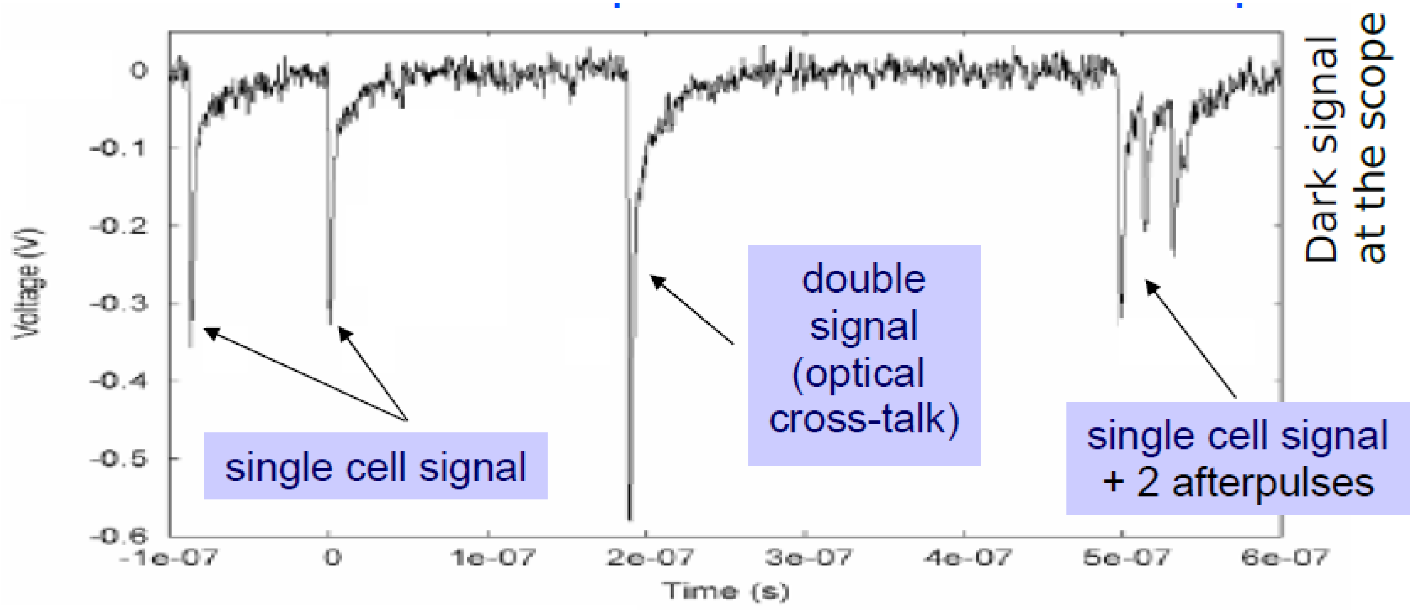
Main limitations of SiPMs

1) Dynamic Range





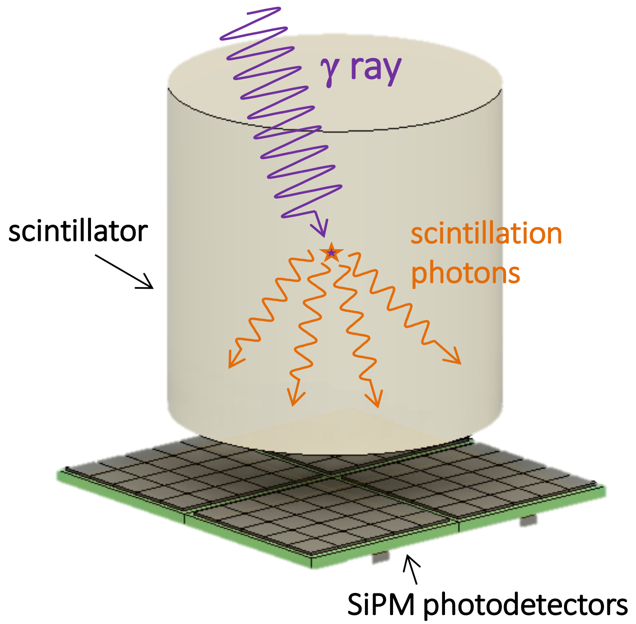
2) Noise



- Primary source: Dark count
- Secondary sources: After pulse, Cross talk

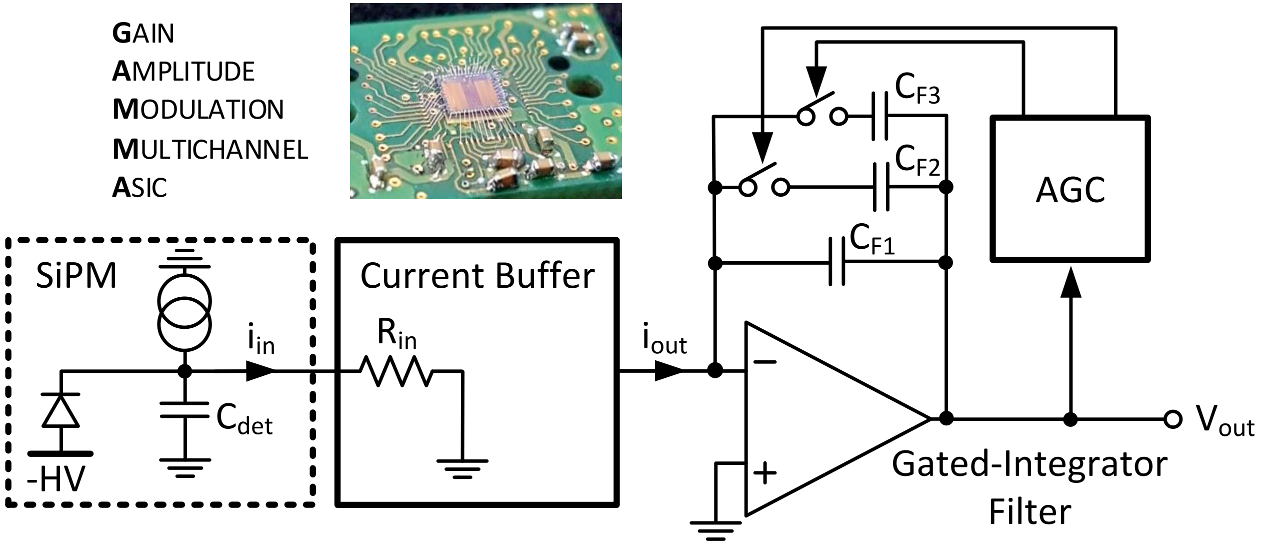
3) Small pixels → to cover large areas, need for a readout ASIC

Automatic Gain Control (AGC) ASIC to cover a high dynamic range (1ph→10.000ph) in γ-spectroscopy

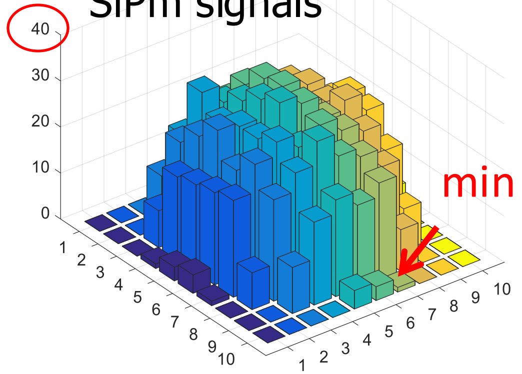


High-dynamic range gamma detectors

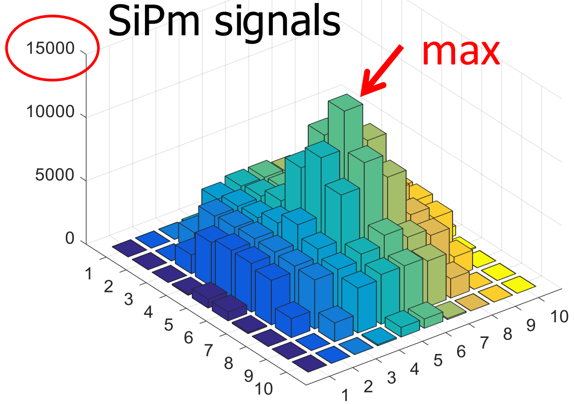
GAIN
AMPLITUDE
MODULATION
MULTICHANNEL
ASIC

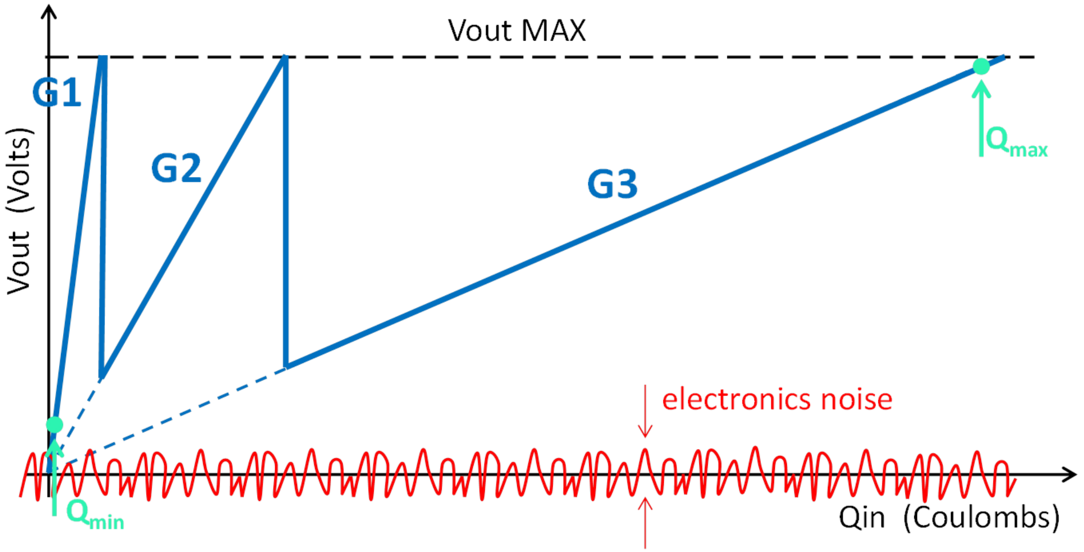


200keV gamma ray:
SiPm signals

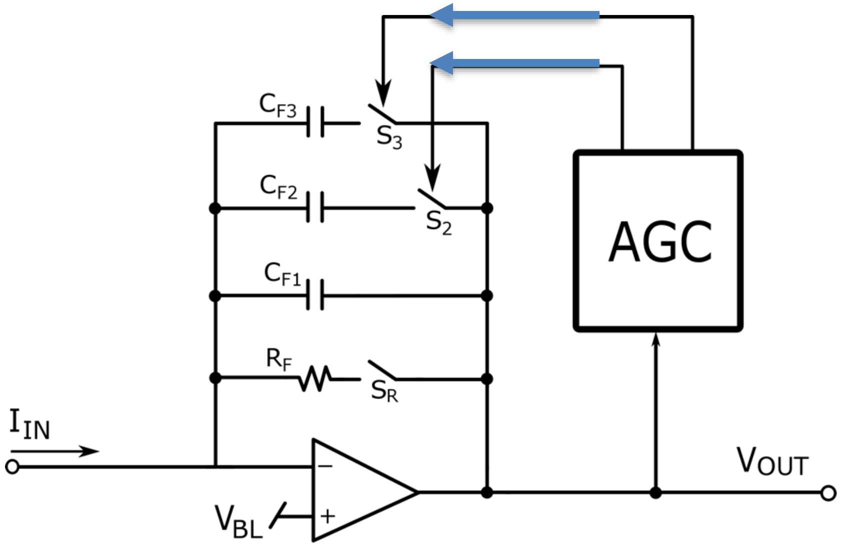


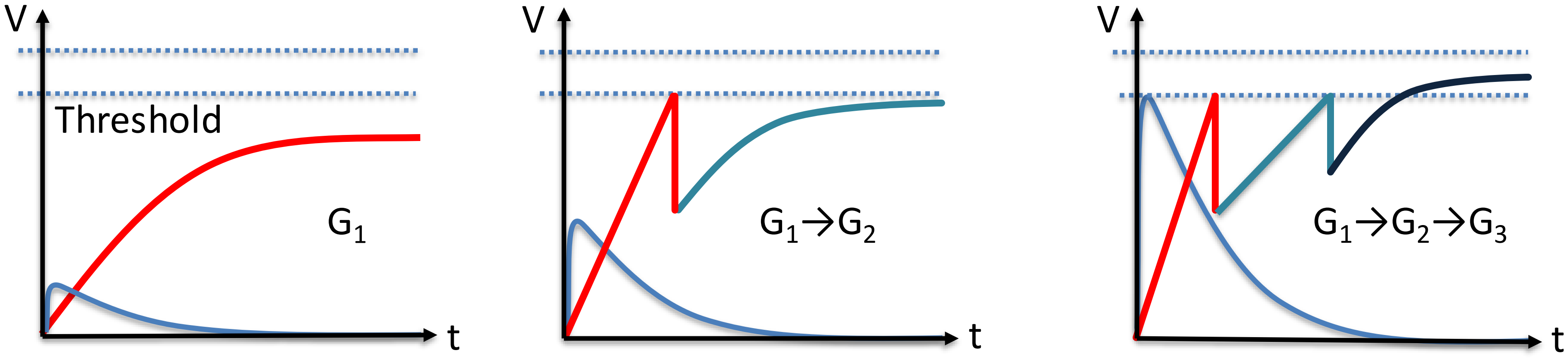
20MeV gamma ray:
SiPm signals



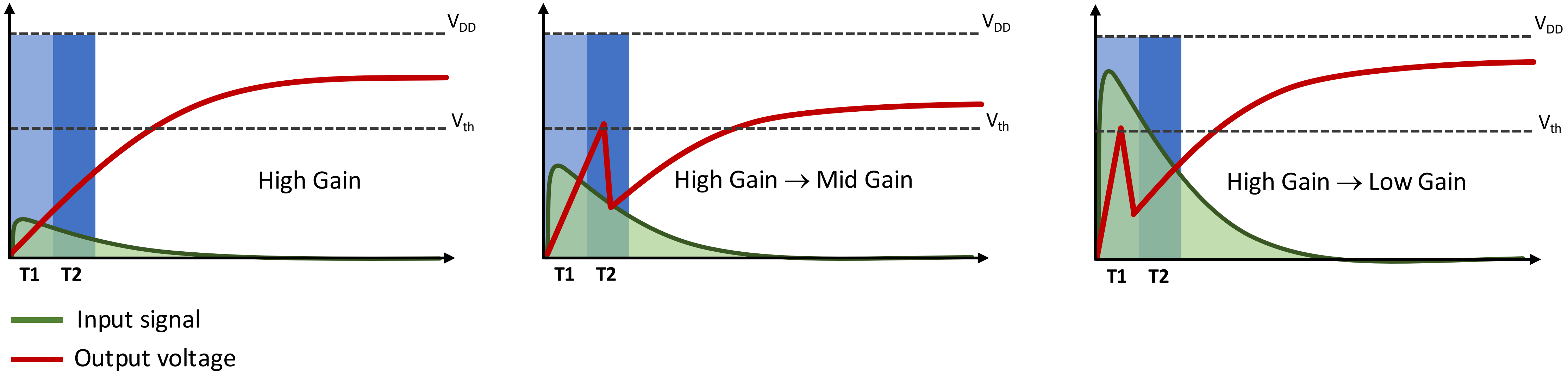


Gain-switching: standard approach





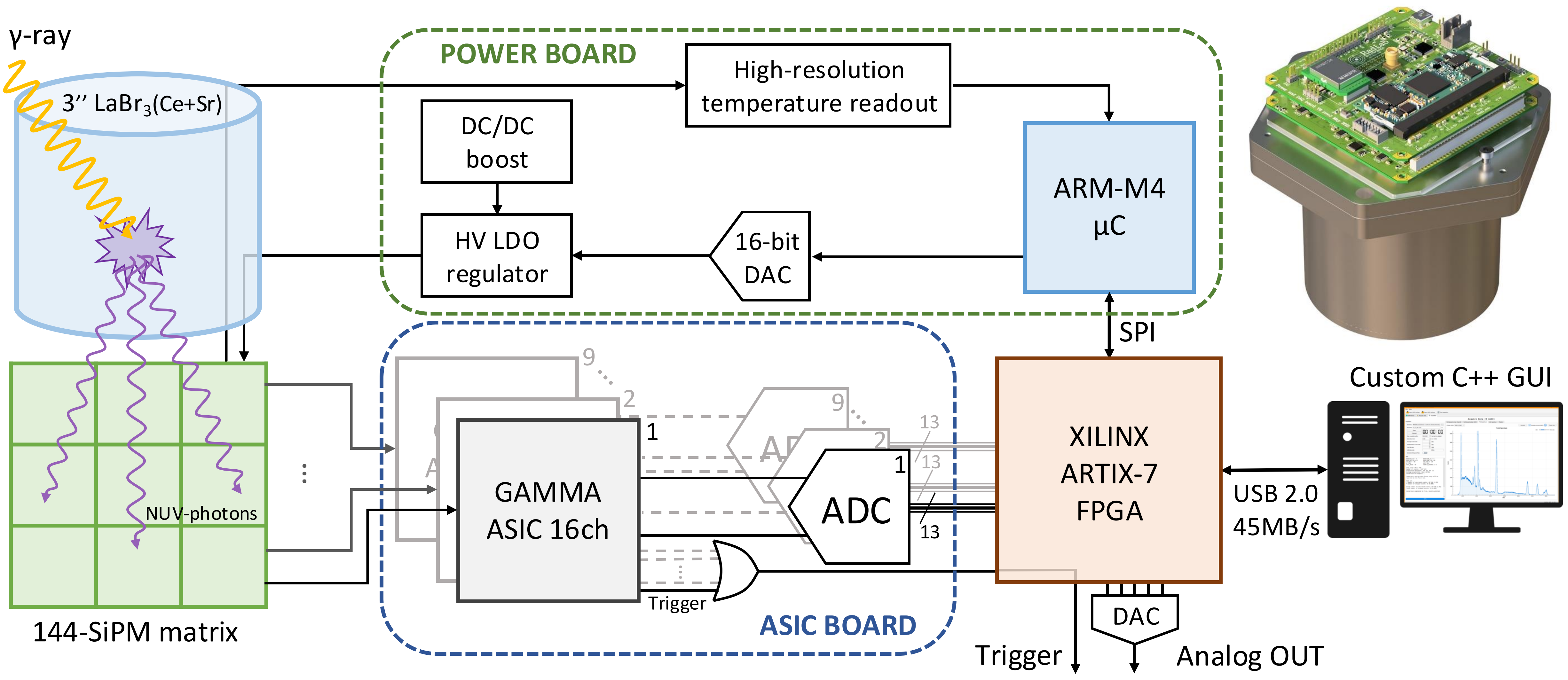
Gain-switching: 'predictive' approach



Features:

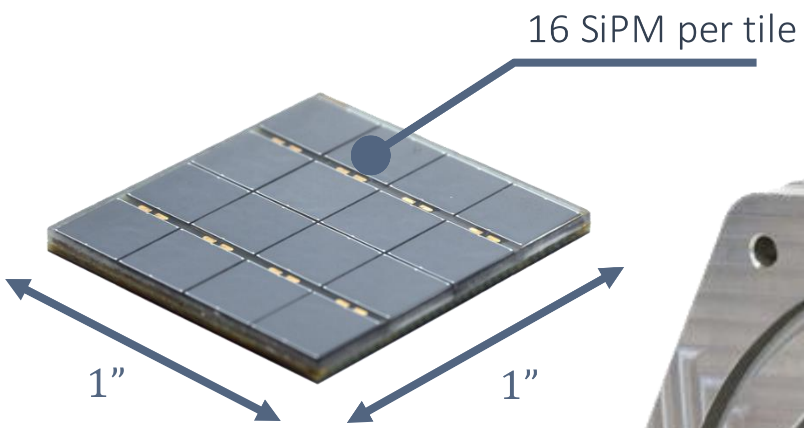
- Only one gain transition among multiple gains
- Relative freedom in setting the threshold
- Gain-switch decision taken quite early vs. end of integration
- Gain modulation allows for 84dB Dynamic Range on each channel!

The GAMMA detector - General architecture



FBK NUV-HD SiPM custom tile

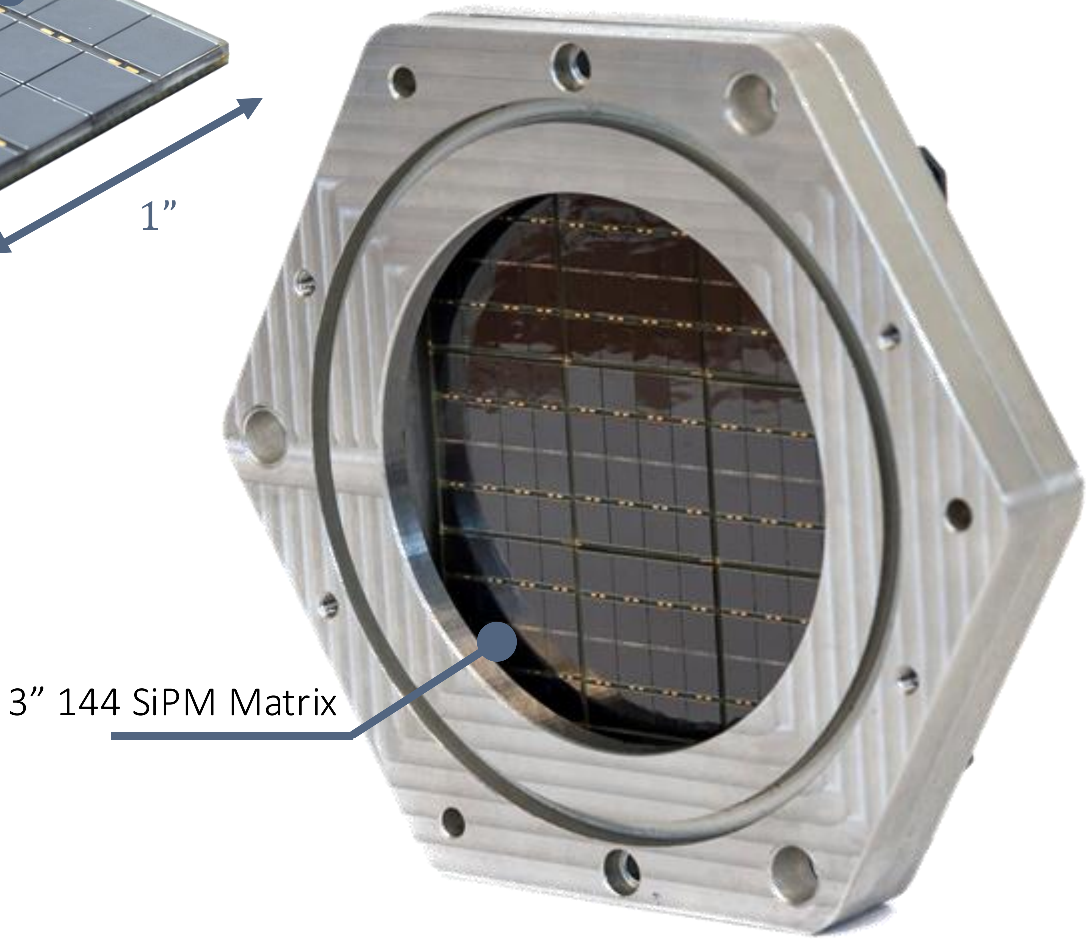
- 6 x 6 mm^2 SiPMs
- 9 tiles, 1” x 1” size each, 4-side buttable
- Custom high-reliability connectors
- Temperature sensor under each tile



Two microcell options: 30µm and 15µm cells

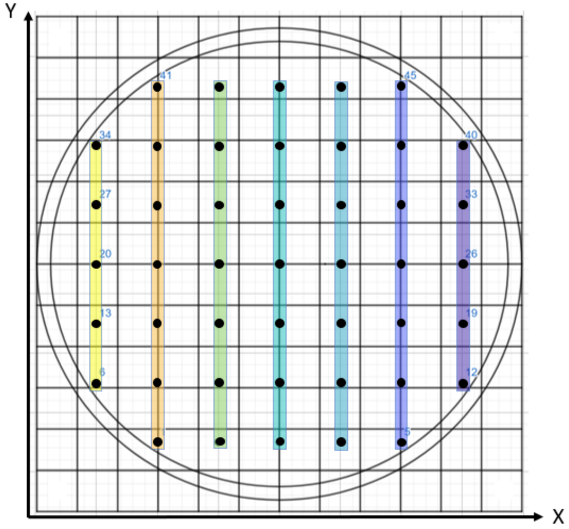
30µm cells:
- 45% PDE
- 77% FF
- V_{BD} = 26.5V
- 40kHz/mm^2 DCR
- 1% non-linearity due to cell saturation at 9 MeV, 4% at 15.1 MeV
- 30 MeV FSR

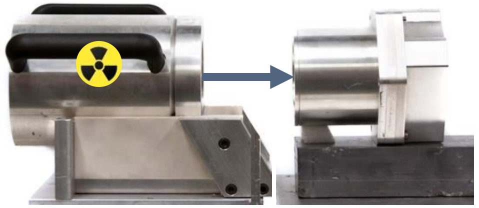
15µm cells:
- 40% PDE
- 61% FF
- V_{BD} = 31.5V
- 60kHz/mm^2 DCR
- 1% non-linearity due to cell saturation at 35 MeV
- > 50 MeV FSR



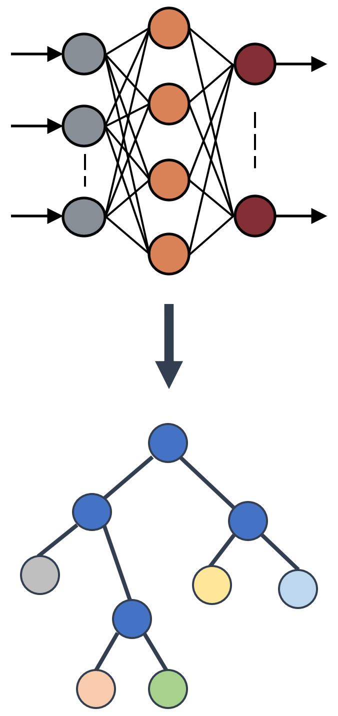
Machine learning for position reconstruction

Training dataset
- 45 spots (1cm spaced)
- 7 classes (1D-recostruction)

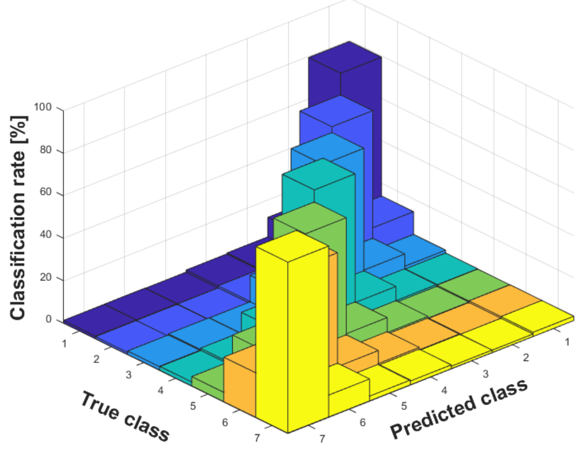




NN filter + DT classifier

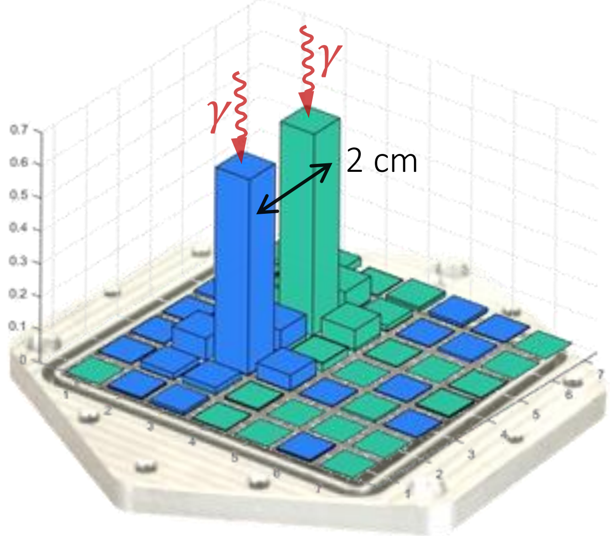


Confusion matrix (1D)



Decision Tree
- Mean error: 0.47cm
- RMS error: 1.08cm

Neural Network
- Mean error: 0.42cm
- RMS error: 1.02cm



2cm spaced irradiations

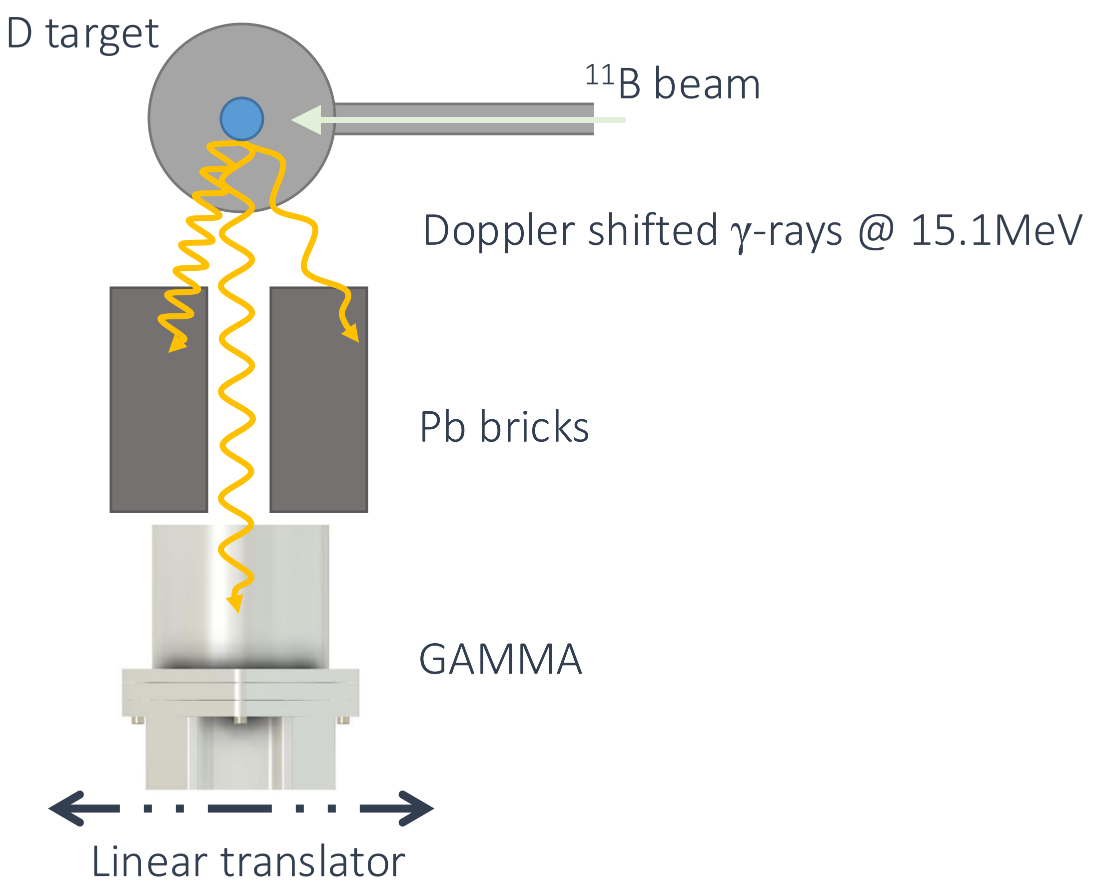
G. Ticchi, L. Buonanno, D. Di Vita, et al., "**Embedded Artificial Intelligence for Position Sensitivity in Thick Scintillators**," *Nuclear Instruments and Methods in Physics Research Section A (2022)*

RadLab POLITECNICO MILANO 1863

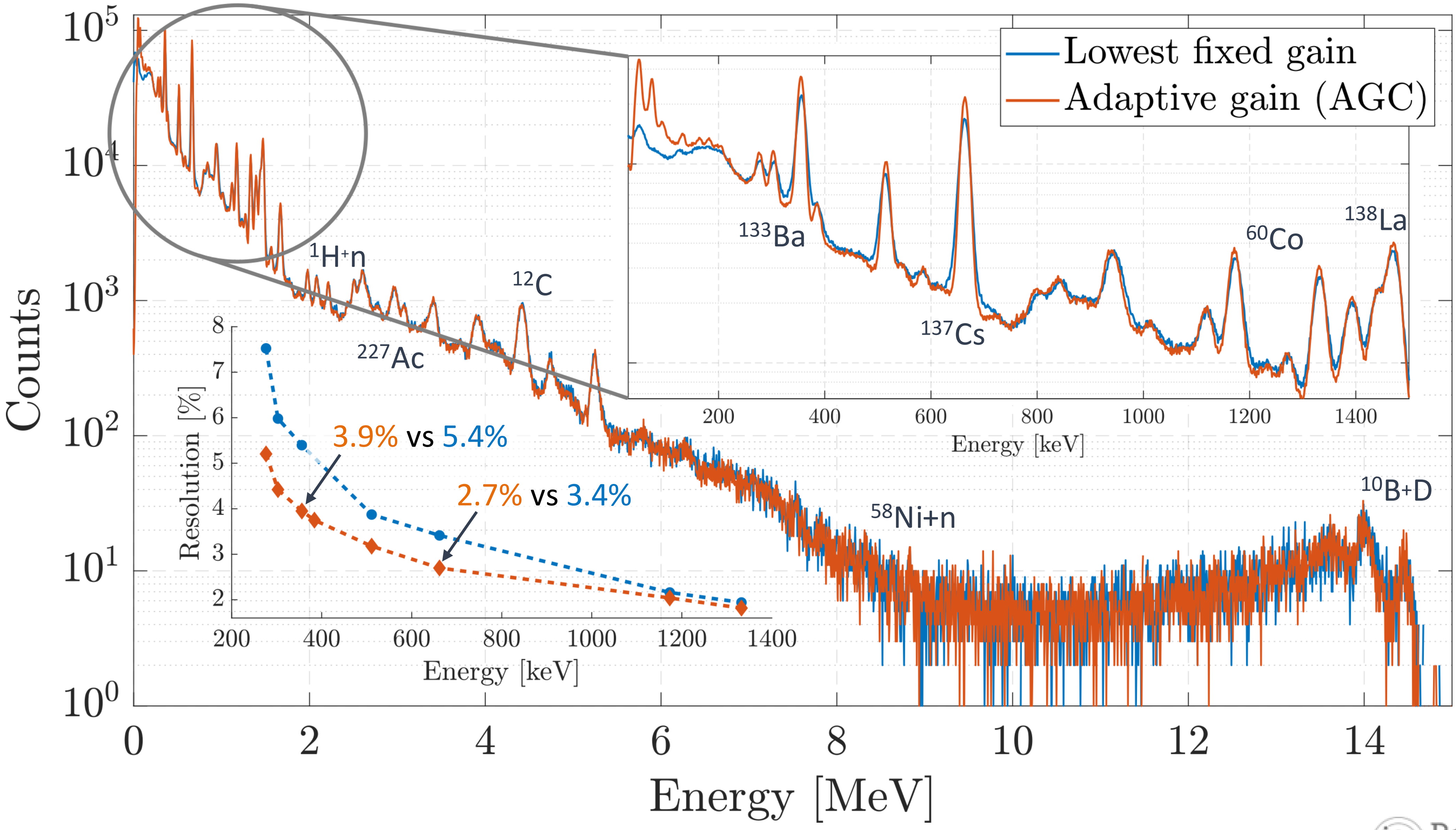
Measurements setup

Beamline experiments performed at IFIN-HH Tandem accelerator (Măgurele, Romania)

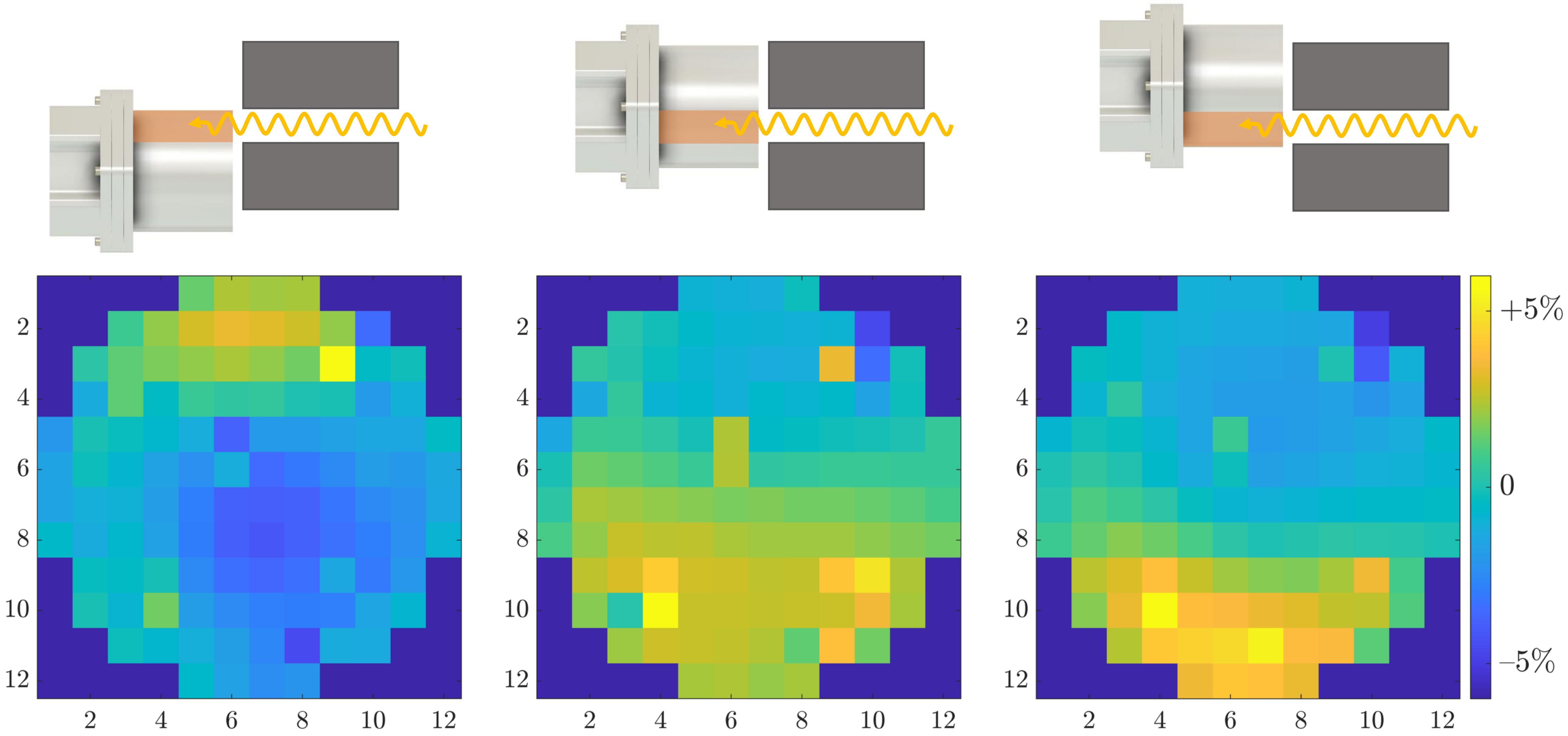
Reaction: $^{11}B + D \longrightarrow {}^{12}C + \gamma + n$



SiPM+LaBr$_3$ energy resolution: fixed gain vs AGC

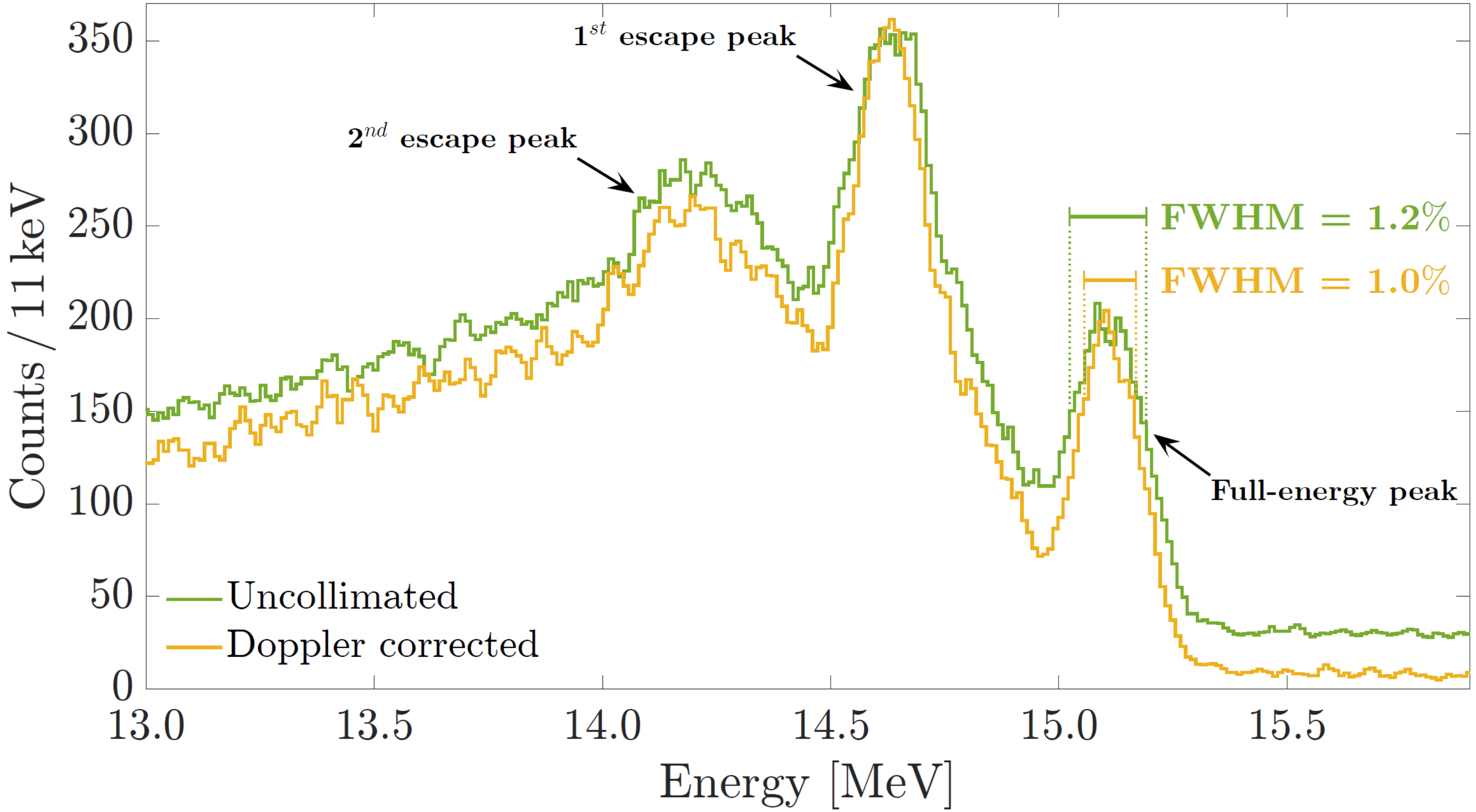


SiPM illumination at 15.1MeV with collimation



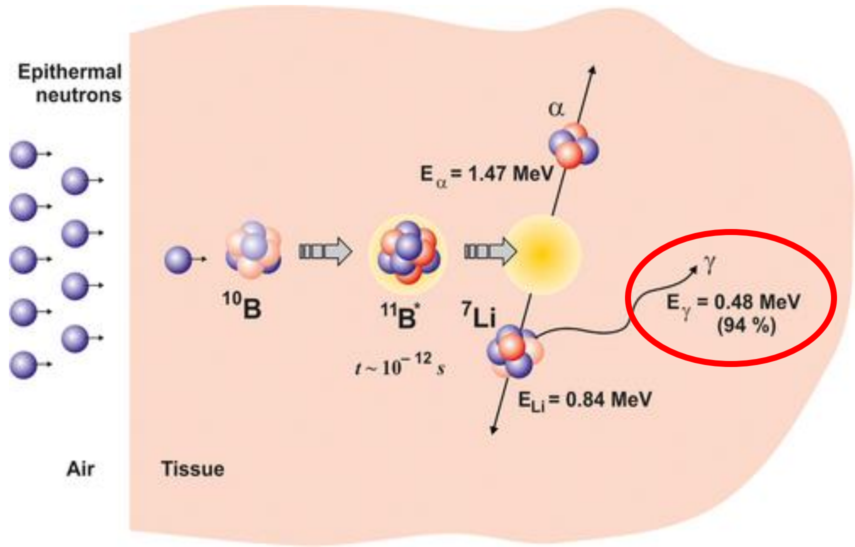
SiPMs signal patterns for different collimations

Uncollimated spectrum corrected for Doppler broadening



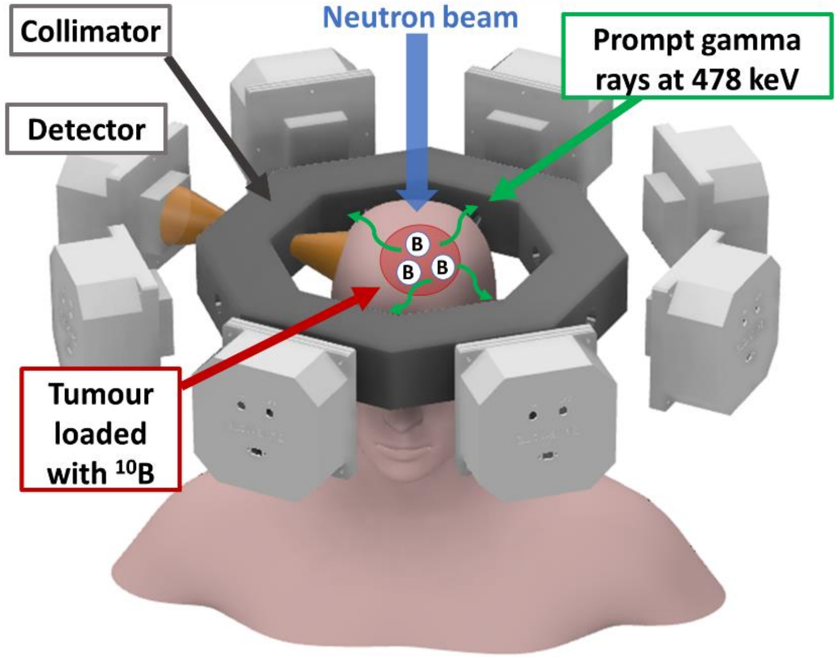
The uncollimated spectrum has been moved upward and recalibrated to be superposed with the corrected one

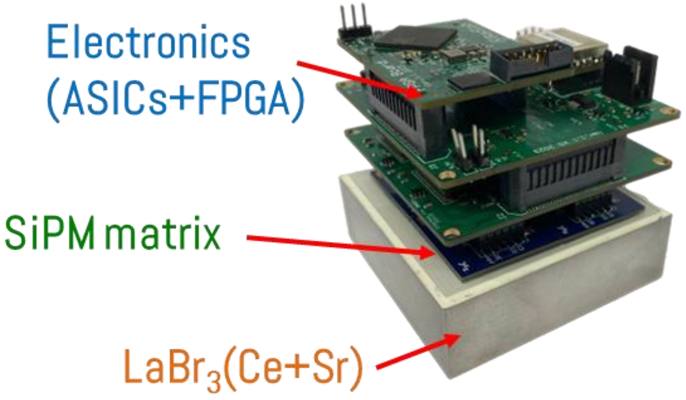
Application in BNCT (Boron Neutron Capture Therapy)



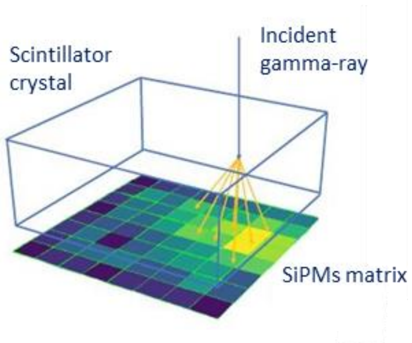
Detection of emitted **478keV gamma photons** may let to estimate ^{10}B neutron captures and support therapeutic outcome (personalized dosimetry).

Goal: Development of a SPECT (Single Photon Emission Thomography) system) for BNCT

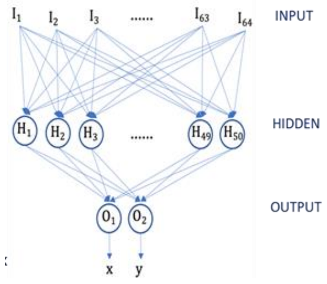




BeNEdiCTE (Boron NEutron CapTurE) detector

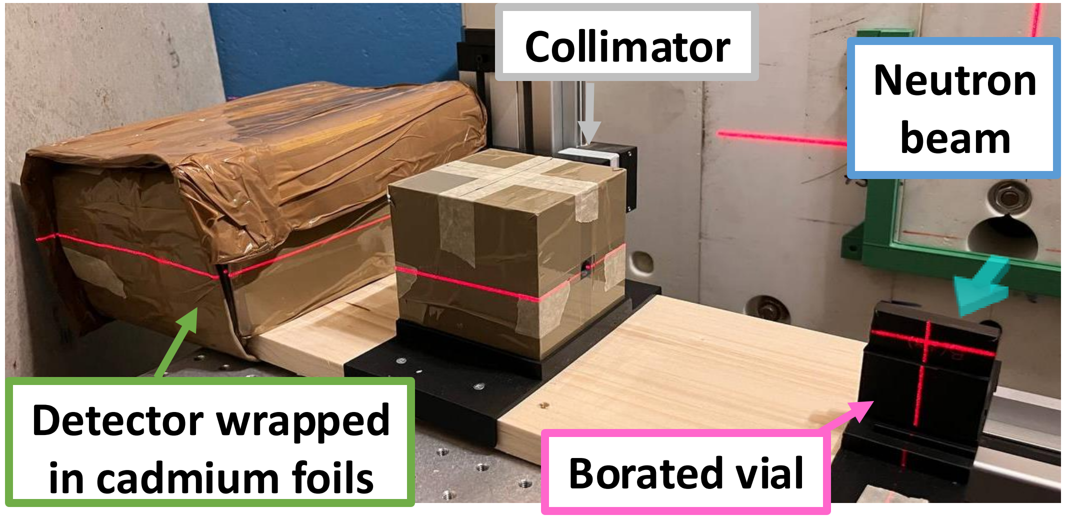


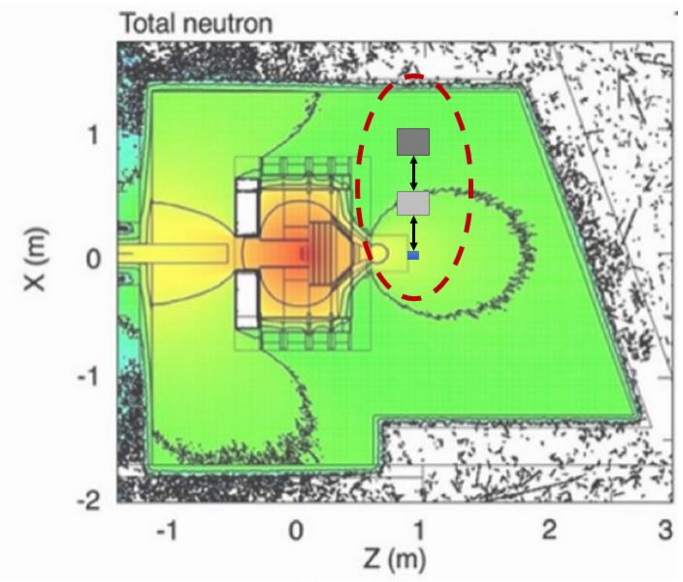
Scintillator/SiPMs-based gamma-ray detector

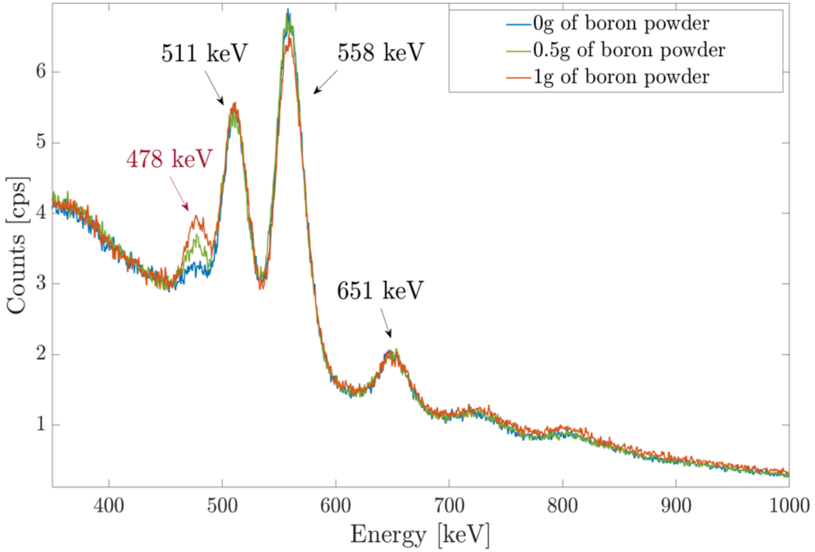


Neural-Network for event reconstruction

Experiments at nuclear reactor in Pavia (and BNCT facilities)

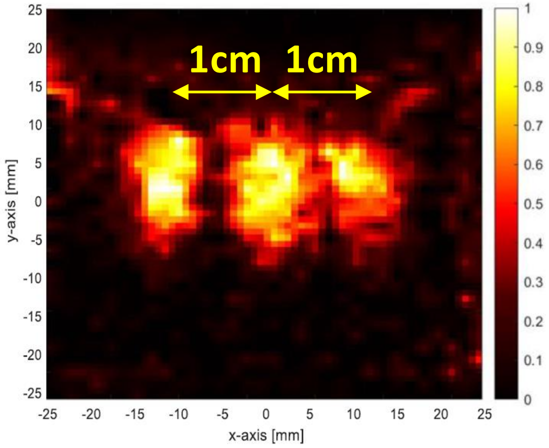






Spectroscopic Results

Identification of the BNCT photopeak at 478 keV and linear response at different boron quantities



Imaging Results

The ANN algorithm is able to track shifts of 1 cm of the borated sample

Thanks to Franco and Silvia for their constant support to this activity!

Thanks to all of you for your attention!

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