Compact signal processing of a Compton camera system for medical imaging

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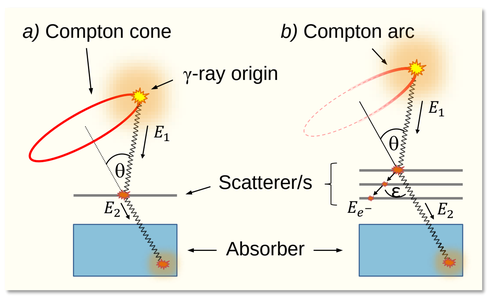
Motivation

- Particle beams offer accurate tumor targeting thanks to their rising dose distribution along their stopping trajectory culminating in the **Bragg peak**.
- The accuracy is partially hampered by particle beam **range uncertainties**.
- The need for **(in-vivo) beam range verification** of particle beams via the localization of the Bragg peak is the key issue of particle therapy.
- A **Compton Camera** (CC) system can provide an in-vivo proton / ion beam range monitoring via detecting **secondary prompt-γ rays** (PG) emitted from nuclear reactions of the particle beam with biological samples [1] and correlated to the Bragg peak position.
- A **Compton Camera system** is composed of a scatterer and an absorber component and can be arranged for two different ways of operation:
  - **Thick single scatter detector (a)**: register incident and scattered γ energies and positions to allow for the reconstruction of the Compton cone
  - **Array of thinner multiple scatter detectors (b)**: e^- tracking is possible → reduction of Compton cone to a Compton arc, enabling the reconstruction of incompletely absorbed photon events
  - Exploiting **Compton kinematics** $cos\vartheta = 1 - m_e c^2 \left[\frac{1}{E_a} - \frac{1}{E_s}\right]$ of many photon events, the **PG** (prompt gamma) **image** can be reconstructed (from the intersection of Compton cones / arcs).



Garching Compton camera:

Scatterer: stack of 6 DSSSD (Double Sided Silicon Strip Detectors) (0.5 mm thick, 50 x 50 mm², 128 strips/side)

Absorber possibilities: monolithic scintillator (50x50x30 mm³)
- $LaBr_3$:Ce + PMT H9500 (256 ch)
- $LaBr_3$:Ce + PMT H8500 (64 ch)
- $CeBr_3$ + PMT H12700A-10 (64 ch)

SIGNAL PROCESSING AND DATA ACQUISITION

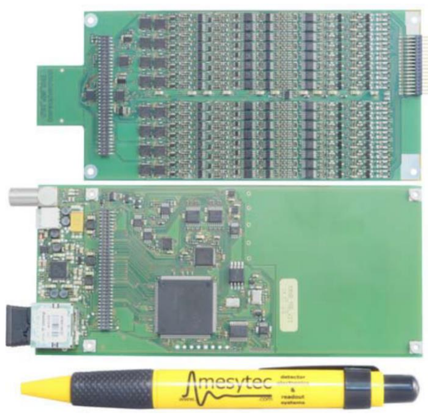
Many channels: 1536 DSSSD signals (=128 x 2 x 6) + 256 or 64 PMT signals (Energy and Time)

High rate capabilities needed to handle Mcps rates expected

Trigger preferably on scatter component → Compton events: from coincidence with absorber

Materials and Methods

MMR-64 module:

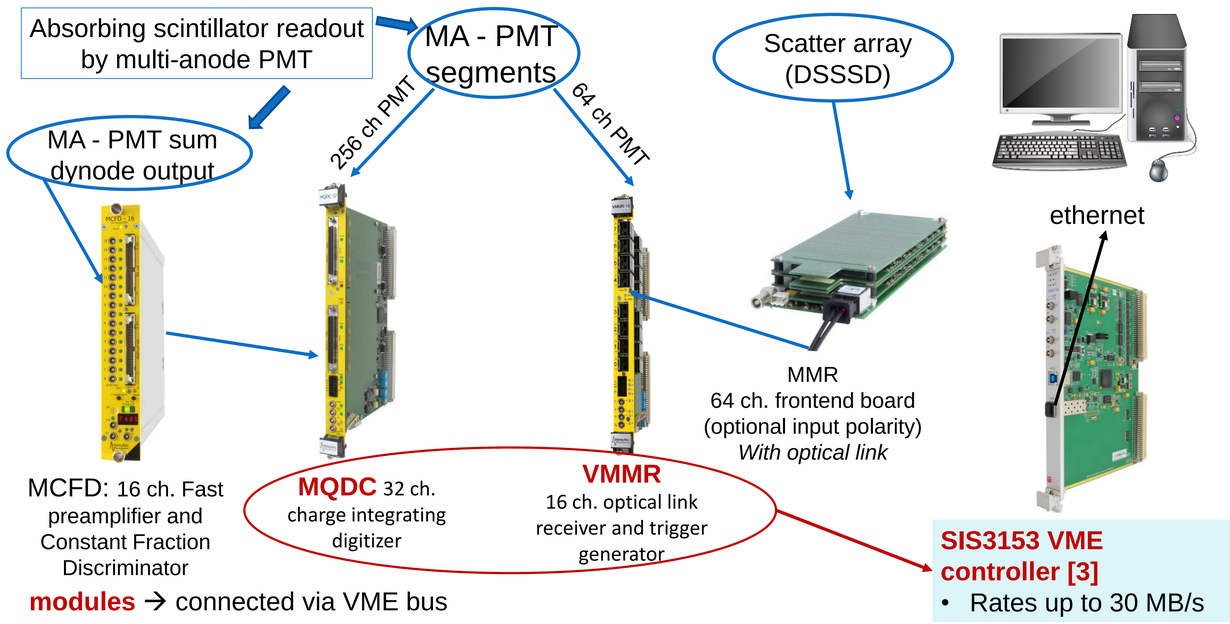


New development by Mesytec according to our parameter specifications and meant to replace an outdated, ASIC-based signal processing system for the scatter detectors

2 x 32 channels per board
- Based on discrete components
  - Bias filter and supply
  - Charge sensitive preamplifier
  - Shaper + stretcher
  - Timing filter amplifier
  - Individual discriminators
  - Multiplexer
- 600 keV maximum range
- 12 bits ADC
- Shaping time: 1 μs
- Conversion time: 400 ns / 32 channels
- Noise < 3keV FWHM for 0pF input capacitance

Signal transfer:
- Performed via a fiber-optical link
- Receiver module: VMMR → Up to 16 busses (max 64 ∗ 16 = 1024 channels per 1 receiver module)

Signal processing and data acquisition for the complete Garching Compton Camera setup [2]:



SIS3153 VME controller [3]
- Rates up to 30 MB/s

Monolithic absorbing scintillator - reduction of readout complexity

- Spatial resolution of monolithic absorber is obtained using the k-NN (k-Nearest Neighbours) algorithm and its improved version CAP (Categorical Average Pattern) [5]
- Comparable performances obtained for 256 and 64 segmented PMT readout [6]

γ-energy [MeV]	Spatial res. CAP (256 ch) [mm]	Spatial res. CAP (64 ch) [mm]
0.662	4.9(1)	4.4(1)
1.1	3.2(1)	3.0(1)
1.3	3.0(1)	2.9(1)

Enabling reduction of channels and complexity of the system

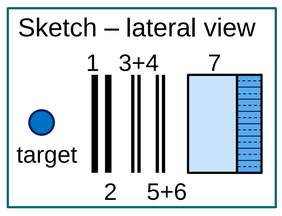
- new MMR-64 frontend boards can be adapted to perform also signal processing for scintillator signals
- 1 MMR-64 board sufficient to process all data (PMT segments' signals) from CC absorber

Trigger for the system - possibilities: *Values to be set in modules' registers*

Define different triggers for the Compton Camera system by defining internal registers of each module:
- **Scatter component**: enable the bus of the VMMR module receiving data from the scatter array to be the trigger generator
- **Absorber component**: enable the bus of the VMMR module receiving data from the PMT pixels OR enable the sum dynode signal of the PMT (readout using CFD + QDC modules) to be the trigger generator
- **Hardware coincidence**: enable in the VMMR module the busses containing signals from both scatter and absorber component to be the trigger generator for the CC system

Results

Tests @ MLL Tandem (Garching) – 20 MeV proton beam

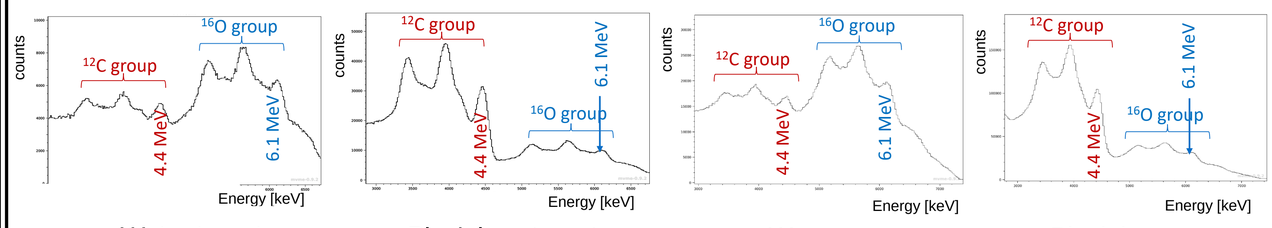


backside view of the Compton camera, with both detector components read out by MMR-64 modules via optical links

1. DSSSD: 1 mm thick
2. DSSSD: 1 mm thick
3. DSSSD: 0.5 mm thick
4. DSSSD: 0.5 mm thick (turned by 90° to 3)
5. DSSSD: 0.5 mm thick
6. DSSSD: 0.5 mm thick (turned by 90° to 5)
7. $LaBr_3$(Ce) or $CeBr_3$ coupled to PMT (Hamamatsu H8500 / H12700)

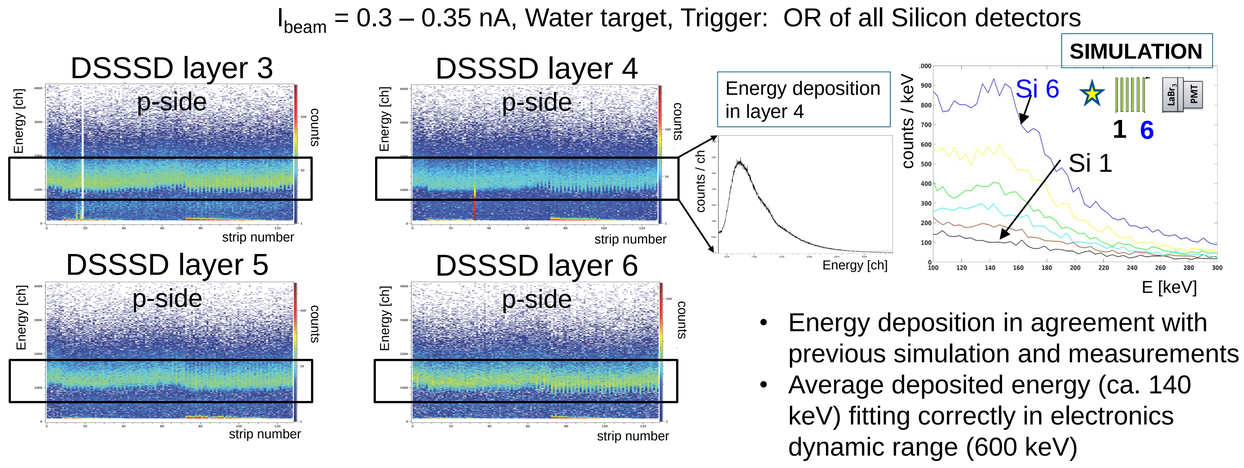
I_{beam} = 0.2 nA, Trigger: PMT segments in VMMR

$LaBr_3$(Ce) [HV = -645 V] **$CeBr_3$** [HV = -720 V]



Water target | Plexiglass target | Water target | Plexiglass target

I_{beam} = 0.3 – 0.35 nA, Water target, Trigger: OR of all Silicon detectors



- Energy deposition in agreement with previous simulation and measurements
- Average deposited energy (ca. 140 keV) fitting correctly in electronics dynamic range (600 keV)

Count rate and data throughput improvement:

DSSSD readout based on Gassiplex ASIC chip + RIO + Marabou readout [7]

Beam current	Free rate (Hz)	Accepted rate (Hz)	Trigger
500 pA	~1.5 k	~1 k	absorber
1.5 nA	~15 k	~1.1 k	absorber

DSSSD readout based on MMR-64 module + VMMR module + mvme software [4]

Beam current	Free rate (Hz)	Accepted rate (Hz)	Trigger	Data rate (MB/s)
200 pA	~5 k	~5 k	scatterers	0.5
300 pA	~6k	~6k	scatterers	0.6
400 pA	~9 k	~9 k	scatterers	1.2

- Scattering probability in (6 * 0.5 mm) Si layers: ca. 1.5%
- Drastic improvement in acquisition rate

Overall data quality can be improved by up to 3 orders of magnitude by a drastic increase of the acquired scatter/absorber coincidences

Conclusions and Outlook

- ✓ New compact signal processing and DAQ system tailored for specifications of our DSSSD array signals
- ✓ Same architecture can be adapted to scintillator-based absorber signals
- ✓ Compact, flexible and low-noise readout system
- ✓ Selectable trigger options (scatterer and/or absorber)
- ✓ Drastic increase in accepted counting rate and data throughput with low dead time
- ✓ Readout successfully tested with the CC system during a beamtime @ MLL using 20 MeV proton beam with water and plexiglass targets
- ✓ Perspective of a compact integrated signal processing and DAQ signal for the full CC
- ✓ Next characterization test: performance of timing behaviour

References :
[1] J. Krimmer et al.: Prompt-gamma monitoring in hadrontherapy: A review, *Nuclear Inst. And Methods in Physics Research, A*, 2017.
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[5] Van Dam H.T. et al.: Improved Nearest Neighbor Methods for Gamma Photon interaction position determination in monolithic scintillator PET detectors, *IEEE Trans. Nucl. Sci.*, 58: 2139-2147, 2011.
[6] S. Liprandi et al.: Sub-3mm spatial resolution from a large monolithic $LaBr_3$ (Ce) scintillator, *Current Directions in Biomedical Engineering 3(2): 655-659, 2017.*
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