MULTISPECTRAL PHOTON-COUNTING FOR MEDICAL IMAGING AND BEAM CHARACTERIZATION

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[1]on behalf of the consortium of research groups from HIP, Aalto, LUT and STUK.

Idea and motivation

For medical imaging we need photon-counting detectors that

- are capable of high radiation fluence rate ($> 10^8 \text{mm}^{-2}\text{s}^{-1}$),
- have good timing resolution,
- have good stopping power,
- good energy discrimination.

Our approach: combining two worlds for something new

- In-house development of detectors using high Z materials.
- Readout technology and expertise from involvement in high energy physics experiments.

In-house detector development

History at HIP

- Radiation-hard silicon strip detectors.
- Detectors made of high-resistivity magnetic Czochralski silicon (MCz).
- Silicon strip detectors (n-type) for High Luminosity LHC.
- Defect studies and quality assurance of semiconductor detectors.
- Mechanics and comissioning of the current CMS Tracking detector.

Modern processing techniques

- Access to Micronova, Centre for Micro and Nanotechnology in Finland.
- Present key technology: Atomic Layer Deposition (ALD).

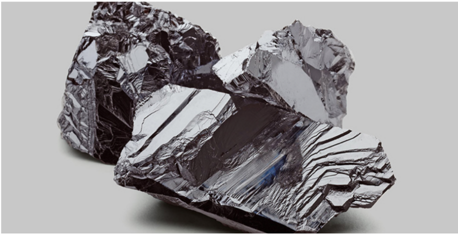
Local detector characterization techniques

- Probestations, scanning Transient Current Technique (TCT), IR-imaging and spectroscopy scanner.

Cadmium Telluride

Material

- High stopping power (high Z).
- Usable at room temperatures.
- Wide band gap of 1.44 eV (usable at room temperatures).
- Very brittle, difficult to grow.
- Processing temperatures $< 150^\circ$C.
- Not all chemicals from Si processing can be used.



from www.5nplus.com/cadmium-telluride.html

Crystals

- We use currently CdTe crystals of size 1×1 cm^2.
- 1 and 2 mm thickness available.

Quality assurance

CdTe material

Max. 2 inch ingot available, not fully mono-crystalline. Come with various crystallographic defects that affect detector performance:

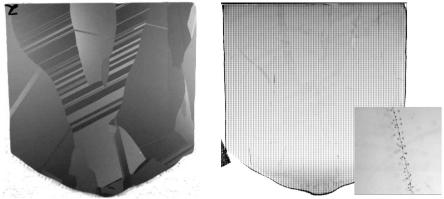
- Grain and twin boundaries
- Fractures
- Tellurium inclusions, etc ...

Quality assurance

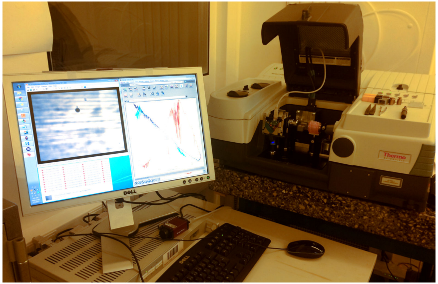
3D characterization using IR scanning microscope

- Resolution close to 1μm (diffraction limit)
- Spectroscopy possible
- Result (with aid of neural networks): Detailed 2/3D maps of defect occurrences.

see A. Winkler et al., NIM A 924 (2019) 28



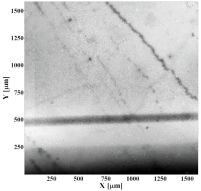
from Szeles et. al., doi:10.1117/12.683552.

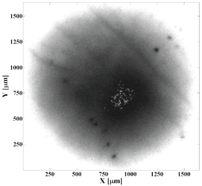


Quality assurance

Under investigation

- How do Te inclusions affect locally the charge collection efficiency (CCE)?
- Currently we study CCE using scanning TCT and micro proton beam (IBIC) in collab. with Ruđer Bošković Institute.
- Goal: correlation between local Te inclusions and drop of CCE.





see M. Kalliokoski et al., IEEE Trans. Nucl. Sci., 66, 5 (2019)

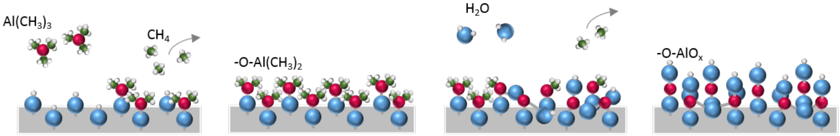
Example of scanning through CdTe crystal

Size: 200 $\times$ 160 μm; 15 μm step per frame.

Atomic Layer Deposition

ALD principle

- Self-terminating gas-solid reactions.
- E.g.: layer by layer growing of Al_2O_3 on high-resistivity MCz silicon in Beneq TFS-500 ALD reactor. (presented at VCI conference by Jennifer Ott, paper submitted)

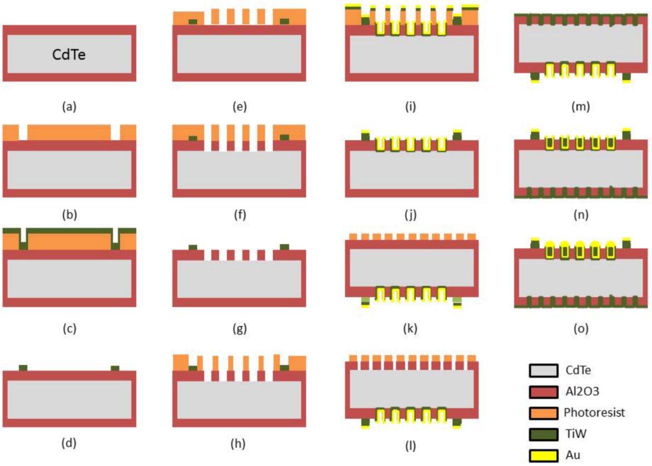


Details of aluminium oxide growth at 120°C

- First $Al(CH_3)_3$ pulse as metal precursor followed by N_2 purge.
- Next H_2O pulses followed by N_2 purge.
- Repeating cycles until sufficient layer thickness (here around 90 nm).

Processing of CdTe pixel sensor

- a) Low temp. ALD of Al_2O_3
- b,c,d) Alignment marks (TiW)
- e,f,g) Opening contacts to ALD passivation layer (wet chemical etching)
- h,i) Contact metallization (sputtering of TiW and Au)
- j) Lift-off process
- k,l,m) Backside processing similar to front side with TiW sputtering
- n,o) Electroless Ni growth and Au metallization, UBM



see A. Gädda et al. 2017 JINST 12 C12031

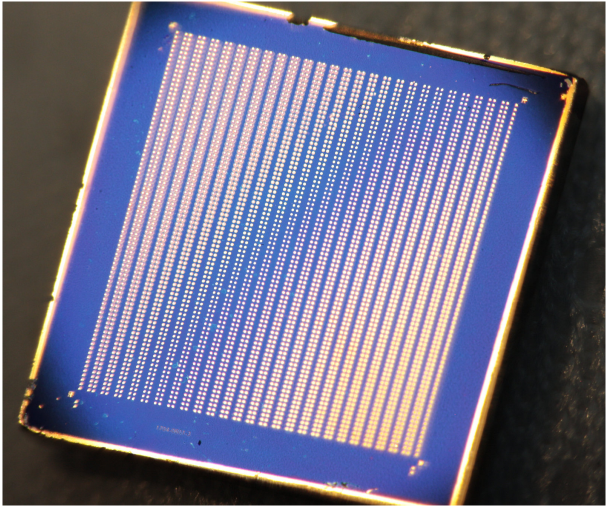
The CdTe pixel sensor

Ingredients

- Detector grade CdTe crystal, (111) orientation.
- Resistivity $> 10^9\ \Omega$cm.
- Size: $10 \times 10\,\text{mm}^2$.
- Thickness 1 mm.

The ready sensor

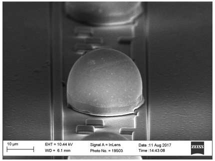
- Schottky type detector.
- 52×80 pixels in 26 double column pattern.
- Layout matching PSI46 ROC structure.
- Patterned backside

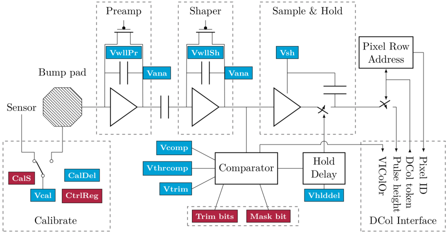


PSI46dig ROC

Readout chip for prototypes

- CMOS ASIC developed by PSI for the pixel sensors of the CMS tracker.
- 4160 pixels (52×80) in $8 \times 7.6\,\mathrm{mm}^2$ active area.
- Photo counting capable.
- Full pulse processing per pixel.
- Charge threshold of 1.5 ke$^-$, resolution $\sim$120 e$^-$.
- Radiation hardness > 2.5 Mrad.
- Available with Indium bumps for low-T processing as required with CdTe.
- Other chips optional, e.g. RD53a chip.





see: B. Meier 2011 JINST 6 C01011,

D. Hits & A. Starodumov 2015 JINST 10 C05029

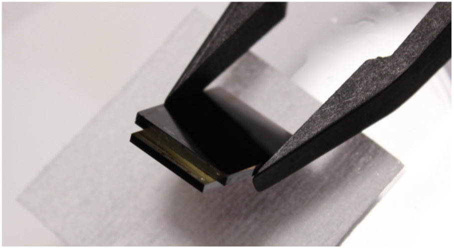
Prototype Detector

Prototype

- Ready single detector, successfully bump bonded (Indium).

Detector readout

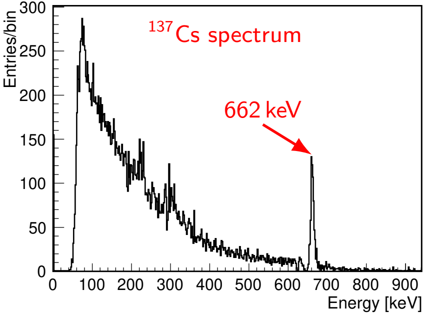
- Currently we use the Detector Test Board (DTB) developed for the PSI46 ROC.
- Features: Altera FPGA, 2x64MB DDR2 RAM, Gigabit Ethernet port, USB 2.0.
- Programmable analog and digital outputs for monitoring.
- Deserializer for 160 MHz and 400 MHz signals.
- Prototype wire bonded to PCB.
- Connected to DTB via passive FEC.

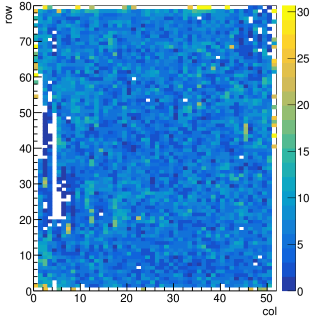


Results

Testing the prototype

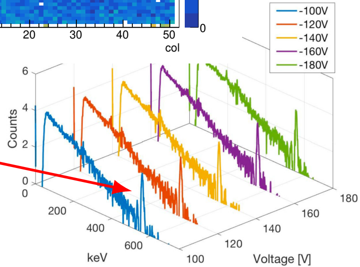
- First results look promising.
- Good energy resolution (< 2%) for ^{137}Cs (11.9 keV for the 662 keV gamma emission line.





Hit map fairly uniform

Detector fully depleted at - 100 V



see A. Gädda et al. 2017 JINST 12 C12031

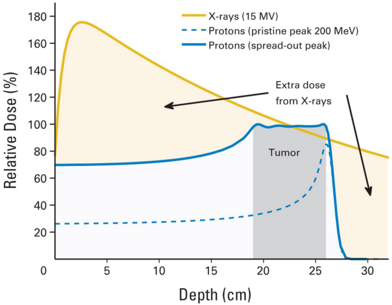
What are my colleagues doing? For example at Aalto University

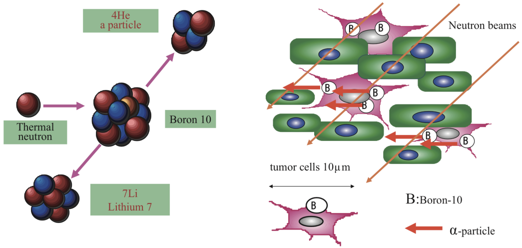
Possible application: Imaging detector for Boron Neutron Capture Therapy (BNCT).

Algorithms for BNCT: The probabilistic model.

Well, let's first introduce Boron Neutron Capture Therapy in short.

Motivation for BNCT



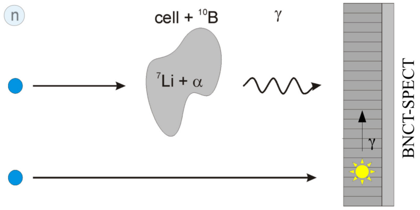


Plot on left from J Clin Oncol. 2014 Sep 10;32(26):2855-63, graphics on right from Kageji et al., JMI 61 3-4 (2014).

Example of application for our detector

Boron Neutron Capture Therapy (BNCT)

- Idea of BNCT: Adding ^{10}B to drug that attaches to cancer cells. Thermal neutron injected to patient captured by ^{10}B. Violent reaction kills cancer cells ($^{10}\mathrm{B} + \mathrm{n} \rightarrow ^7\mathrm{Li} + \alpha + \gamma$).
- PC detectors can shed light on ratio between cancer and healthy cells. Can monitor spatial and temporal development.
- Required for online dosimetry, the last missing piece for full acceptance as alternative radiation therapy.



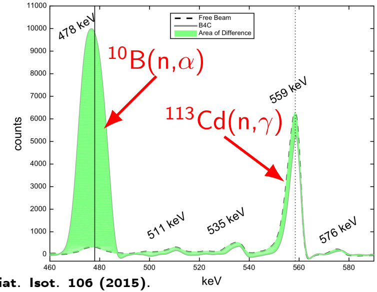
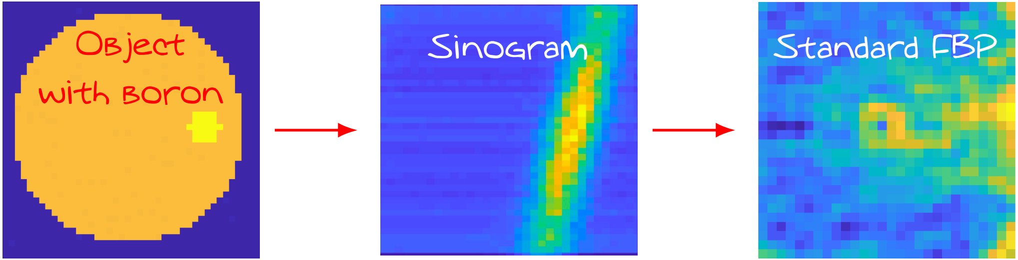


Illustration from Alexander Winkler and Figure from A. Winkler et. al., Appl. Radiat. Isot. 106 (2015).

Challenges

- For imaging we can use direct gammas from BNC or scattered neutrons.
- Neutrons will be caught by ^{113}Cd and resulting gamma detected (558 keV).
- Problem: we do not have a detector with anti-scatter grid for neutrons.

Using standard procedure



At Aalto University

Algorithms for Boron Neutron Capture Therapy: The probabilistic model

- Measurement of the location of BNC events $\mathbf{x}^b$ inside sample.
- Signal for each pixel in detector from BNC events

$$\mathbf{y}^b = \mathrm{I}_0 A\mathbf{x}^b + \varepsilon,$$

where I_0 is the total number of neutrons, A a measurement matrix, and the normal distributed measurement noise $\varepsilon \propto \mathcal{N}(0, \sigma_\varepsilon^2 I)$ with the identity matrix I.

- Next we introduce Gaussian prior for $\mathbf{x}^b$,

$$p(\mathbf{x}^b) \propto \mathcal{N}(\hat{\mathbf{x}}^b, \sigma_{\mathbf{x}^b}^2 I),$$

where $\hat{\mathbf{x}}^b$ is the mean of $\mathbf{x}^b$.

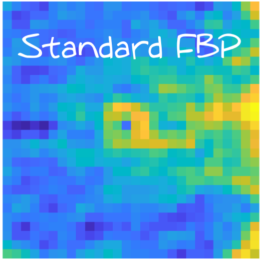
The probabilistic model

- Now we construct the likelihood function:

$$p(\mathbf{y}^b \mid \mathbf{x}^b) \propto \mathcal{N}(0, \sigma_\varepsilon^2 I)$$

- Then, the posterior distribution has the following form:

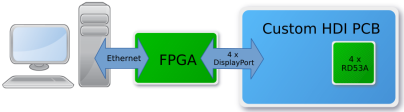
$$p(\mathbf{x}^b \mid \mathbf{y}^b) \propto p(\mathbf{y}^b \mid \mathbf{x}^b) p(\mathbf{x}^b)$$

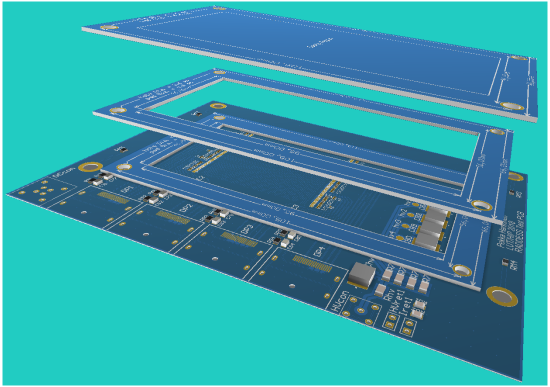


At Lappeenranta University of Technology LUT

The High Density Interconnect

- New HDI for RD53a chip.
- Can host up to 4 detectors.
- FPGA board for low level communication between ROCs and PC.



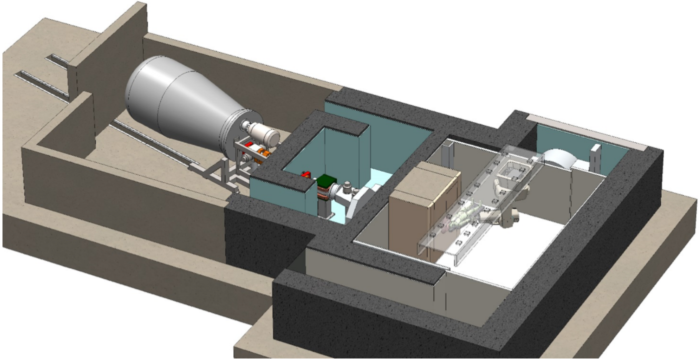


BNCT facility

BNCT setup

Currently a BNCT facility is being built at the Helsinki University Hospital in collaboration with Neutron Therapeutics.

- 2.6 MV / 30 mA Proton Accelerator.
- Neutron generating target.
- Beam Shaping Assembly.
- Moving table for positioning.



Accelerator in accreditation phase by radiation safety authority. Clinical trials start 2020.

Test of detector array under real conditions. Key interest: 478 keV gamma-ray from BNC reactions.

Conclusions and outlook

Achievements

- CdTe pixel detector prototypes successfully manufactured and tested.
- Started production of new CdTe detectors for detector array.
- Algorithms for localizing BNCT events advancing.

Next

- Building detector array based on PSI46dig ROC.
- Preparing for testing array in radiation beams i.e. in the BNCT facilities of the nearby University hospital.