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# Applications of monolithic CMOS pixel sensor to medical physics

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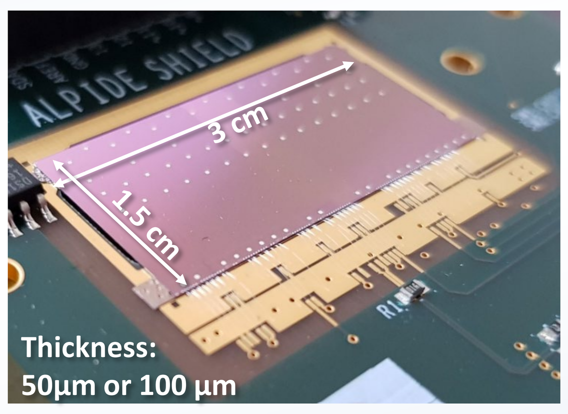
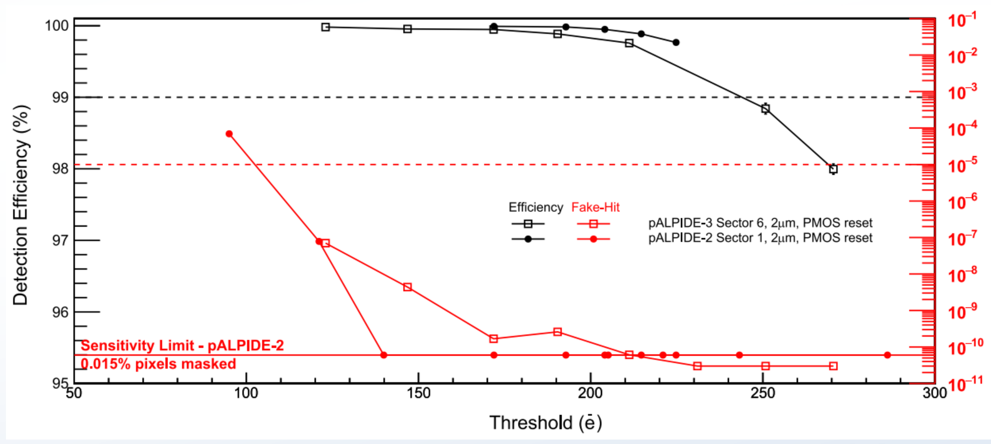
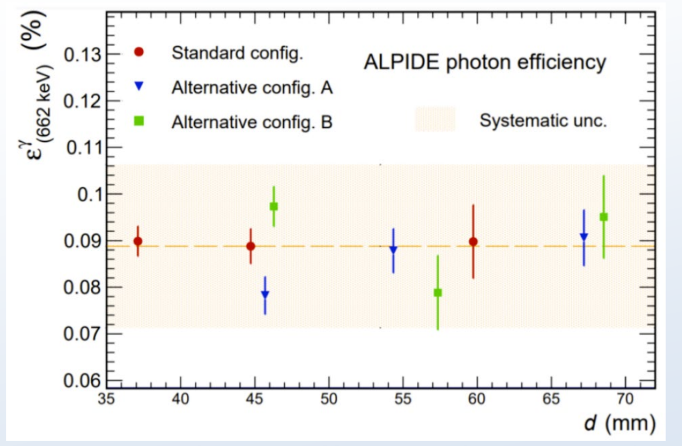
## Introduction and goals of the studies

- **CMOS silicon pixel detectors** have seen significant advancements and a widespread usage across various physics fields, allowing for significant improvements of the particle detection technologies.
- Relevant example: **ALPIDE chip** [1,2], a CMOS Monolithic Active Pixel Sensor developed for the upgrade of the Inner Tracking System of the ALICE experiment at the LHC.
- Its excellent spatial resolution and charged-particle detection efficiency, very limited noise and fake-hit rate, and reduced sensitivity to photons make it suited for several applications in medical physics.
- Two applications in this field are being currently investigated:
  - ➢ The development of an **intraoperative probe** containing an ALPIDE chip as sensitive element, with online imaging capabilities, to be exploited in oncological **radioguided surgery** in association to β-emitting radiotracers for localizing the tumoral mass and possible remnants after its excision.
  - ➢ The design of a **scatterer element** of a **Compton chamber**, composed of a large stack of ALPIDE chip, to cover a large enough sensitive volume, for the online monitoring of hadrontherapy proton or ion beams.




ALPIDE detection efficiency and fake-hit rate [1]




ALPIDE photon efficiency for E = 662 keV

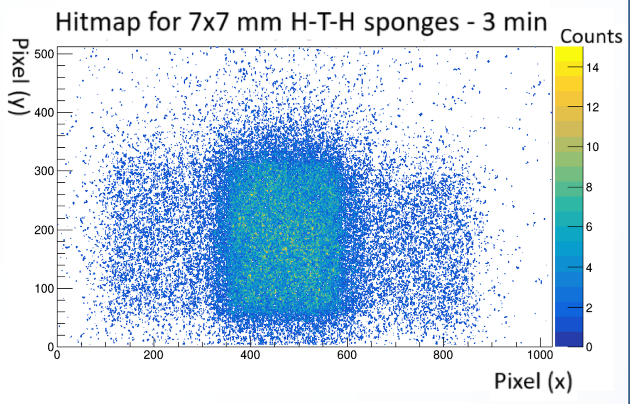
## Imaging probe for radioguided surgery

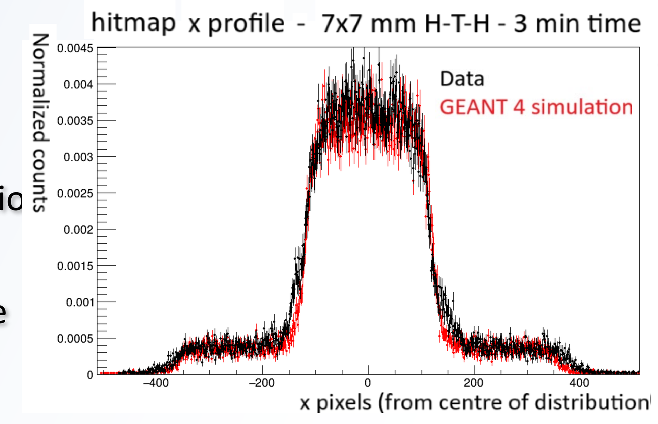
### General concept

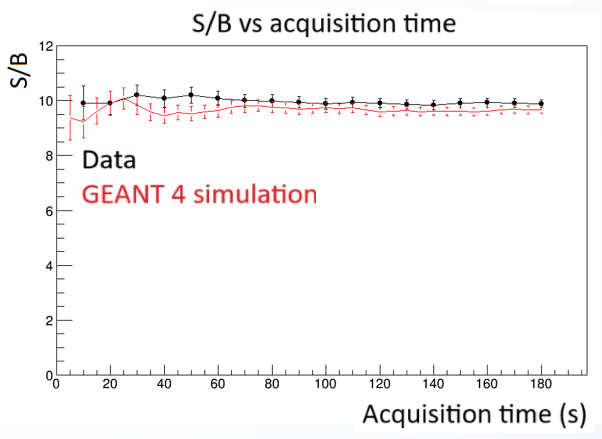
- **Radioguided surgery** (RGS) in oncology currently mostly based on the usage of γ-emitting radiotracers
- Crucial drawback: long mean free path of γ in human tissue (~10 cm at typical energies of few hundred KeV)
  - ➢ Large background of γ emitted from tissues far from the lesion site → Limited spatial resolution for γ probes
- The usage of **$\beta^+$-emitting radiotracers** (e.g. $^{18}$F-FDG, with endpoint E = 635 KeV) would solve this limitation
  - ➢ $\beta^+$ range in human tissues of **few mm** at few hundred KeV
  - ➢ Residual issue: background of γ from positron annihilation
- **Detector requirements for this application**: high detection efficiency for β from 100 KeV to a few MeV, minimal sensitivity to photons, excellent spatial resolution, very low fake-hit rate, small size and compactness
- The **ALPIDE chip** matches all requirements, allowing also for imaging technique to localize the tumor

### Preliminary studies with phantoms using $^{18}$F-FDG radiotracer

- Data acquisition with **7x7x1 mm³ sponges** placed on an ALPIDE, soaked with $^{18}$F-FDG in typical concentrations used in RGS for **tumoral (T)** and **healthy (H)** tissues (10:1)
- Evaluation of **x-profile** and comparison with GEANT 4 simulations
  - ➢ T sponge clearly visible → **significantly more counts** than H sponges in both 2D plots and x profile
  - ➢ **Very good agreement** between data and simulations
- **Signal-to-background (S/B)** ratio for T tissue detection about 10
  - ➢ Stable with acquisition time already after **few seconds**

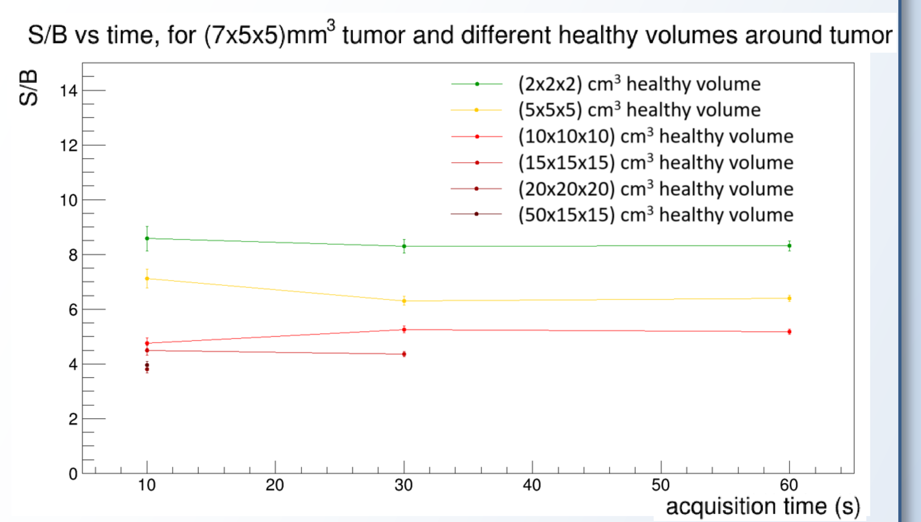


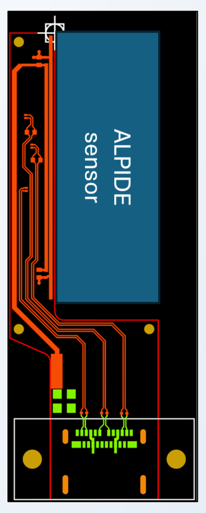

### Extension to larger volumes via GEANT4 simulations

- Matching between measurements and simulations in phantom studies validates the simulations
  - ➢ Possibility of exploiting them to evaluate ALPIDE performance for locating tumoral tissues in **more complex configurations**, not experimentally reproducible
- First pure-simulation study: **S/B vs acquisition time** for a 7x7x5 mm³ tumoral tissue in larger volumes of healthy tissue, with T:H radiotracer concentration ratio of **10:1**
  - ➢ For these studies, human tissues are mimicked with water volumes
- **S/B very close to T:H concentration ratio** for small volumes → small impact from nearby annihilation γ
  - ➢ Performance deteriorates for larger volumes, but tend to stabilize at values **above S/B ≈ 3**
  - ➢ Explained due to decreasing impact of annihilation γ and their products after ≈ 10 cm
  - ➢ S/B values very stable with acquisition time already after **10 seconds**




### First design of a probe prototype

- Developed a first layouy for a compact and portable case to be used as probe prototype for further tests available
  - ➢ **Flex printed circuits (FPC)** to connect the sensor to the acquisition board (MOSAIC) via USB connection
  - ➢ Light and rigid **cover case** for the sensor and the FPC, in plastic, with minimal size and an open window on the ALPIDE sensitive side
- FPC and case **currently in production**, procedure and machinery for **bonding** connections to ALPIDE already available, as well as **readout software**



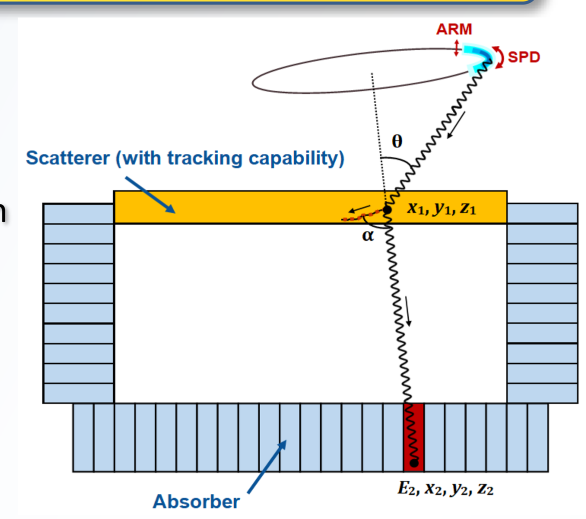

### Ongoing and future activities

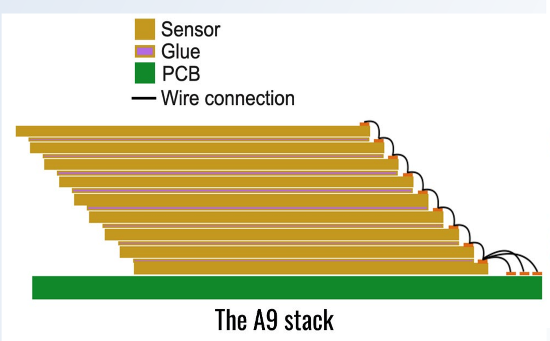
- Assembly of a **functional probe prototype** based on the above design
- Extensive **campaign of data acquisition** with phantoms using the prototype
  - ➢ Repeat tests performed with the standalone ALPIDE to evaluate the impact of the case and circuitry material on the tumoral tissue localization performance
  - ➢ Explore **different geometrical configurations** of T and H sponges and check the performance stability
- Implement the full prototype in **GEANT4 simulations** and repeat their validation exploiting the data from the phantom studies with the prototype probe
- Evaluate the prototype performance, using GEANT4 simulations, on **more realistic arrangements** of tumoral and healthy tissues
  - ➢ Ultimate goal: **full-body simulations**, with tumoral mass geometries mimicking typical clinical cases

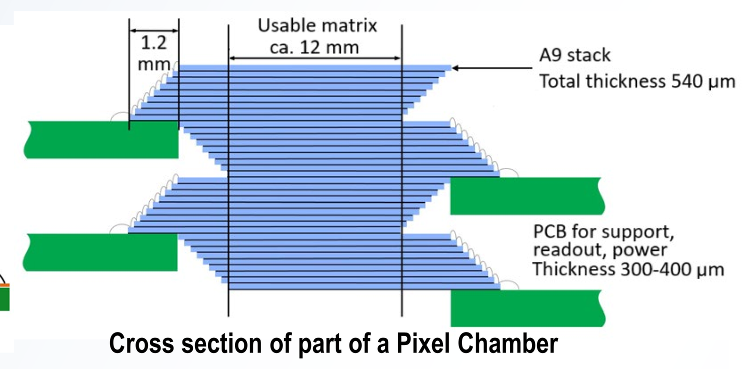
## Pixel Chamber for Compton scattering reconstruction

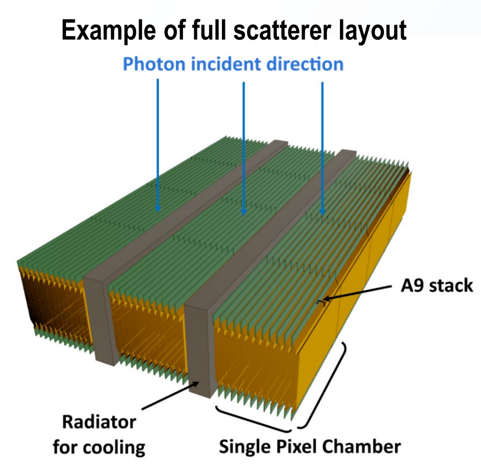
### General concept

- Compton cameras consist of two sub-detectors: **scatterer** and **absorber**
  - ➢ A γ undergoing a Compton interaction in the scatterer and stopped in the absorber only constrains the original direction of the γ to a **cone**
  - ➢ Multiple reconstructions needed to locate the source position
- We propose a new concept of Compton Camera that exploits a **Pixel Chamber** as the **scatterer**, made of stacks of ALPIDE chips
  - ➢ Allows for the reconstruction of the **emitted electron direction**
  - ➢ Original γ direction constrained already by **single photon → significantly faster** than standard chambers
- Basic element of Pixel Chamber: **A9** (stack of **9 ALPIDE** with 150 um horizontal pitch for connections)
  - ➢ Pixel chamber composed of 24 overlapping A9 stacks, each connected to a PCB for support, powering and readout, for a total thickness of 13 mm and a total active volume of 30x12x13 mm³
- **Scatterer** composed of multiple Pixel Chambers + cooling elements (exact design depending on final goal)
- Possible applications: **in-vivo monitoring** of **hadron therapy proton/light-ion beams**, detection of γ sources in **astrophysics**, **active target** for particle accelerators



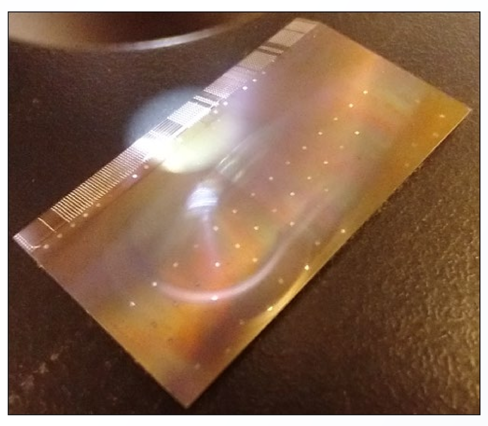



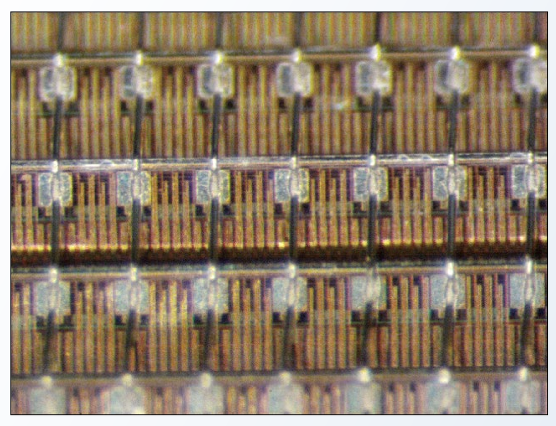




### A9 stack assembly studies and readout system

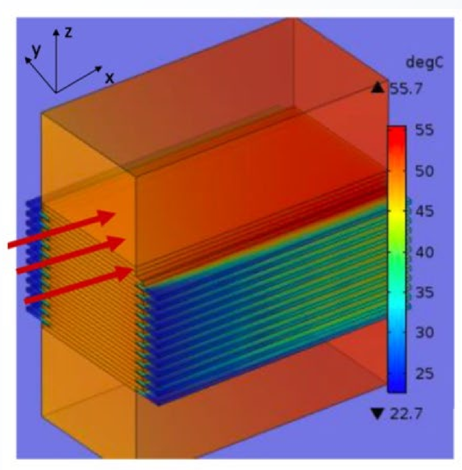
- A9 stack **prototyping**: four test mechanical assemblies, using dummy ALPIDE sensors with 100 µm thickness
- Sensors alignment by Mitutoyo, long curing time glue, relative sensor alignment ≈ **5-10 µm**
- **Wedge wire-bonding investigations**: multiple welding without wire cutting (cascade bonding), loop shape, welding strength, welding failures
  - ➢ Bonding with 150 µm sensor displacement very challenging, considering larger shift (up to 500 µm)
- A9 stack **readout system**:
  - ➢ **PCB** for powering, clocking, communication, data transfer: under production
  - ➢ **MOSAIC board** as data collector
  - ➢ **Firmware** and first version of **readout software** available

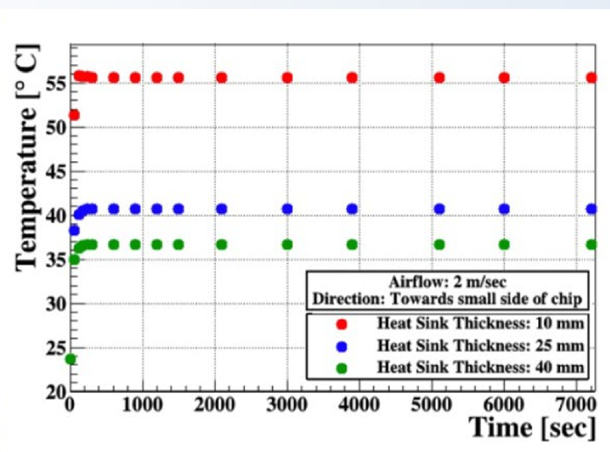




### Cooling studies

- First cooling studies with **COMSOL software** for single A9 stack, Pixel Chamber, and full scatterer element + cooling tests with **mock Pixel Chamber** in aluminum
- For the A9 stack, a simple airflow of 2 m/s is enough to stabilize temperature at 37.9°C
- For the Pixel Chamber, **heat sink radiator elements + airflow** of 2 m/s are mandatory to keep **T < 40°C**
  - ➢ Thickness and material of radiators to be optimized depending on the final geometry
  - ➢ Order of few cm for copper elements




### Ongoing and future activities

- Assembly of a **complete A9 stack** and **PCB readout board**, test the functionality of the stack and of the readout system
  - ➢ Alternate version of **A8 stack**, with 8 ALPIDE, being studied (assembly time reduced by a factor 2)
  - ➢ **Characterization** of the stack with radioactive sources and/or test beam
- Design of a full Pixel Chamber with its support, cooling and readout system
- Development of an **algorithm** for the electron tracking and the **Compton scattering reconstruction**
- Campaign of **GEANT4 simulations** to study the Pixel Chamber performance
  - ➢ To be extended to a full exemplary Compton Chamber (scatterer + absorber) to optimize the geometry and the choice of the absorber detector

## References and acknowledgements

[1] M. Mager, Nuclear Instruments and Methods A 824 (2016) 434
[2] G. Aglieri Rinella, Nuclear Instruments and Methods A 845 (2017) 583

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