Applications of monolithic CMOS pixel sensor to medical physics

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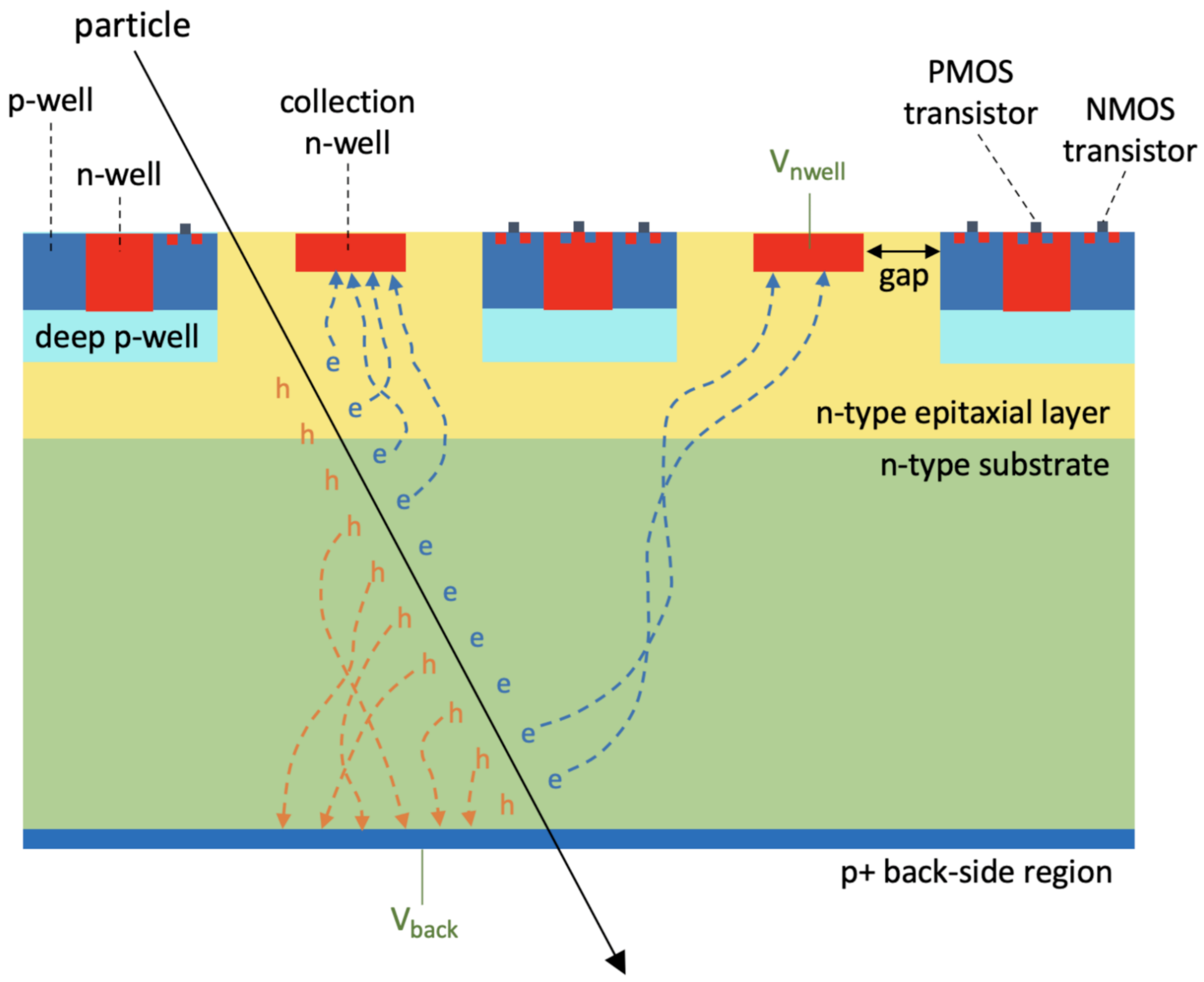
Monolithic Active Pixel Sensors (MAPS)

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.

- **ALTAI chip** is a CMOS Monolithic Active Pixel Sensor developed for the upgrade of the Inner Tracking System of the ALICE experiment at the LHC.



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  - excellent spatial resolution ~5 µm
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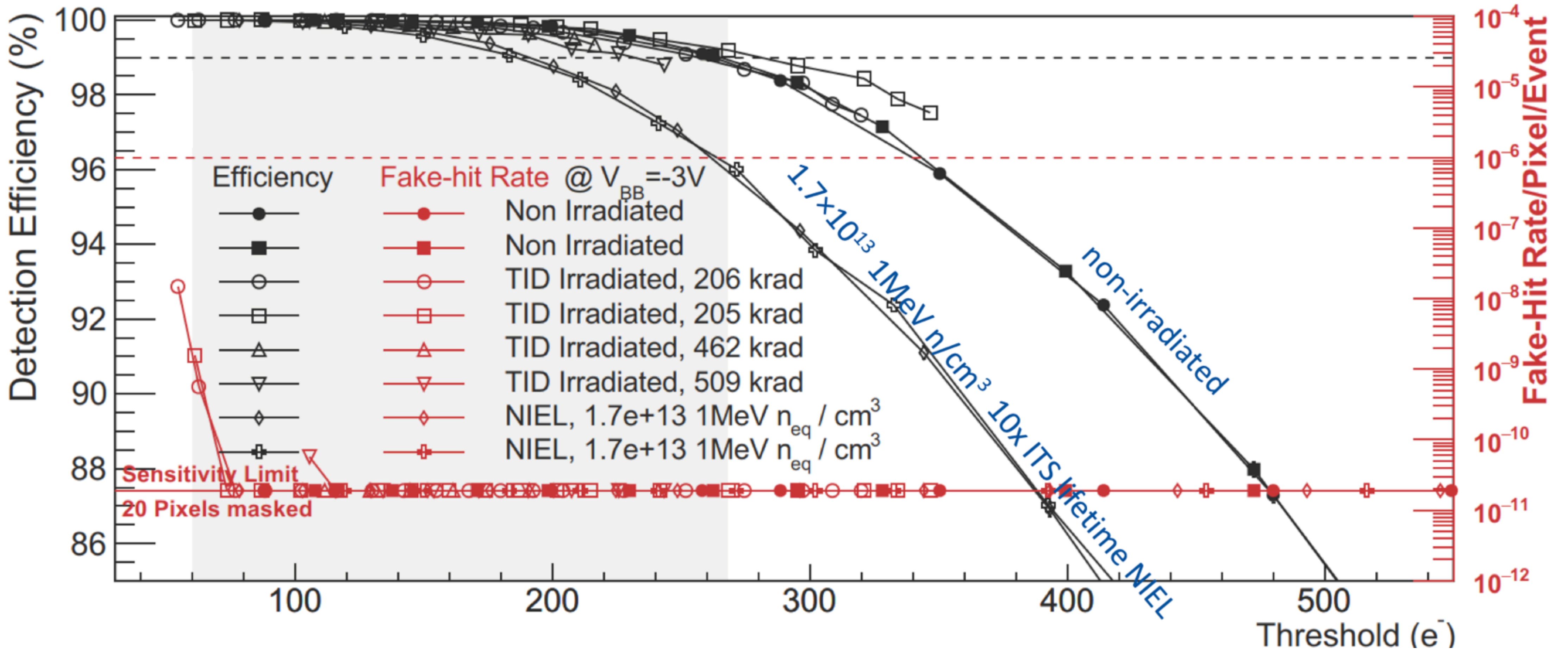
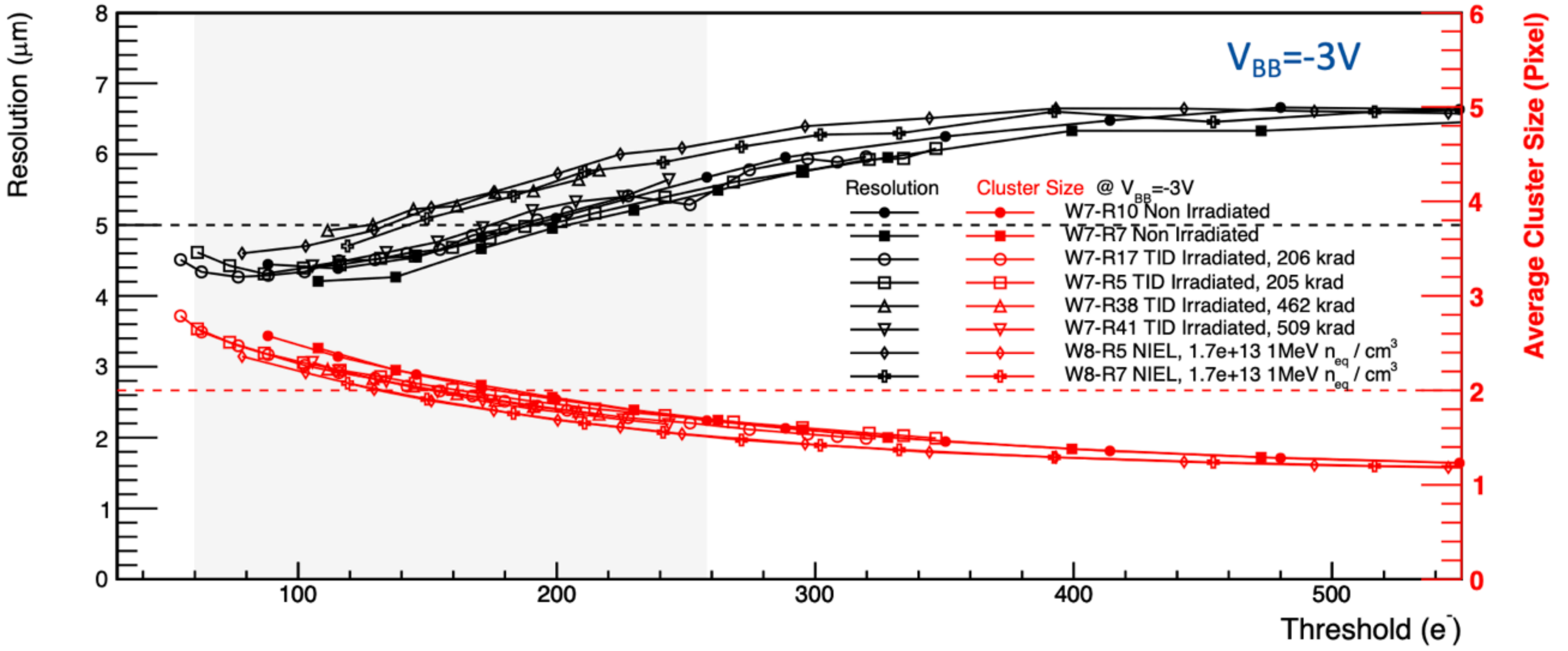
  - very limited noise and fake-hit rate < 10^{-11} hit/pixel/event





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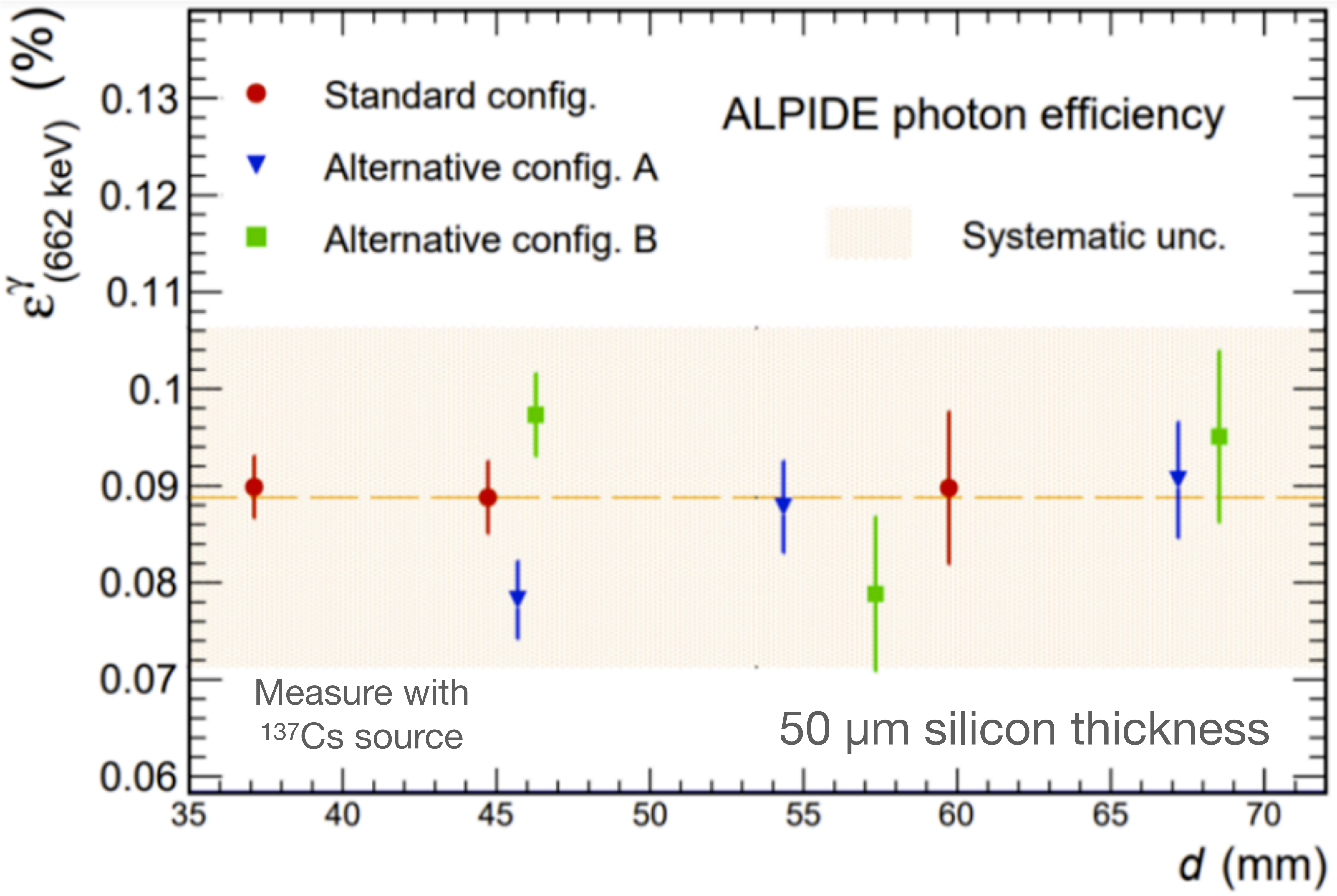

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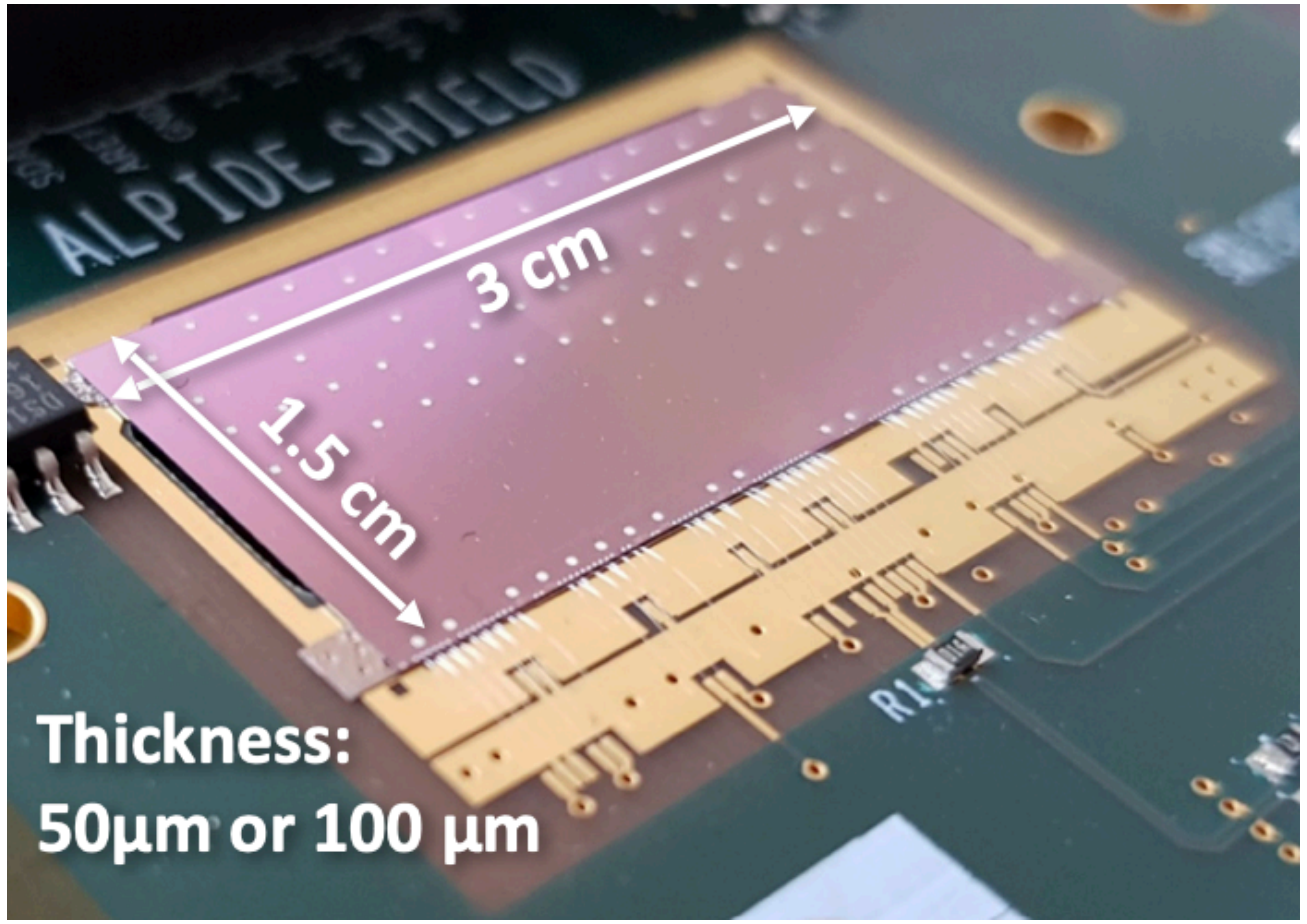

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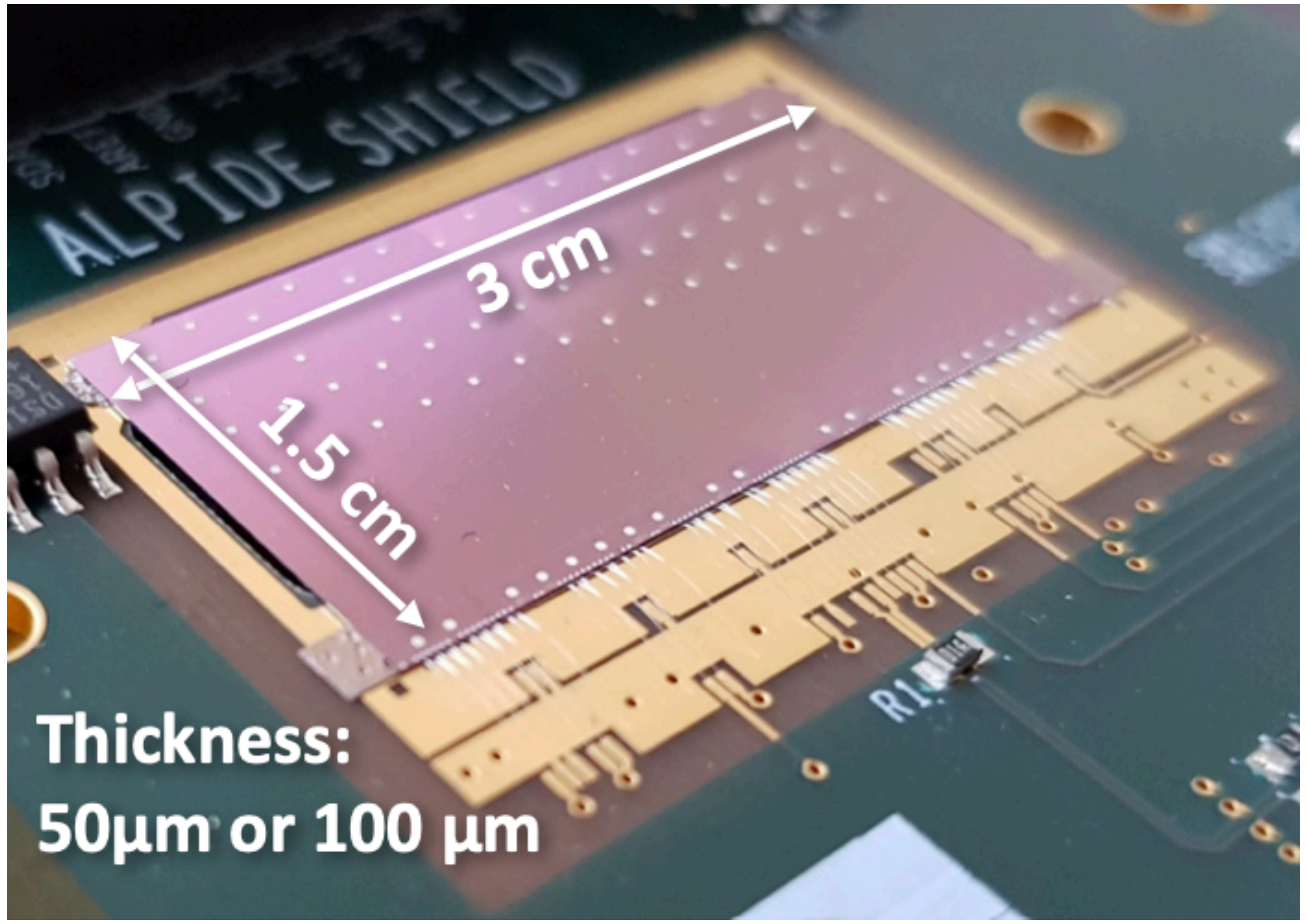
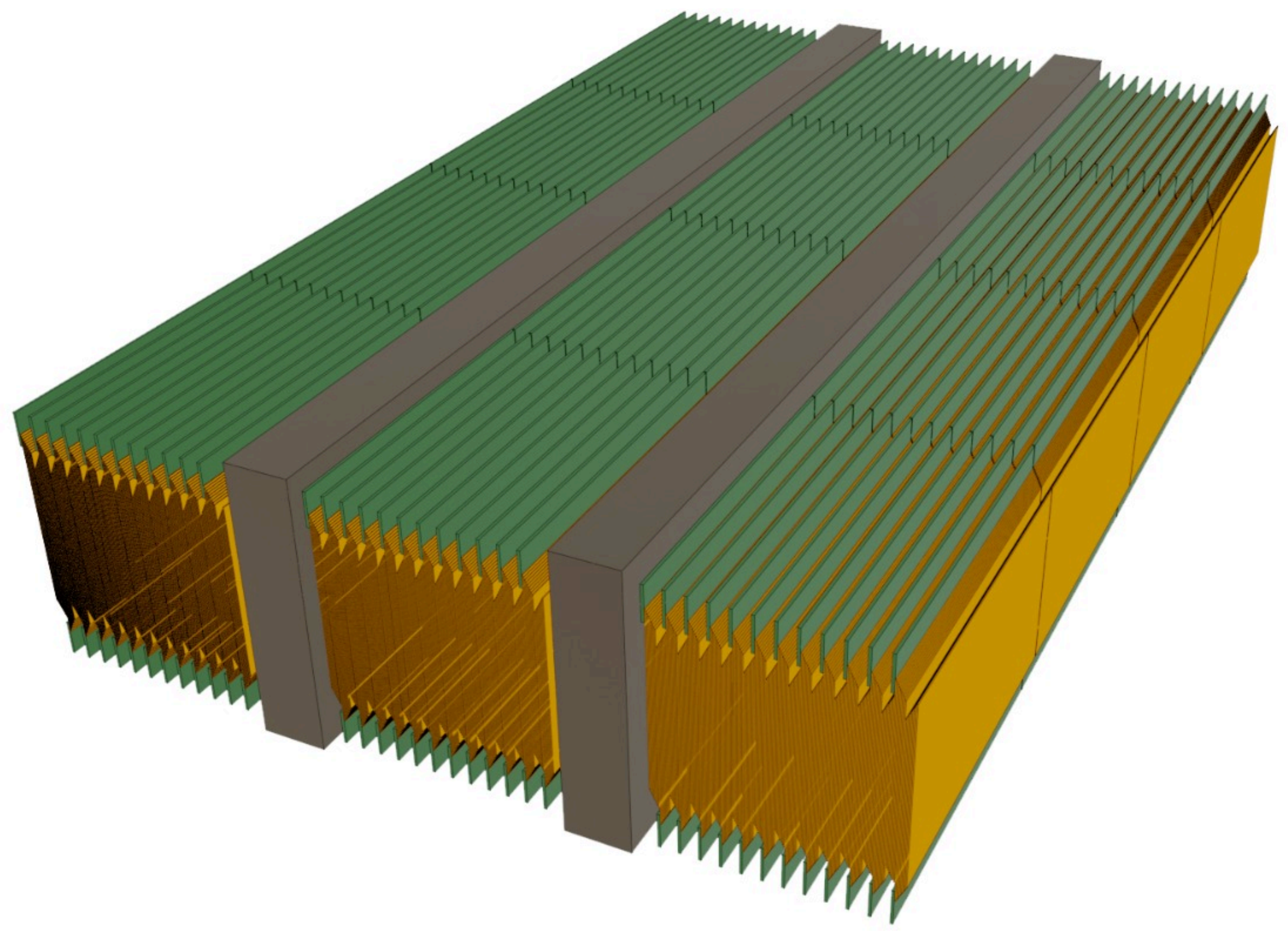


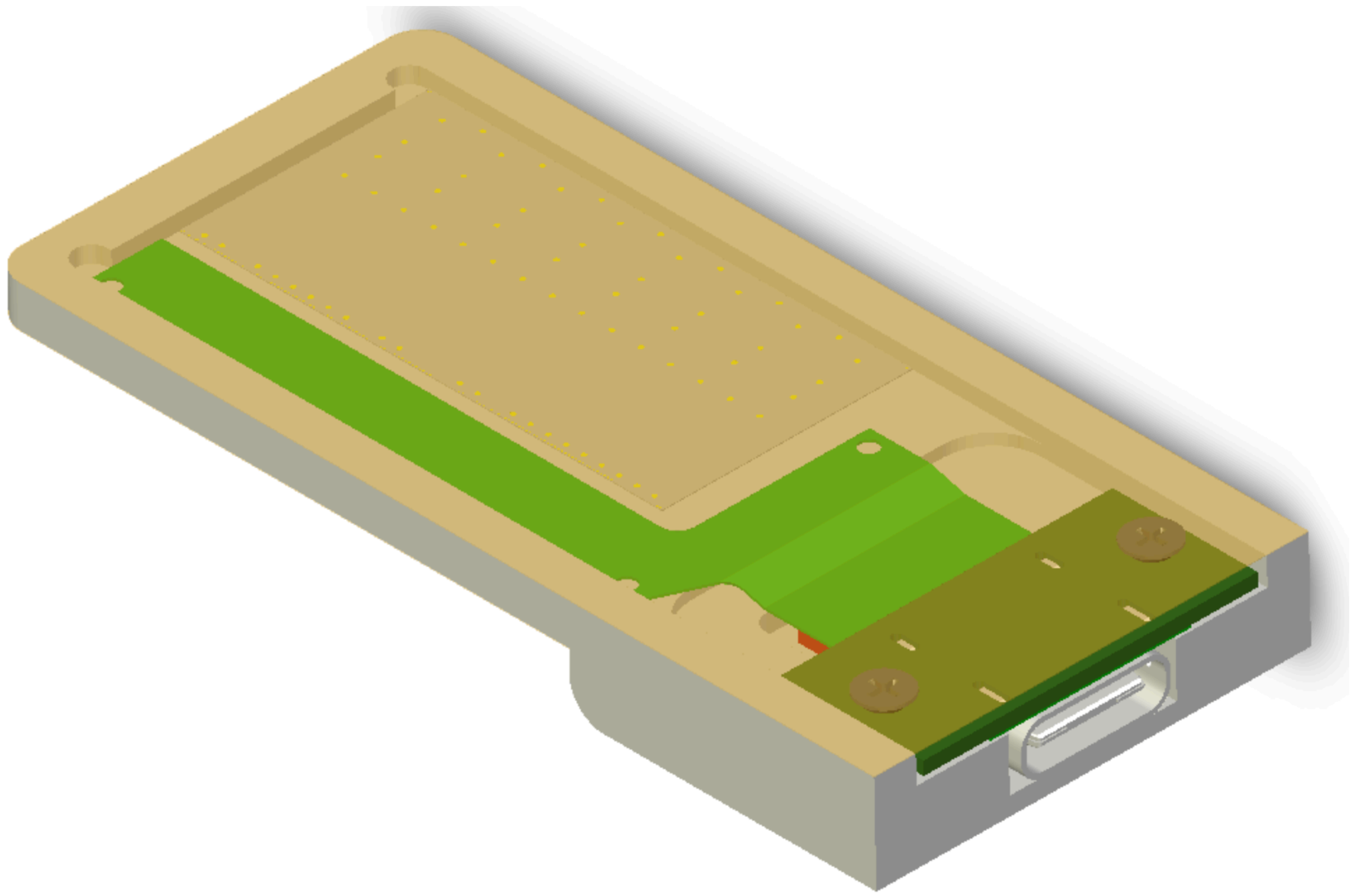
These properties make this sensor **suited for usage in medical physics**.

Applications of MAPS in medical physics

Pixel chamber for Compton camera



Intraoperative probe



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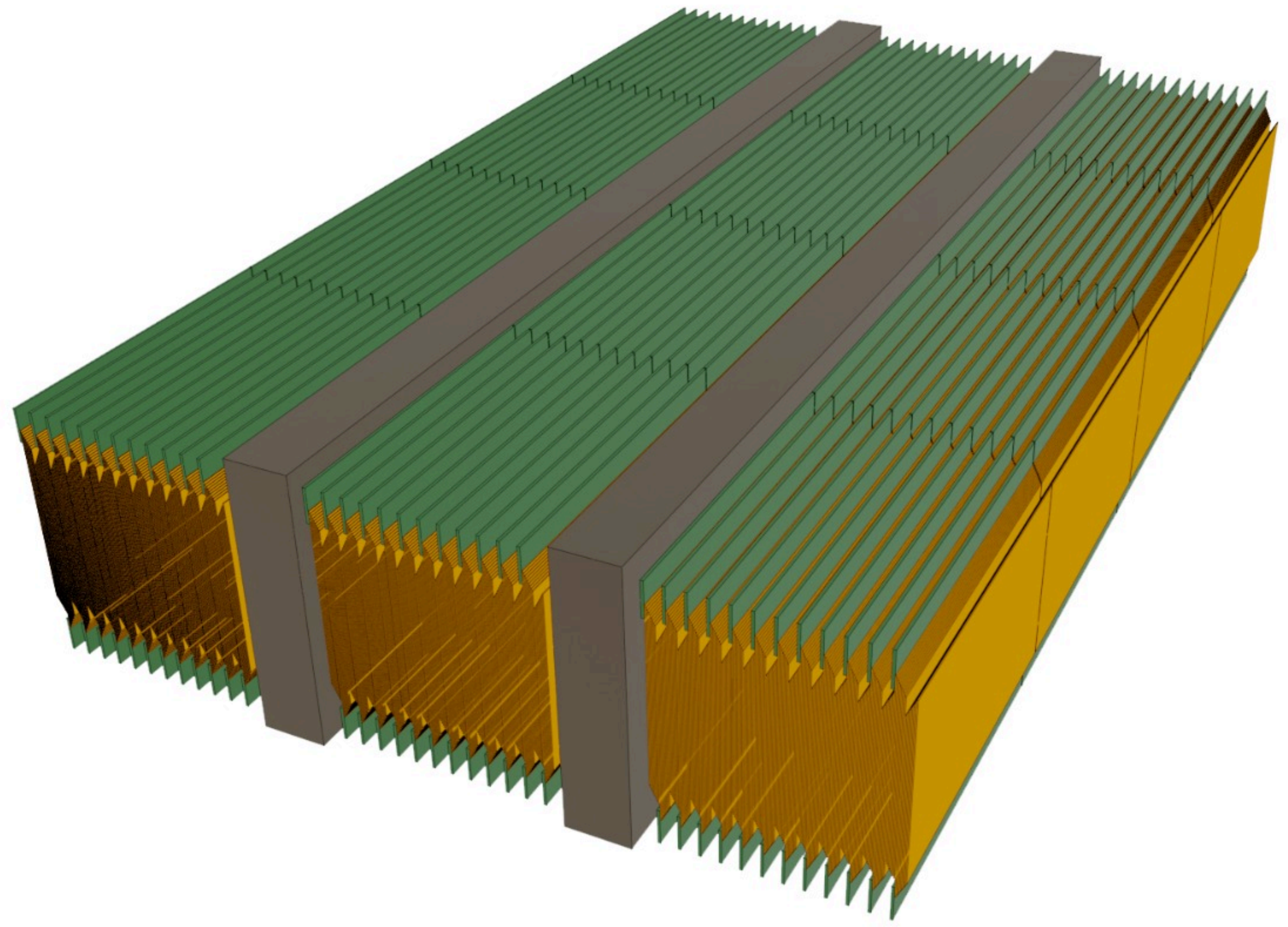
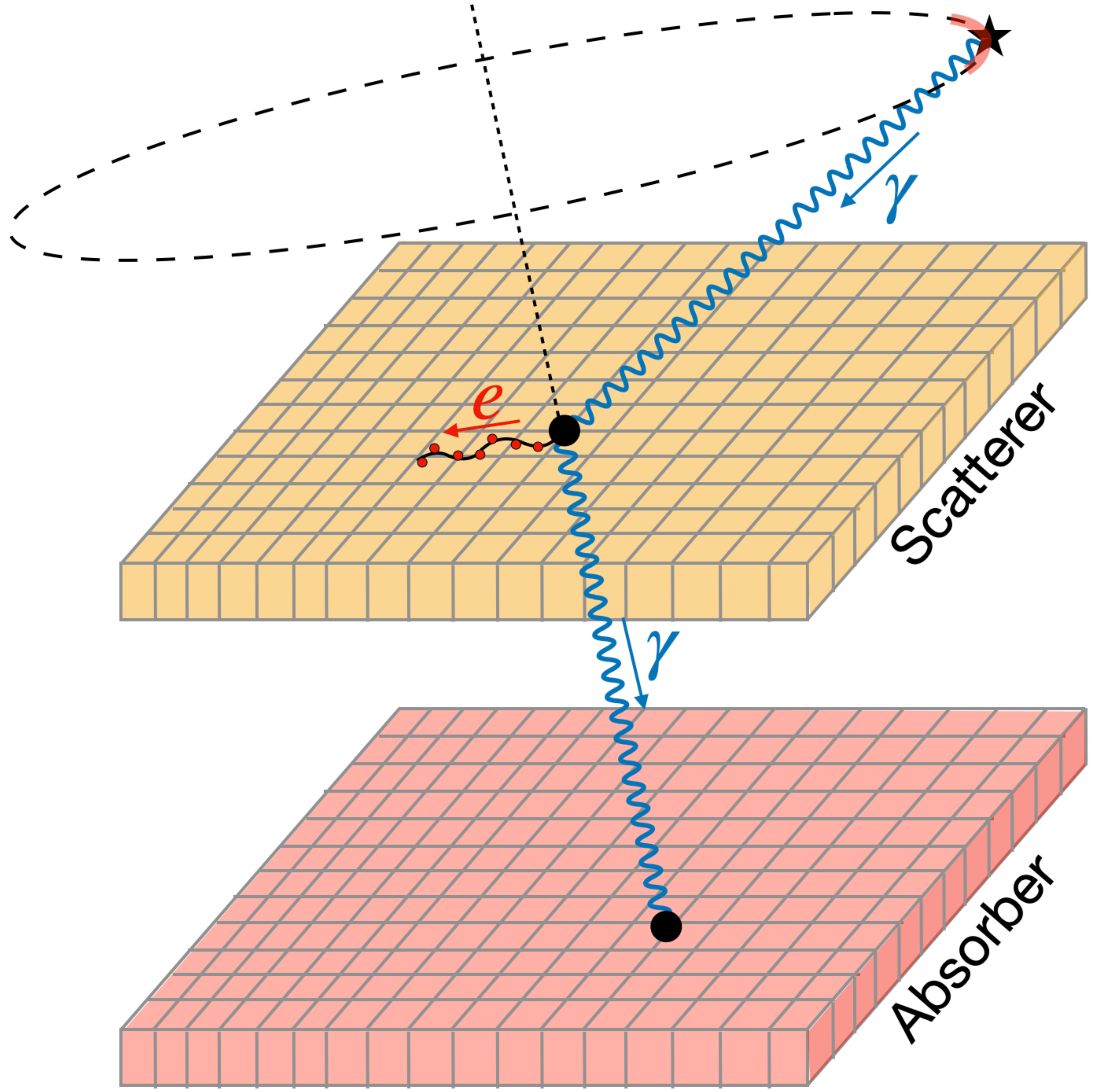


Intraoperative probe

Working principle

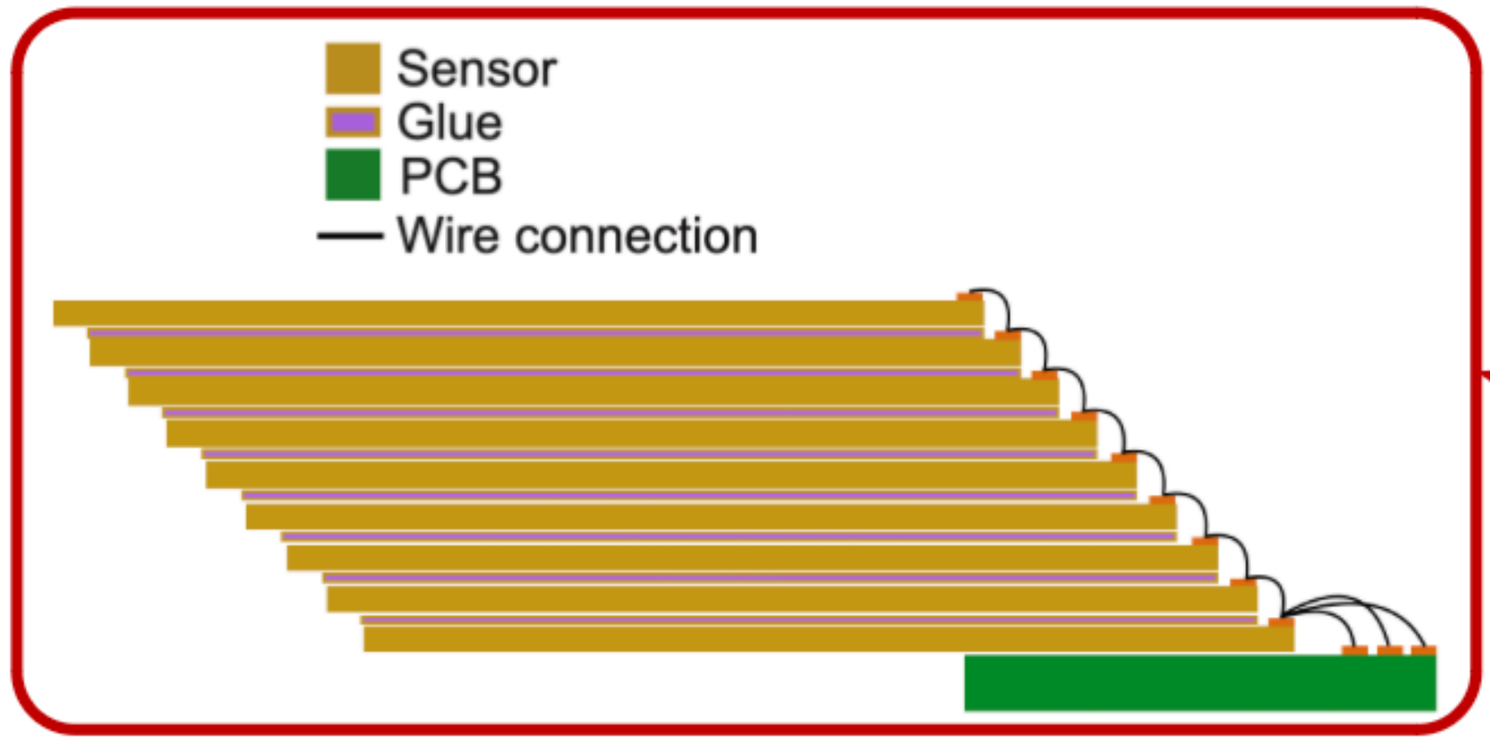
- Compton cameras consist of two sub-detectors: **scatterer** and **absorber**
  - A γ undergoing a Compton interaction in the scatterer and stopped in the absorber only constrains the original direction of the γ to a **cone**
  - Multiple γ reconstructions needed to locate the source position

- A Compton camera implementing an **active scatterer**, having tracking capabilities, would:
  - allow for reconstruction of **emitted electron direction**
  - constrained direction of original γ already by **single photon** → **significantly faster** than standard chambers



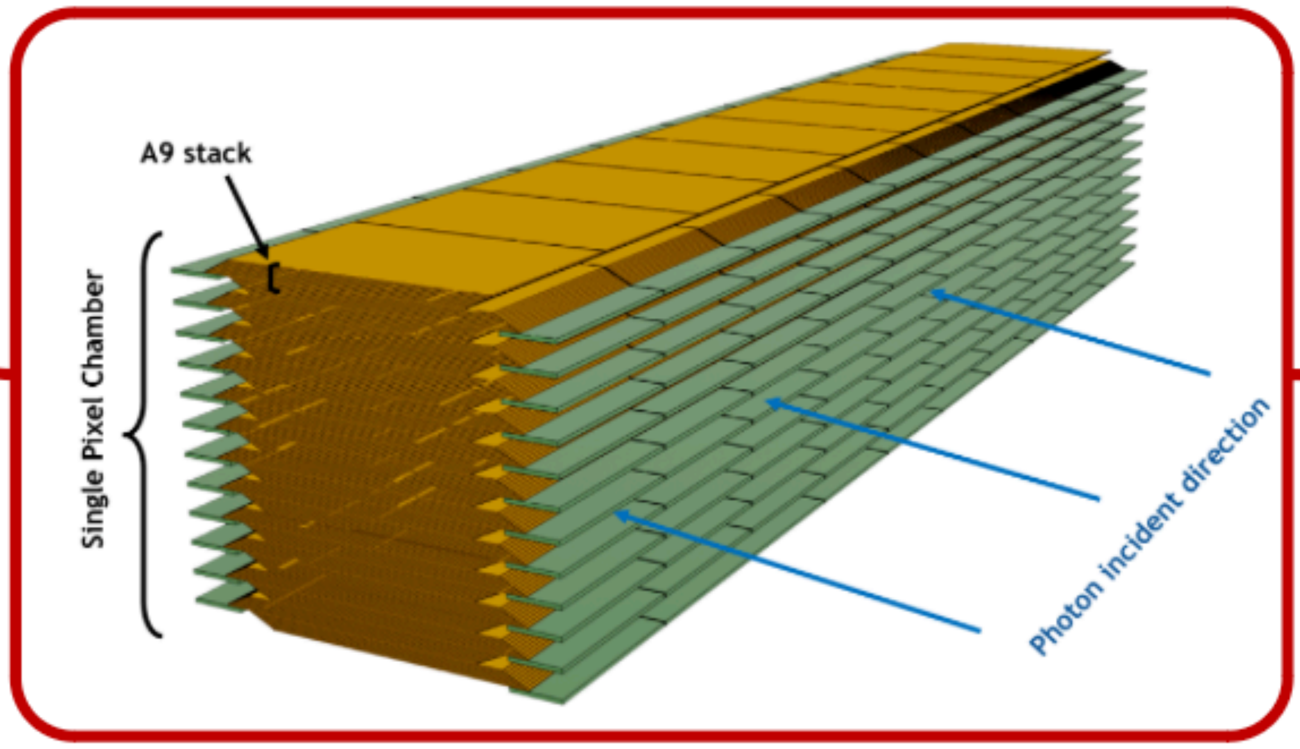
Pixel chamber for Compton camera

How to build an active scatterer Compton chamber



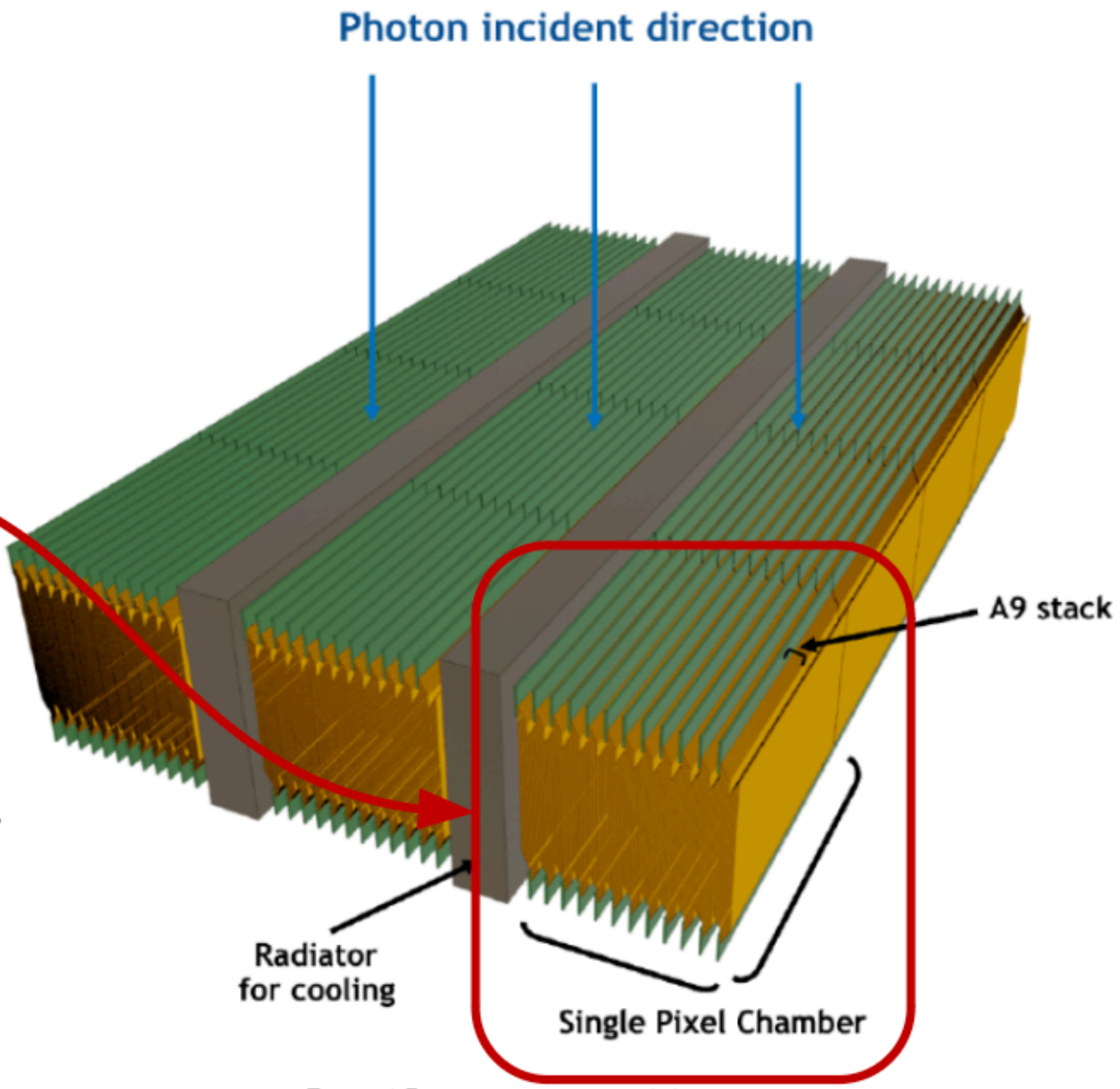
Cross section of A9 stack

Stack of 9 sensors horizontally shifted by ~500 µm for connection needs



Cross section of part of a Pixel Chamber

Assembly of 24 A9 stack equipped with relative pcb for powering and data transferring

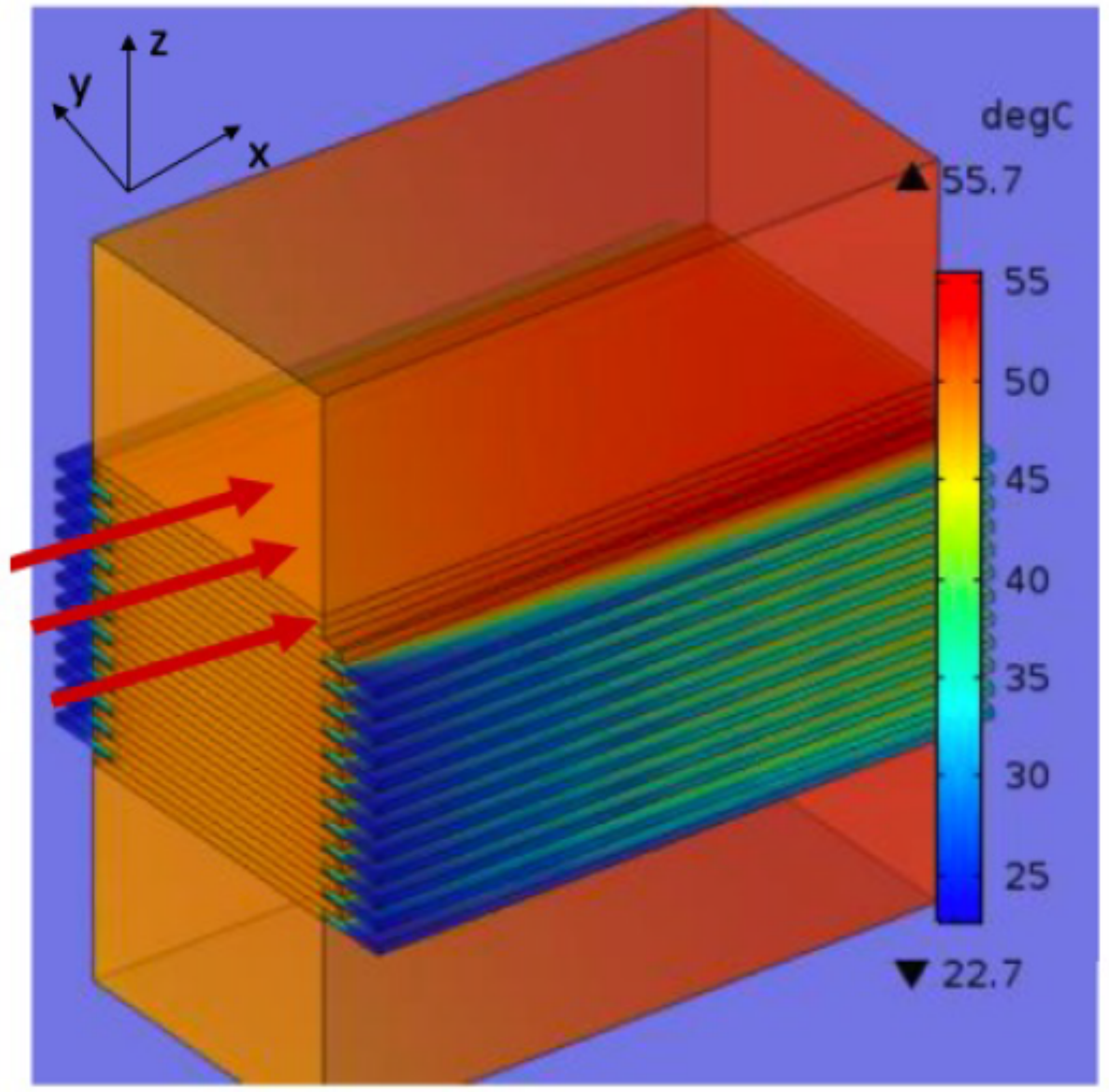


Active scatterer

Multiple Pixel Chamber integrated with cooling system

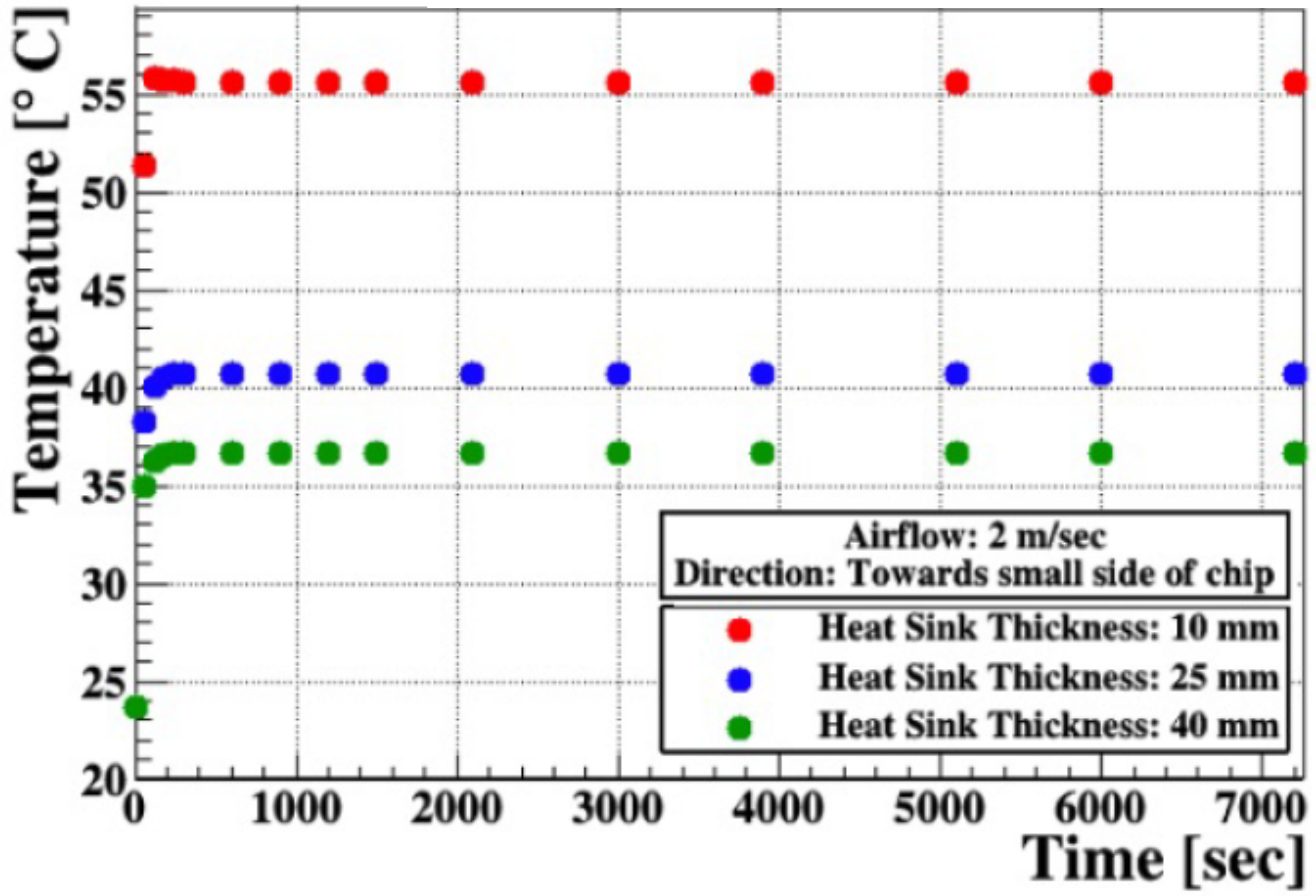
Possible applications: **in-vivo monitoring** of **hadron therapy**, fast detection of γ sources in multi-messenger **astrophysics**, **active target** for particle accelerators

Power dissipation



Cooling studies with **COMSOL software** and **cooling tests** with mock up in aluminum

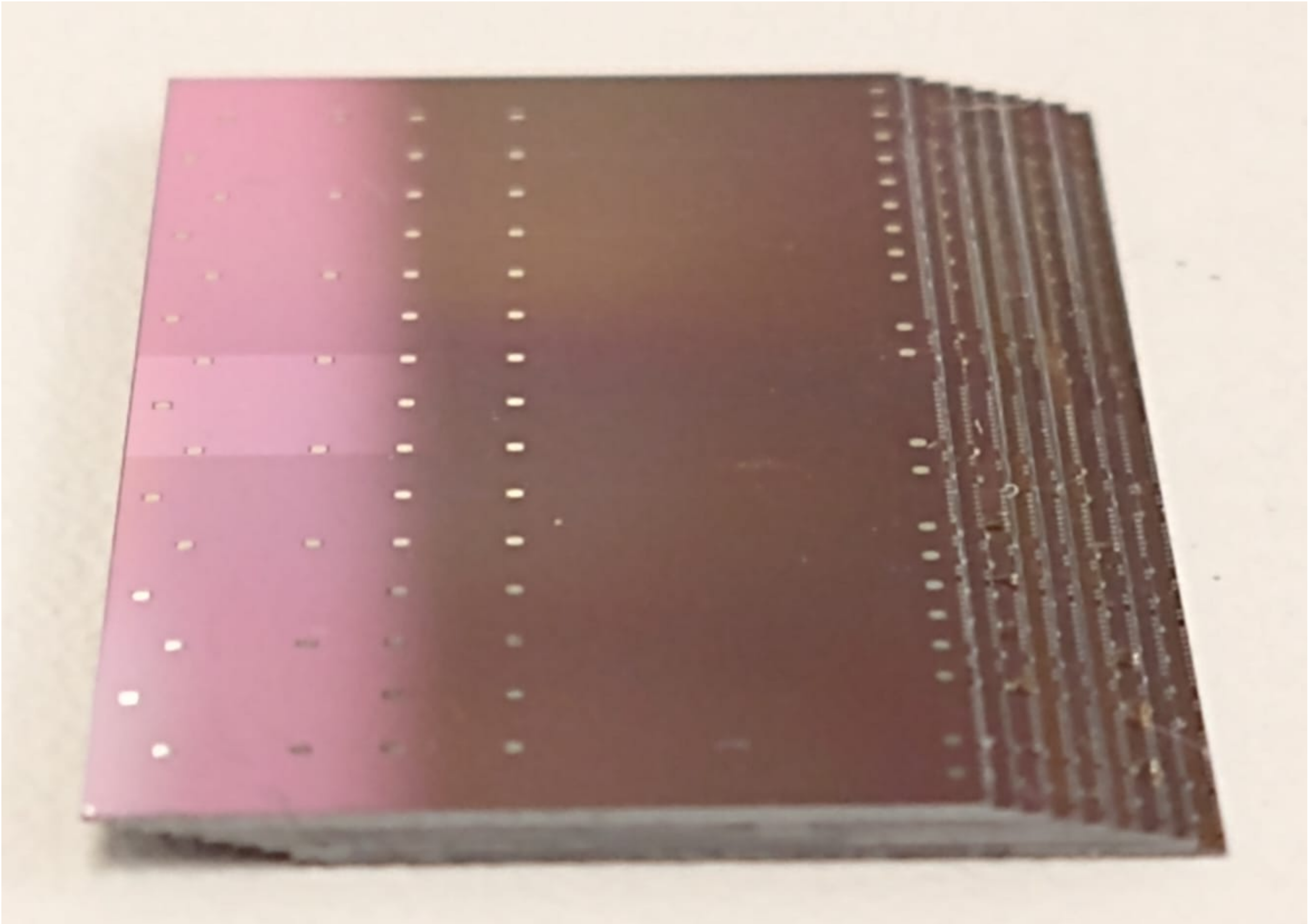
- For the A9 stack, a simple airflow of 2 m/s is enough to stabilize temperature at 37.9°C
- For the Pixel Chamber, **heat sink radiator elements + airflow** of 2 m/s are mandatory to keep **T < 40°C**
  - thickness and material of radiators to be optimized depending on the final geometry
  - order of few cm for copper elements

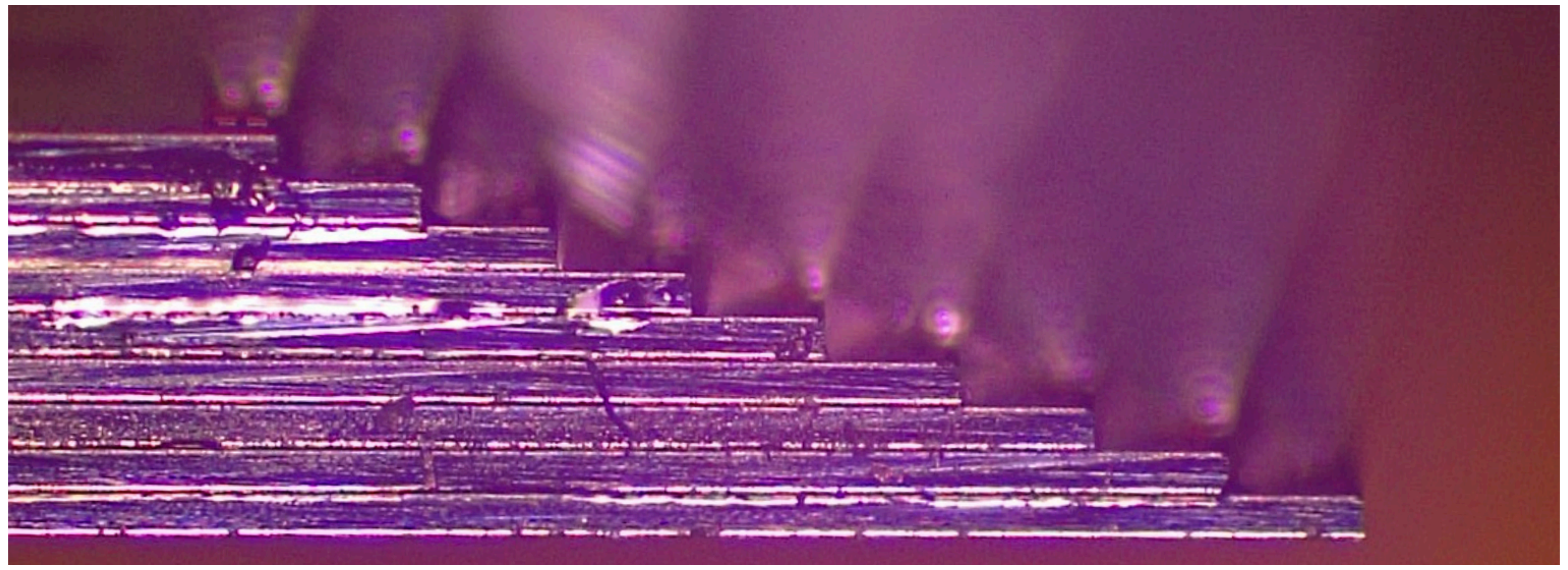


Pixel chamber for Compton camera

Prototyping campaign

- A9 stack **prototyping**: many mechanical assemblies, using ALTAI sensors with 50 μm thickness
- Sensors alignment by Mitutoyo, equipped with custom vacuum sensor handling tool, using a long curing time glue (EP601LV) → relative sensor alignment **≈ 5 μm**





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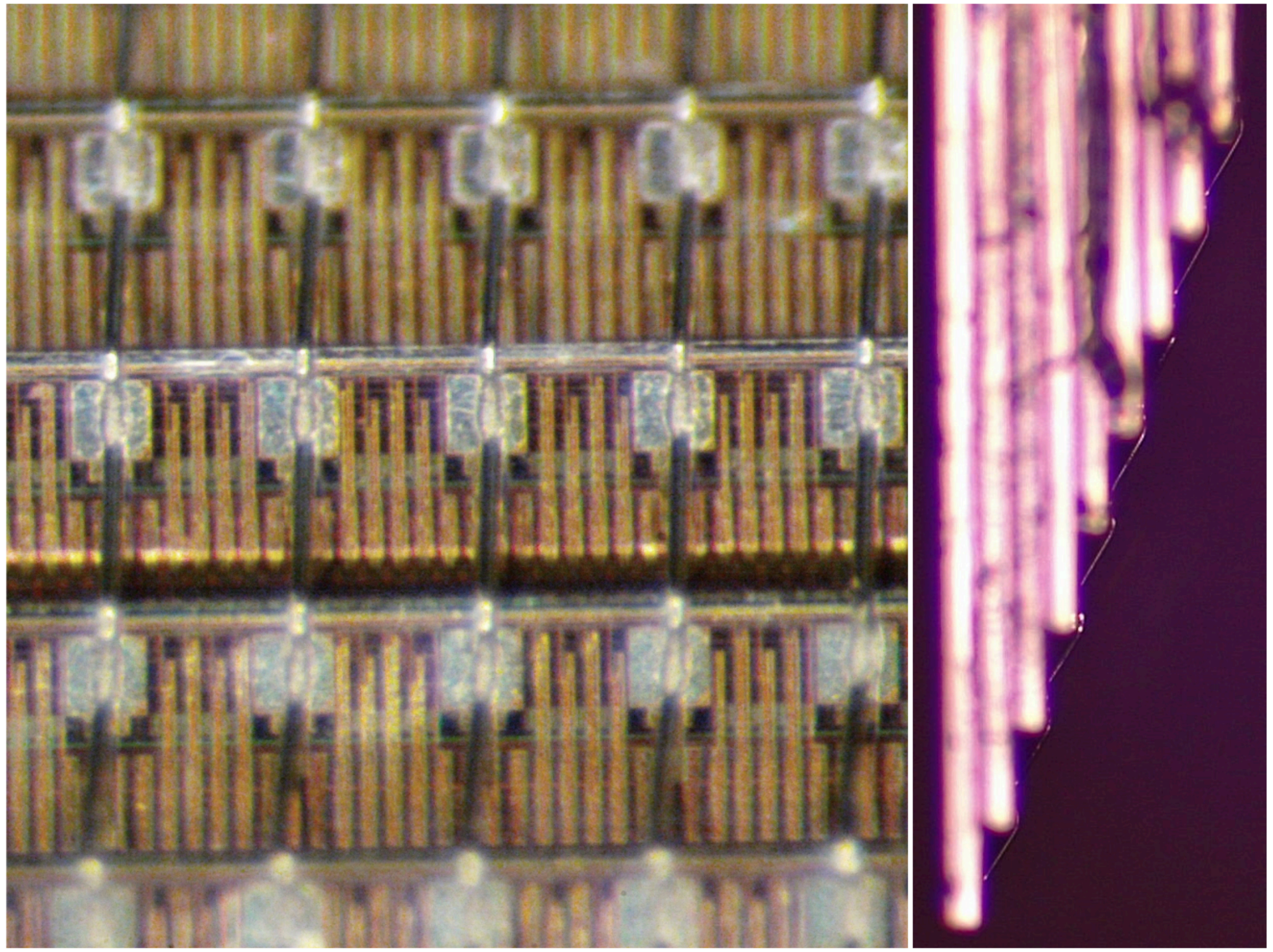
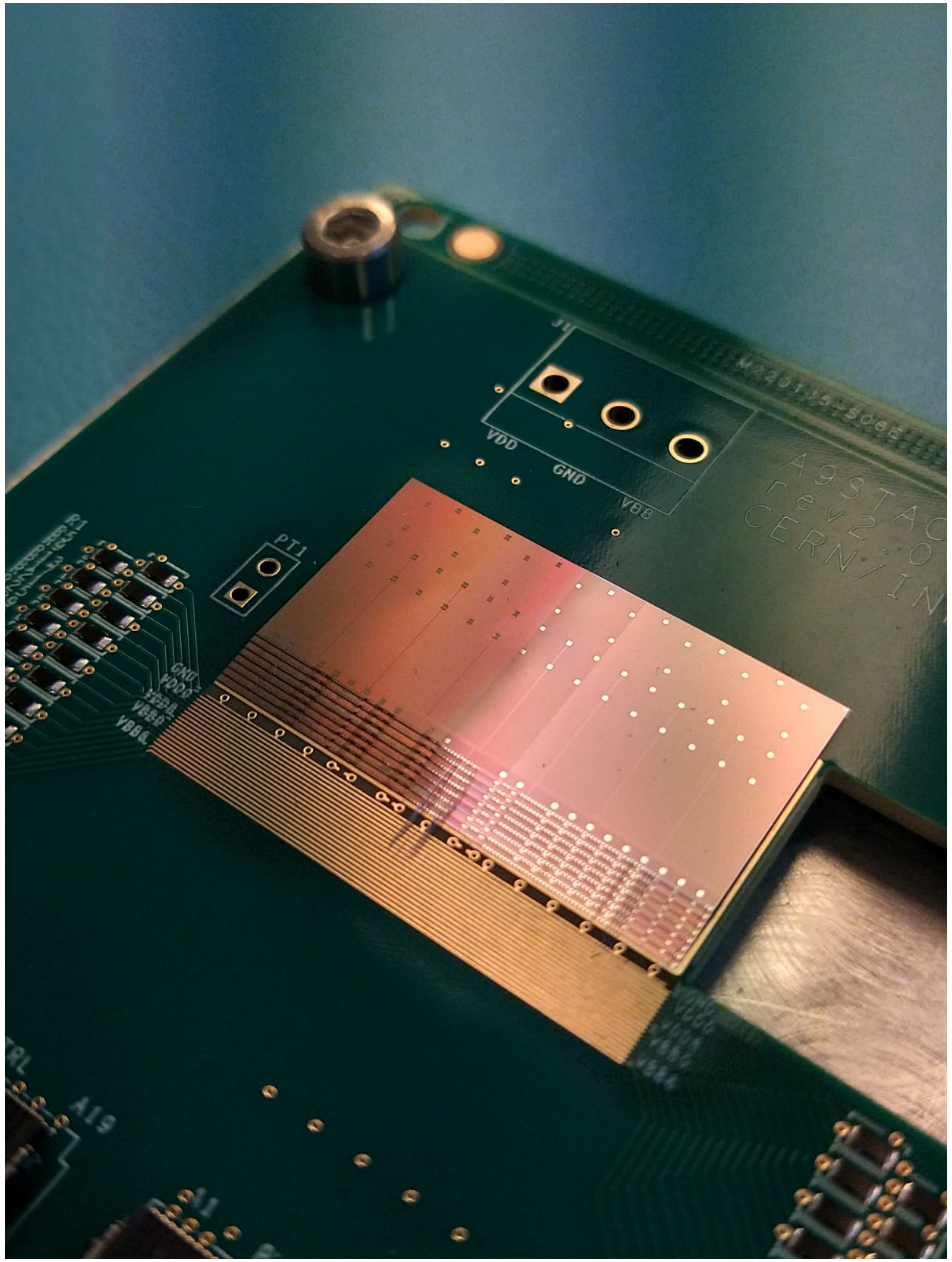
- **Wedge wire-bonding investigations**: multiple welding without wire cutting (cascade bonding), loop shape, welding strength, welding failures



Pixel chamber for Compton camera

Outlook

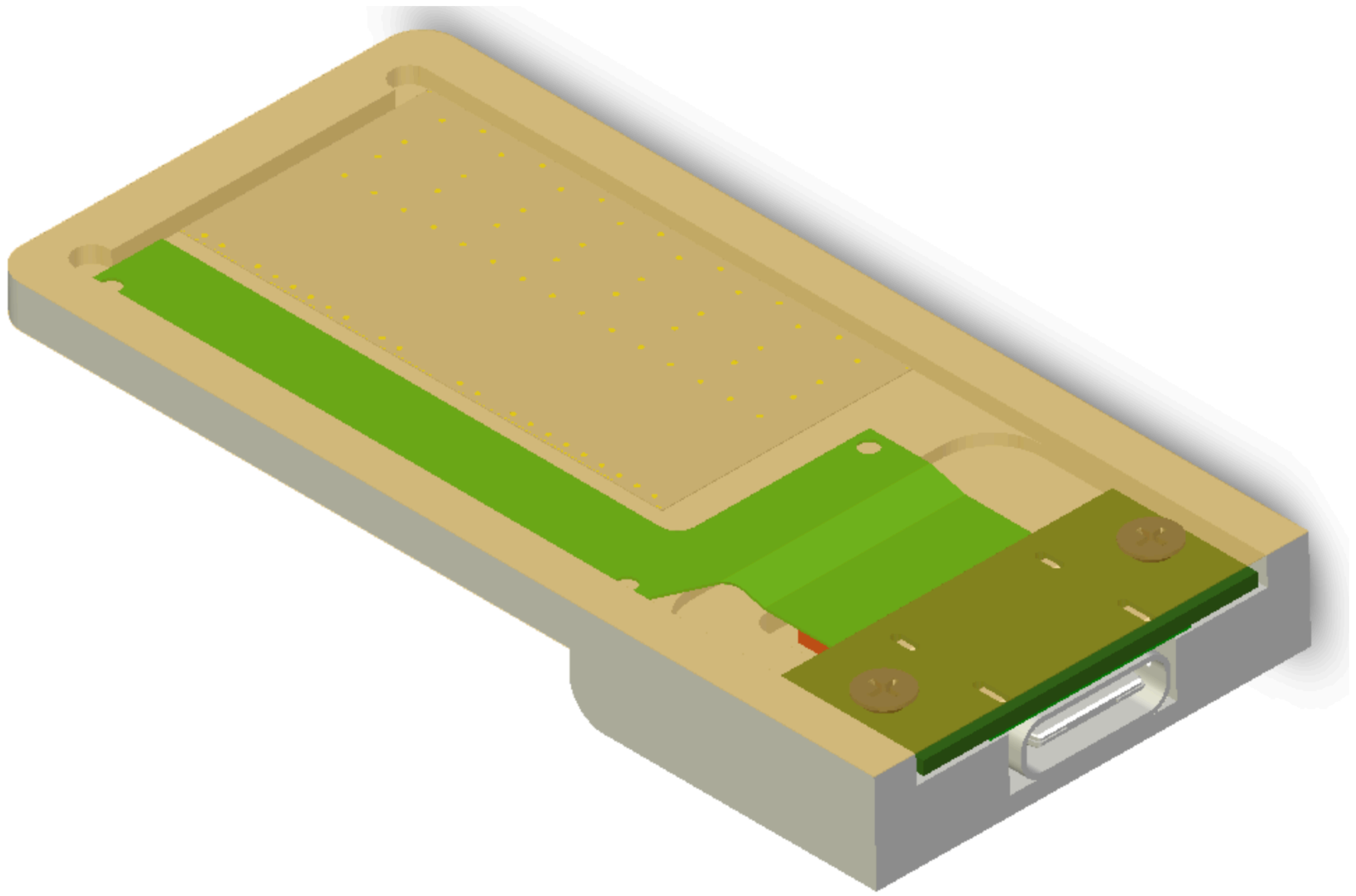


- Assembly of first **stacks of working sensors** and connection to **PCB readout board** done
- Functional test and **characterization** of the stack and of the readout system, using sensor internal protocols, radioactive sources and beams soon
- Next further activities:
  - Detailed design of a full Pixel Chamber with its support, cooling and readout system
  - Development of **algorithm** for the electron tracking and the Compton scattering reconstruction
  - Campaign of **GEANT4 simulations** to study the Pixel Chamber performance and optimize the geometry and the choice of the absorber detector

Applications of MAPS in medical physics

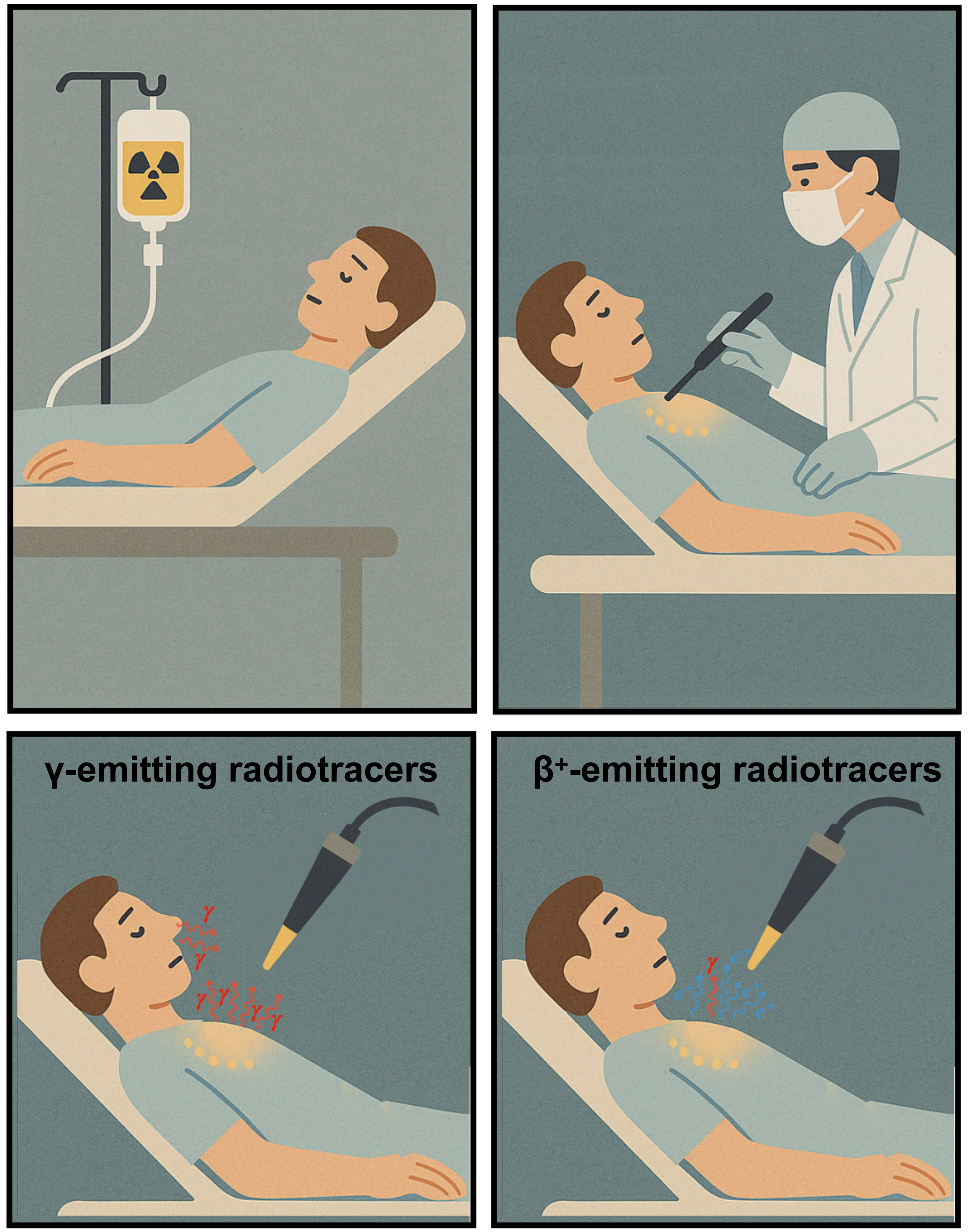
Pixel chamber for Compton camera

Intraoperative probe

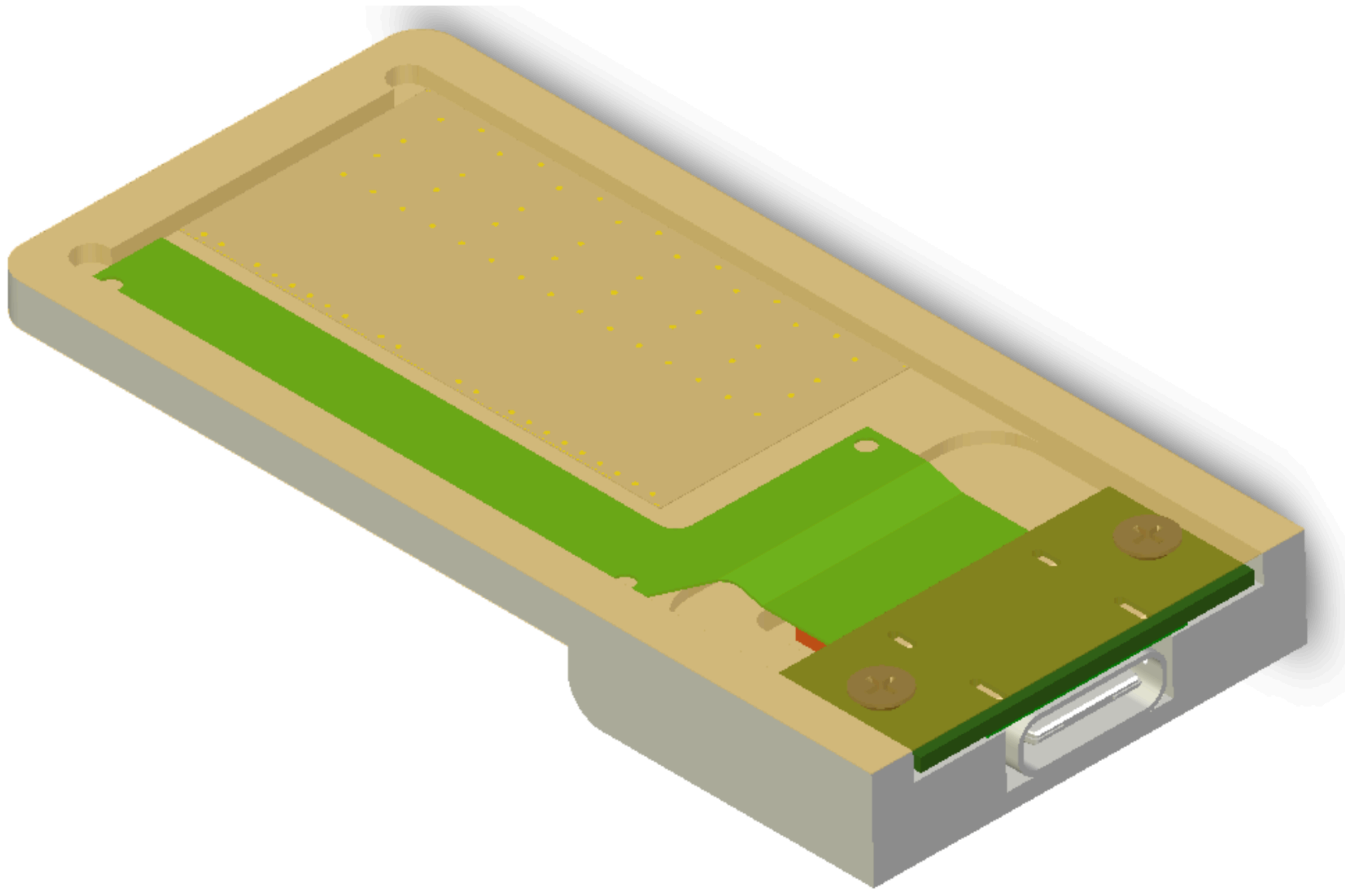


Working principle

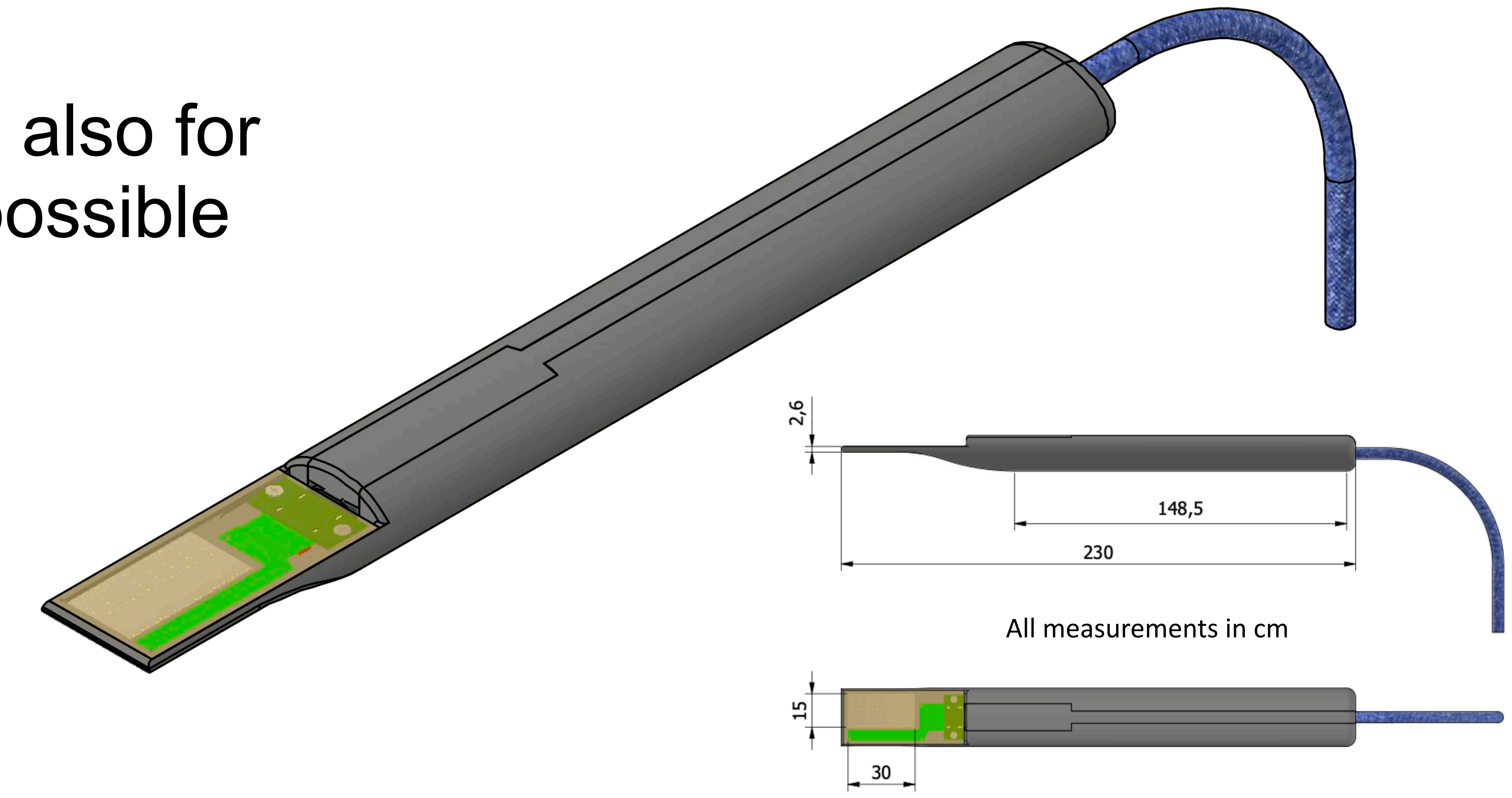
- **Radioguided surgery** (RGS): technique that uses radioactive tracers and specialized detectors to help surgeons localize and remove target tissues (tumors/sentinel lymph nodes) during an operation
- Currently mostly based on usage of **gamma (γ) emitting radiotracers** having a crucial drawback: long mean free path of γ in human tissue
  - About 10 cm at typical energies of few hundred KeV
  - Large γ background emitted from tissues far from lesion site
  - Consequently, limited spatial resolution for γ probes
- Usage of **β^+-emitting radiotracers** (e.g. ^{18}F-FDG, with endpoint E = 635 KeV, half-life = 109.7 min, commercially convenient given the large usage in PET) would solve this limitation
  - β^+ range in human tissues of **few mm** for energies of few hundred KeV
  - Residual issue: background of γ from positron annihilation



How to build a MAPS based probe

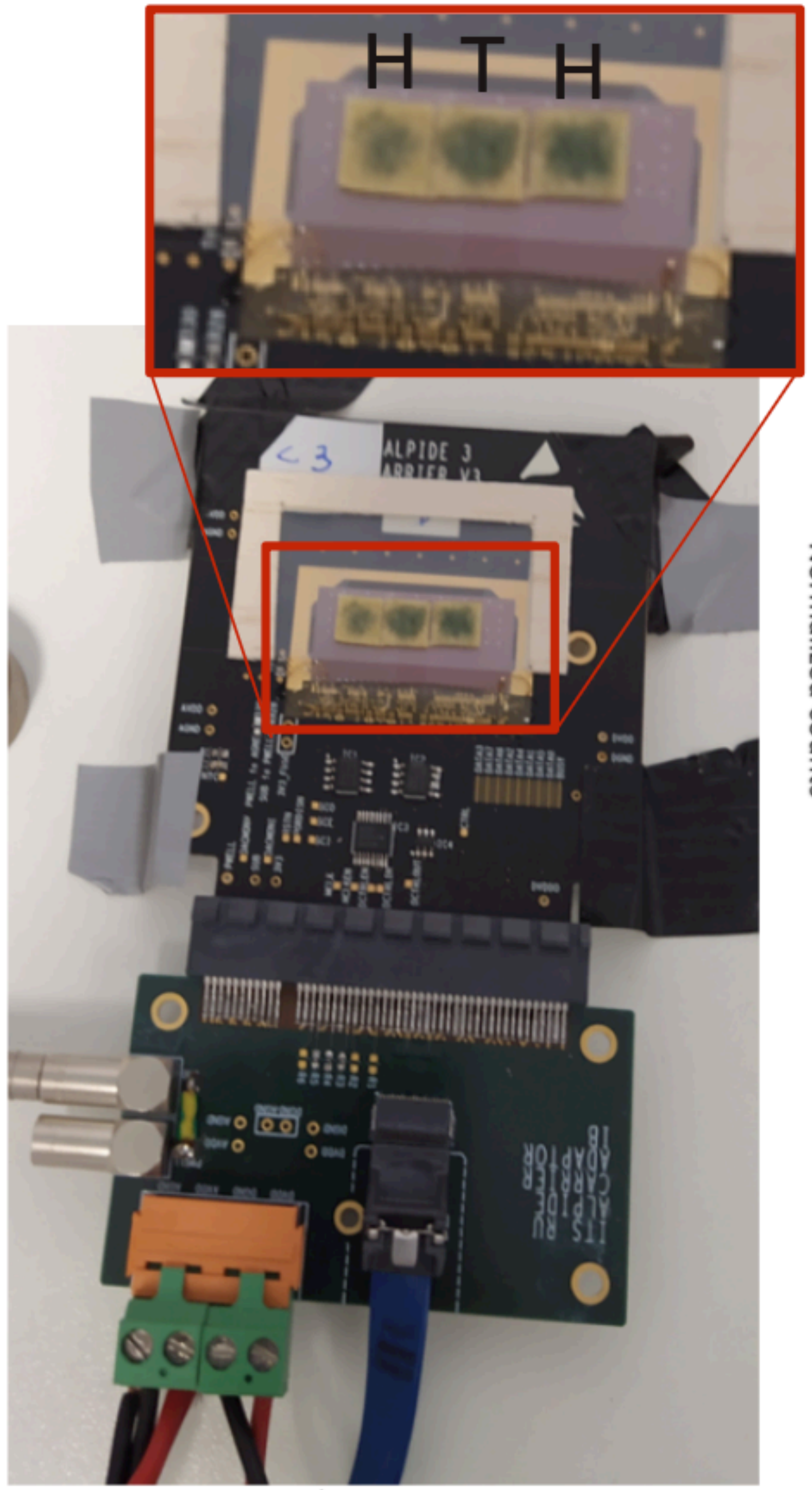


- **Detector requirements for this application**:
  - high detection efficiency for β from 100 KeV to a few MeV
  - minimal sensitivity to photons
  - excellent spatial resolution
  - very low fake-hit rate
  - small size and compactness
- The **ALTAI chip** matches all requirements, allowing also for imaging technique to localize the tumor mass and possible remnants after the surgery

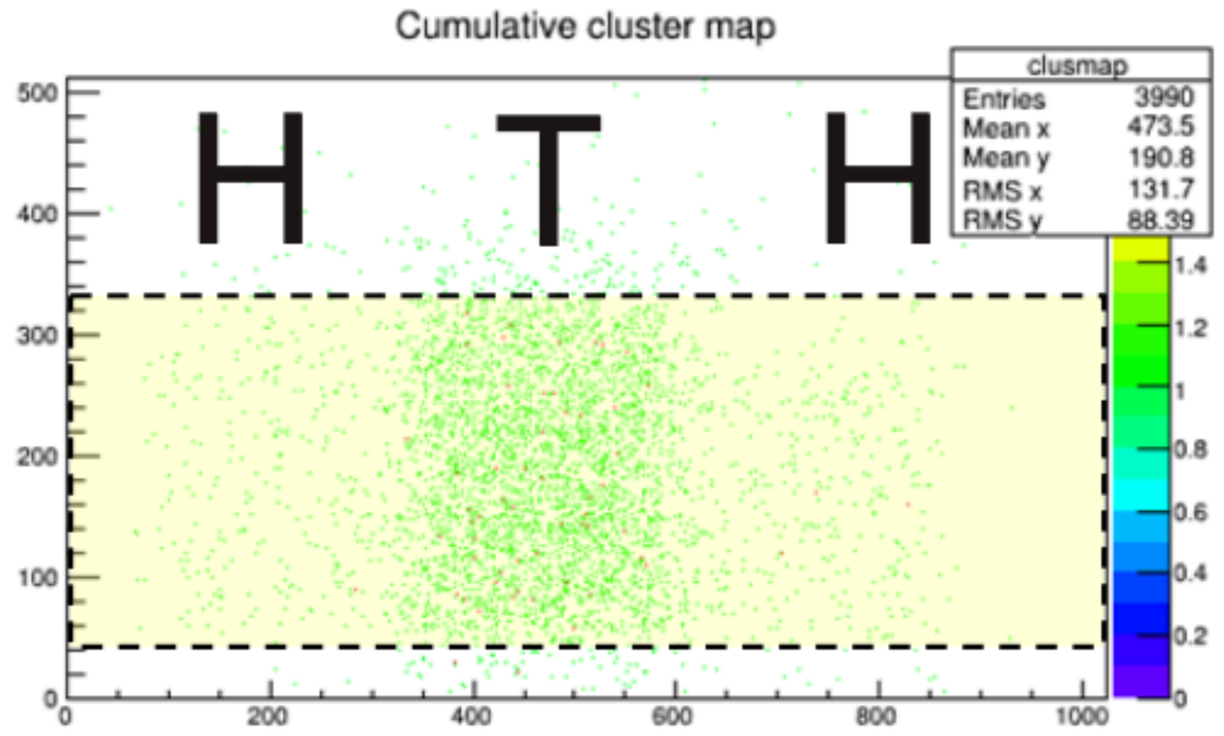


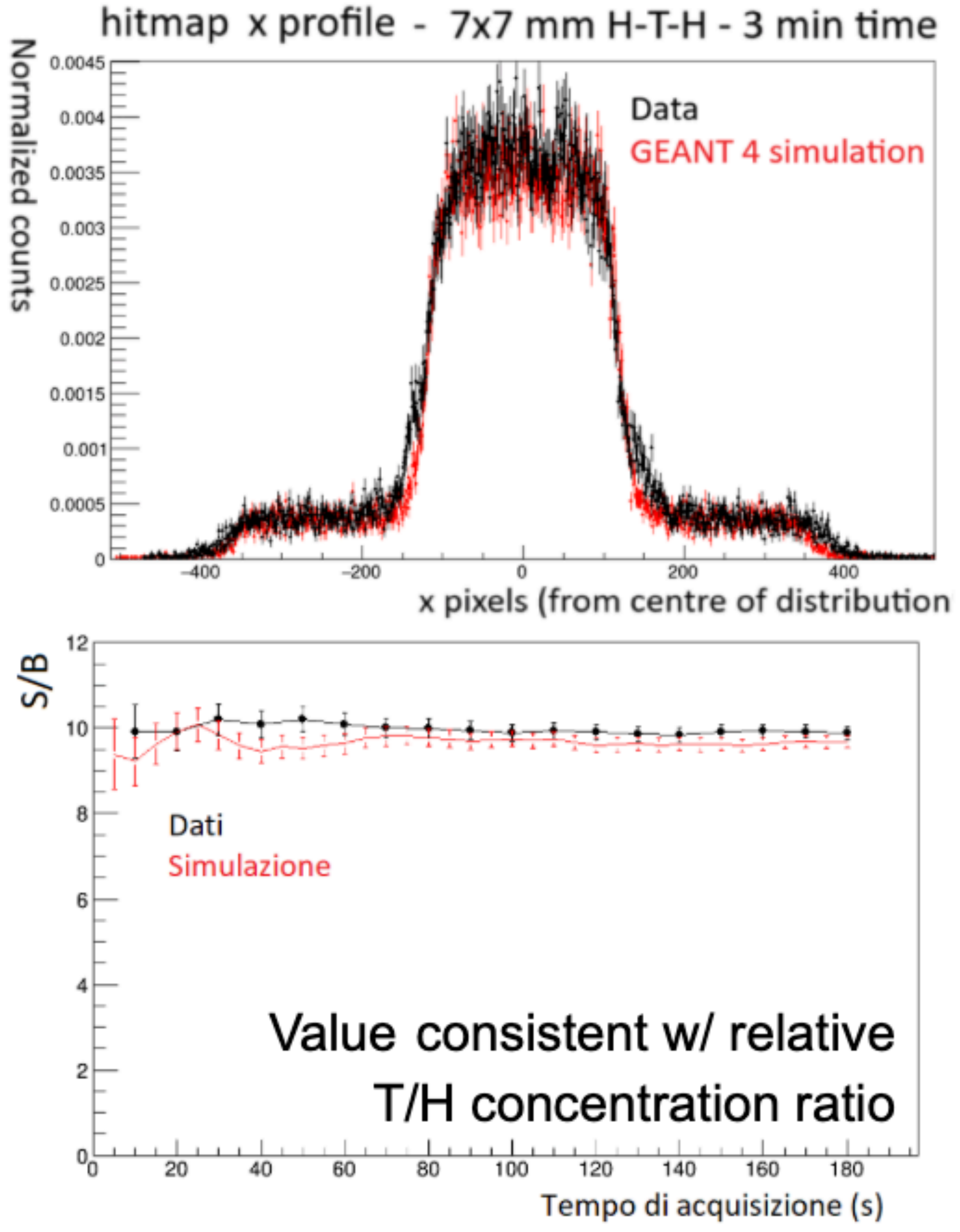
First measurements

- **Sponges soaked with ^{18}F-FDG** in typical concentration ratios present in RGS for **tumor (T)** and **healthy (H)** tissues (10:1), placed on an sensor:
  - measure **x-profile** compared to simulations
  - T sponge clearly visible both in 2D plots and x profile → **significantly more counts** than H sponges
- **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**



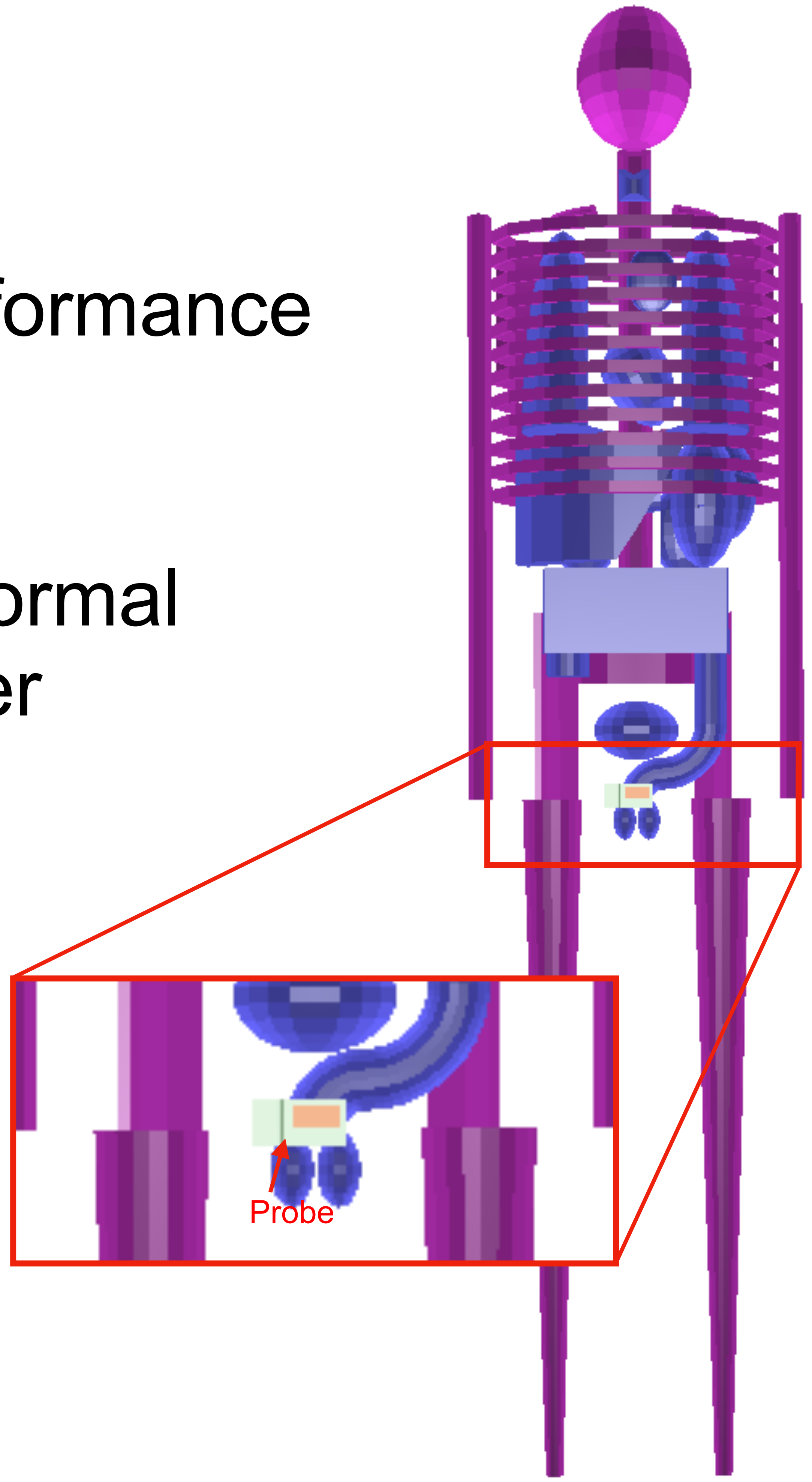
7x7x1 mm^3 sponges placed on a sensor



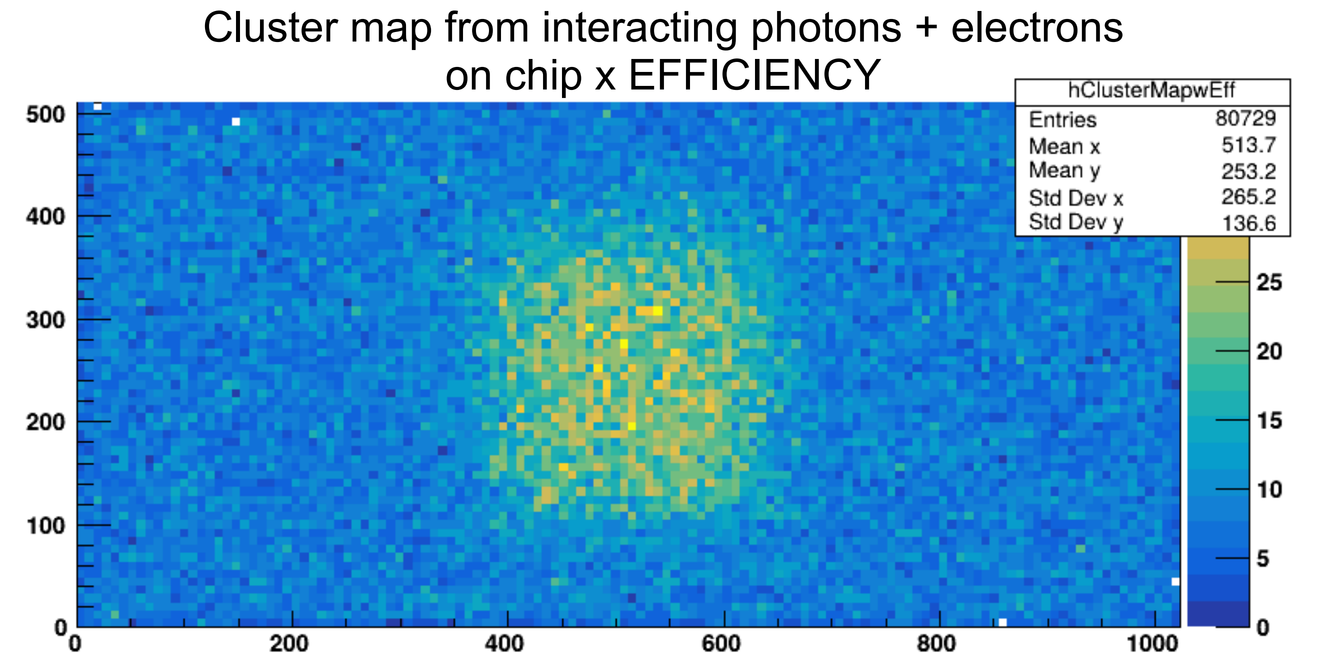


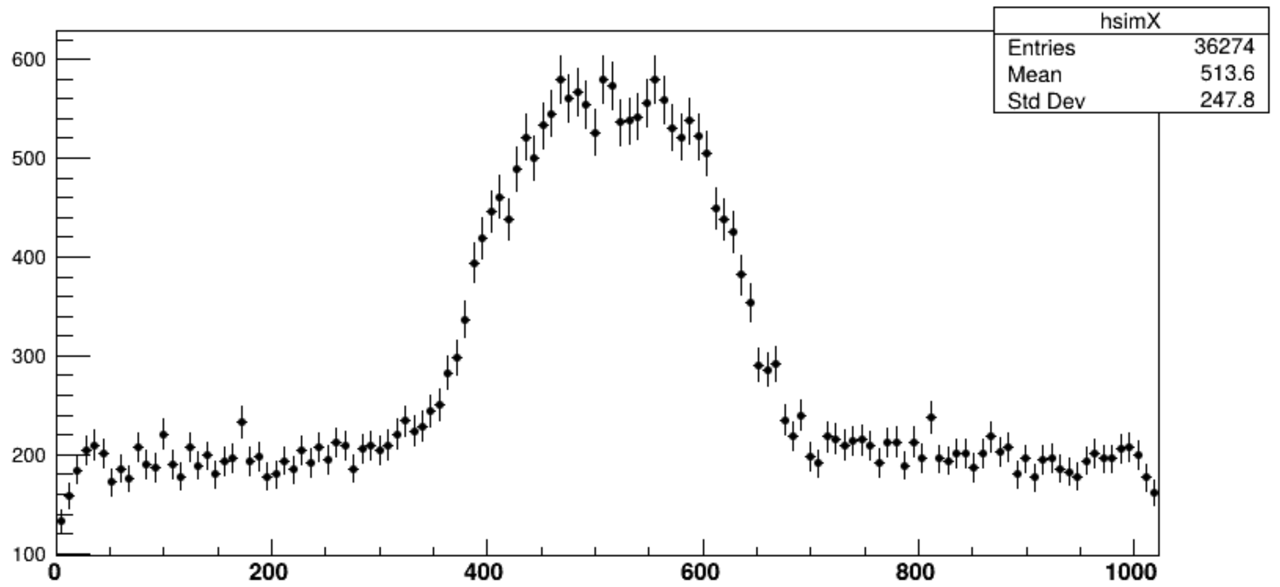
Full boby simulation

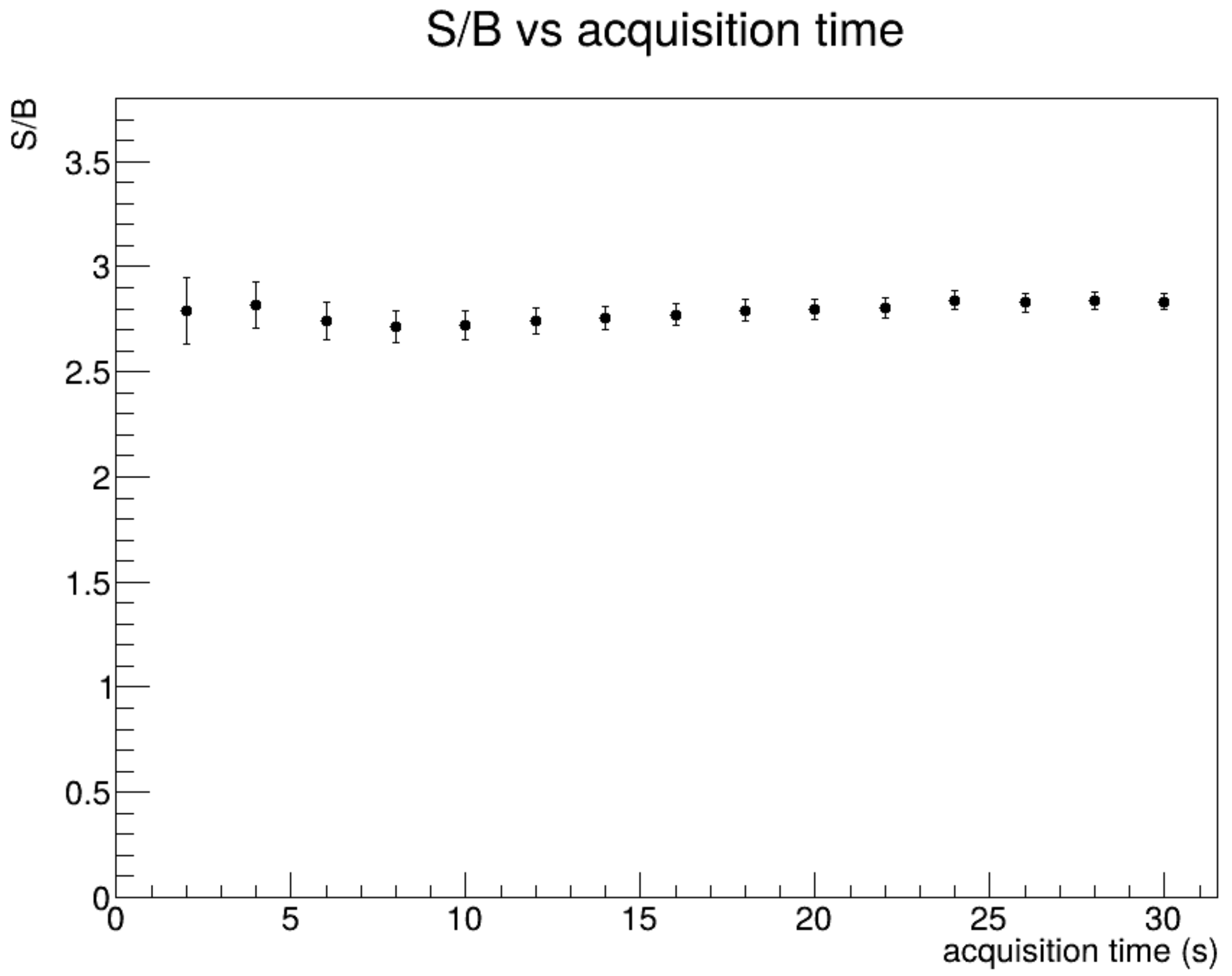
- Full body simulation to evaluate sensor performance for locating tumor tissues in **more complex configurations**, not easily accessible
- Tumor tissue absorbs x10 with respect to normal tissue and almost x3-x4 with respect to other organs of the trunk and abdomen
- **Tumor region still clearly visible**
- **Signal-to-background (S/B)** ratio reduced due to the large amount of annihilation photons coming from the rest of the body



Full body having a tumor mass with size 7 mm x 7 mm ("visible" surface) x 5 mm (thickness) in the lower abdomen at skin surface

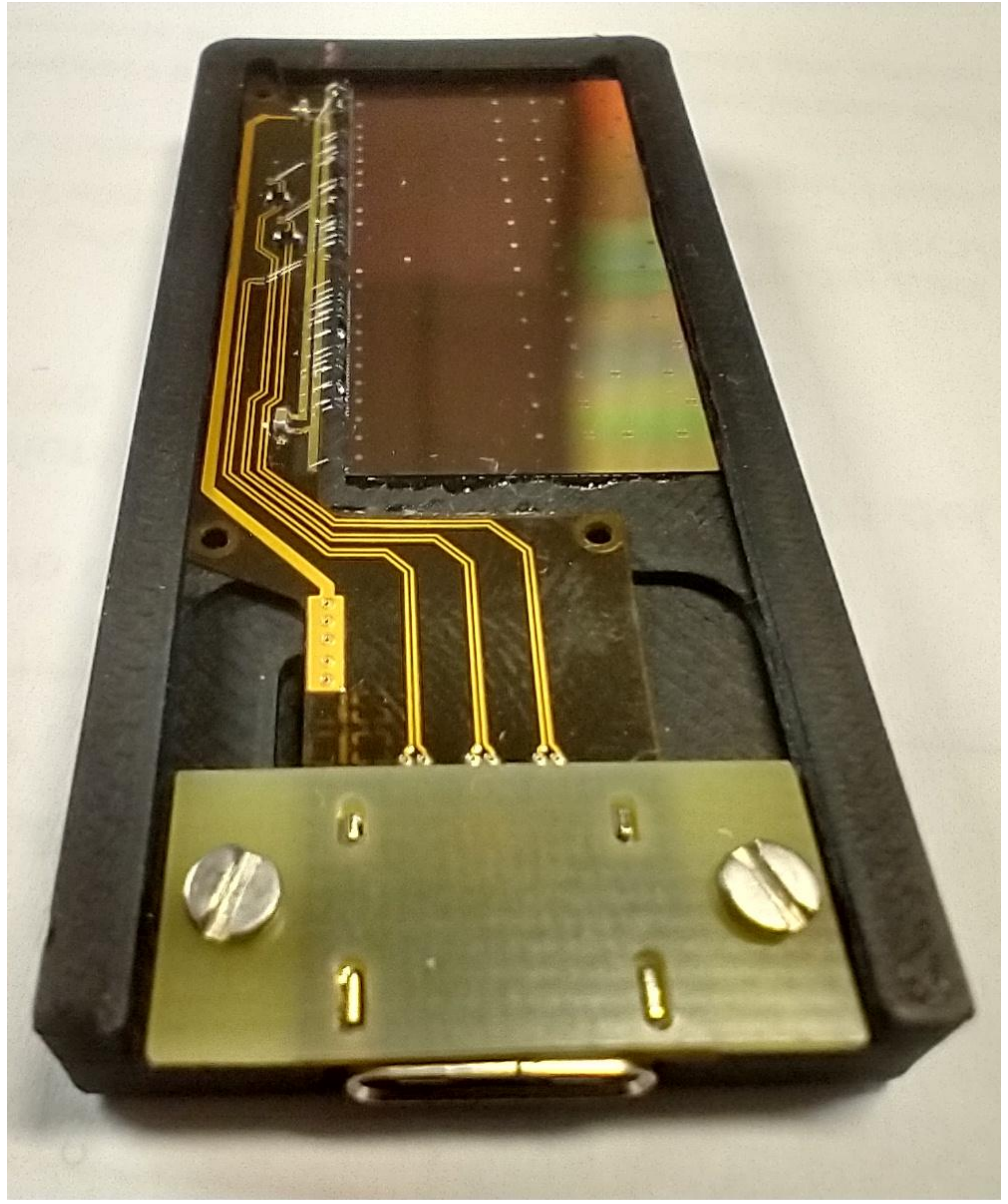






Outlook

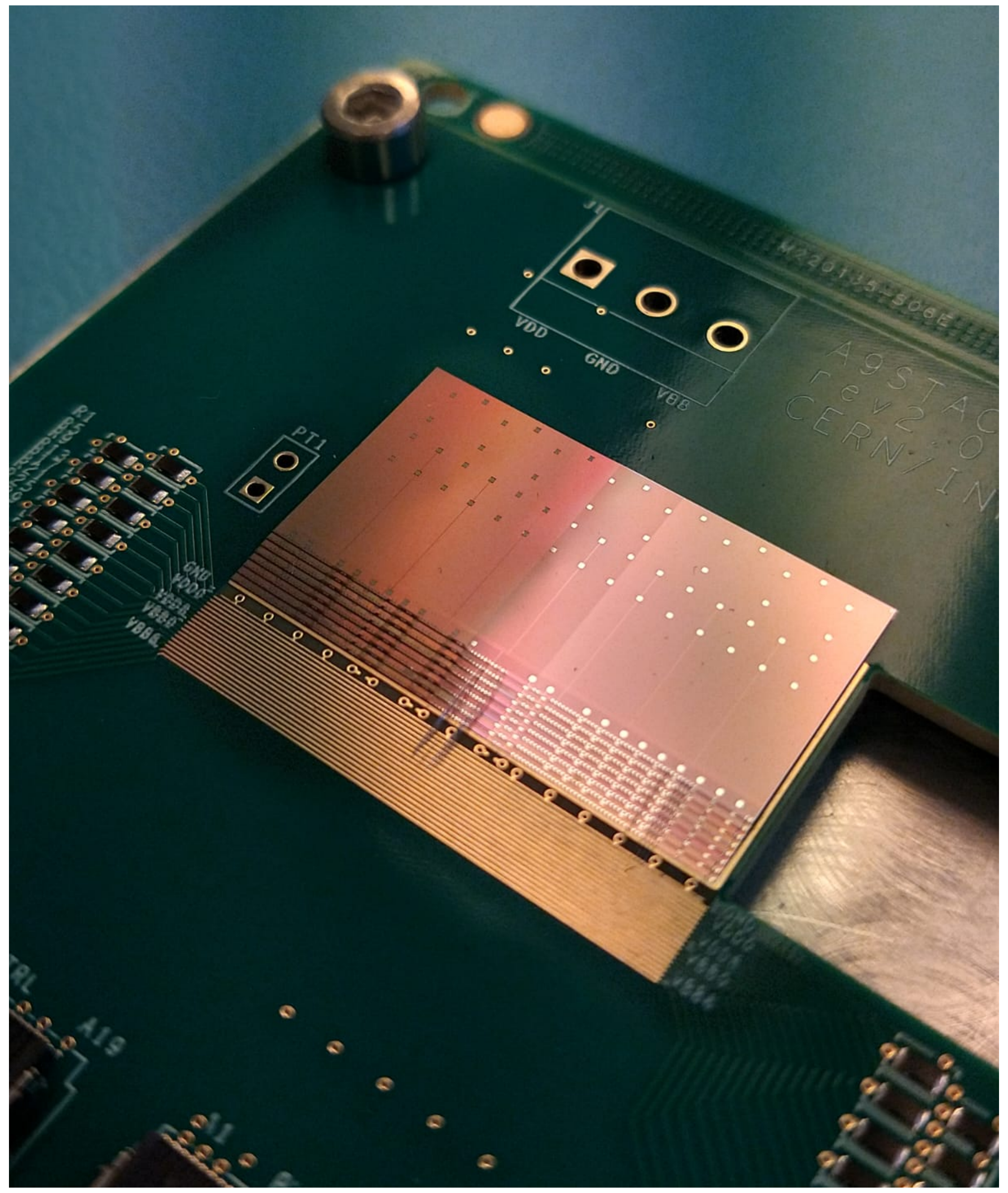
- **First prototypes** successfully **assembled**
  - Performance verification using radioactive sources
- Soon, extensive **campaign of data acquisition** with phantoms
  - Repeat tests performed with the standalone ALPIDE to evaluate impact of case and circuitry
  - Explore **different geometrical configurations** of T and H sponges and check the performance stability
- Implement full probe prototype in **simulations** and repeat validation exploiting the data from the phantom studies
- Evaluate prototype performance, using GEANT4 simulations, on **more realistic arrangements** of tumor and healthy tissues
  - Ultimate goal: **full-body simulations**, with tumor mass geometries mimicking typical clinical cases



Conclusions

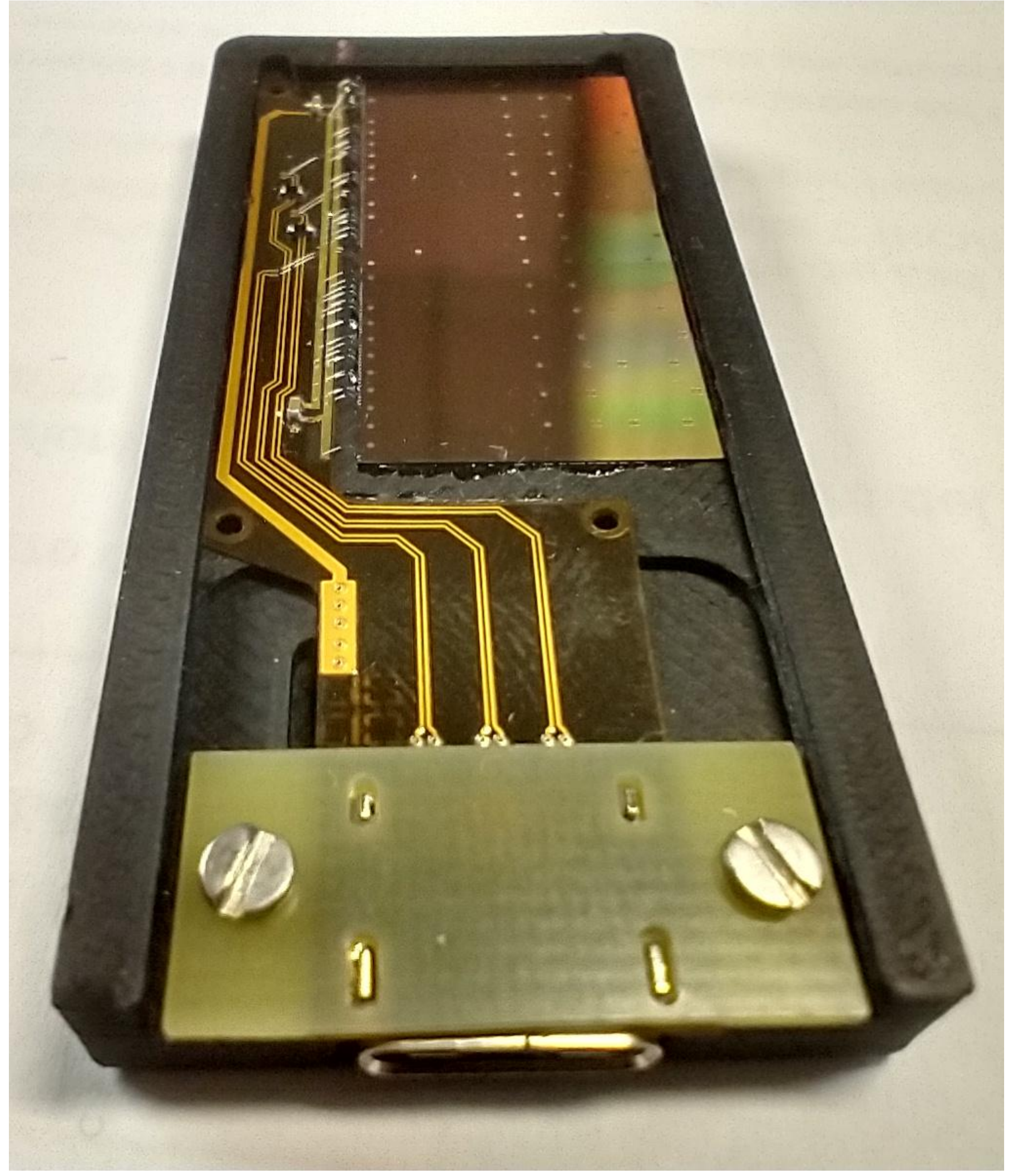
Two applications of MAPS to medical physics

Pixel chamber for Compton camera



First functioning and verified prototype by the end of the year

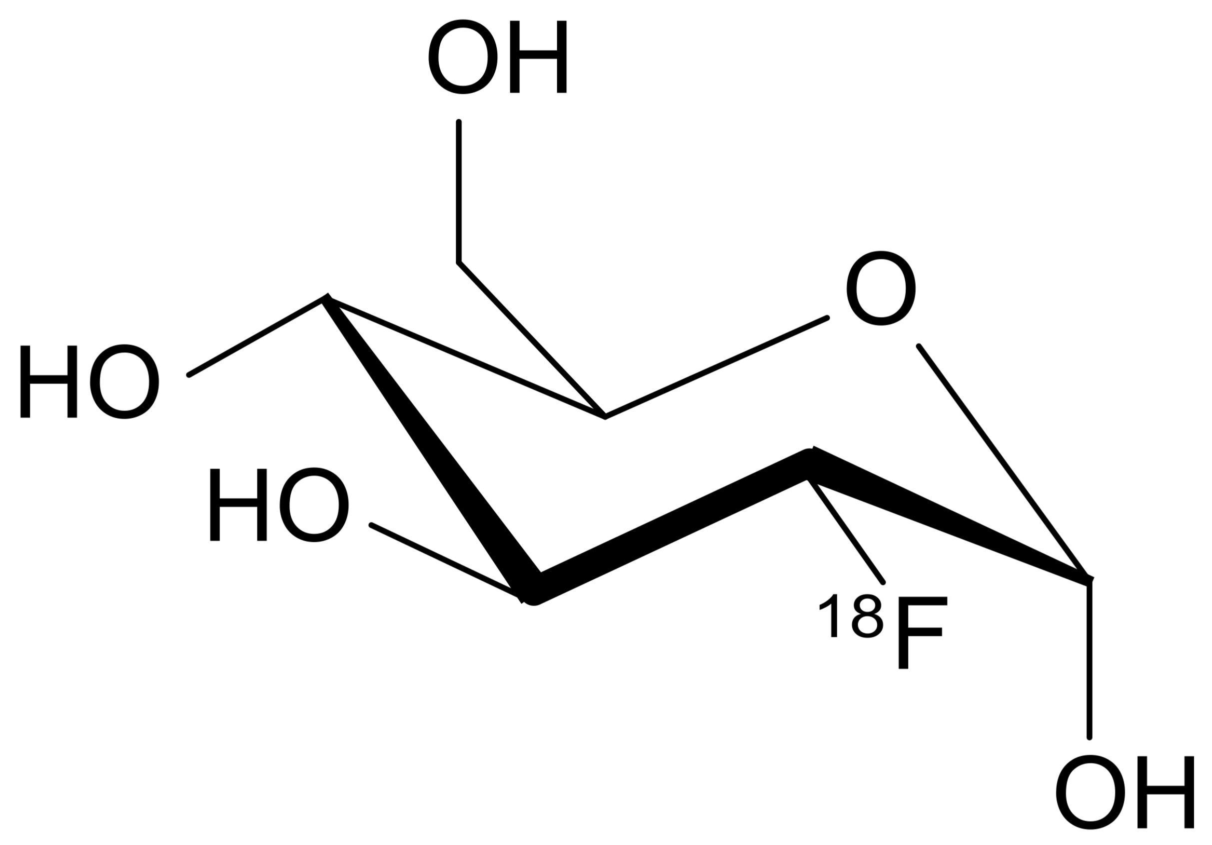
Intraoperative probe



First functioning prototype completed and ready for measurements with radiotracers

Backup

^{18}F-FDG



Fluorodeoxyglucose (FDG) is a radiopharmaceutical, specifically a radiotracer, widely employed in positron emission tomography (PET). Chemically, it corresponds to 2-deoxy-2-[^{18}F]fluoro-D-glucose, a structural analog of glucose.