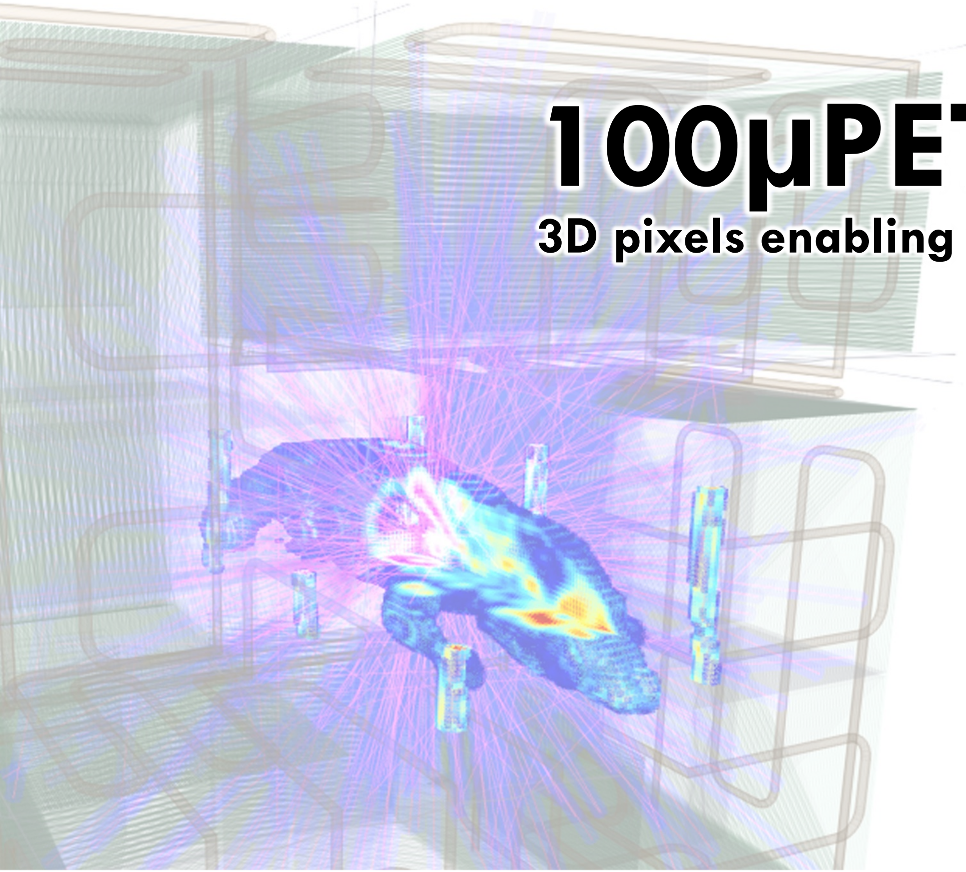
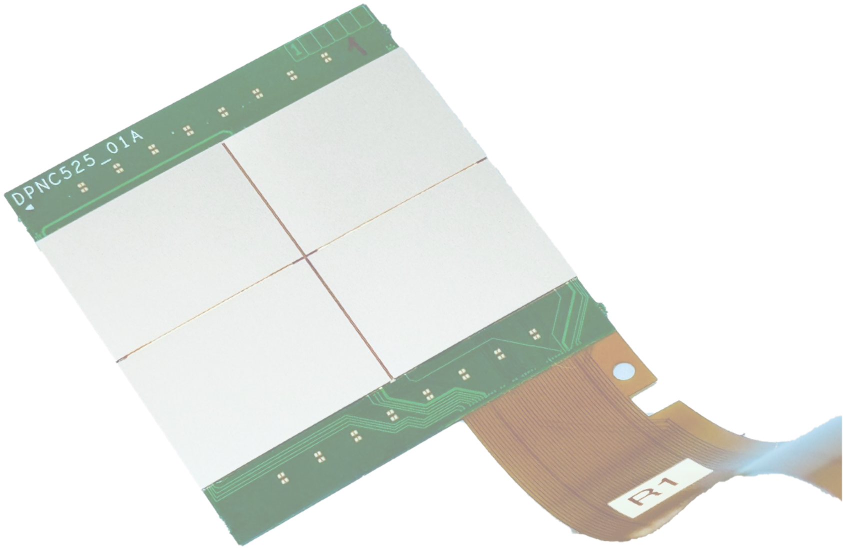
UNIVERSITÉ DE GENÈVE

100µPET MAPS stack:

3D pixels enabling ultra-high resolution PET imaging





1st DRD3 week – WG7/WP4

19 June 2024

Mateus Vicente (UNIGE)
on behalf of the 100µPET collaborators

Introduction (1/3)

Positron Emission Tomography (PET)

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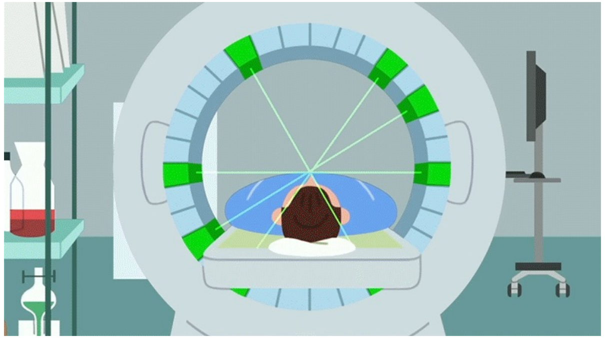
- PET is a nuclear medicine method to study metabolic processes in the body
  - A Radiotracer (typically 18FDG) is injected in the body;
    Positrons from the radionuclide annihilates with electrons of the nearby tissue;
    Two **back-to-back** 511 KeV photons are emitted and detected in **coincidence**
  - **Lines-of-Response (LoR)** are defined by the volume between the **sensitive elements** detecting the two photons, and the LoRs are processed to generate density maps of the detected annihilations
  - Today, due to the lack of spatial resolution, PET imaging must be done in hybrid mode (combining MRI or CT measurements)



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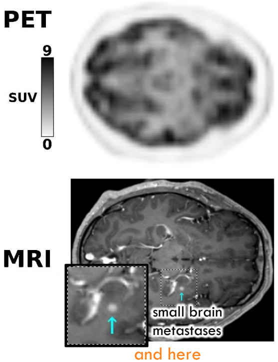

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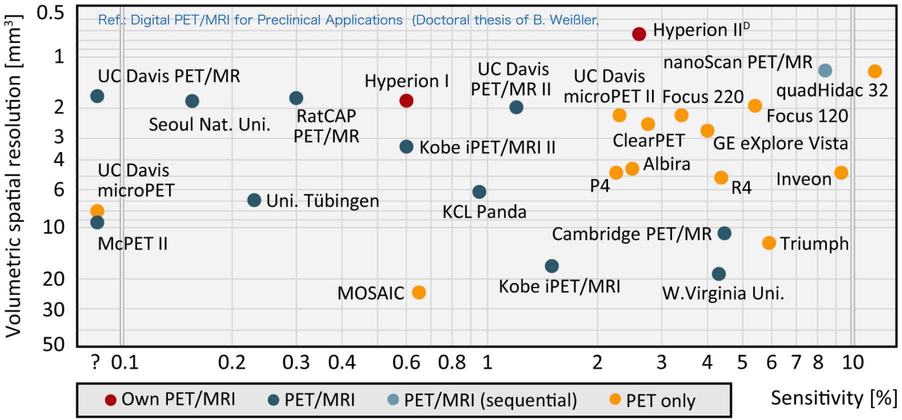
Overview of current small animal PET scanners



Introduction (2/3)

Positron Emission Tomography (PET)

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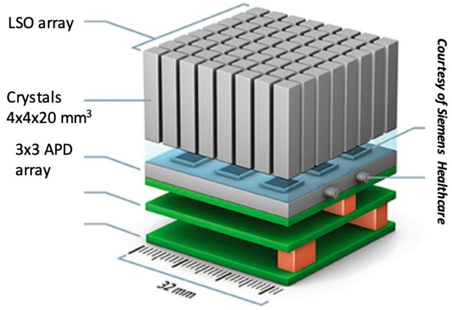
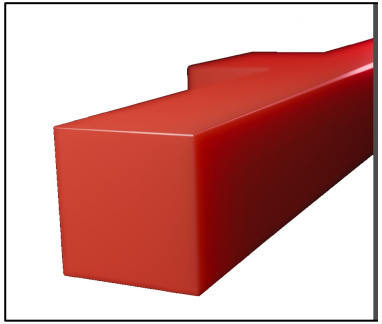
- Current PET scanner technology employs arrays of scintillating crystals with typical size $\gtrsim 1\text{mm}^3$
  - Small blood vessels can only be visualized in their entirety (A).
- To access ultra-high resolution molecular imaging, one must **reduce the LoR volumes** by exploiting:
  - Better timing resolution for coincidence measurement (TOF-PET), or increased <u>detection volume granularity</u>

PET tower with LSO crystals



<u>DOI:</u> 20 mm

<u>Sensor granularity:</u> **320 mm^3**



Introduction (3/3)

Positron Emission Tomography (PET)

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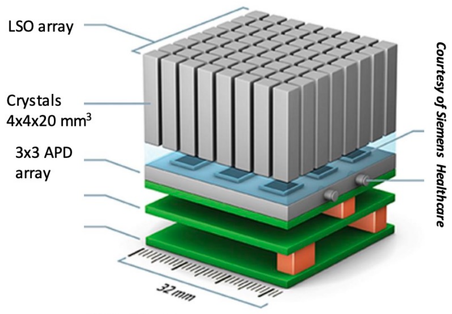
- Current PET scanner technology employs arrays of scintillating crystals with typical size $\gtrsim 1\,mm^3$
  - Small blood vessels can only be visualized in their entirety (A).
- To access ultra-high resolution molecular imaging, one must **reduce the LoR volumes** by exploiting:
  - Better timing resolution for coincidence measurement (TOF-PET), or increased detection volume granularity
- The **100µPET** SNSF Synergia project: **UNIGE** (scanner production) **EPFL** (imaging reconstruction) and **UNILU** (medical study)
  - Ultra-high resolution imaging by employing **multi-layer stacks of monolithic pixel detectors**, allowing the study of changes in small blood vessels, as atherosclerotic plaques (B)

PET tower with LSO crystals



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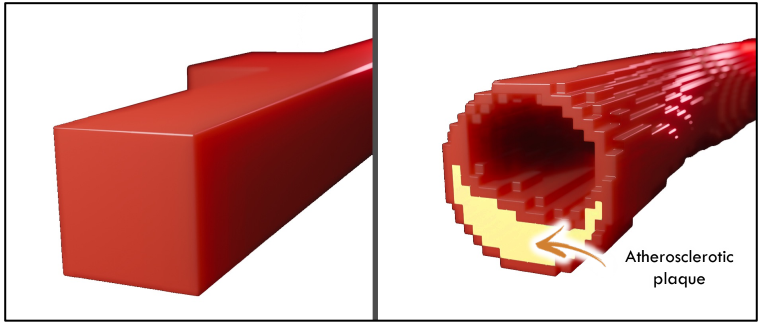
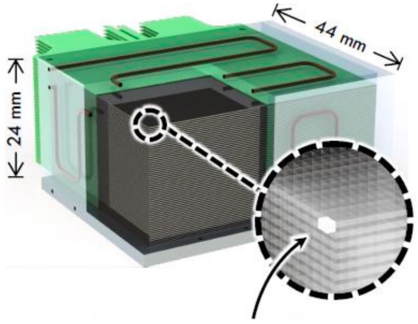


Images: © Xavier Ravinet - UNIGE

100µPET stack



Pixel pitch: 150 µm | DOI: 550 µm
Sensor granularity: **0.012 mm³**

The 100µPET scanner

ASIC, module/layer, tower

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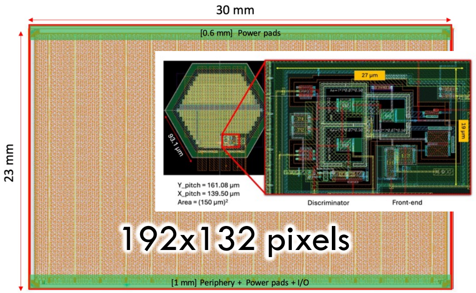
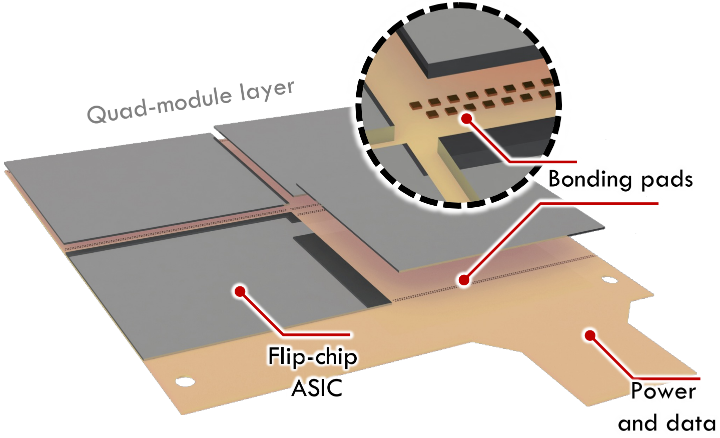
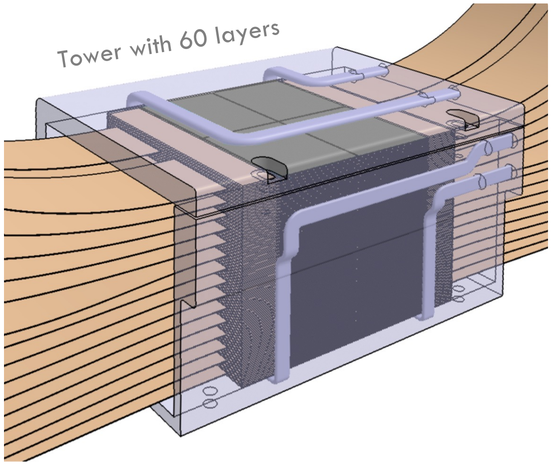
- <u>Multi-layer stack of CMOS imaging sensors</u>
  - **100µPET** MAPS: **130 nm** <u>SiGe BiCMOS</u>; **2.3 x 3 cm^2**; **150 µm** pixel pitch; **270 µm** thick; **~0.5W** power (ETA Aug-Sep)
    - Designed foreseeing flip-chip bonding, the size and pitch of the bonding pads allows integration with standard PCB/FPC production
  - Single silicon detection layer composed by **2x2 ASICs** <u>flip-chip</u> to a flex printed circuit, covering **24 cm^2**
  - **60** detection layers compose each scanner **tower,** with 4 towers per scanner (for a grand total of **<u>960 chips!)</u>**



Event rate	10 kHz/cm^2
Equivalent Noise Charge (ENC)	200 [e-]
Operation Threshold	3000 [e-]
Time resolution RMS (Qin > 7 ke-)	200 [ps]
ToA	Yes, 1 pixel/event
ToT	Yes, for ToA time walk correction
Power consumption	< 100 [mW/cm^2]





Performance simulations (1/3)

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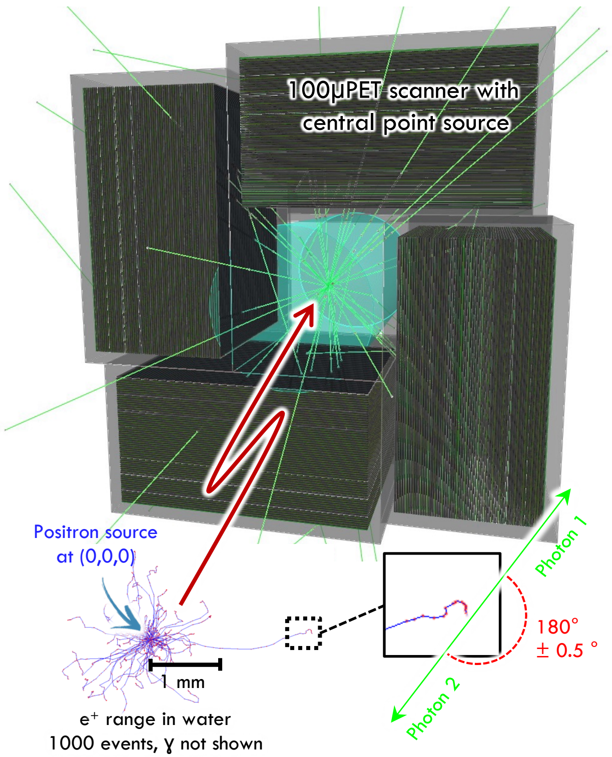
- **Performance** simulations with (Geant4 + AllPix^2)
  - Scanner geometry (silicon chips, flex, cooling block) + scatter water volume
  - [^{18}F]FDG positron spectrum (positron range and photons acollinearity)
  - Photon interactions + sensor/ASIC response + pixel clustering
    - No time information (event based) and no energy window used
  - Positron sources: Single point; Derenzo phantom; High resolution medical images



Performance simulations (2/3)

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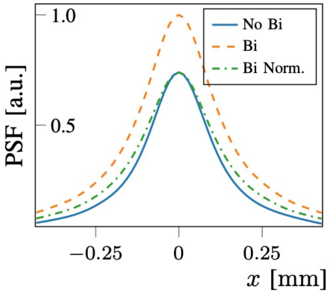
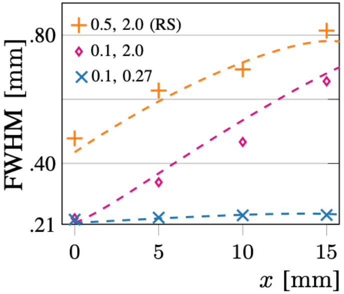
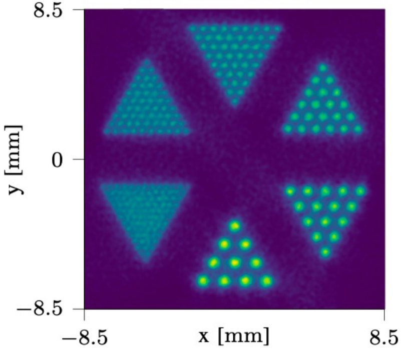
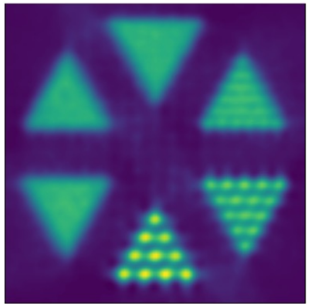
  - Positron sources: Single point; Derenzo phantom; High resolution medical images
- Expected performance:
  - Sensitivity: **3.1** / **5%** (with / without bismuth)
  - Point spread function: **0.21-0.24 mm** / 0.28-0.30 mm (w/wo bismuth)
  - Valey-to-peak ratio: 0.57 for 0.25 mm rods, 0.25 for 0.5 mm rods)









Reference scanner ∼ state of the art

Performance simulations (3/3)

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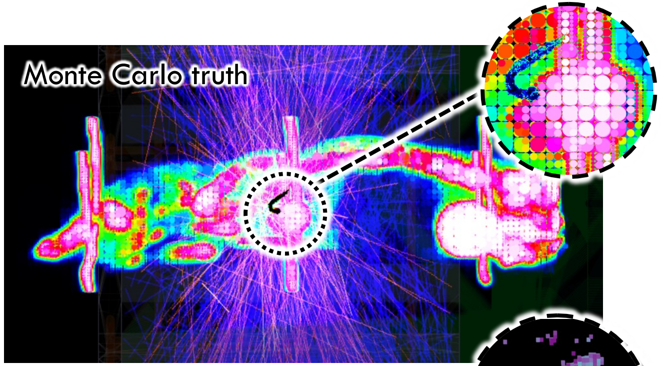
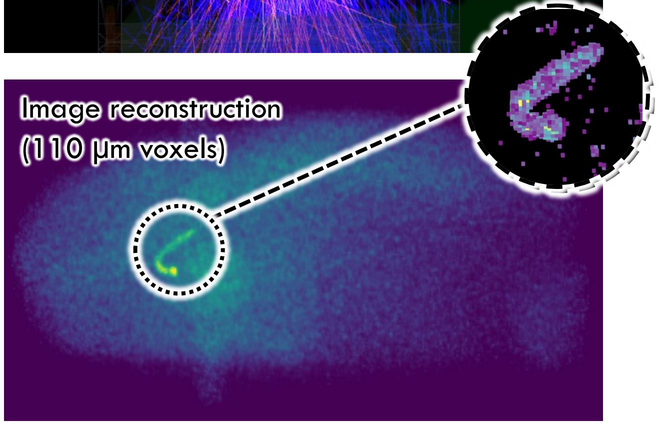
  - Valey-to-peak ratio: 0.57 for 0.25 mm rods, 0.25 for 0.5 mm rods)
  - Mouse phantom from Digimouse PET and atherosclerotic plaque microCT
    - Simulations and reconstruction ongoing





100µPET flip-chip module

Flip-chip testing

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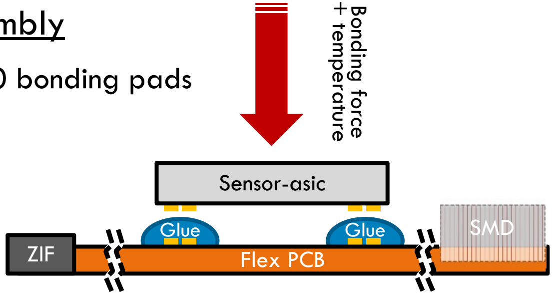
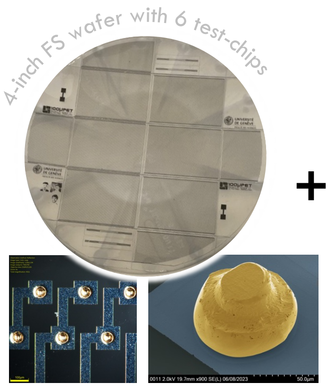
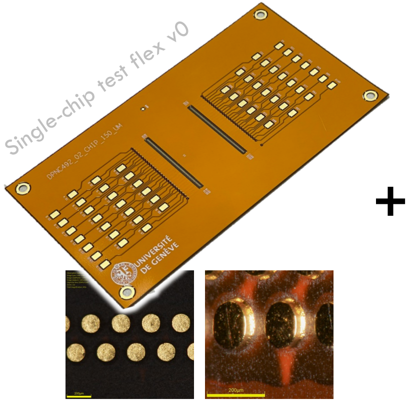
- A **modular** and **compact** scanner design is achieved with ASIC/flex flip-chip assembly
  - ACF/ACP and NCP flip-chip was investigated with dedicated test assemblies with 400-500 bonding pads
    - Pad-wafer produced at CMi-EPFL: 525 µm thick, Ti/Al metal patterning, Au stud bumped
    - Flex to probe flip-chip bonding yield: 4 layers, ~180 µm total thickness, ENIG pad finishing
    - Flip-chip machine for the thermocompression using an epoxy adhesive (Araldite 2011), 20 kgf bonding force and 100 °C for 7 minutes





Pads and gold stud

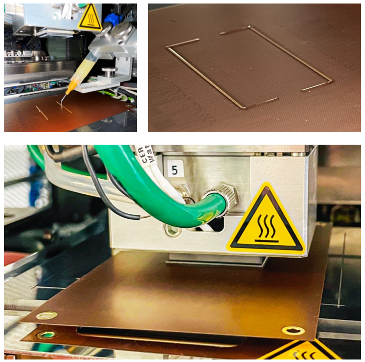
+



Bonding pads

+

Glue dispensing and bonding



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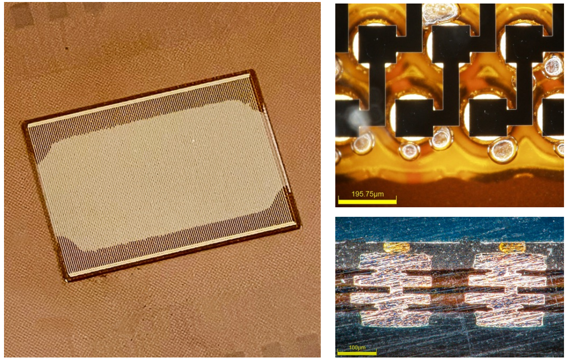

Flip-chip qualification tests

Temperature cycles (TC) and current injection

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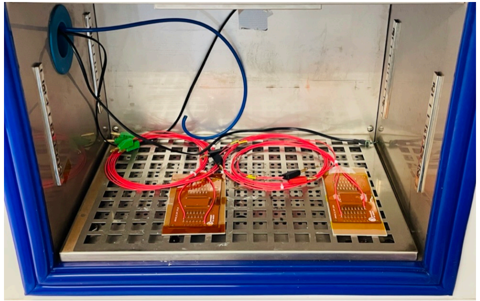
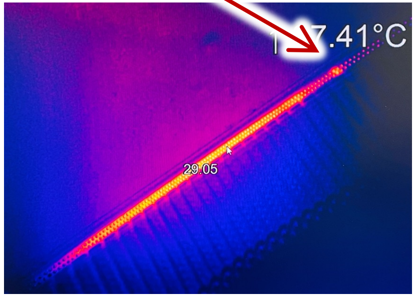
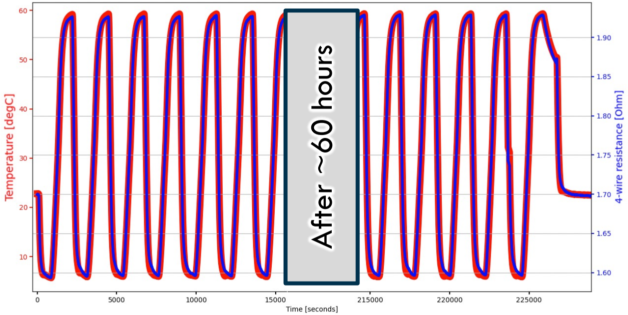
- 100% yield connection among hundreds of pads
- (Direct) Current stress-tests to verify bonding failure
  - Limit DC to 200 mA, avoiding local heating exceeding Tg of the glue (60-80 °C)
    - Visible permanent defects (hot spots – higher bonding resistance) after reaching 300 mA
- 100 TCs from +5 to +60 °C
  - No effect on connections







100μPET pre-production

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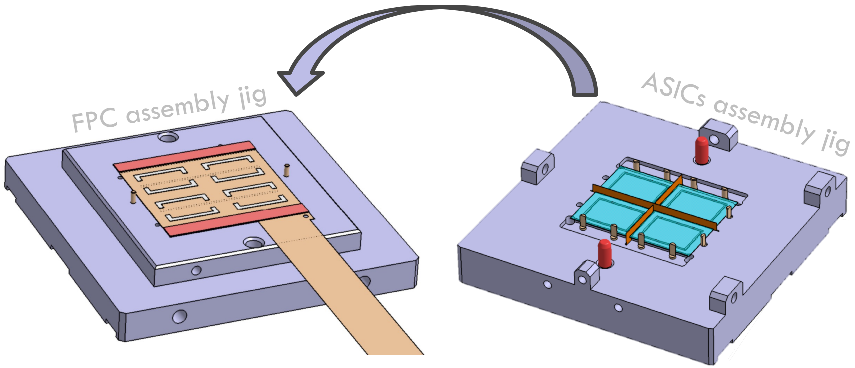
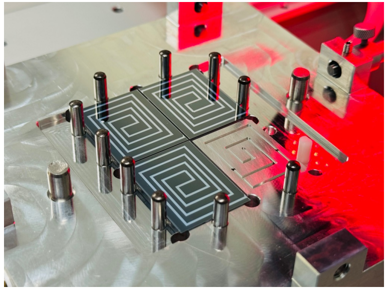
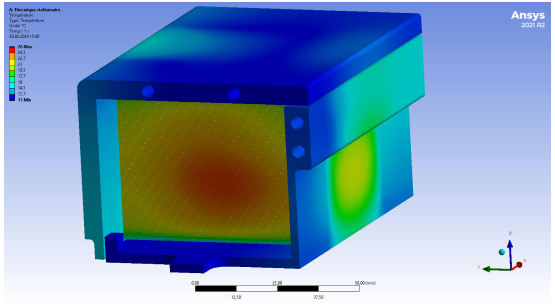
- Electro + thermal + mechanical prototype under design/production
  - Test-chip with the same dimensions, electronic interface and power consumption (resistance heater)
  - Test-flex with the same dimensions, circuit stack-up and tail connection to MAB
- Validation of module assembly, layer stacking, cooling performance and back-end connections







100μPET module demonstrator

Design and production

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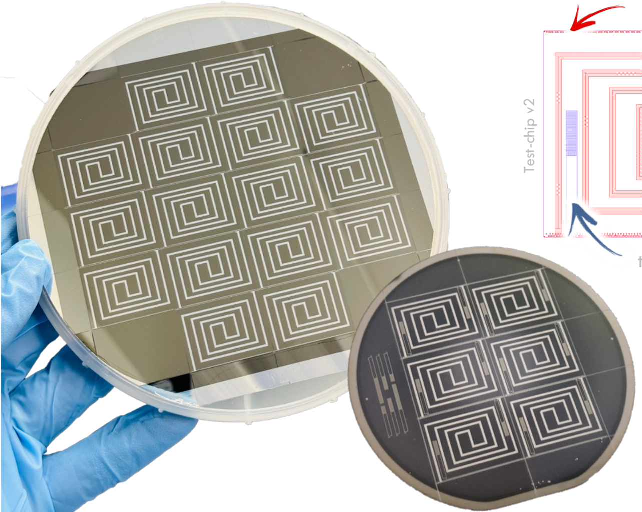
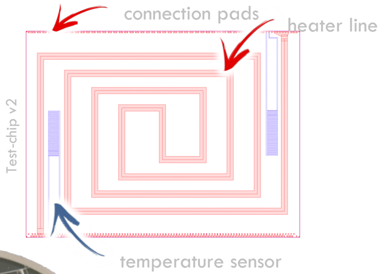
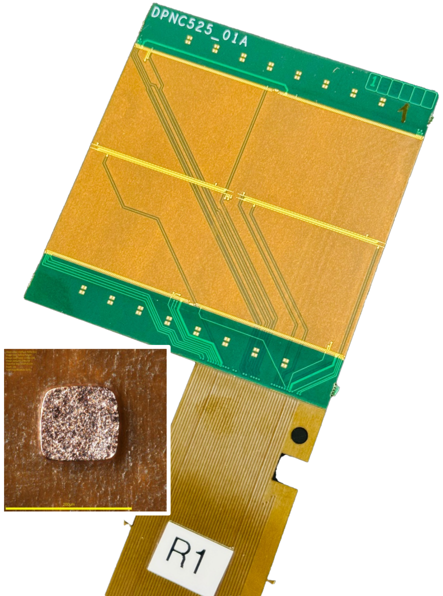
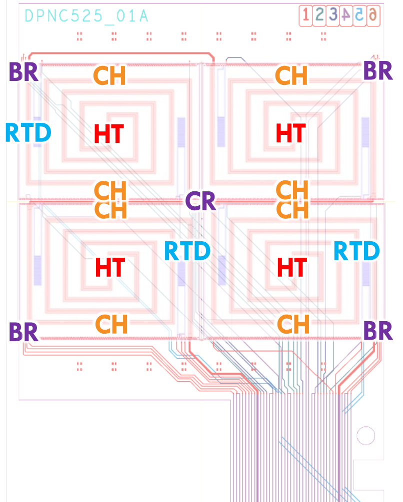
- **240x** 300 μm thick test chips:
  - 4x 4-point bond-resistance, 1x resistive heater (1 μm thick Al), 2 RTDs (PT1000-ish), 1x 162-pads chain and 1x 82-pads chain
    - 4x 4-inch wafers produced at NMP-FCBG and 15x 6-inch wafers from CMi (no RTDs)
- **60x** test flex (+ 2x beck-end prototype system)







3x Resistive Temperature Detectors
5x Bond Resistance (4-wires)
4x Heaters in series
8x Chains (4x w/ 162 pads, 4x w/ 82)



100µPET module demonstrator

Reference module

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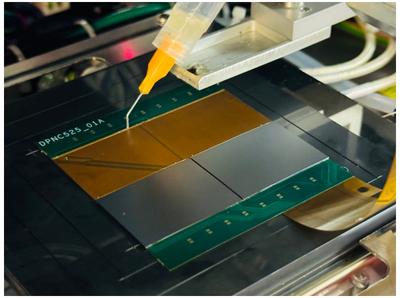
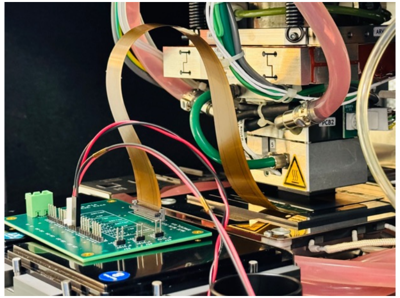
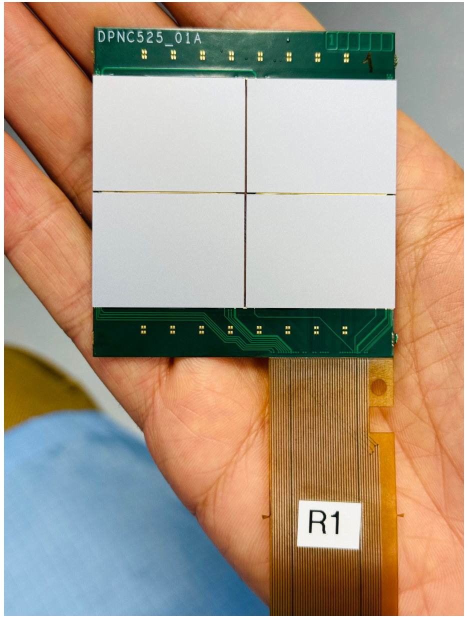
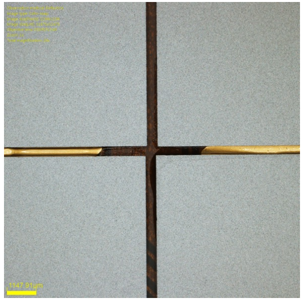
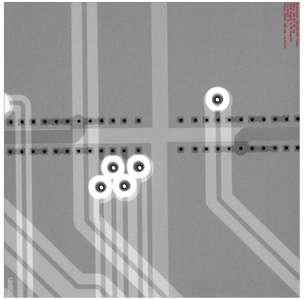
- Bonding reference module with flip-chip machine
  - We are putting in place the data-base tracking, handling the temporary storage, module quality control tests and etc











100µPET module demonstrator

Reference module characterization

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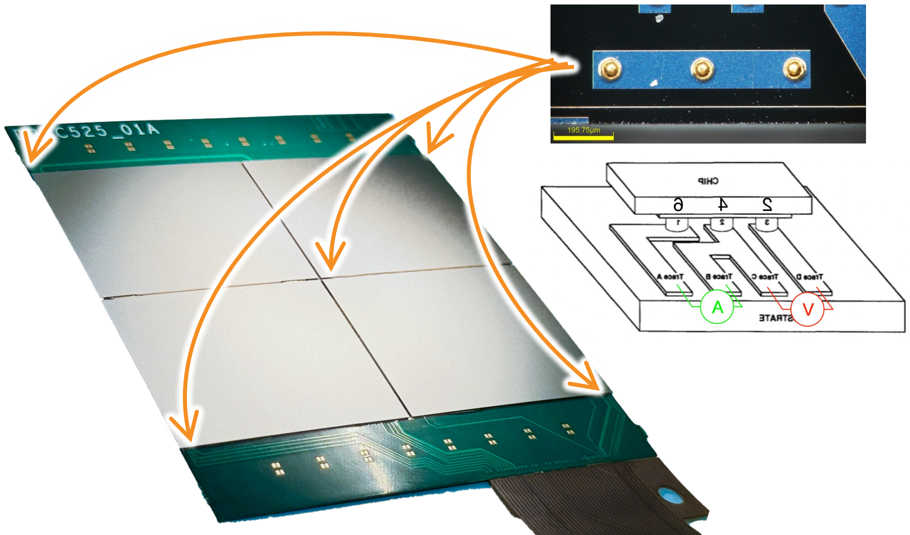
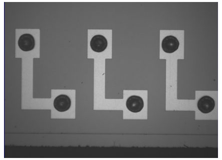
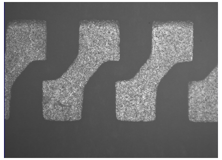
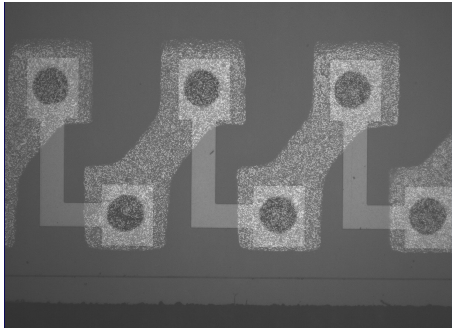
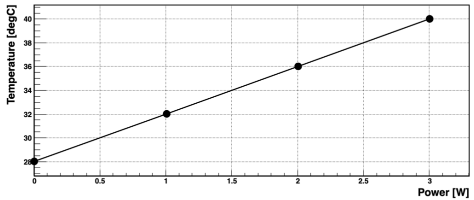
- Bond resistance of **~10 mOhm** and uniform over module's 4 corners and center
- Chains of pads indicating no open connection in ~1000 pads (**bonding yield >99.9%**)
- Heater system is working as expected, with 8°C increase in temperature at nominal module power (2W)

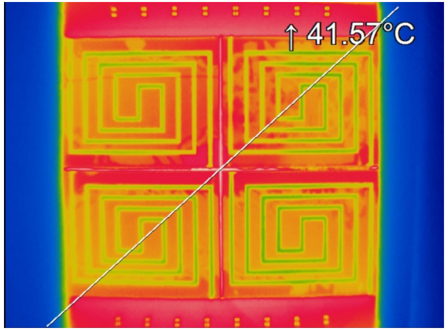












Summary and conclusions

- Potential <u>ultra-high-resolution molecular imaging</u> using **MAPS**
  - **<u>5%</u>** and **<u>3.3% scanner sensitivity</u>** (w/ or w/o Bismuth layer)
  - **0.21 mm** FWHM **PSF** → **<u>00.017 mm^3 volumetric resolution</u>**
- ASIC designed within the UniGE DPNC group
  - Development of module construction technique based on flip-chip bonding for minimal packaging
- <u>Flip-chip bonding</u> qualified with test-chips
  - Characterization tests indicates **<u>good yield</u>** and **<u>reliability</u>**
- Module and Tower <u>demonstrators</u> under construction
  - Module reference assembled and tested. Next…
    - 2nd module with RTD (for calibration procedure)
    - Stacking of first layers into a tower
    - Electronic back-end services and cooling system