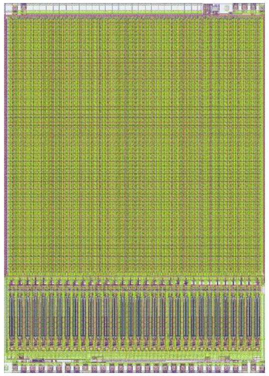

SpacePix2

a novel detection ASIC for cosmic radiation

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On behalf of the SpacePix group

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Status report

Project	AO9018
Start	02/2019
ESA TO	Marco Vuolo

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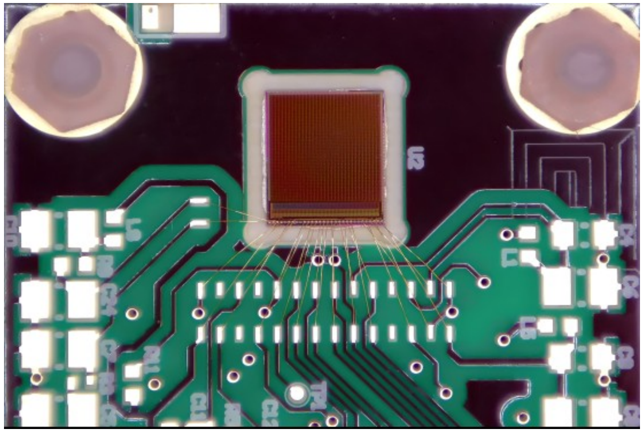
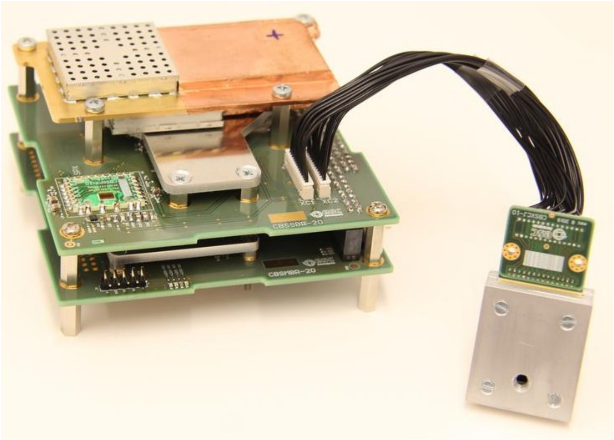
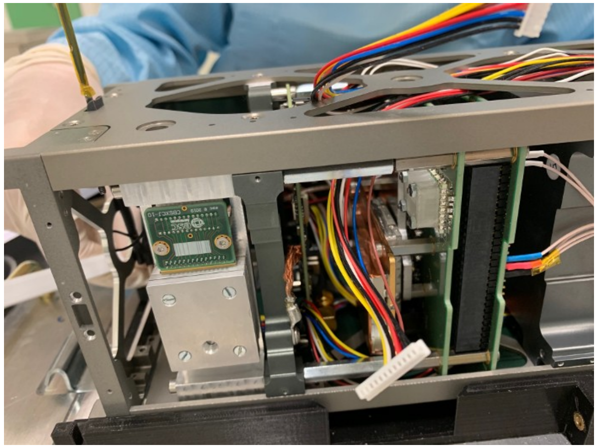
17.12.2019

Talk outline

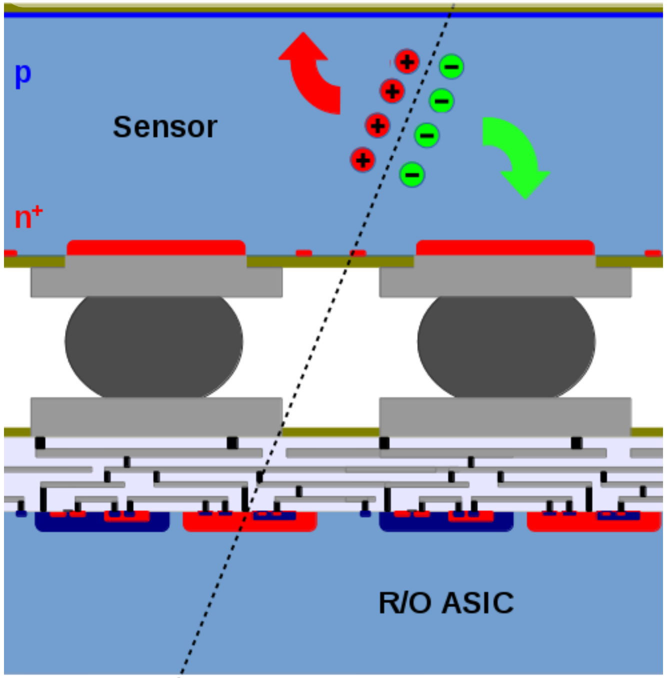
- Monolithic 180 nm SoI CMOS technology
- SpacePix2 heritage: X-CHIP-03 ASIC
- Signal response, TID & SEU characterization
- SpacePix2 architecture
- The SpacePix Radiation Monitor – space grade version



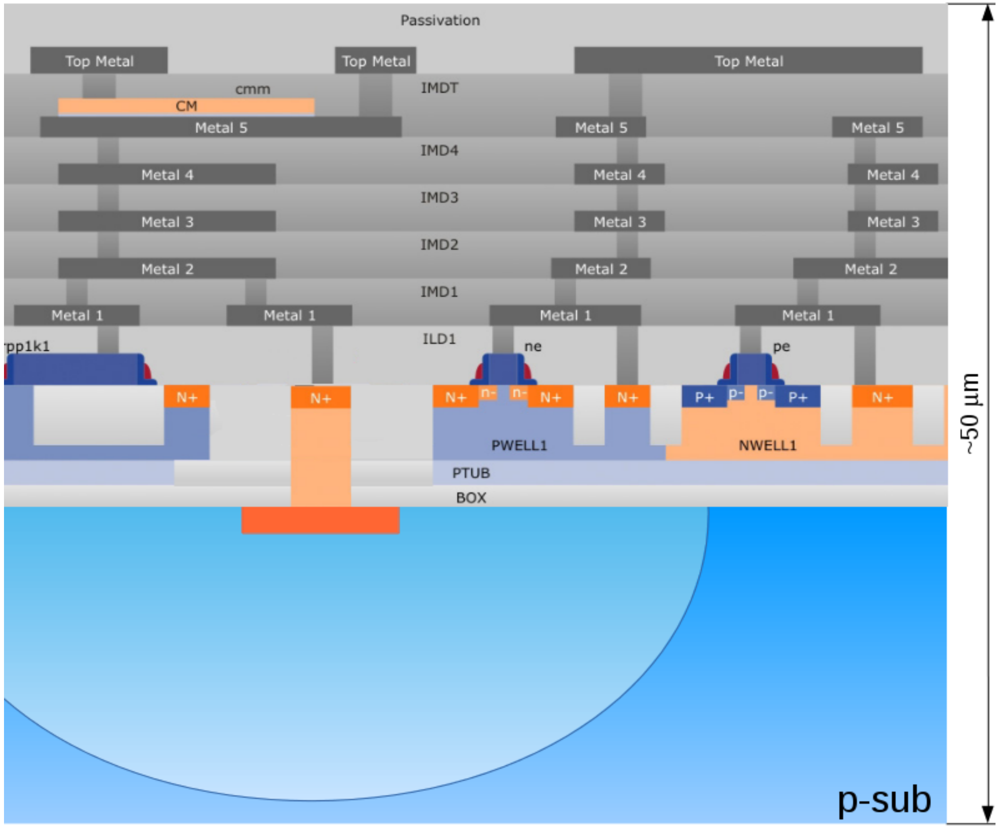




Monolithic SoI Technology



The cross section of the hybrid detector



The cross section of the SoI monolithic detector (not to scale)

Hybrid detectors

- Classical detectors with extensive HEP heritage
- Sensor and readout electronics on separate wafers
- Large material budget
- Complicated assembly

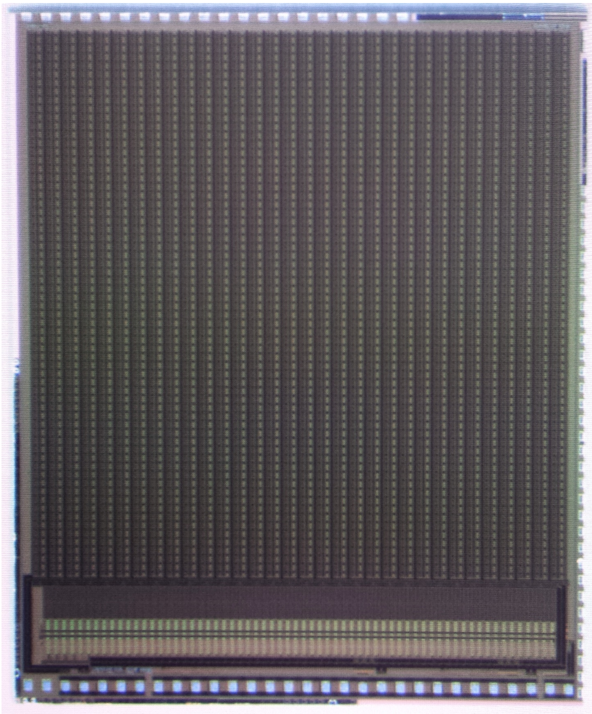
Monolithic SoI detectors

- Sensor and electronics are implemented in the same silicon substrate, currently up to 35 µm depleted layer
- Detection of particles in a handling wafer
- A commercial process in an European foundry
- Partially depleted electronics layer (PD SoI)
  - Higher tolerance towards SEE
  - Limited effect of BOX (Buried OXide) charging
- Temperature operating range of -40 to 175 °C
- Wafer thinning down to 50 µm → low material budget

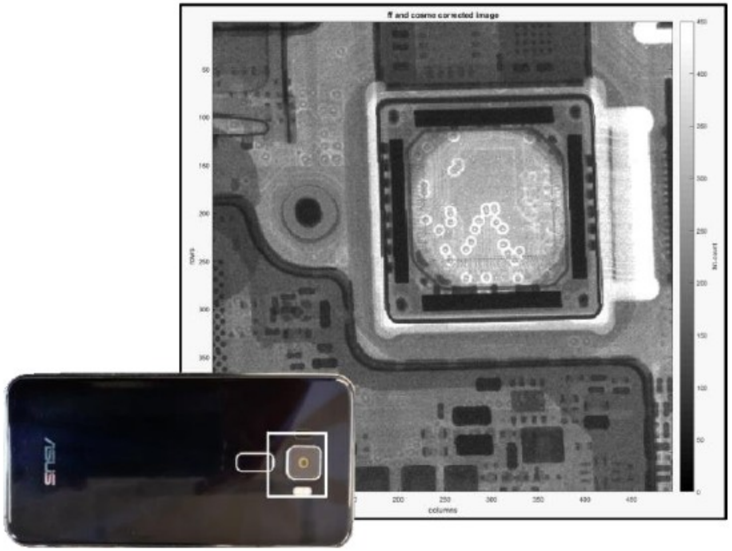
The X-CHIP-03 ASIC

- Predecessor to SpacePix ASIC family
- A monolithic pixel detector for soft X-ray imaging
  - Photon counting mode (16-bit counter)
  - Energy deposition mode (10-bit column ADC)
- 64×64 pixels, 60 µm pitch
- 3.9×3.9 mm^2 sensitive area, 4.5×5 mm^2 total
- SPI and LVDS readout, < 50 mW power consumption
- CSA optimized for 1-10 ke$^-$
- Approximately 3M transistors

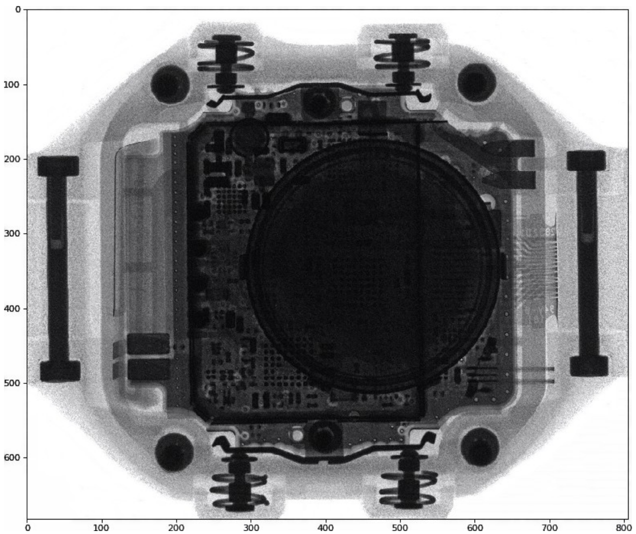
X-CHIP-03: SOI MAPS radiation sensor with hit-counting and ADC mode
IEEE NSS MIC 2018, DOI: 10.1109/NSSMIC.2018.8824681



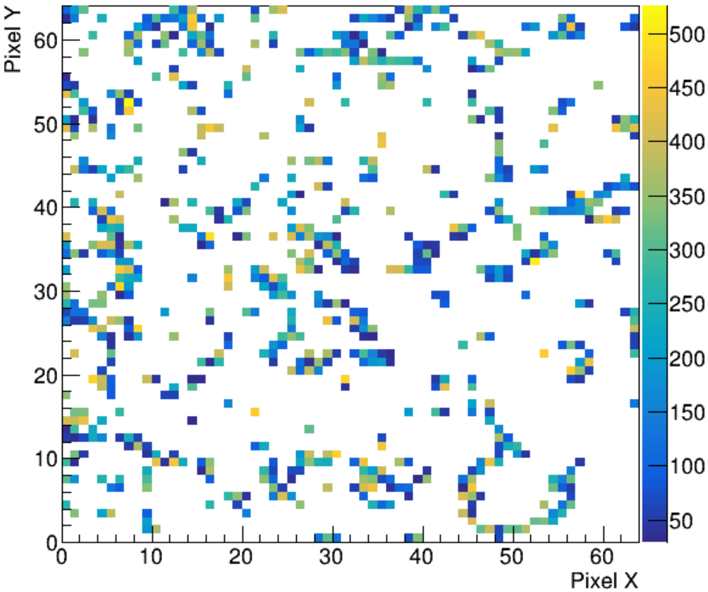
The X-CHIP-03 ASIC



An X-ray image of a cell phone

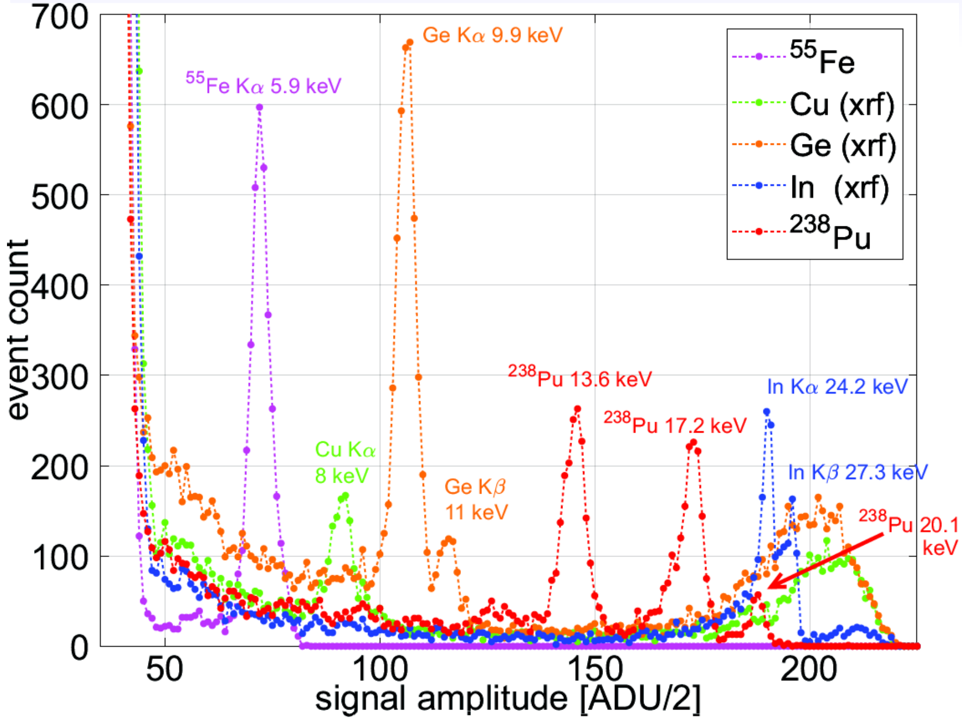


An X-ray image of a wristwatch



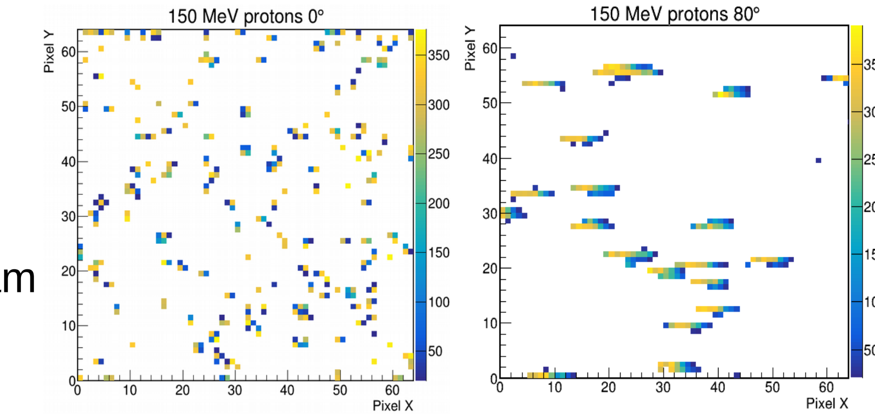
^{90}Sr electrons

Spectral and imaging capabilities

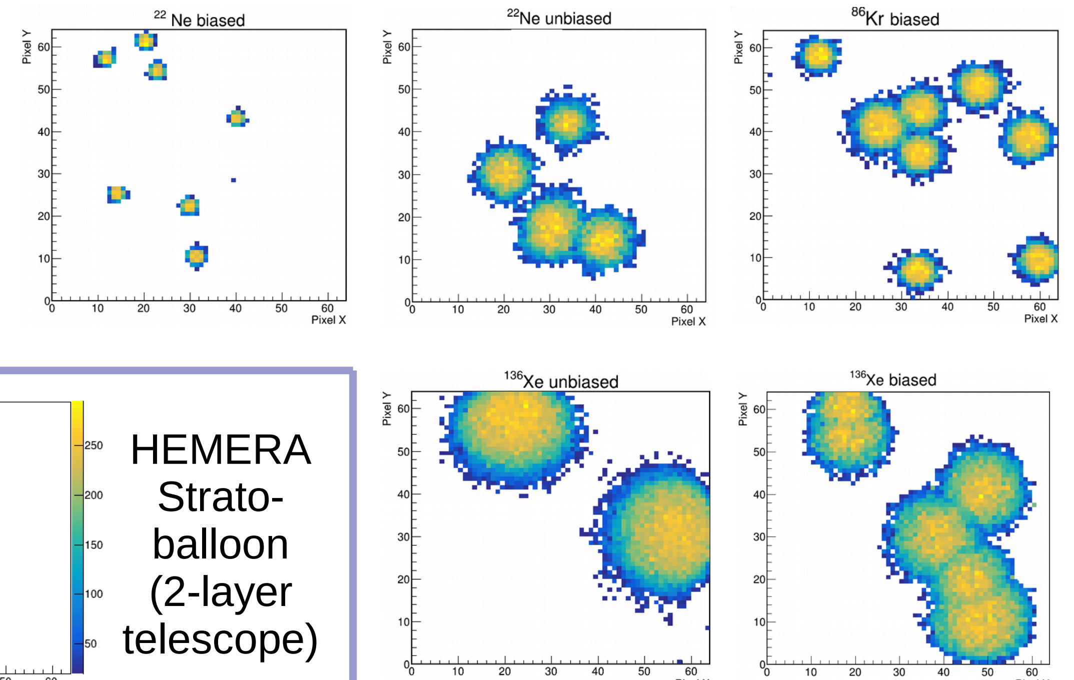


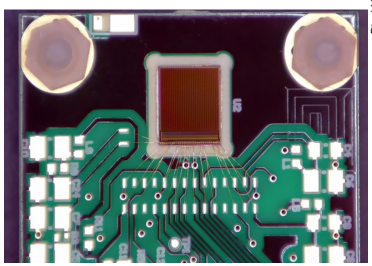
An uncalibrated X-CHIP-03 single-pixel response to soft X-rays

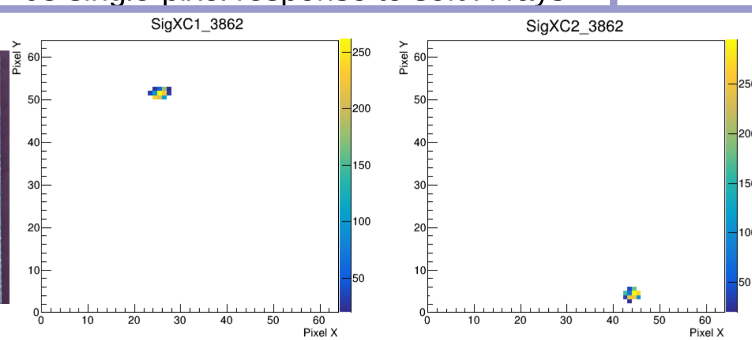
150 MeV proton beam



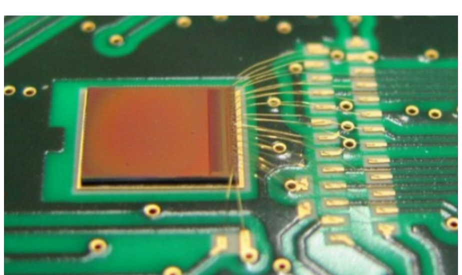
U400M ion beam



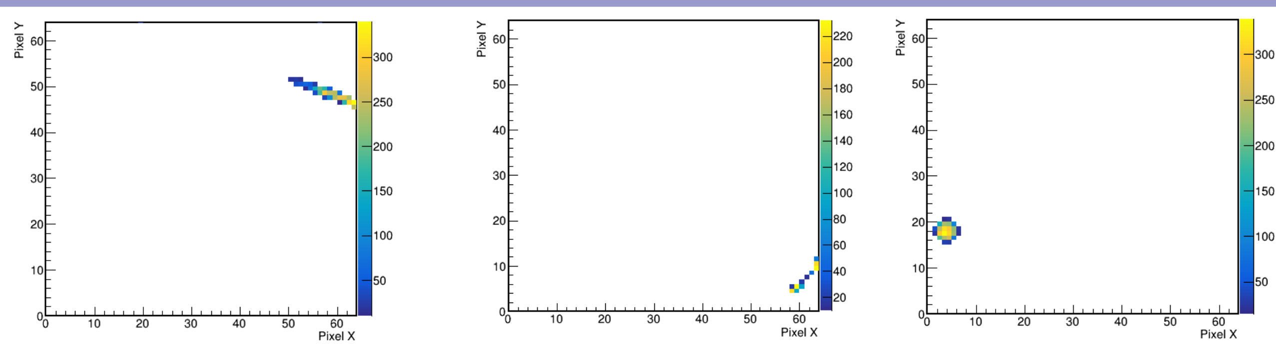




HEMERA Strato-balloon (2-layer telescope)



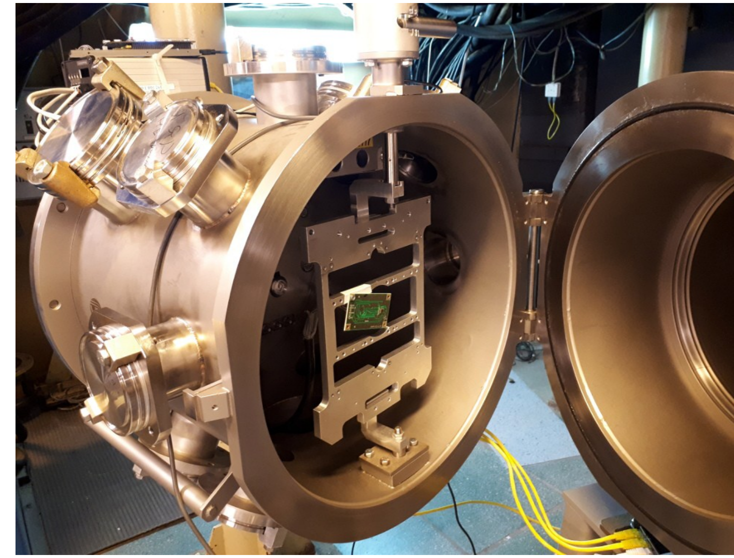
Single X-CHIP-03 ASIC @ SPD



Aircraft @ 10km

SEU testing of the technology

- ECSS 25100 SEE Test Method and Guidelines
- Ions by U400M isochronous cyclotron & Tandetron 4130MC
  - ^{4}He, ^{7}Li, ^{22}Ne, ^{40}Ar, ^{86}Kr and ^{136}Xe
- Cosmic cocktail with LET in range of 0.5 - 75 MeVcm^{2}mg^{-1}
- The DUT - shift register with 1024 custom D flip-flops
- Chessboard pattern; R/O using the SpacePix-D recorder
- No destructive SEE were observed, the bit-flip cross section was found to be low w.r.t. the bulk CMOS

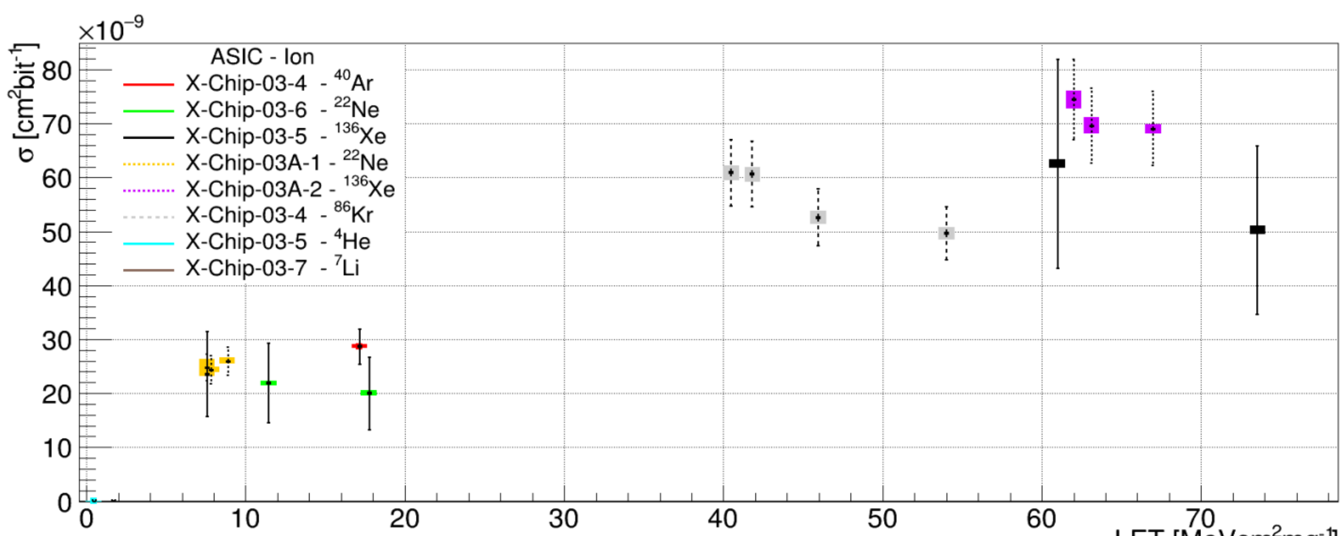


In vacuo measurement of the the SEE cross section and signal detector response at heavy ion beam-line with SpacePix-D readout.

Extracted ion	Energy [MeV/n]	Range [μm]	LET$_0$ [MeV·cm^2·mg^{-1}]
$^{4}He^{2+}$	2	36.91 ± 0.02	0.45 ± 0.02
$^{7}Li^{3+}$	1.42	27.5 ± 0.05	1.27 ± 0.05
$^{22}Ne^{10+}$	3.33	36.91 ± 0.35	6.67 ± 0.1
$^{40}Ar^{16+}$	3.48	36.60 ± 0.44	15.09 ± 0.24
$^{86}Kr^{32+}$	3.49	40.8 ± 0.48	40.25 ± 0.75
$^{136}Xe^{46+}$	3.16	36.38 ± 0.52	68.97 ± 1.03

A study of single event effects induced by heavy charged particles in 180 nm SoI technology
2018 IEEE NSS MIC, DOI: 10.1109/NSSMIC.2018.8824677

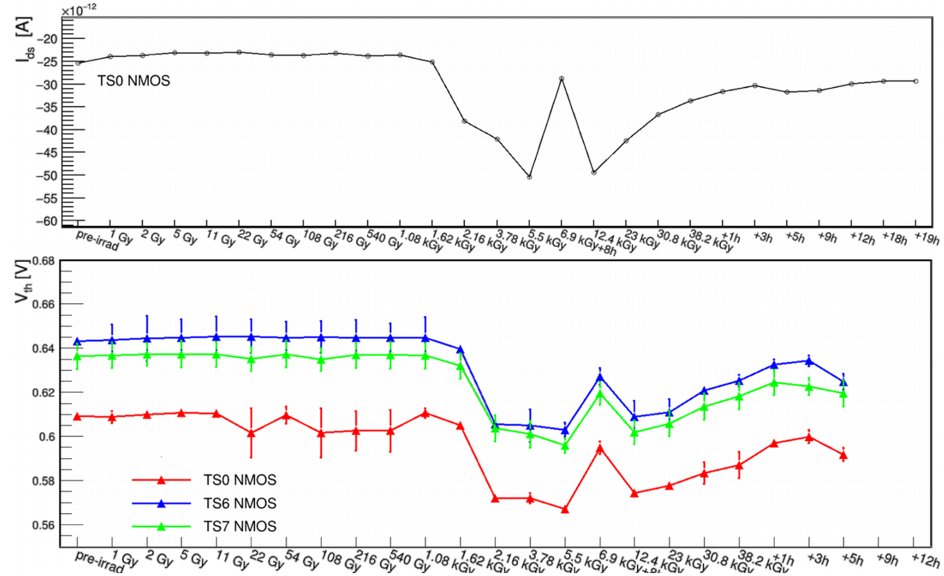
The SpacePix-D technology demonstrator.
Journal of Instrumentation, 13(12):C12017, 2018



The measured bit-flip cross section as a function of LET

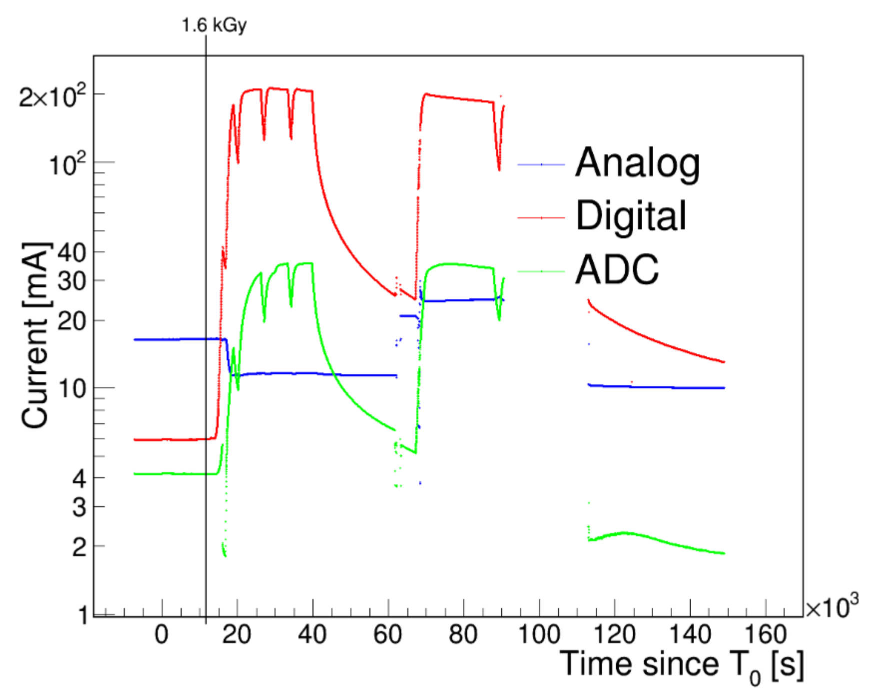
^{60}Co TID testing

- ECSS 22900 Total Dose Steady-State Irradiation Test Method
- The ASICs were irradiated in electron equilibrium conditions with powered electronics
- The transistor test structures and overall power consumption was evaluated in order to assess the TID effects
- TID response characterized at large dose rate ~150 Gy/min and at lower doses (16 Gy/min)
- The CMOS V_{TH} shift is small, emergent parasitic transistors increase power consumption
- Threshold of TID effects is ≈ 2 kGy @ 16 Gy/min, affecting primarily digital part of the ASIC
- Significant annealing effects observed

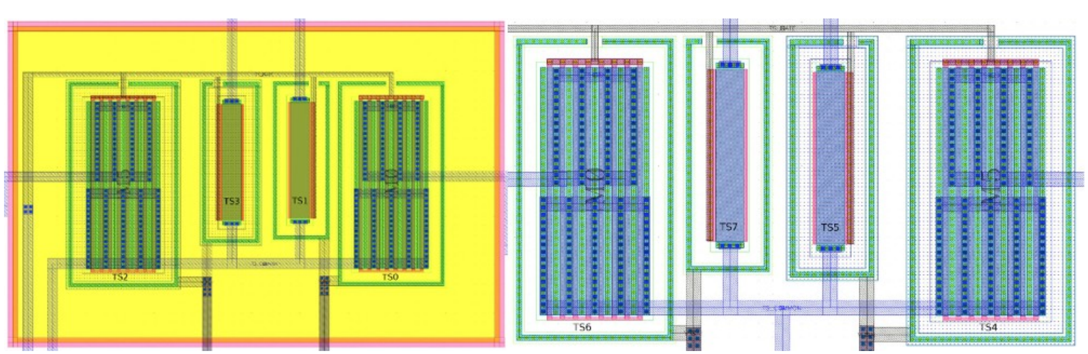


An example of V_{TH} shift and leakage current measurements

A Comparative Study of the TID Radiation Effects on ASICs Manufactured in 180 nm Commercial Technologies
Journal of Instrumentation, 13(12):C12003, 2018.



The power consumption of X-CHIP-03 powering domains

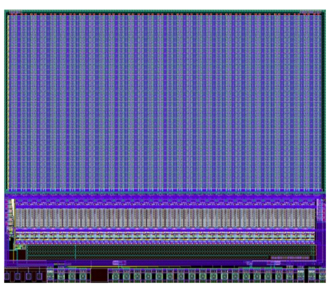


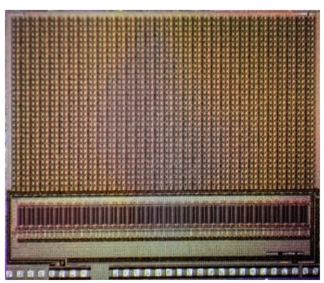
The transistor test structures – HVP (left), wide and long NMOS / PMOS

SpacePix2 architecture – requirements

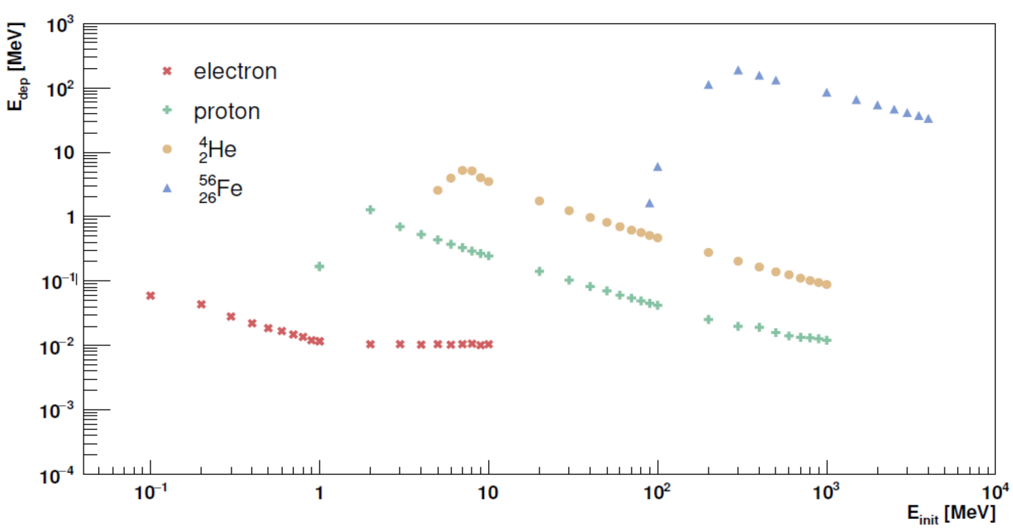
The SpacePix is a family of ASICs based on a monolithic 180 nm PDSoI technology designed for detection of charged particles in space.

- Low-power (<100 mW), thin detector capable of processing 10^7 - 10^8 pixel hits $cm^{-2}s^{-1}$
- Capable of dE/dx measurements of electrons, protons and heavy ions (large dynamic range)
  - Measurement of signal in pixels (e^-) and sensor backside layer (h^+)
- Designed for standalone operation, in a telescope configuration or with a scintillator/SiPM
- Simple and robust architecture for a reliable operation in space environment
- Operated by a microcontroller or an FPGA in continuous or pulsed mode (field sampling)

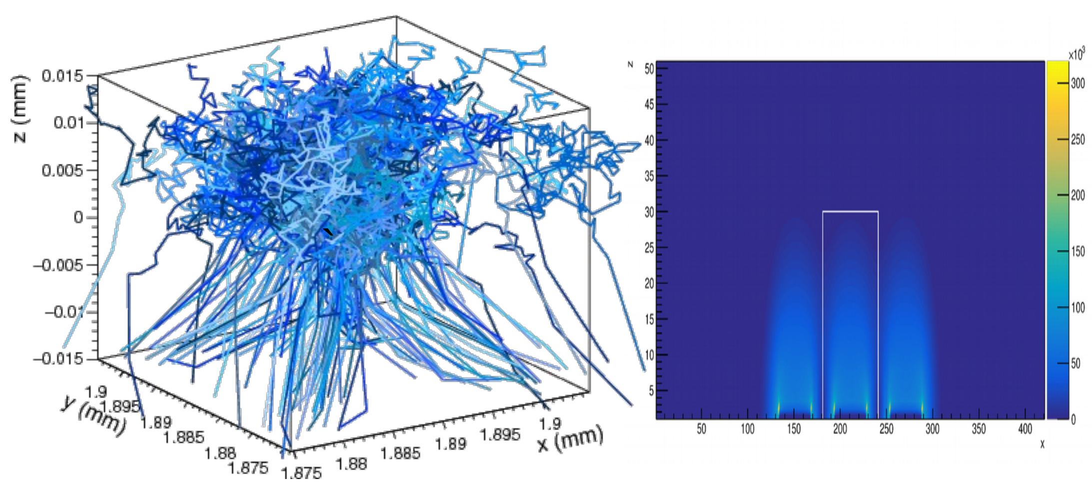

SpacePix 1 layout


Manufactured ASIC

Operational experience was acquired from previous ASICs including the SpacePix 1 test structure.



The Geant4 simulation of the deposited energy for benchmark ions

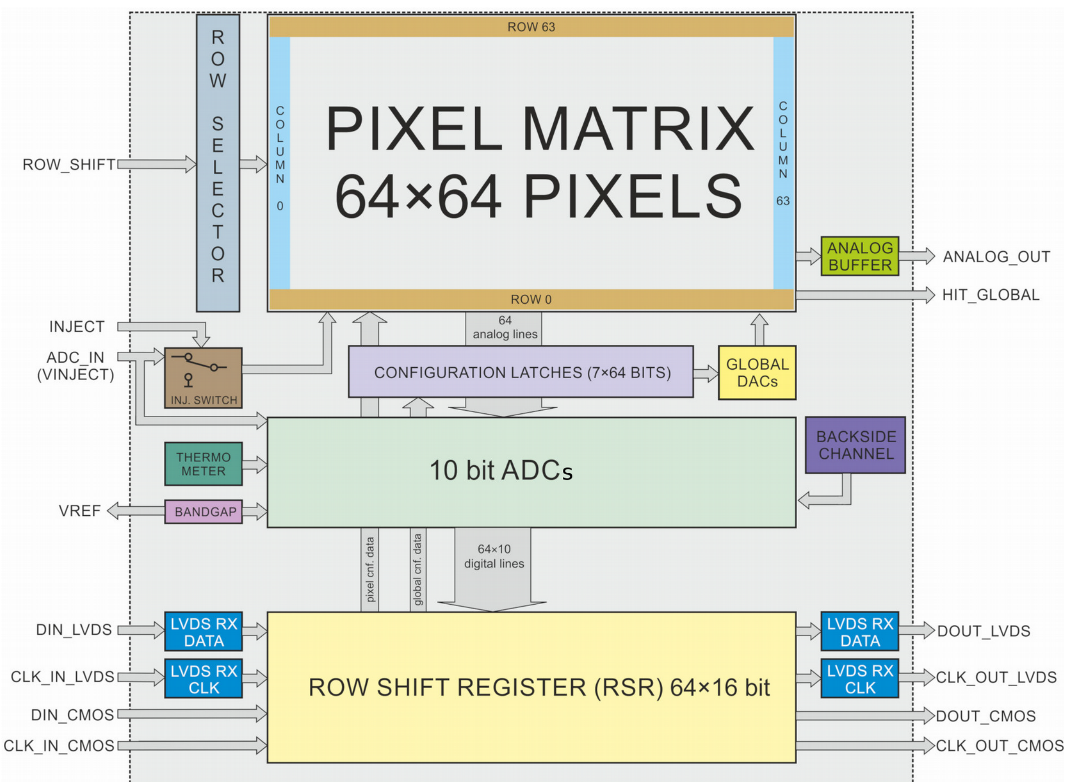


The pixel E-field, charge collection and implant shape optimized using TCAD and AllPix²

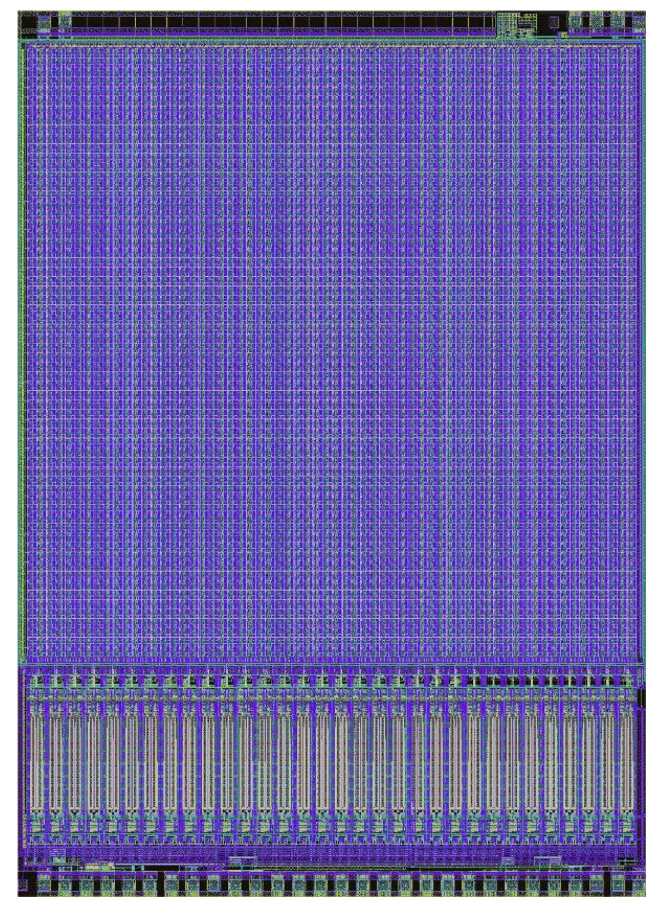
The SpacePix2 ASIC

- Dimensions 4.5 × 5.5 mm^2
- Built-in:
  - Thermometer (<0.5 °C precision)
  - Voltage references
  - Pixel analog signal output
- Architecture **scalable** to larger ASICs
- Selectable communication interface for MCU (SPI) and FPGA (LVDS)
- SEE hardened logic
- **ASIC submitted for manufacturing**

Pixel matrix	64 × 64 pixels, 60 μm pitch
Signal dynamic range	Pixel amplifier 1 to 65 ke$^-$ Backside 0.25 to 30 Me$^-$
Digitization	10-bit fast ADC
Power consumption	< 80 mW in continuous mode
Comm interface	50 MHz SPI, 500 MHz LVDS
Triggering	Fast particle hit signal
Calibration	Charge injection circuit



The internal architecture of the SpacePix2 ASIC



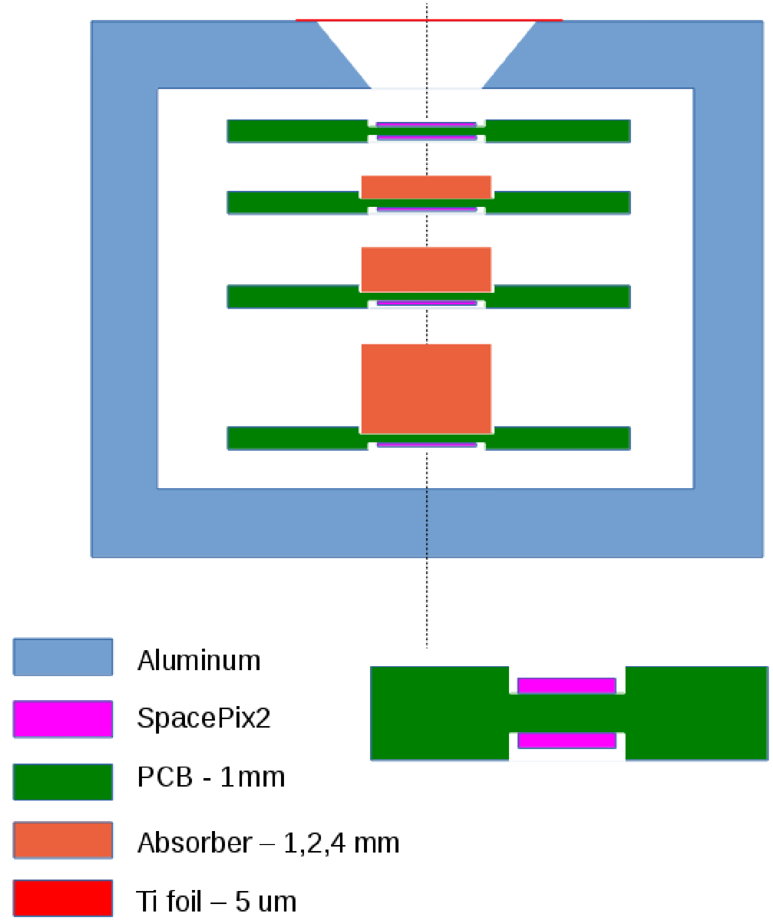
The final layout of the ASIC

The SpacePix Radiation Monitor (SXRM)

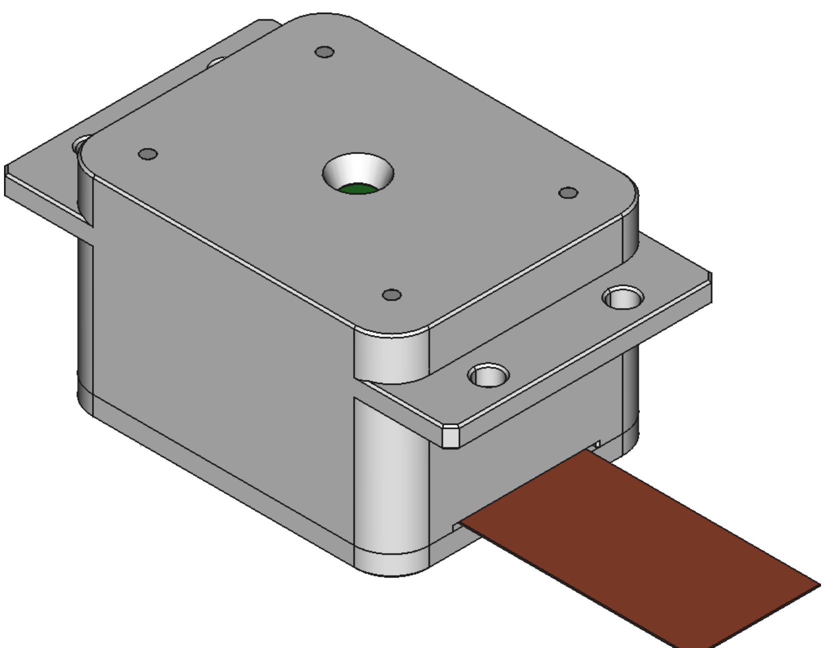
The SXRM is a telescope with interleaved layers of SpacePix2 ASICs, PCB, and W/Cu absorber layers.

Particle energy and species determination:

- Sampling of dE/dx in multiple layers
- Pattern recognition techniques (clustering, topologies) and partial reconstruction of particle trajectory in a DPU
- Supports operational modes of radiation imaging, clustering, tracking and particle energy / LET histogramming



The conceptual design of the 5-ASIC SXRM



The detection stack engineering model

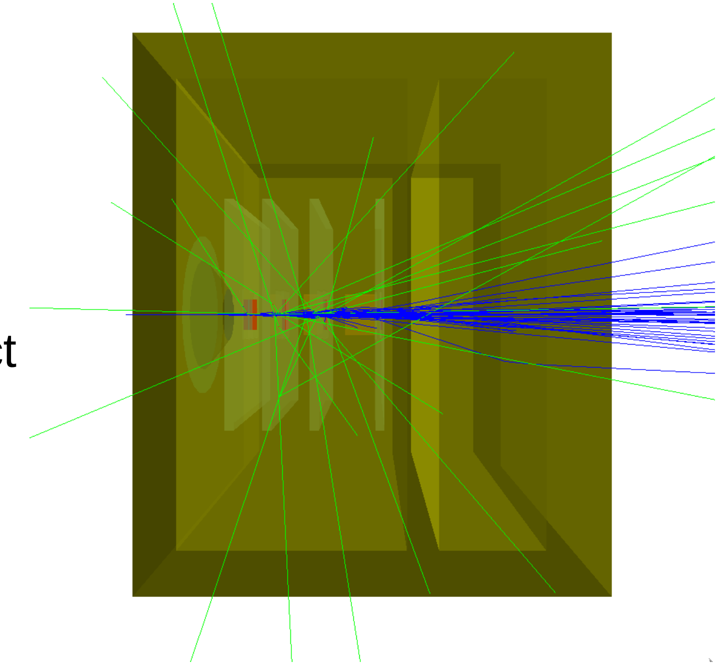
The SXRM space-grade version concept

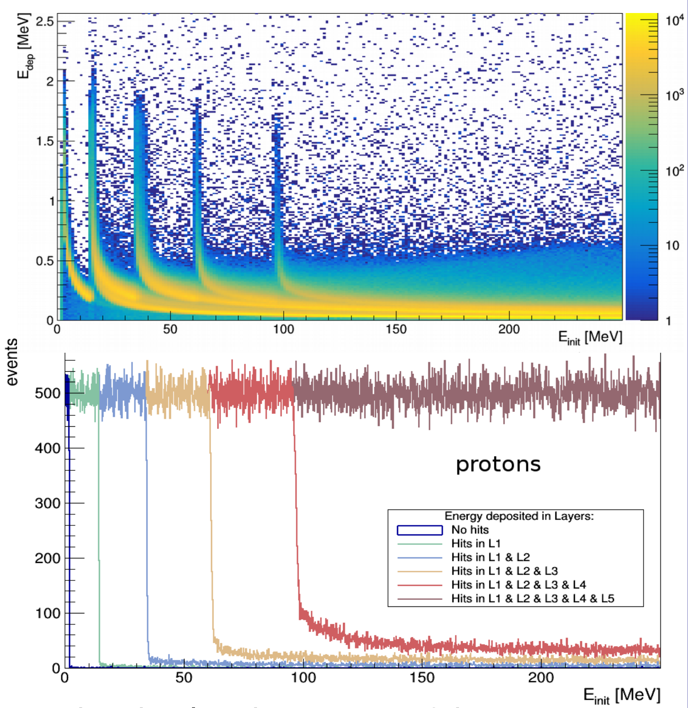
- The detection “box” connected to a readout DPU
- The box design dimensions are $40 \times 30 \times 25$ mm^3
  - Weight less than 60 g (Al case) or 135 g (Inconel)
  - Can be also connected to a non-space grade DPU
- The overall SXRM envelope $100 \times 60 \times 40$ mm^3
- Expected total weight < 500 g

The SXRM detection box

Simulations and optimization performed using Geant4 model
- Charge sharing and plasma effect
- Pixel transfer curves extracted from ASIC simulation

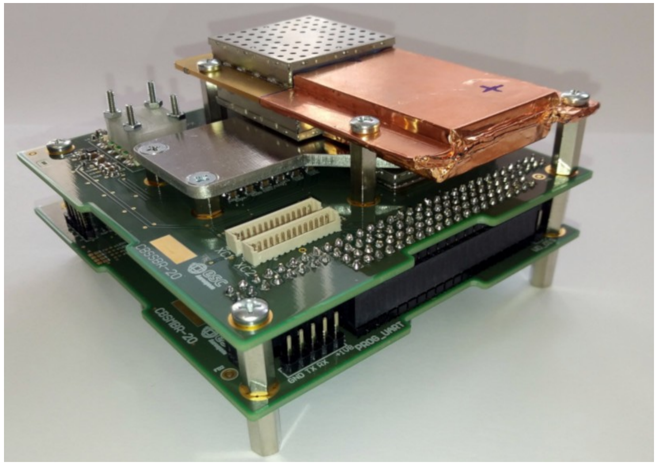
With hit coincidence, the SXRM is able to detect or reconstruct particle trajectories and estimate the species and energy of:
- **electrons** from 80 keV to 10 MeV
- **protons** from 1.5 MeV to 150 MeV
- **heavy ions** up to 50+ MeVcm^{2}mg^{-1}

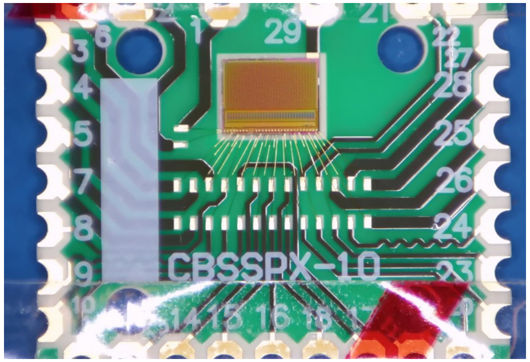


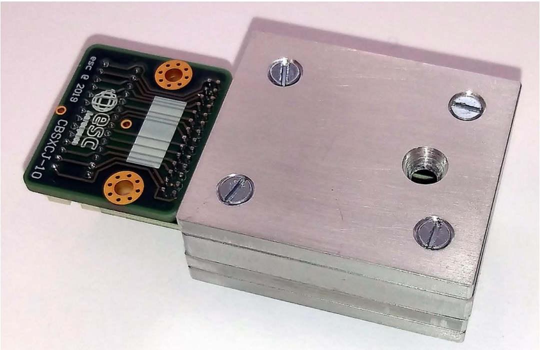


The simulated response of the SXRM model to protons.

In-orbit demonstrator for X-CHIP-03 telescope







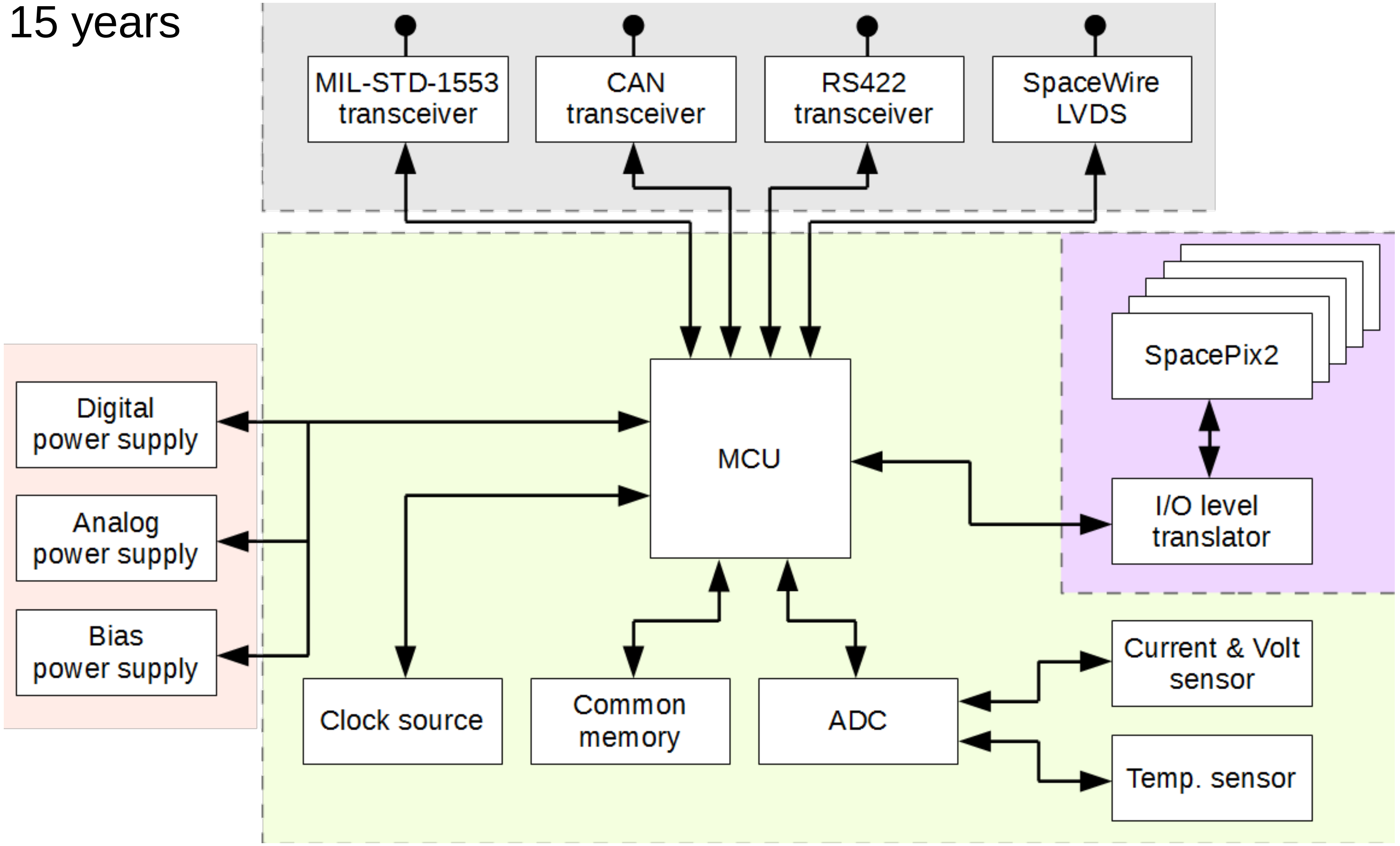
SpaceRad @ Socrat-R 3U
- Proto-SXRM proton telescope
  - 2 X-CHIP-03
- SpacePix1 GCR monitor
- SPACEDOS (NPI CAS)

The SXRM electronics

- Measured data will be reconstructed in a local rad-hard MCU, storage in MRAM
- The power consumption (depending on comm I/F used) of the 5-ASIC detector setup
  - < 1.5 W in continuous operation mode
  - < 0.3 W in radiation field sampling mode
- Communication via MIL-STD-1553B, RS-422, CAN, SpaceWire
- Powered from 28, 50 or 100 V rail
- On-board LV, HV PSU for ASIC sensor layer biasing
- Projected GEO lifetime of 15 years

2020 schedule

- EQM ready Q2/2020
  - Beam tests
  - Thermal vacuum
  - EMC, vibrations
- PFM ready Q4/2020
  - Radiation tests



The functional block diagram of the SXRM

Conclusions

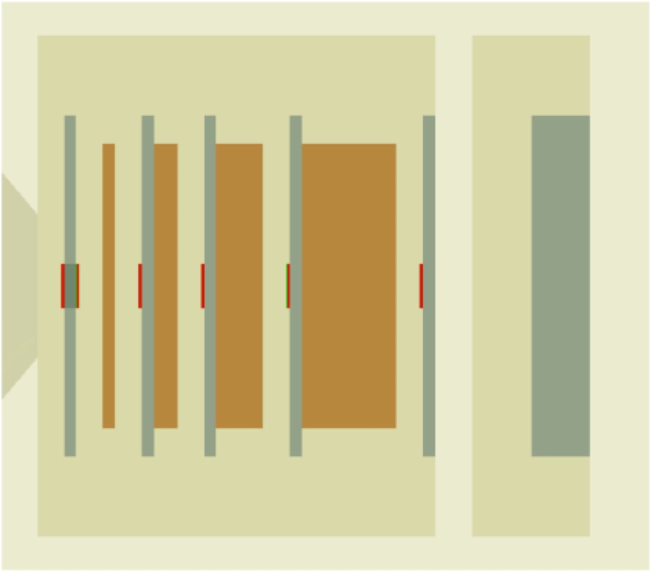
- Monolithic pixel detectors developed with commercial SoI CMOS technologies combine the advantages of silicon hybrid and MAPS detectors
- The SpacePix2 ASICs have been submitted for manufacturing
- The SXRM is a new low-power, highly-miniaturized proton, electron and heavy ion monitor with individual particle identification, classification and tracking capabilities
- The dynamic range of the SpacePix2 ASICs and multiple particle ionization dE/dx sampling will allow event reconstruction and identification using pattern recognition algorithms implemented in the CPU
- The current prototype with two detection ASICs is being validated in orbit and in testbeams
- The five-layer space-grade SXRM prototype will be constructed and tested in 2020

BONUS SLIDES

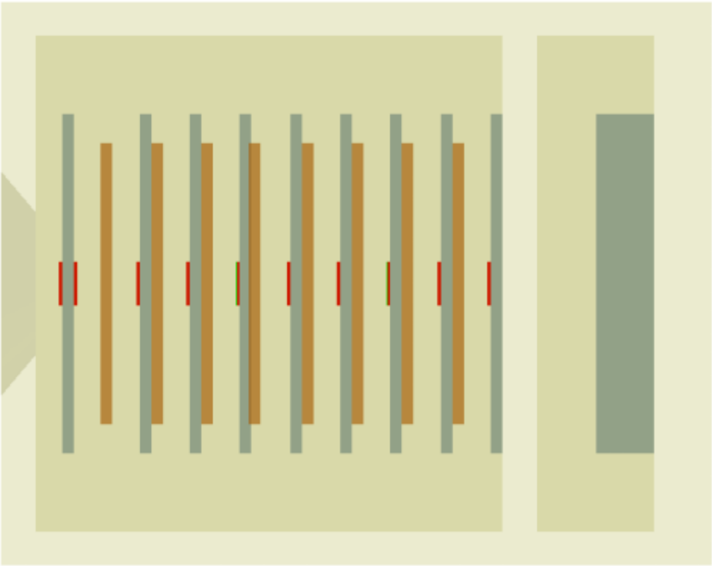
The SXRM variants under study

- Several variants are under consideration, varying in the number of detection layers and absorber thickness.

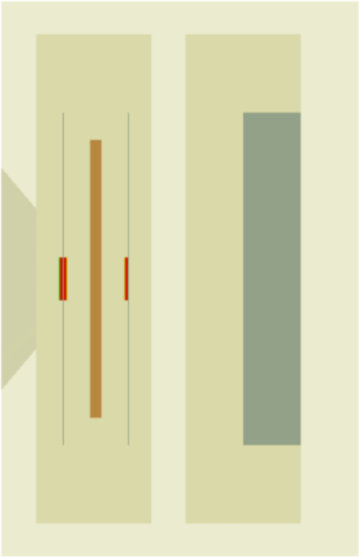
- The Geant4 simulations are being performed to find optimal geometry for:
  - Proton/electron/HI energy and angular resolution
  - Particle scattering in the absorber layer
  - Acceptance angle / geometric factor as a f(E)
  - Number of necessary SpacePix2 ASICs for required performance
- Inconel 600 / Al casing (shielding vs. backscattered electrons etc.)
  - Electronics (FPGA/µCPU) shielded in the bottom part of the SXRM
- ASICs glued and wire-bonded onto the flex



The 5-layer SXRM model



The linear SXRM model



The compact SXRM model