15-16 May 2018
ESA/ESTEC

MIRAM ESA-ESTEC Project 4000122160/17/UK/ND

MIRAM
Miniaturized Radiation Monitor
spacecraft platform for GEO telecommunications satellites

ADVACAM*
Imaging the Unseen

Carlos Granja[#@], Benedikt Bergmann[&],
Stanislav Pospisil[&], Erik Heijne[&,%], Stefan Gohl[&], M. Malich[&], M. Holik[&], P. Burian[&], J. Janecek[&], W. Wong[%], A. Smetana[&], Jan Jakubek[#], Pavel Soukup[#], Daniel Turecek[#], Martin Jakubek[#], Stepan Polansky[#], Jiri Pivec[#]

[#] ADVACAM, Prague, Czech Republic

[&] Institute of Experimental and Applied Physics, Czech Technical University in Prague, Czech Republic

[%] CERN, Geneva, Switzerland

**Start-up of the Medipix Collaboration/IEAP CTU Prague*

[@] carlos.granja@advacam.com

MIRAM concept, status
- ❑ Heritage/technology selection
- ❑ Concept, design
- ❑ Model simulations
- ❑ Methodology

MIRAM: Technology selection, heritage, ongoing developments

Timepix deployments in space: in LEO on board ISS since 2012, spacecraft payload on board Proba-V since 2013

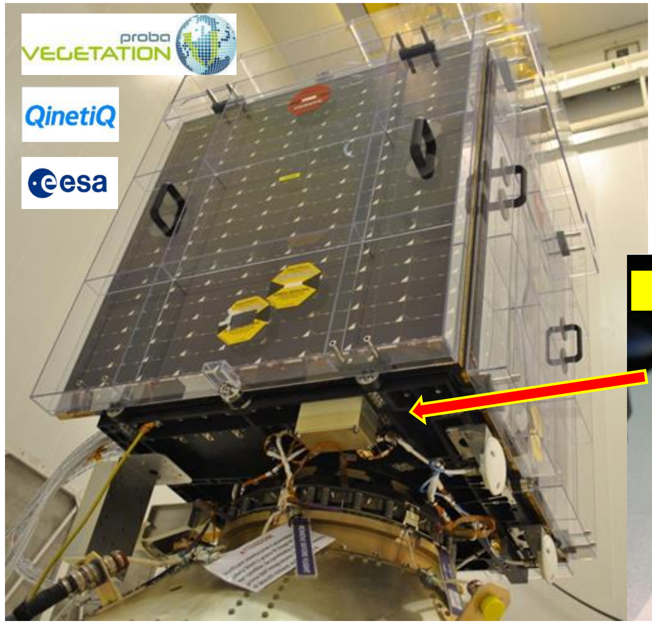
Orbit	Launch	
		Spacecraft payloads: Micro-satellites
LEO, 820 km	May 2013	❑ **SATRAM-Timepix** on board **ESA Proba-V satellite** QinetiQ ESA (in LEO orbit since May 2013), successful commissioning, continuous data taking
LEO, 600 km	July 2014	❑ **LUCID-5xTimepix array payload** on board **TechDemoSat-1 SSTL-UK satellite** Langton Ultimate Cosmic-ray Intensity Detector, successful commissioning, continuous data taking
LEO, 600 km	1Q-2019	❑ **Particle telescope/2x stack Timepix** for **RISESAT satellite** Tohoku U./Japan (ongoing, FM delivery 3Q 2018, launch 4Q 2018/1Q2019)
		Spacecraft payloads: nanosatellites/cubesats
LEO, 500 km	June 2017	❑ **Focal plane X-ray detector 1xTimepix/X-ray telescope 1D optics** on board **Cubesat VZLUSAT-1**, successful commissioning continuous data taking
CIS-lunar/deep space	2020	❑ **Timepix radiation monitor payload** on board **BioSentinel cubesat** for **NASA-ORION flight EM1**, NASA Ames Center
		Spacecraft payloads: large satellites
GEO	>2020	❑ **Miniaturized Radiation Monitor MIRAM**, for **ESA/ARTES telecommunication satellites at GEO orbit**
		Sub-orbital sounding rockets
LEO, 200 km	April 2018	❑ **Focal plane X-ray detector 2xTimepix/X-ray telescope 2D optics REX** payload Penn State U. for **NASA WRX-R sounding sub-orbital rocket**, launched 4th April 2018, successful operation, data collected, payload retrieved
		Pressurized/manned space modules
LEO, 420 km	Aug 2012	❑ Miniaturized **Quantum imaging on-line space radiation dosimeters/Radiation Environment Monitors REM 5xTPX** on board **NASA-ISS**, successful commissioning, continuous data taking
MEO, 6000 km	Dec 2014	❑ **2x Battery Operated Radiation Detectors BIRD-Timepix** fully autonomous operation, **NASA Orion Exploration Flight Test EFT-1**, successful commissioning, continuous data taking
LEO, 420 km	May 2017	❑ **Energetic Particle Telescope EPT-Timepix 2x stack** on board **NASA–ISS**, successful commissioning continuous data taking
CIS-lunar/deep space	2020	❑ **Hybrid Electronic Radiation Assessor HERA-Timepix** for **NASA-ORION flights EM1** and **EM2**

MIRAM Heritage: Timepix deployments in LEO orbit

LEO orbit on board ISS/2012, spacecraft payload on board Proba-V/2013, MEO on ORION EF-1/2014

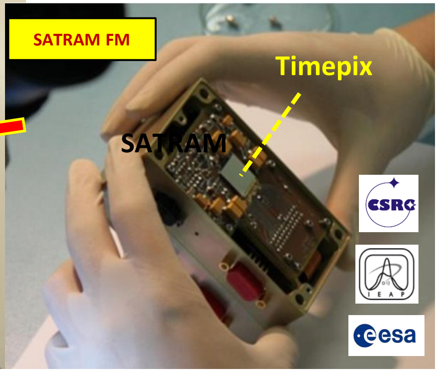
Advacam in 2017 became certified NASA supplier

ADVACAM
Imaging the Unseen

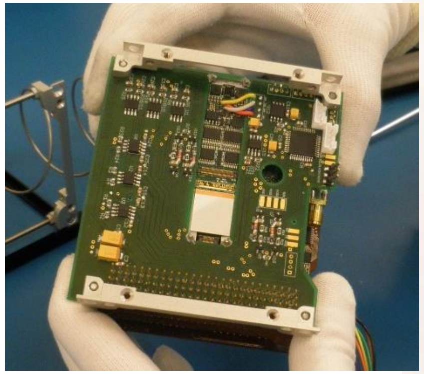


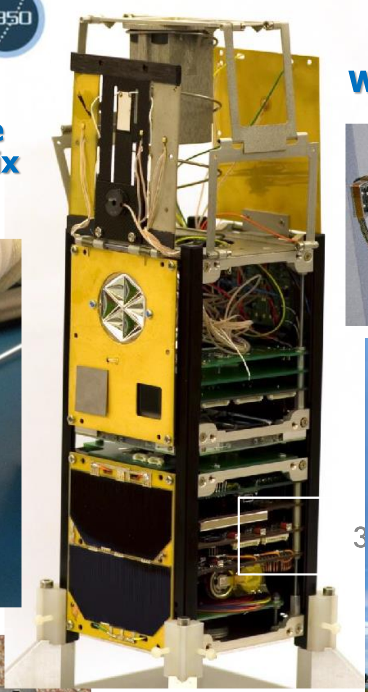
SATRAM: Space Application of Timepix Radiation Monitor on board Proba-V, LEO orbit/May 2013

Size: 11 cm × 6 cm × 5 cm, mass 340 g, power 2W

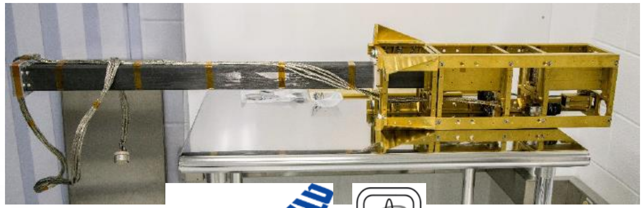


VZLUSAT-1 Cubesat X-ray 1-D optics telescope focal plane detector Timepix LEO orbit/June 2017

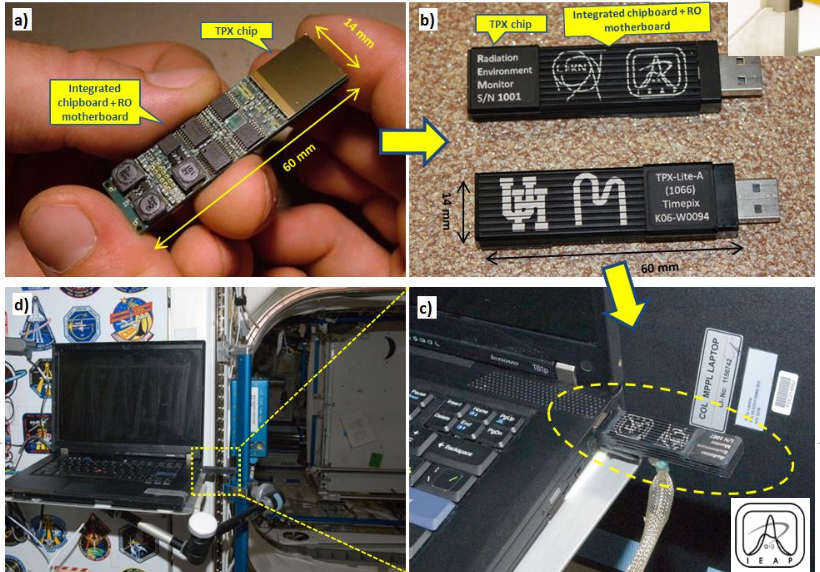




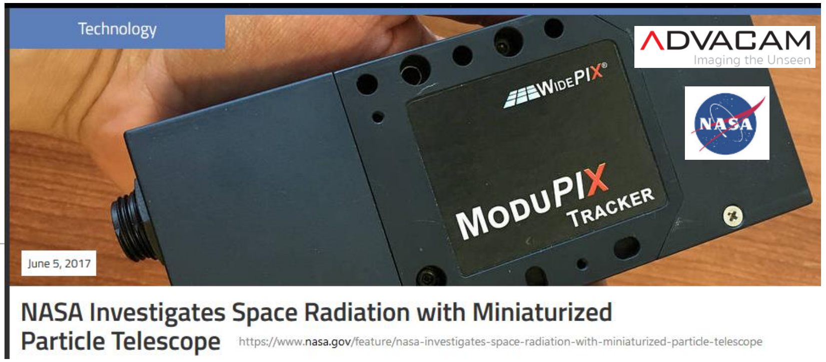
Focal plane detector 2xTimepix/X-ray telescope 2D optics payload on board WRX-R sub-orbital rocket, LEO/April 2018



Online quantum imaging spacecrew dosemeters on ISS LEO orbit/Aug 2012



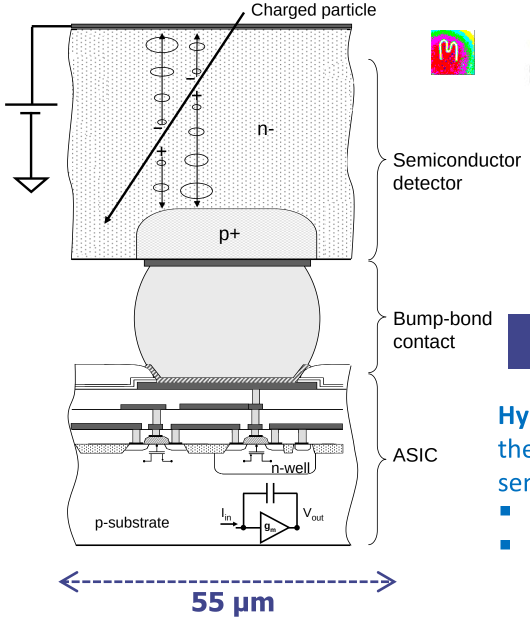
Energetic Particle Telescope EPT-Timepix on board ISS-NASA module, LEO orbit/May 2017

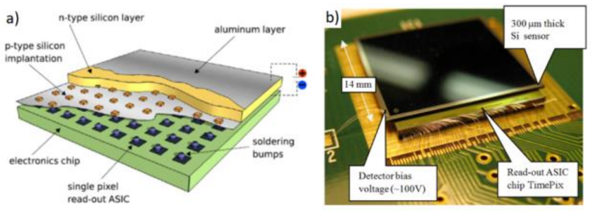


MIRAM Heritage: Timepix, SATRAM

Spacecraft Radiation Monitor Payload SATRAM/Timepix in LEO on board Proba-V

C. Granja, IEAP CTU
Prague 2015





Hybrid architecture

Hybrid architecture: sensor is bump-bonded to the **Timepix readout ASIC chip**. Different semiconductor sensors can be used:

- material (Si, CdTe, GaAs)
- thickness (e.g. 100, 300, 500, 700, 1000, 1500 µm).

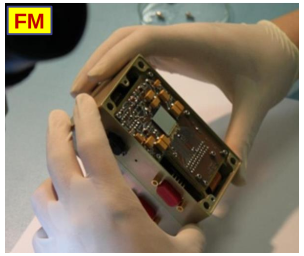
Quantum imaging detection

- Hybrid architecture, high pixel granularity
- Per-pixel signal processing electronics

- Dark-current free detection
- Threshold ~ 4 keV
- Track visualization of single particles

Active nuclear emulsion

SATRAM*



Size: 10.8 cm × 6.3 cm × 5.6 cm, full mass 340 g

SATRAM: Space Application of Timepix Radiation Monitor

- Technology demonstrator miniaturized platform for small spacecraft
- High-resolution radiation monitor: Space radiation environment and effects
- Quantum imaging radiation monitor / radiation camera / wide FoV 2p
- Characterization and visualization of space radiation
- In open space in LEO orbit on board PROBA-V satellite
- Launched 7th May 2013, successful commisioning
- Altitude ~ 820 km, polar sun synchronous orbit, 82º inclination
- Timepix for the first time in open space – currently TRL 9

- ❑ Active detector, integrated/miniaturized device, low mass, low power
- ❑ Single-particle/quantum counting, noiseless detection/dark-current free
- ❑ Per-pixel-sensitivity/high granularity, high-resolution particle tracking
- ❑ Wide dynamic range (counting particle fluxes, per-pixel energy sensitivity)
- ❑ Directionality, no collimators, wide FoV 2π, omnidirectional

SATRAM DATA PRODUCTS

- ❑ Quantum imaging detection and track visualization of the mixed radiation field
- ❑ Dose rates and particle fluxes at detector position with sensitivity/discrimination
- ❑ Spectral characterization, energy loss and LET spectra of energetic charged particles
- ❑ Directional/angular distributions of energetic charged particles in wide FoV (limited resolution)

* Granja C., Polansky S., Vykydal Z., Owens A., Pospisil S., et al., *The SATRAM Timepix spacecraft payload in open space on board the Proba-V satellite for wide range radiation monitoring in LEO orbit*, **Planetary and Space Science 125** (2016) 114-129
http://dx.doi.org/10.1016/j.pss.2016.03.009

see S. Gohl Talk, Wednesday 16.5.2018

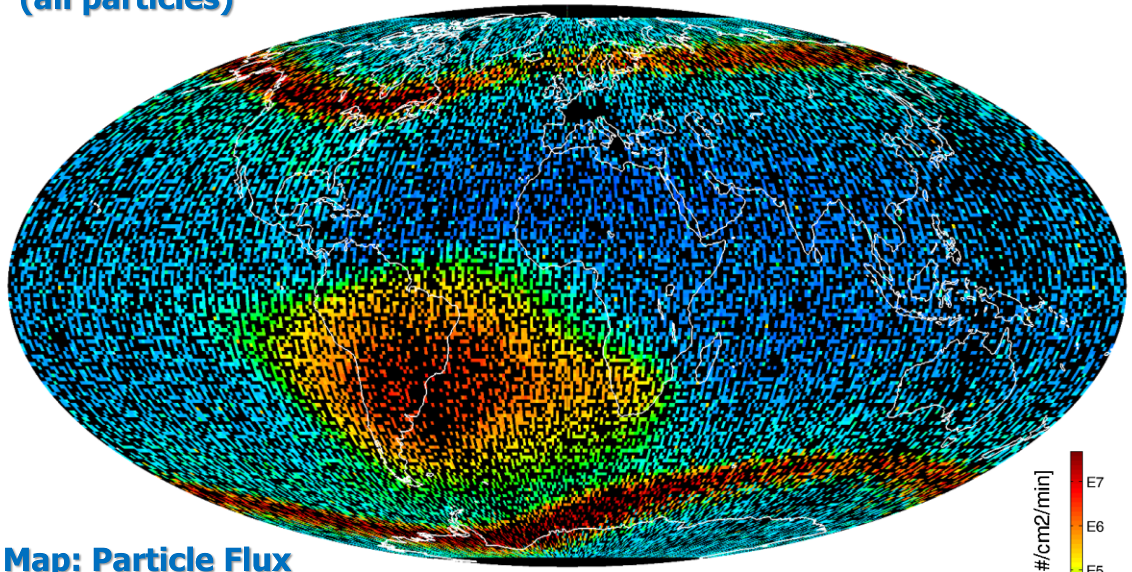
SATRAM/Timepix on Proba-V

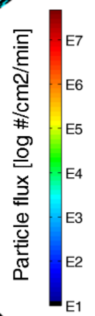
Quantum imaging detection of space radiation

Detection and track visualization of space radiation by Timepix operated in Timepix operated in energy mode along Proba-V 820 km LEO orbit. Frames shown at different orbit locations

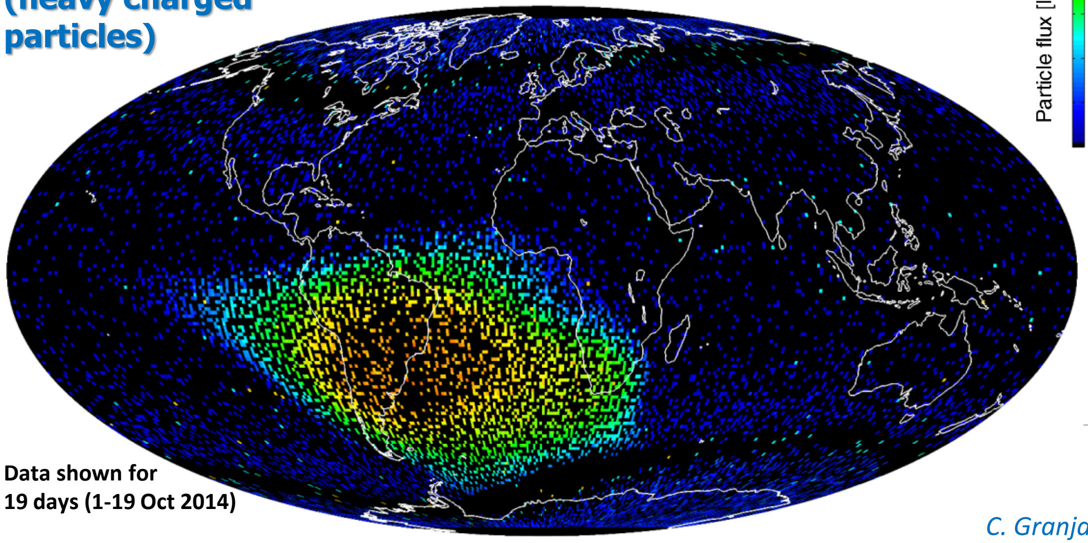
C. Granja, IEAP CTU Prague 2015

Map: Particle Flux (all particles)

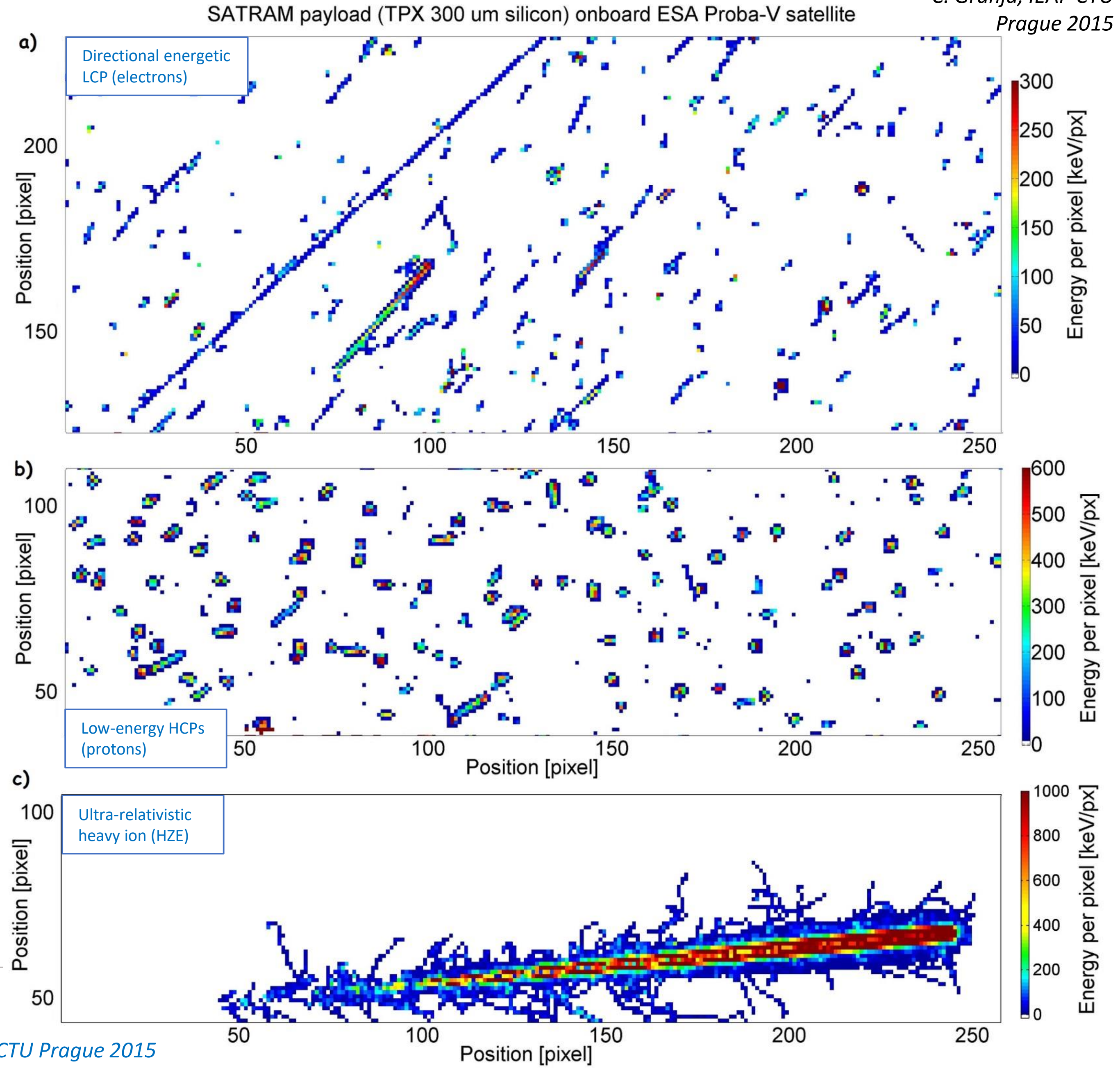




Map: Particle Flux (heavy charged particles)



Data shown for 19 days (1-19 Oct 2014)



C. Granja, IEAP CTU Prague 2015

MIRAM: Requirements + Objectives + Data products

ADVACAM Imaging the Unseen

OBJECTIVE

- To design, develop and test a **Miniaturized Radiation Monitor** (**MIRAM**) based on ASIC chip technology, of small size and mass (< 150g)
- Capability of **broad sensing of energetic charged particles** for GEO telecommunications satellites and EP orbit raising.
- **Real-time monitoring** of the **radiation environment** at multiple locations in the satellite
- Provision of **alerts** to **intense radiation fluxes** (e.g. solar storms)

REQUIREMENTS

- An order of magnitude reduction in the mass and volume as compared to present-day radiation monitors
- Significant cost reduction compared to products available today (cost target is <50 k euros per unit in a batch production)
- Reduced power consumption (< 1W)
- Target lifetime compatible with GEO telecom missions (12-15 years)

Environmental Requirements
The radiation detector single chip shall have a radiation TID tolerance of at least 100 krad.
The radiation detector single chip shall be latch up free.
The radiation detector single chip shall have an operating temperature range of -40 to +80 deg C
The radiation detector single chip shall have a storage temperature range of -60 to +125 deg C
The MIRAM shall have a lifetime of 15 years to be compatible with the typical GEO telecom missions.

Radiation Environment

Orbit	Particle Energy	Particle Flux
LEO	Electrons: 100 keV to 7 MeV Protons: 100 keV to 400 MeV	Electrons E> 500 keV: up to $5 \cdot 10^4$ (/cm2/sec) Protons E>10 MeV: up to 10^4 (/cm2/sec)
MEO	Electrons: 100 keV to 7 MeV Protons: 100 keV to 400 MeV	Electrons: E> 500 keV up to 10^7 (/cm2/sec) Protons: E > 10 MeV up to 10^3 (/cm2/sec)
GEO	Electrons: 100 keV to 7 MeV SEP (protons): 100 keV to 400 MeV Cosmic rays: $10\text{-}10^{13}$ MeV.	Electrons: E> 500 keV up to $5 \cdot 10^6$ (/cm2/sec) SEP (protons): E>10 MeV up to 10^4 (/cm2/s)
Interplanetary	Cosmic rays: $10\text{-}10^{13}$ MeV. SEP (protons): 100 keV to 400 MeV	Cosmic Rays: 2-4 (/cm2/sec) SEP (protons): E>10 MeV up to 10^4 (/cm2/s)

OUTPUT/DATA PRODUCTS

- Dose rates, accumulate dose/TID, particle fluxes
- LET spectra, LET discrimination, estimates of particle energy range
- Alert/alarm levels to radiation storms

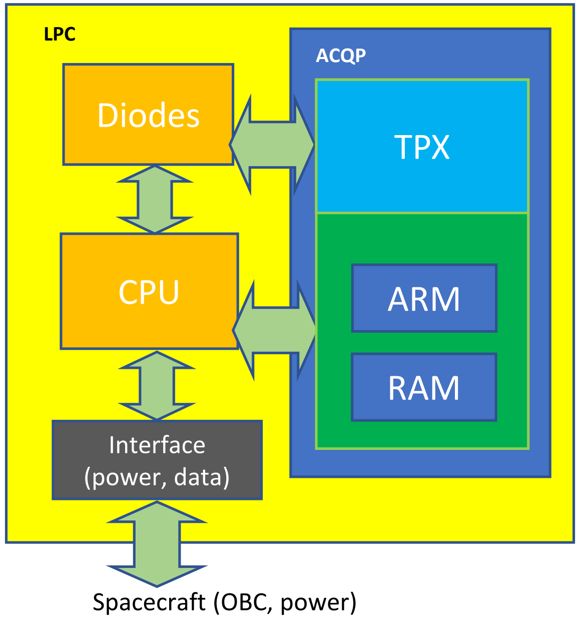
MIRAM: Concept, miniaturized/low-power architecture

J. Jakubek/ADV ,
B. Bergmann/IEAP CTU

Pixel detector Timepix/ACQP module coupled to semiconductor diodes/LCP module

Miniaturized radiation monitor payload for spacecraft, low power (<1 W), high-sensitivity, photon counting, wide dynamic range (particle types, energy, fluxes, direction (wide FoV/2π)

MIRAM: LCP and ACQP modules

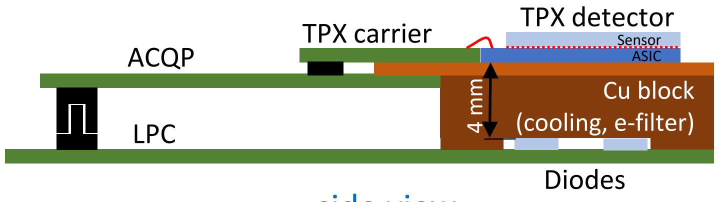


Preliminary concept architecture of MIRAM design

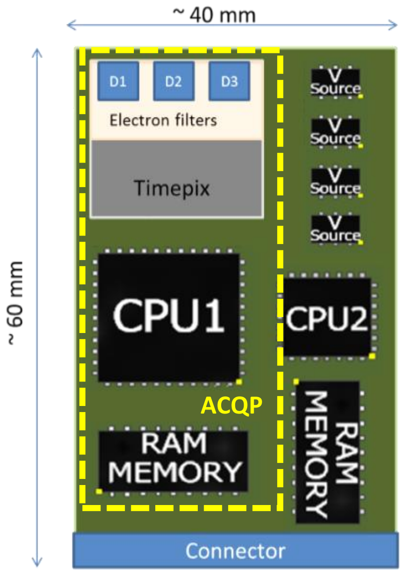
Acquisition & processing module (ACQP/slave):

- Pixel detector Timepix
- Triggered by LPC, synchronized
- Standby, low, medium, high intensity field modes
- High-resolution wide-range sampling of radiation field
- On board processing of TPX data
- Transfer and storage of evaluated data.

MIRAM layout consisting of the semiconductor pixel detector Timepix, electron stopping filters (2 elements - labelled "electron filters"), single pad diodes (3 units – labelled D1-3 as one of the possible options), power (V sources), CPUs and memory elements. Mass of architecture/electronic components shown < 100 g.

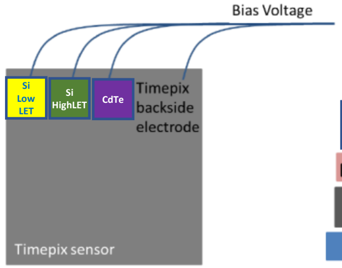


side view

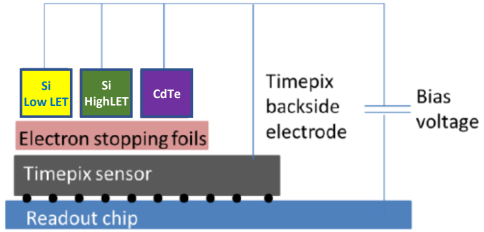


front view

Accommodation of TPX and diodes



front view



side view

Low Power Circuit (LPC/master):

- Diodes (low-, high-LET, Si, CdTe)
- Continuous (coarse) sampling of radiation field
- Analysis of incoming particles and dose calculation.
- Compress data and store to RAM storage.
- Communication with satellite (report status, receive commands which control acquisition parameters and power control).

MIRAM: Concept, miniaturized/ low-power architecture

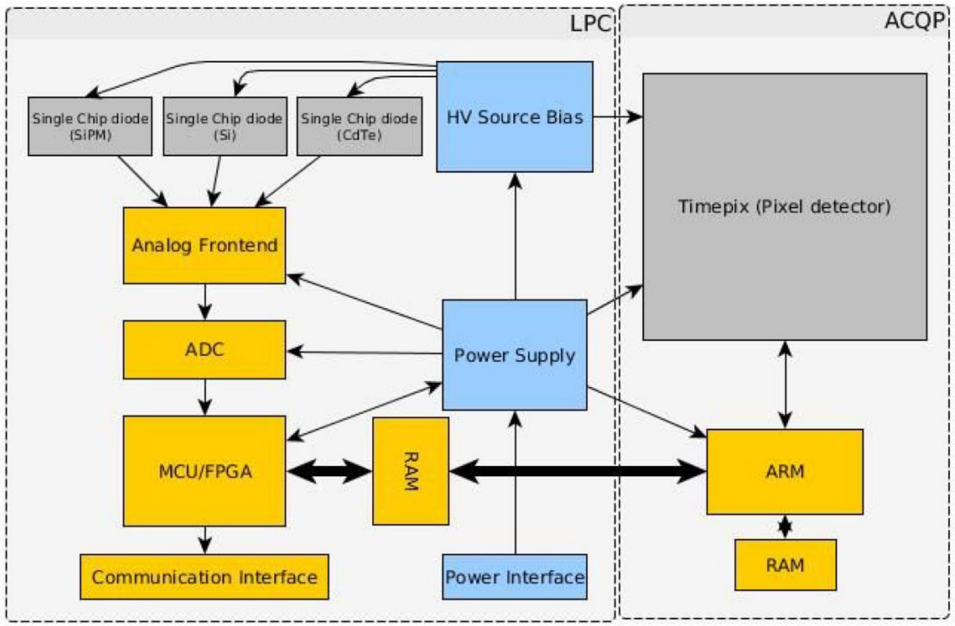
B. Bergmann/IEAP CTU
C. Granja/ADV

Pixel detector Timepix/ACQP module coupled to semiconductor diodes/LCP module

Miniaturized radiation monitor payload for spacecraft, low power (<1 W), high-sensitivity, photon counting, wide dynamic range (particle types, energy, fluxes, direction (wide FoV/2π)

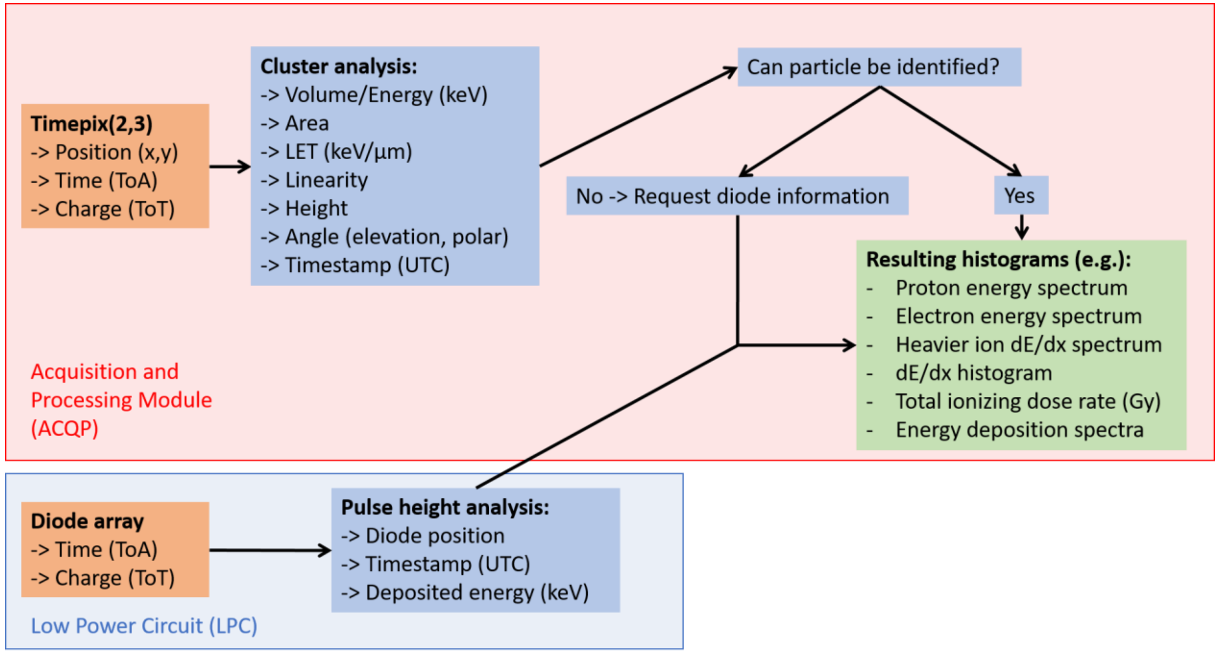
Preliminary concept functional of MIRAM design

Block scheme and operation layout of MIRAM



- LCP: Low power circuit (master)
- ACQP Acquisition and Processing Module (slave)

MIRAM: Data-flow schematic diagram



MIRAM: Concept, miniaturized/ low-power architecture

Pixel detector Timepix/ACQP module

ADVACAM
Imaging the Unseen

MiniPIX Timepix

ADVACAM
Imaging the Unseen

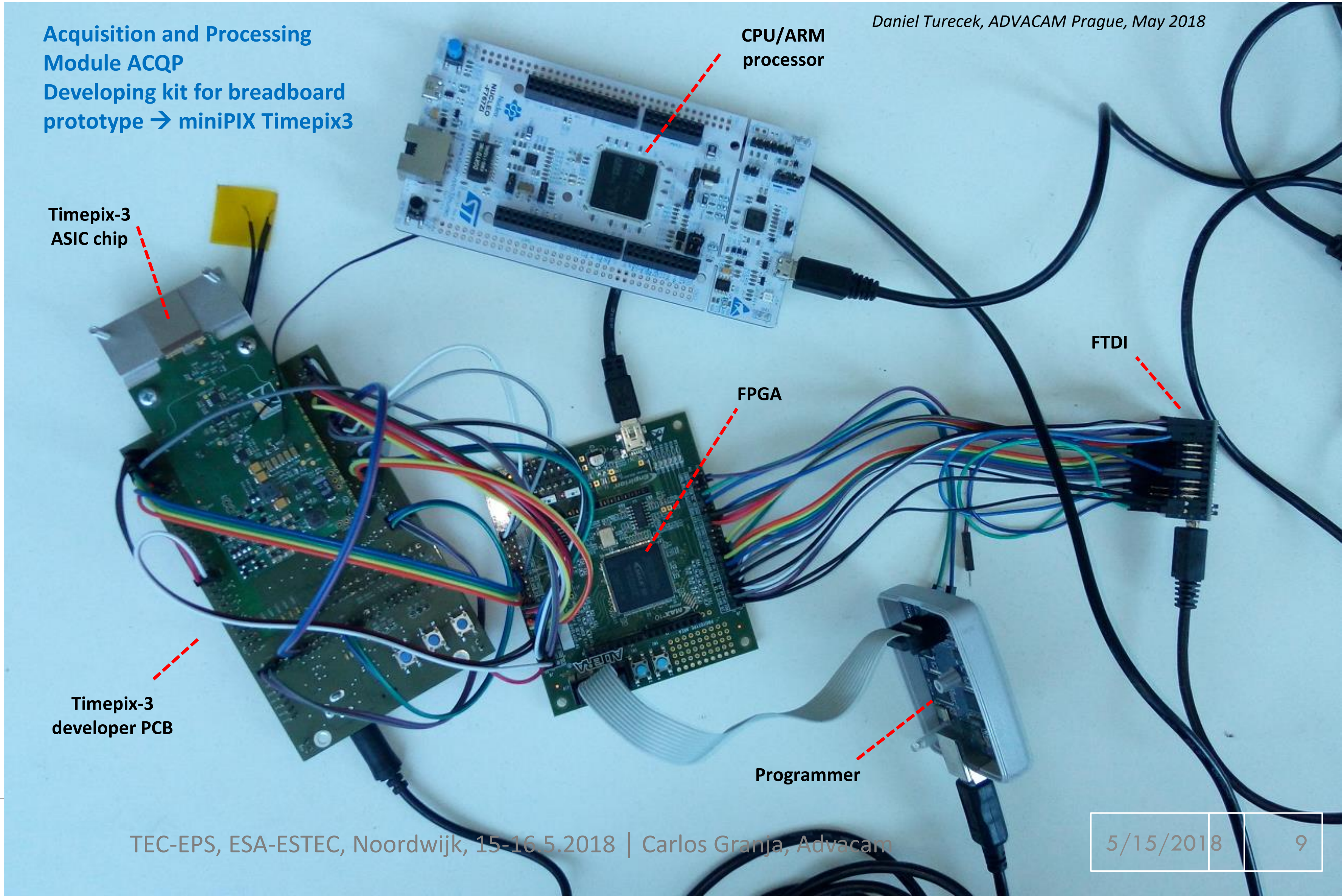
Medipix family ASIC chips

Medipix family ASIC chips
- ❑ Timepix (TPX-1)
- ❑ Timepix3 (available)
- ❑ Timepix2 (3-4Q 2018)
- ❑ Medipix3 (available)

Timepix (TPX-1 available)
- ❑ Per-pixel analog/digital signal chain 1x
- ❑ Per-pixel energy or time
- ❑ Frame-based readout
- ❑ TRL=9 in LEO

Timepix3 (newly existent)
- ❑ 2x per-pixel signal chains (energy & time)
- ❑ Event-by-event readout
- ❑ Minimum/nearly zero readout deadtime

Timepix2 (in development, 3-4Q 2018)
- ❑ 2x per-pixel signal chains (energy & time)
- ❑ Frame-based readout
- ❑ No deadtime
- ❑ No commercial/license restrictions



ADVACAM
Imaging the Unseen

MIRAM: ACQP module/Timepix detector

C. Granja, ADV, March 2018

ADVACAM Imaging the Unseen

Operation modes + estimates/ranges of event/data rate → Sampling frequency → Power consumption → Duty factor

Physics environment

Event/cluster rate on detector
[# clu/2 cm^2/s]

min	average	max
10^{1-2}	10^{3-5}	10^{6-7}

⇩

Typical size distribution of clusters
[# pixels/cluster]

- Small (<5 px): 70%
- Medium (6-15 px): 20%
- Large (16-50): 8%
- Very large (> 50px): 2%

⇩

Resulting rate # hit pixels
[# px/2 cm^2/s]

min	average	max
10^{1-2}	10^{3-6}	10^{6-8}

⇩

Duty factor: scalable according:
- Power consumption
- Memory/data transfer rate

Detector/data processing

Optimal mode

Data processing I level →
Pattern recognition →
Cluster analysis →
morphology CA parameters

- Time-stamp
- Area
- Volume
- Height
- Roundness/linearity
- Track length
- Polar angle (on sensor plane)
- Elevation angle
- Track width

⇨

Optimal mode

Data processing II level →
Derived physics parameters

- LET
- Height to angle ratio
- Width to length ratio

⇩ *Optimal mode*

Dose rates, particle fluxes, event list
- Differential: part. type
- Event classification (up to 8 event types) → histograms

Operation modes
→ Data products

- Basic:
  - Dose rate, TID
  - Event/particle flux (integrated all particles)
- Optimal:
  - Dose rate, TID
  - Particle types fluxes
  - Angular distributions
- Extended: includes
  - full frames
  - angular distributions (energetic ch. particles)

Data products → differential fluxes/event type classification

- X-rays, low-energy electrons omnidirectional, high-energy light charged particles (electrons, muons) at high-angles/perpendicular.
- Low-energy protons omnidirectional
- Low-energy light ions omnidirectional
- Low-energy heavy ions omnidirectional
- High–energy light charged particles (electrons, muons) non-perpendicular
- High-energy protons non-perpendicular
- High-energy light ions at medium and small angles
- High-energy heavy ions at medium and small angles

ACQP performance

Average power consumption

- Target: < 0.3 W
- Max: < 0.6 W

Radiation field sampling frequency

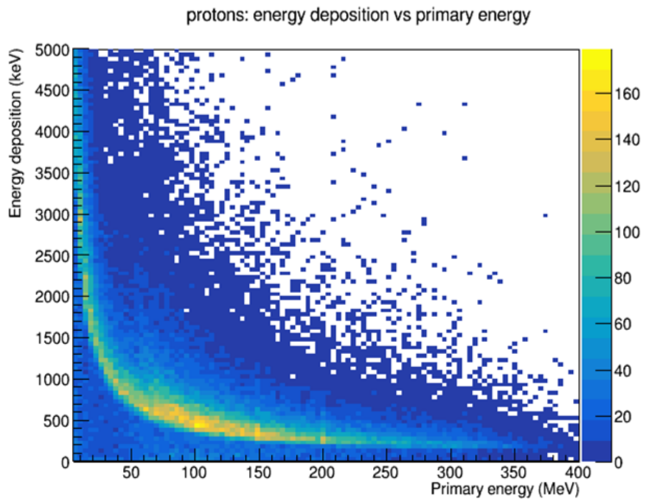
- Continuous (low intensity fields)
- Low/spare: few 6x/min
- Medium: 1x few sec
- High: 1-2x /sec

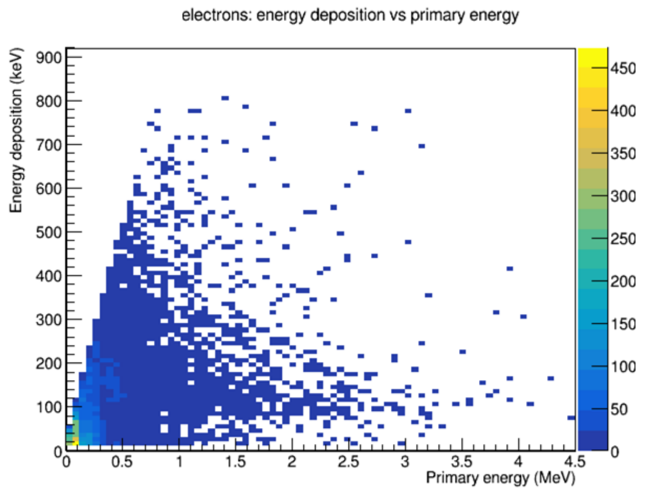
MIRAM: Simulations

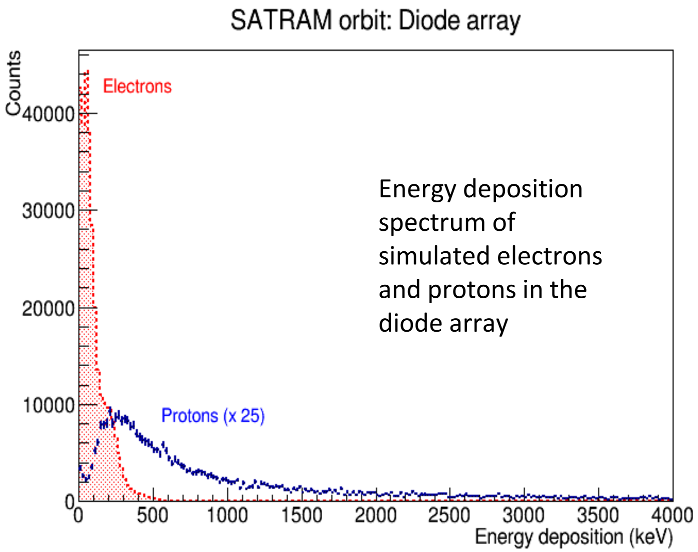
Response of Diode detector array to LEO-MEO radiation: deposited energy, field-of-view

S. Gohl, B. Bergmann, IEAP CTU

Simulated **solid energy deposited** on a **diode of MIRAM**



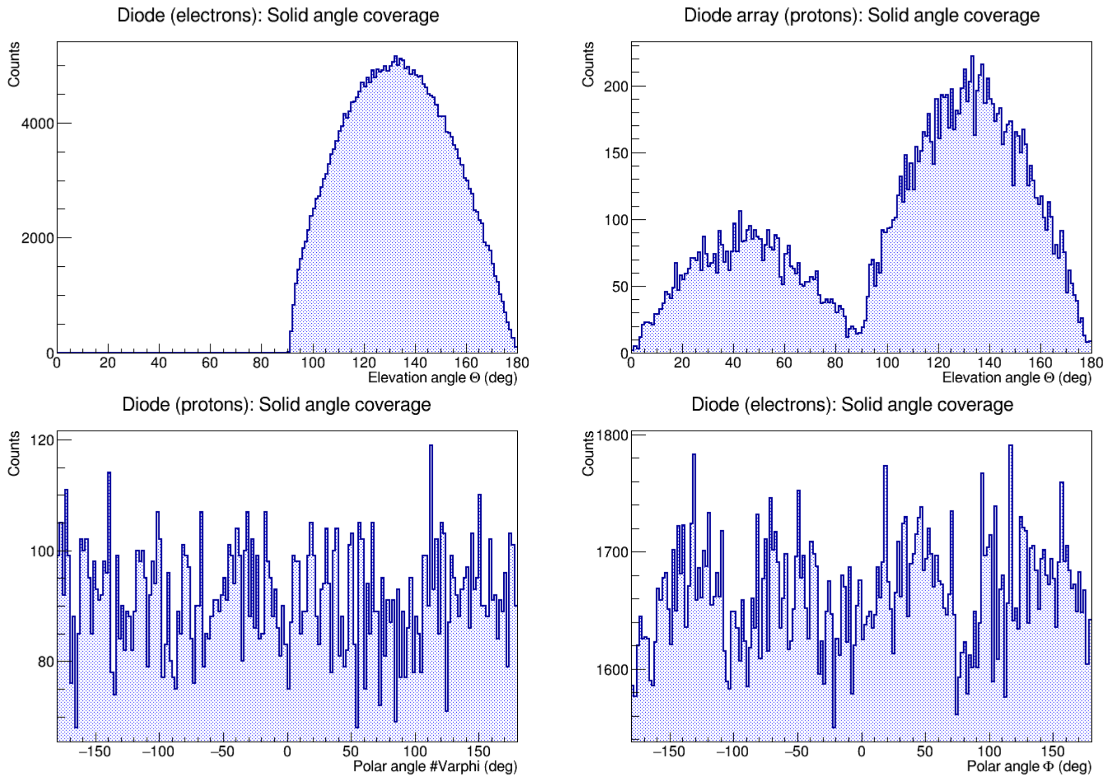




Energy deposition spectrum of simulated electrons and protons in the diode array

Simulated spectral response to LEO electrons and protons. A random set of 1000 electron and 100 proton tracks are shown

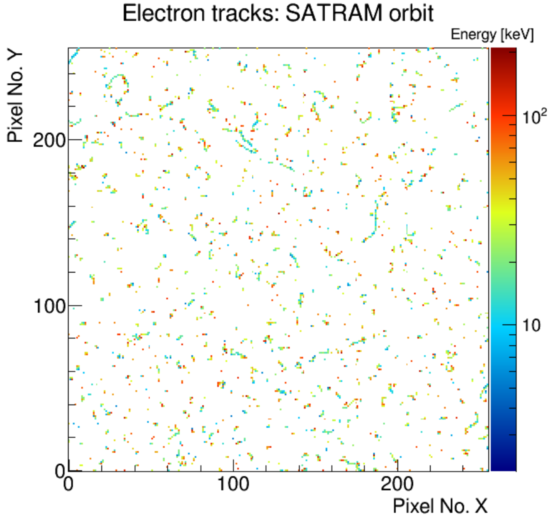
Simulated **solid angle acceptance** of the **diode array of the MIRAM device**. Due to the copper electron filter, electrons are seen when coming from the lower hemisphere. The filter also reduces the amount of protons from the upper hemisphere

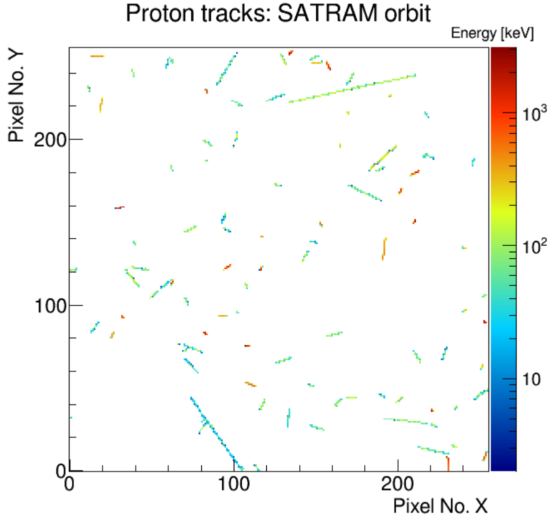


MIRAM: Simulations

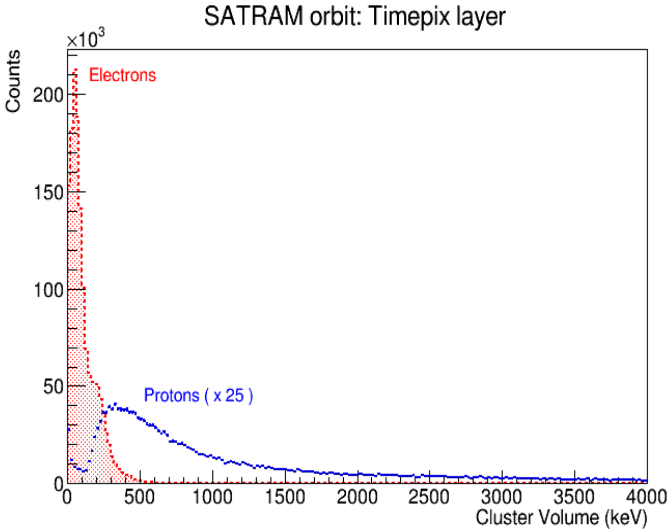
Response of the Timepix detector to LEO-MEO radiation

S. Gohl, B. Bergmann, IEAP CTU

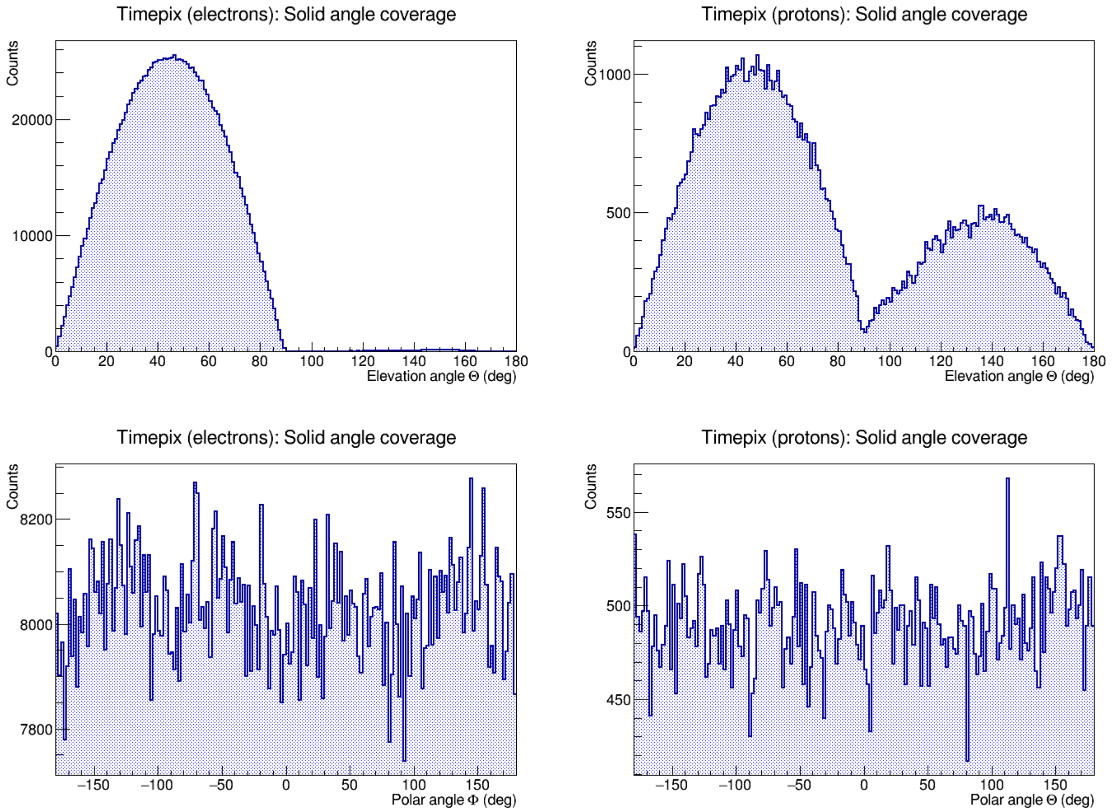




Simulated Timepix response to LEO electrons and protons. A random set of 1000 electron and 100 proton tracks are shown



Energy deposition of simulated electrons (red) and protons (blue) in the **Timepix** detector. $4x10^5$ protons and 10^7 electrons were simulated. To account for the differing number of simulated events the proton spectrum was scaled by a factor of 25.



Simulated Solid angle acceptance of the Timepix element integrated in the MIRAM. Due to the electron stopping filter (shielding) below the Timepix it sees electrons mainly from the upper hemisphere. This also causes the asymmetry of upper and lower hemisphere in the proton response

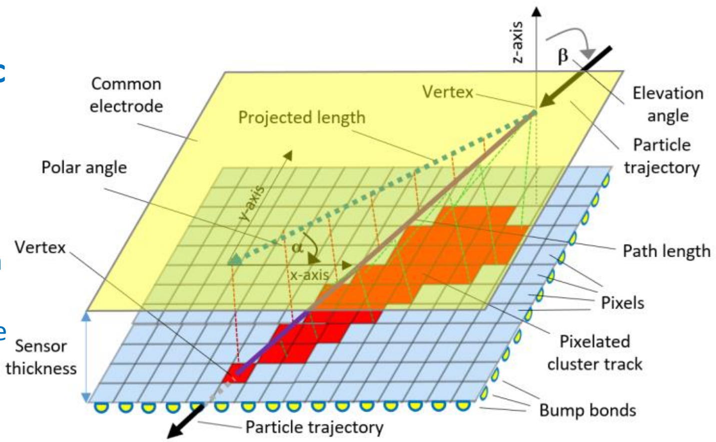
MIRAM: Timepix detector → Spectral detection, particle tracking

Quantum imaging and wide dynamic range detection of charged particles with spectral (energy loss) and directional sensitivity in wide range of (i) particle types/fluxes, (ii) spectral response/LET spectra and (iii) direction

C. Granja, ADV, April 2018

Single particle tracking for energetic charged particles

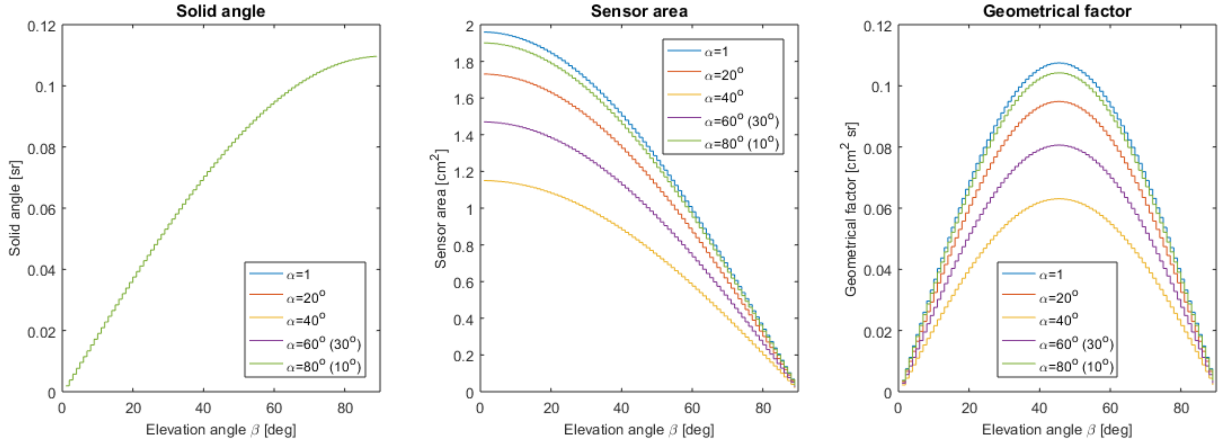
- Micro-scale pattern recognition analysis
- Derivation of the path length in 3D
- Entrance and exit points
- Direction: projected polar (α) and elevation (β) angles
- charge sharing effect along the depth of the sensor helps determining the particle direction in 3D



Classification of radiation events in the Timepix detector (300 µm silicon). Event types are listed with filters/proposed range of selected values of cluster parameters

#	Event	CAP 1	CAP 2	CAP 3
1	X rays; LE e OD; HE e, µ PP	A≤3	Lin<0.72	
		H<140; C<2.8	β<20	LET < 1.6
		0.9<C<2.8	β>20; Lin<0.83	LET < 1.6
		R<0.70	C > 2.5	LET < 1.6
2	LE p's PP	140<H<700; C≥2.8	8<HL<30; R>0.87	3.0 < LET < 8.0
3	LE light ions PP	700<H<2500	40<HL<70; R>0.87	15< LET<42
4	LE heavy ions PP	2500<H	70<HL; R>0.87	90< LET
5	HE e's, µ's nP	A>3; H<60	β>20; Lin≥0.65	LET < 0.9
6	HE p's nP	140<H<400	2<HL<8; Lin≥0.65	1.85 < LET < 3.0
		25<H≤140	2<HL<8; Lin≥0.85	0.50 < LET ≤ 1.85
7	HE light ions nP	400<H<1050	15<HL<40	4.0< LET<15
8	HE heavy ions nP	800<H<2500	10<HL<50	42<LET<90

LE = low energy, HE = energetic, PP = Perpendicular (β<20), CAP = cluster analysis parameter, A = area [# px], R = roundness [a.u.], H = height [keV/px], LET = linear energy transfer [keV/µm], e = electrons, µ = muons, p = protons, OD = omnidirectional, nP = non perpendicular (β≥20), C = curliness



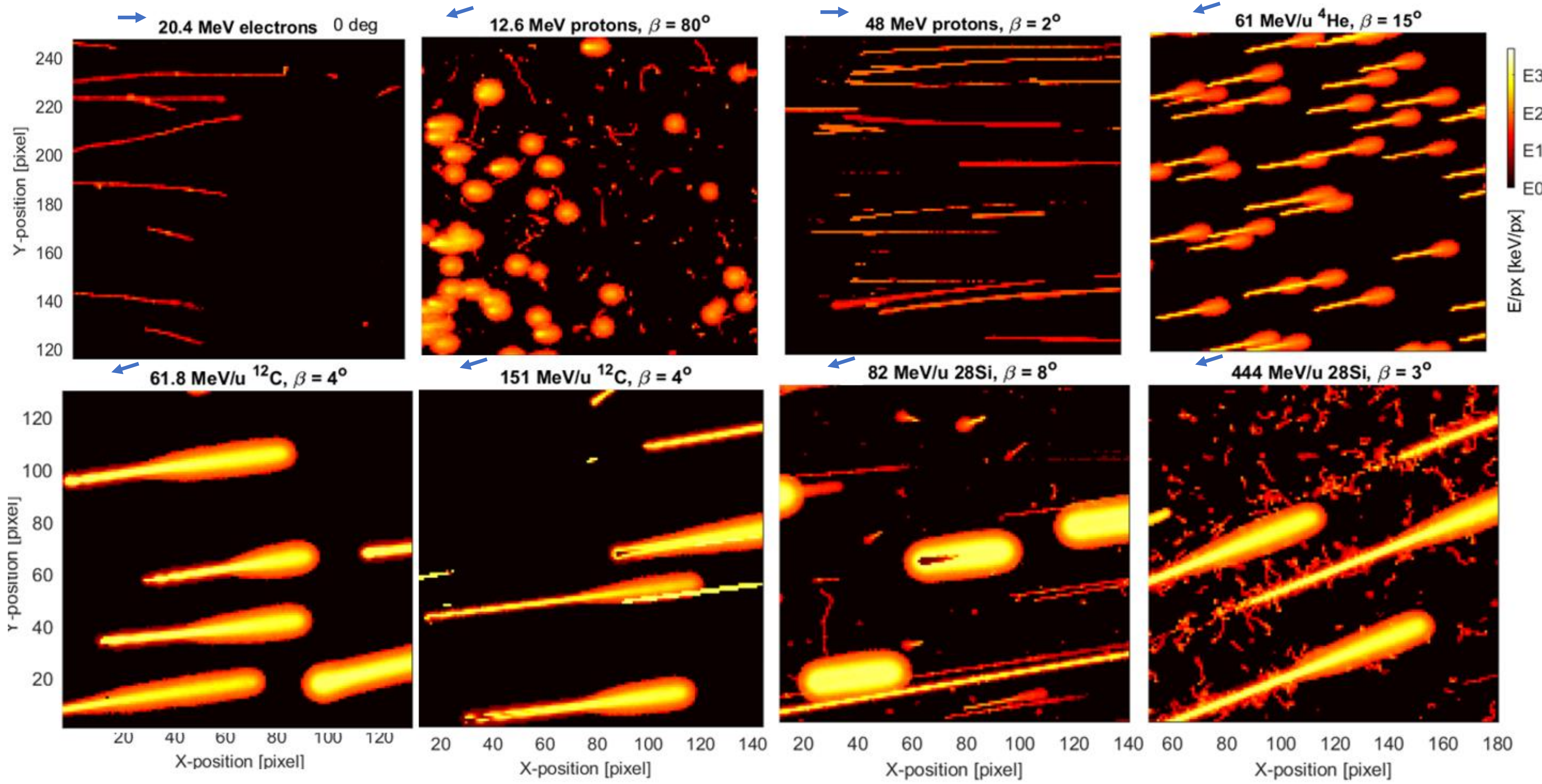
Solid angle (left), size of sensor (middle) and resulting geometrical factor (right) for a single Timepix detector

Degrees of freedom:
- **Particle type**
- **Particle energy, stopping power**
- **Particle direction**

Timepix: Resolving power: particle types + energy loss + direction

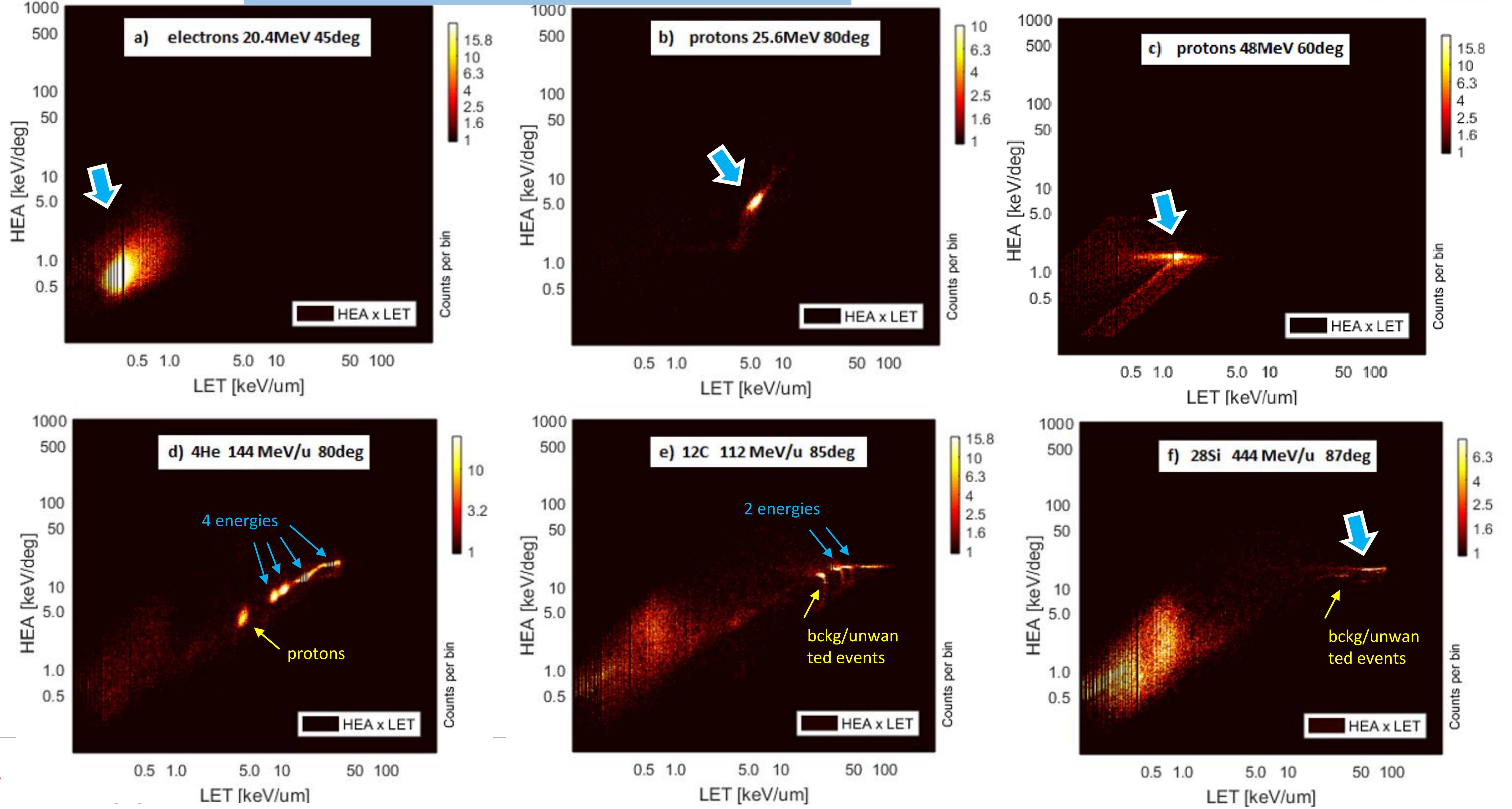
ADVACAM
Imaging the Unseen

NIRS
HIMAC



TWO-PARAMETER ANALYSIS

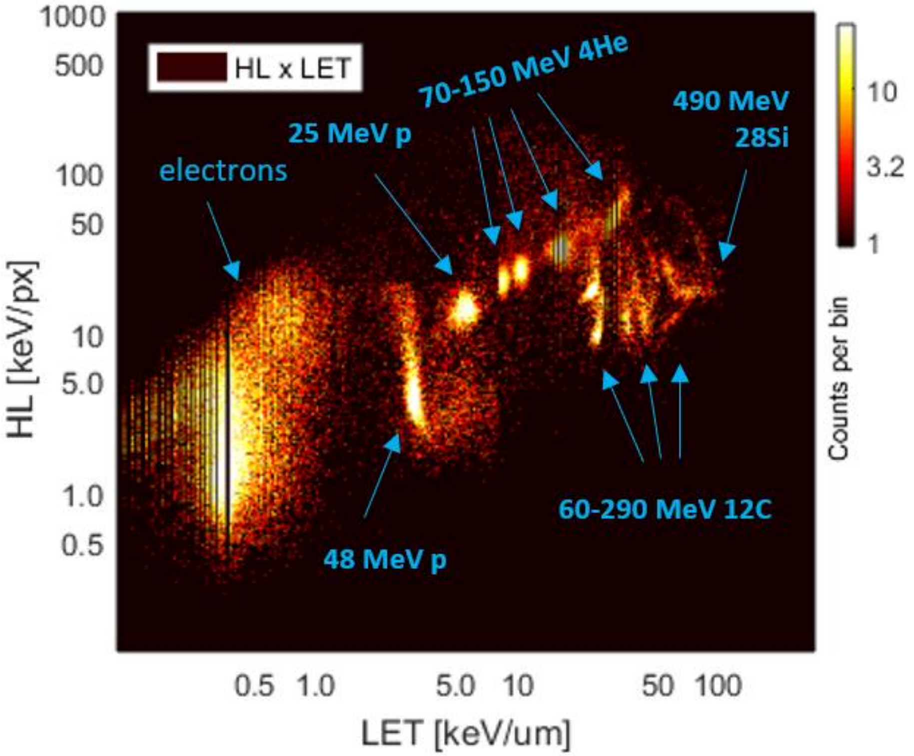
Electrons, protons, ions



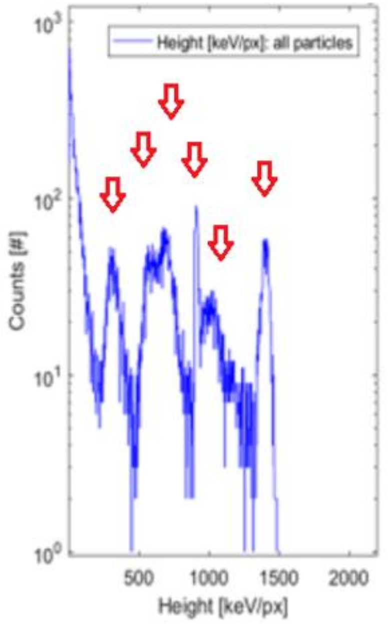
Timepix: Resolving power: particle types + energy loss + direction

ADVACAM
Imaging the Unseen

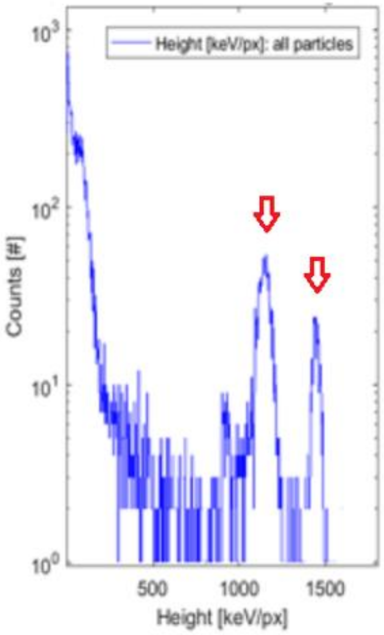
TWO-PARAMETER ANALYSIS
Electrons, protons, ions



^{4}He ions of selected energies between 40-150 MeV/u



^{12}C ions of selected energies between 80-290 MeV/u



MIRAM
Webpage

https://artes.esa.int/projects/miram

ESA | BUSINESS APPLICATIONS | LOGIN | REGISTER

artes

HOME | FUNDING | PROJECTS | CONTRACTORS

Search

MIRAM MINIATURISED RADIATION MONITOR

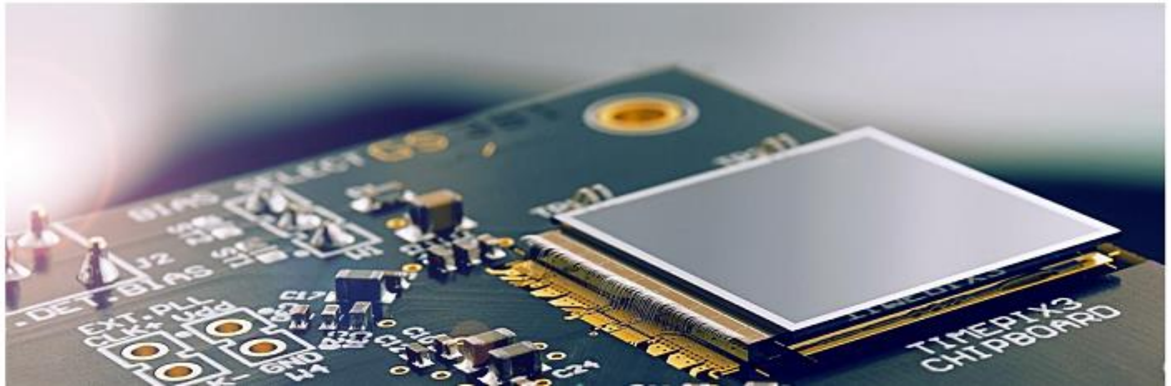
Space Segment - Platform | Core Competitiveness | Advanced Technology

Status: Ongoing **Last updated:** 2018-04-03 00:00:00 **Activity Code:** 4A.070

OBJECTIVES

The objective of the project is to design, develop and test four prototypes of Miniaturised Radiation Monitor (MIRAM) which

- is planned for GEO Telecom satellite missions to monitor the cosmic radiation dose
- is based on pixel detector TimePix,
- is designed for 12-15 years of latch-free operation,
- is small with an order of magnitude reduction in the mass and volume as compared to previous radiation monitors,
- has lower complexity and replaces expensive materials compared to previous solutions,
- has reduced power consumption.



Acknowledgments, ongoing/future work, references I

Future work MIRAM:

- Selection of diodes, selection of Medipix pixel detector (Timepix, Timepix3)
- Continue the model simulations, Al vs Cu shielding, include charge diffusion and repulsion
- Design (3-4Q 2018) and development (1-2Q 2018) of prototype/BB

MIRAM project funded by ESA grant 4000122160/17/UK/ND

References: **Space instrumentation, in-orbit deployments, evaluation of space radiation data**

2017

- Urban M., Nentvich O., Baca T., Daniel V., et al. **VZLUSAT-1**: **Nanosatellite** with miniature lobster eye **X-ray telescope** and qualification of the radiation shielding composite for space application, Acta Astronautica 140 (2017) 96-104.
- Gaza R., Kroupa M., Rios R. et al., Comparison of novel active semiconductor **pixel detector** with passive radiation detectors during the **NASA Orion Exploration Flight Test 1 (EFT-1)**, Rad. Measurements 106 (2017) 290-297.
- Granja C., Polansky S., Vykydal Z., Owens A., et al., The **SATRAM Timepix spacecraft payload** in open space on board the Proba-V satellite for wide range radiation monitoring in LEO orbit, Planetary and Space Science 125 (2016) 114-129
- Gohl S., Bergmann B., Granja, C., Pospisil S., et al., Measurement of **particle directions in low earth orbit with SATRAM-Timepix**, J. of Instrumentation 11 (2015) C11023
- Kroupa M., Bahadori A., Campbell-Ricketts T., et al., A **semiconductor radiation imaging pixel detector for space radiation dosimetry**, Life Sci. Space Res. 6 (2015) 69-78.
- Stoffle, Nicholas; Pinsky, Lawrence; Kroupa, Martin; et al, **Timepix-based radiation environment monitor measurements aboard the International Space Station**, NIM-A 782 (2015) 143-148.
- Granja C., Polansky S., Vykydal Z., Pospisil S., et al., **Quantum Imaging Monitoring and Directional Visualization of Space Radiation with Timepix based SATRAM Spacecraft Payload in Open Space on board the ESA Proba-V Satellite**, IEEE Nucl. Science Symposium Conf. Record (2014)
- Vykydal Z., Holik M., Pospisil S., et al., A Highly **Miniaturized and Sensitive Thermal Neutron Detector for Space Applications**, IX Latin American Nuclear Physics Symposium, AIP Conference Proceedings, Book Series Volume 1423 (2012)
- Turecek, D., Pinsky L., Jakubek J., Pospisil S., et al., **Small Dosimeter based on Timepix** device for **International Space Station**. J. of Instrumentation 6 (2011) C12037
- Urbar J., Scheirich J., Jakubek J., **Medipix/Timepix cosmic ray tracking** on **BEXUS stratospheric balloon flights**, NIM A 633 (2011) S206-S209.

2011

Acknowledgments, ongoing/future work, references II

References: **Timepix instrumentation/methodology, research space-related**

2018

- Stoffle N., Pinsky L., **Identification of stopping ions in a silicon Timepix detector**. Nucl. Instr. Meth. A 880 (2018) 35-39.
- Ballabriga R., Campbell M., Llopart X., **ASIC developments** for **radiation imaging** applications: The **Medipix and Timepix** family, Nucl. Instr. Meth. A 878 (2018) 20-23.
- Burian P., Broulim P., Georgiev V., Pospisil S.; et al., **Particle telescope with Timepix3 pixel detectors**, J. of Instrumentation 13 (2018) C01002
- Granja C., Jakubek J., Polansky S., et al., **Resolving power of Pixel Detector Timepix for Wide-Range Electron, Proton and Ion Detection**, Nucl. Instr. Meth. A (2018) *submitted*
- Kroupa M., Bahadori A., Campbell-Ricketts T.; et al., **Kinetic energy reconstruction with a single layer particle telescope**, Appl. Phys. Lett. 112 (2018) 134103
- Bergmann B., Pichotka M., Pospisil S., et al., **3D track reconstruction** capability of a **silicon hybrid active pixel detector**, Eur. Phys. J. C77 (2017) 421.
- Kroupa, M.; Campbell-Ricketts, T.; Bahadori, A.; et al., Techniques for precise **energy calibration of particle pixel detectors**, Rev. Sci. Instr. 88 (2017) 033301.
- Granja C., Pospisil S., **Quantum imaging dosimetry** and **online visualization of X-ray and charged particle radiation** in **commercial aircraft** at operational flight altitudes with the **pixel detector Timepix**, Adv. Space Res. 54 (2014) 241-251.
- Asbah N., Leroy C., Pospisil S., et al., Measurement of the efficiency of the **pattern recognition of tracks** generated by **ionizing radiation in a TIMEPIX** detector, Journal of Instrumentation, 6 (2014) C05021, pp. 1-10.
- Heijne E.H.M., Ballabriga R., Campbell M., et al., **Measuring radiation environment in LHC or anywhere else**, on your computer screen with **Medipix**, Nucl. Instr. Meth. A 699 (2013) 198–204.
- Granja C., Chvatil D., Pospisil S., Jakubek J., et al. **Energy loss and online directional track visualization** of fast electrons with the **pixel detector Timepix**, Rad. Measurements 59 (2013) 245-261.
- Stoffle N., Pinsky L., Hoang, S., Jakubek J., et al. Initial results on **charge and velocity discrimination for heavy ions using silicon-Timepix detectors**, J. of Instrumentation 7 (2012) C12009

2006

- Z. Vykydal, J. Jakubek, T. Holy, S. Pospisil, A **portable pixel detector** operating as an **active nuclear emulsion** and its application for X-ray and neutron tomography, Proc. 9th Conf. on astroparticle, particle and space physics, detectors and medical applications, Como, World Scientific (2006) 779–784

Patent: **Timepix instrumentation/methodology/know-how, research space-related**

- Heijne Erik and Pospisil Stanislav, Method, apparatus and computer program for measuring the dose, dose rate or composition of radiation, CERN/CTU in Prague, US Patent 8,168,953, May 1, 2012