Development of Depleted Monolithic Active Pixel Sensors (DMAPS) for Dosimetry in Space

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The MIDAS device

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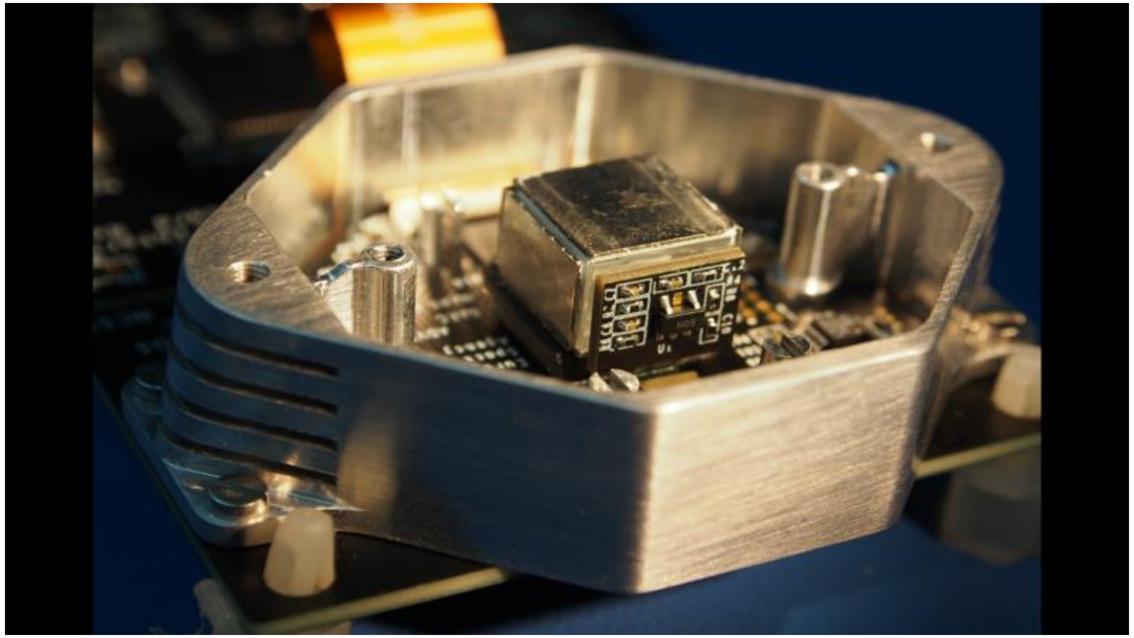
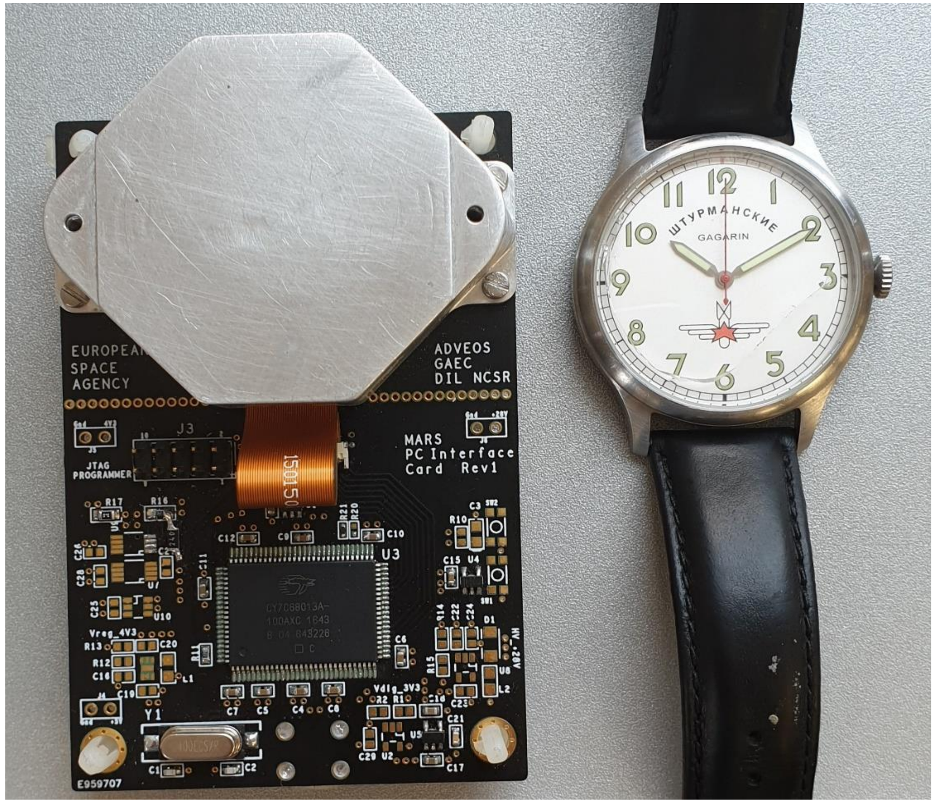
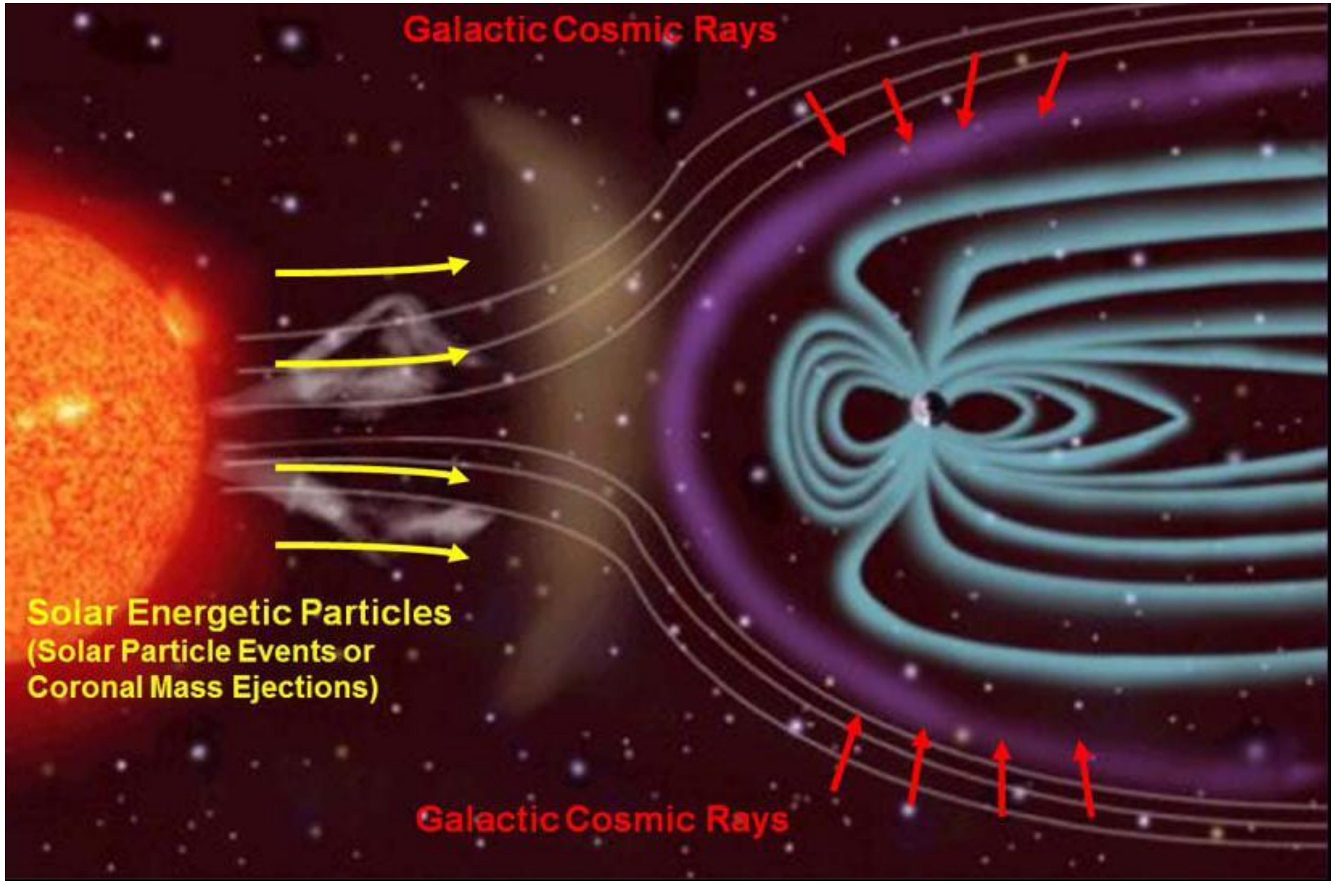
The MIDAS Device is developed in the context of a Technology Research Project funded by the European Space Agency under the contract 4000119598/17/NL/LF for a "Highly miniaturized ASIC radiation detector"





Radiation fields - dosimetry in Space



NASA/JPL-Caltech/SwRI - http://photojournal.jpl.nasa.gov/jpeg/PIA16938.jpg

Quantities to be measured are radiation fluence rates, the energy distributions of different types of particles, and linear energy transfer (LET) distributions.

One may either assess the radiation field parameters near to an astronaut and then apply fluence to dose conversion coefficients for all types of particles involved for the assessment of organ doses,
or
one may calculate organ doses in a body using the radiation field data outside of the spacecraft and a code that combines radiation transport into the spacecraft and into the human body.

Excerpt from ICRP Publication 123, Ann. ICRP 42(4), 2013

Quantities to be determined

effective dose equivalent, H_E

$$H_E = \sum_T w_T \cdot H_{T,Q}$$

Sum over all tissues T,
w_T tissue weighting factors defined in ICRP publication 103

Dose equivalent, $H_{T,Q}$

$$H_{T,Q} = Q_T \cdot D_T$$

Q_T : tissue quality factors defined in ICRP publication 123; parameterize the relative biological effectiveness of the high LET radiation
D_T : Dose to tissue

ICRP publication 123 gives tables of dose to fluence conversion factors as a function of tissue type, particle type and energy

ESA requirements and proposal to cope with them

Sensitivity to protons, neutrons and heavy ions:

✓Protons: 2 to 200 MeV

✓Neutrons: 0.1 to 200 MeV

✓LET: $5 \cdot 10^{-4}$ to 10 MeV cm^2/mg

Important Top-Level requirements:

✓volume <50 x 50 x 10 mm3

✓Mass < 50 g

✓Device autonomous operation for 30 days

✓Dose, Dose rate, Dose equivalent, LET spectra

Goal

a device whose size, power consumption and radiation data output will increase the level of crew autonomy as far as it concerns operational decisions related to radiation hazards

Our Proposal was

To construct a "sensitive cube" capable to register:

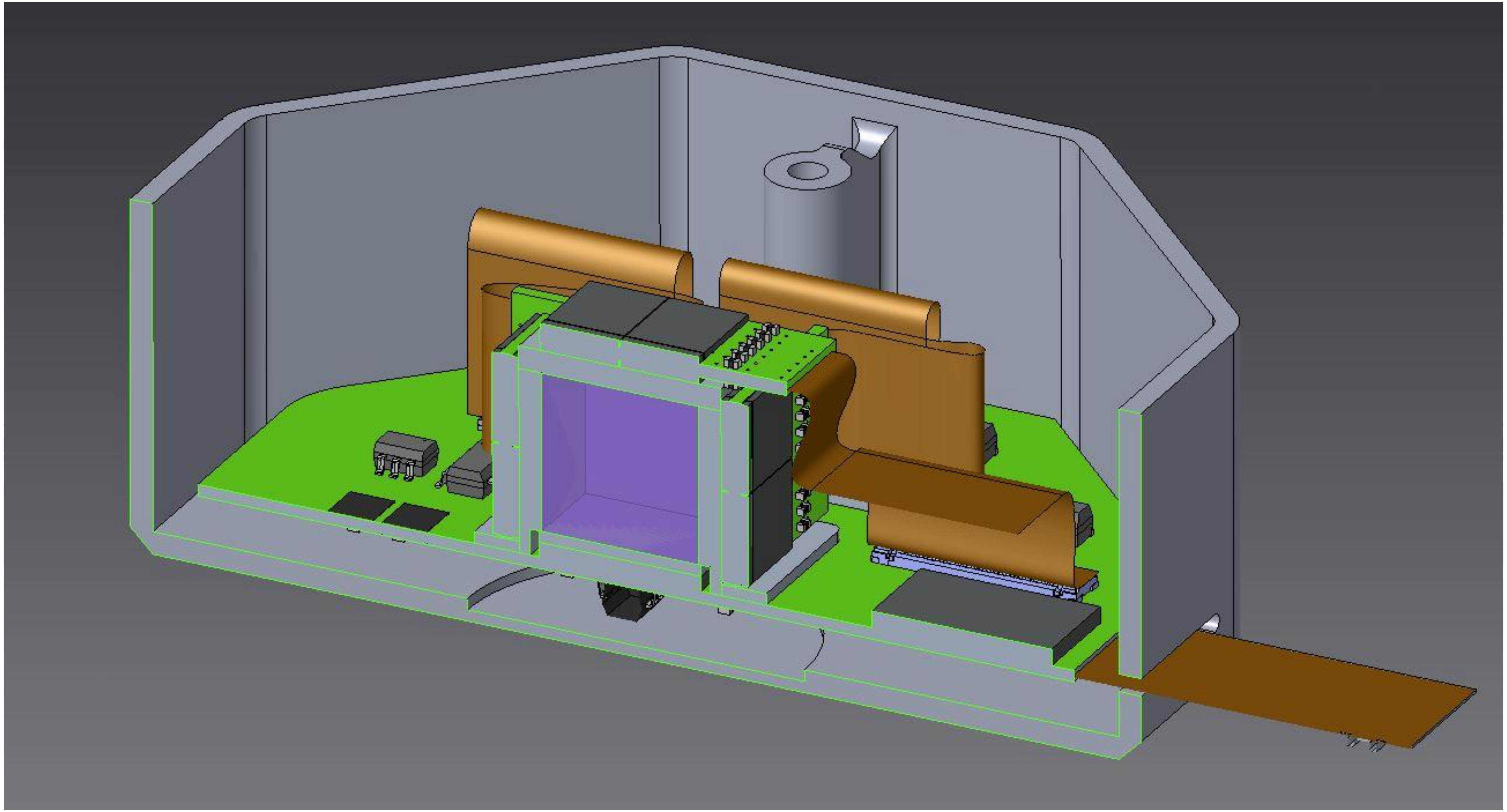
energy depositions by charged particles and neutrons coming from all directions

Direction of charged particle track

To infer the particle type and energy from their energy depositions

To calculate dose equivalent either by using the particles identity or their Linear Energy Transfer

The device concept



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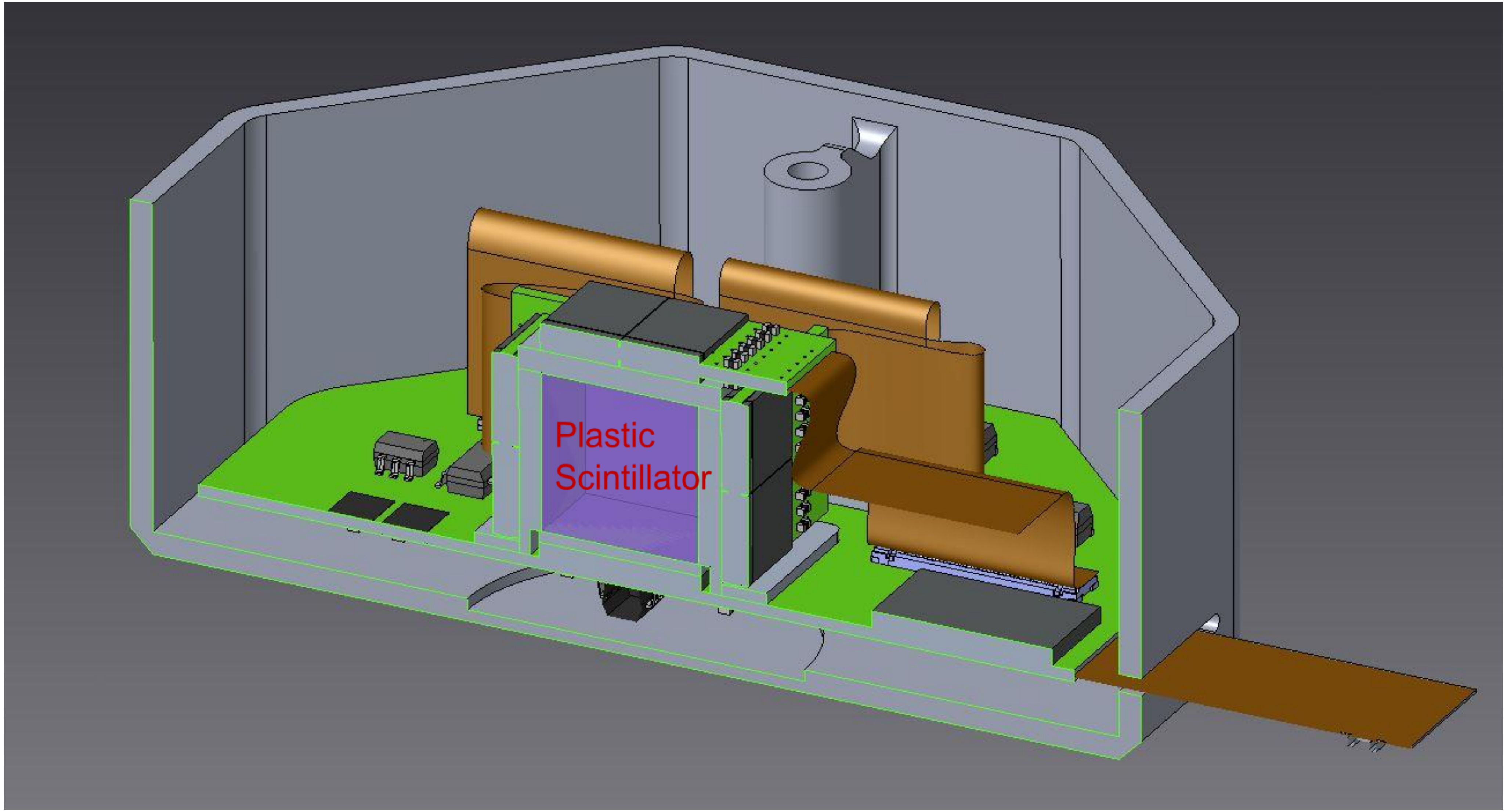
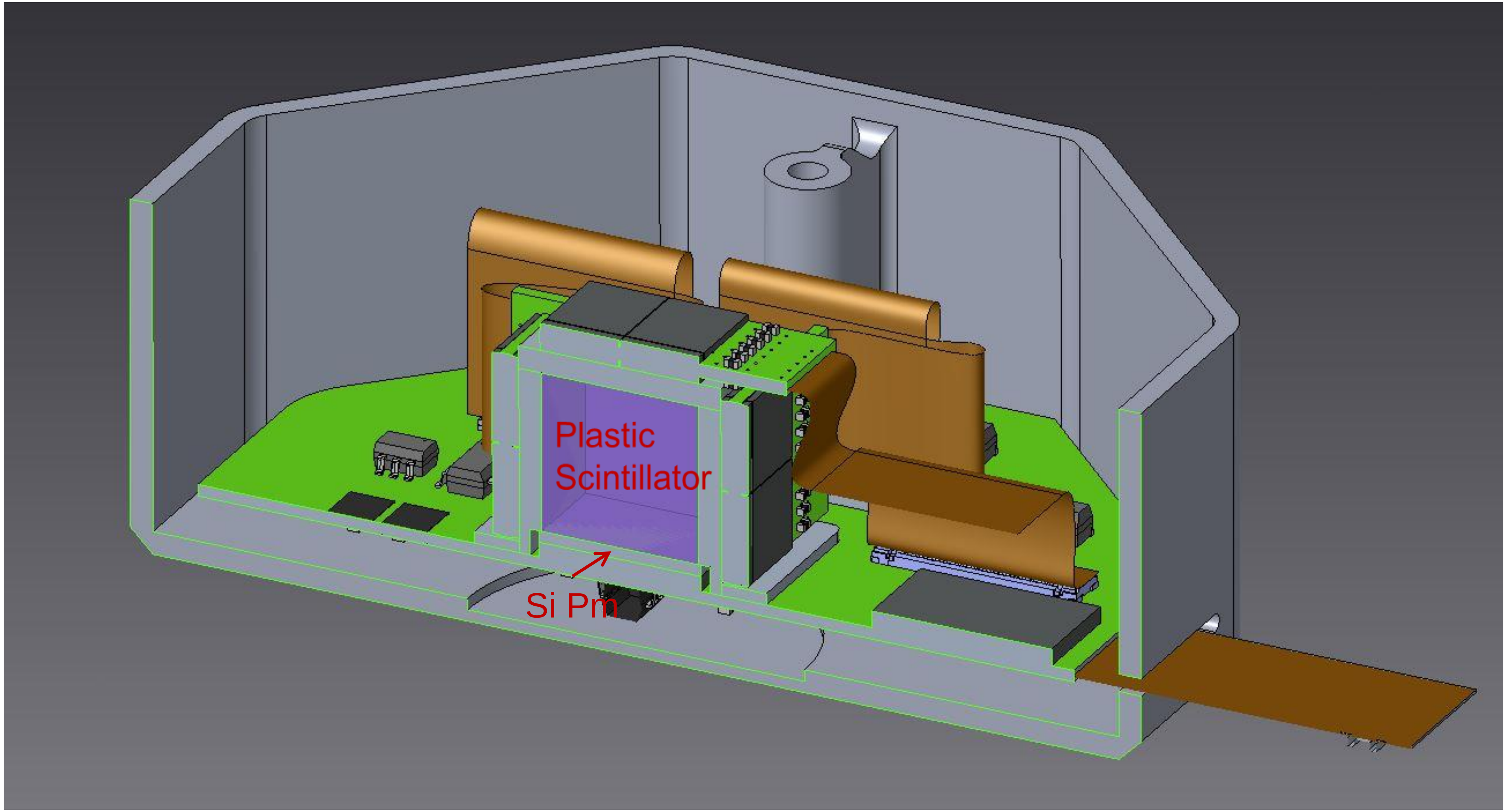
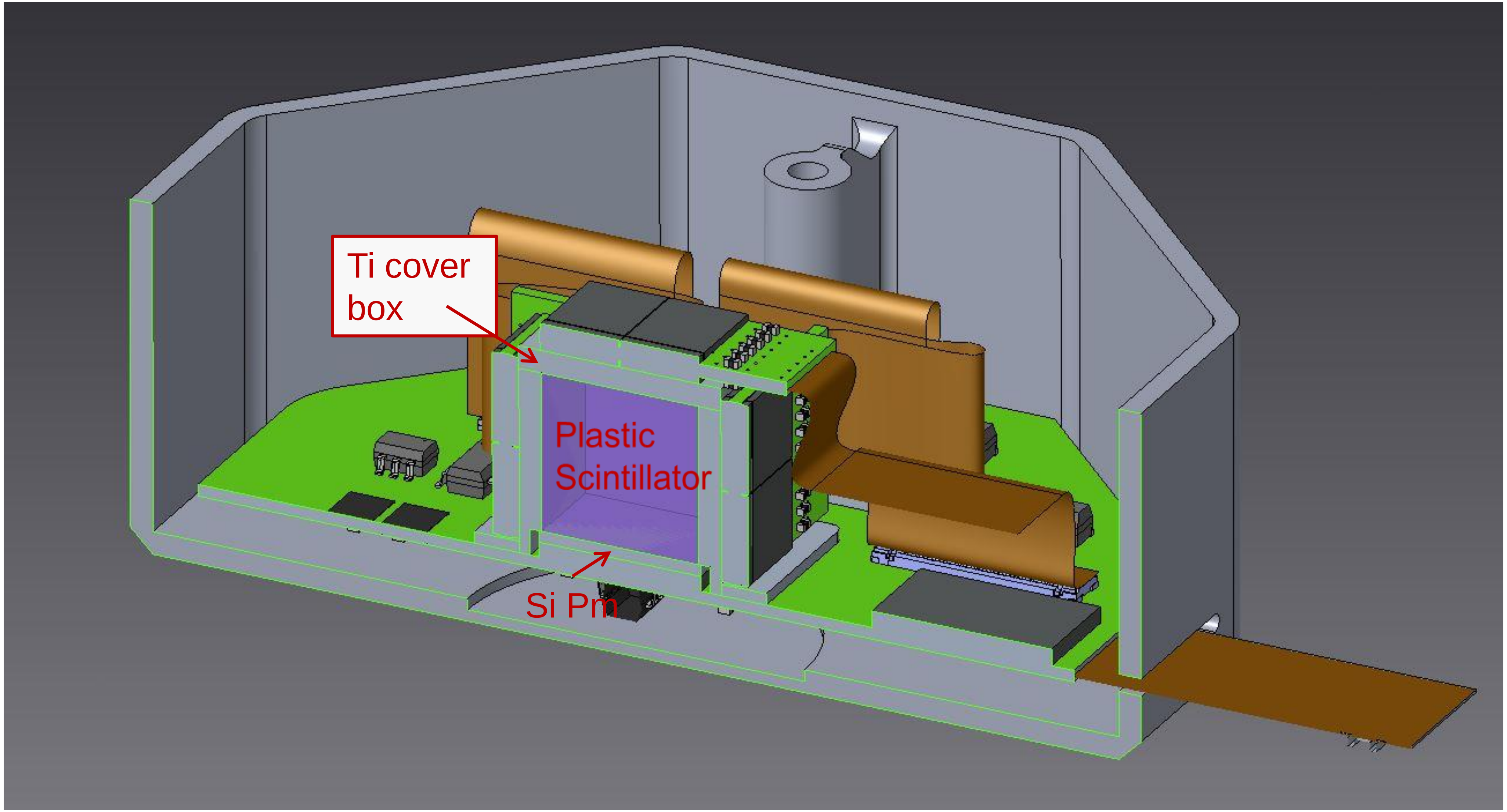


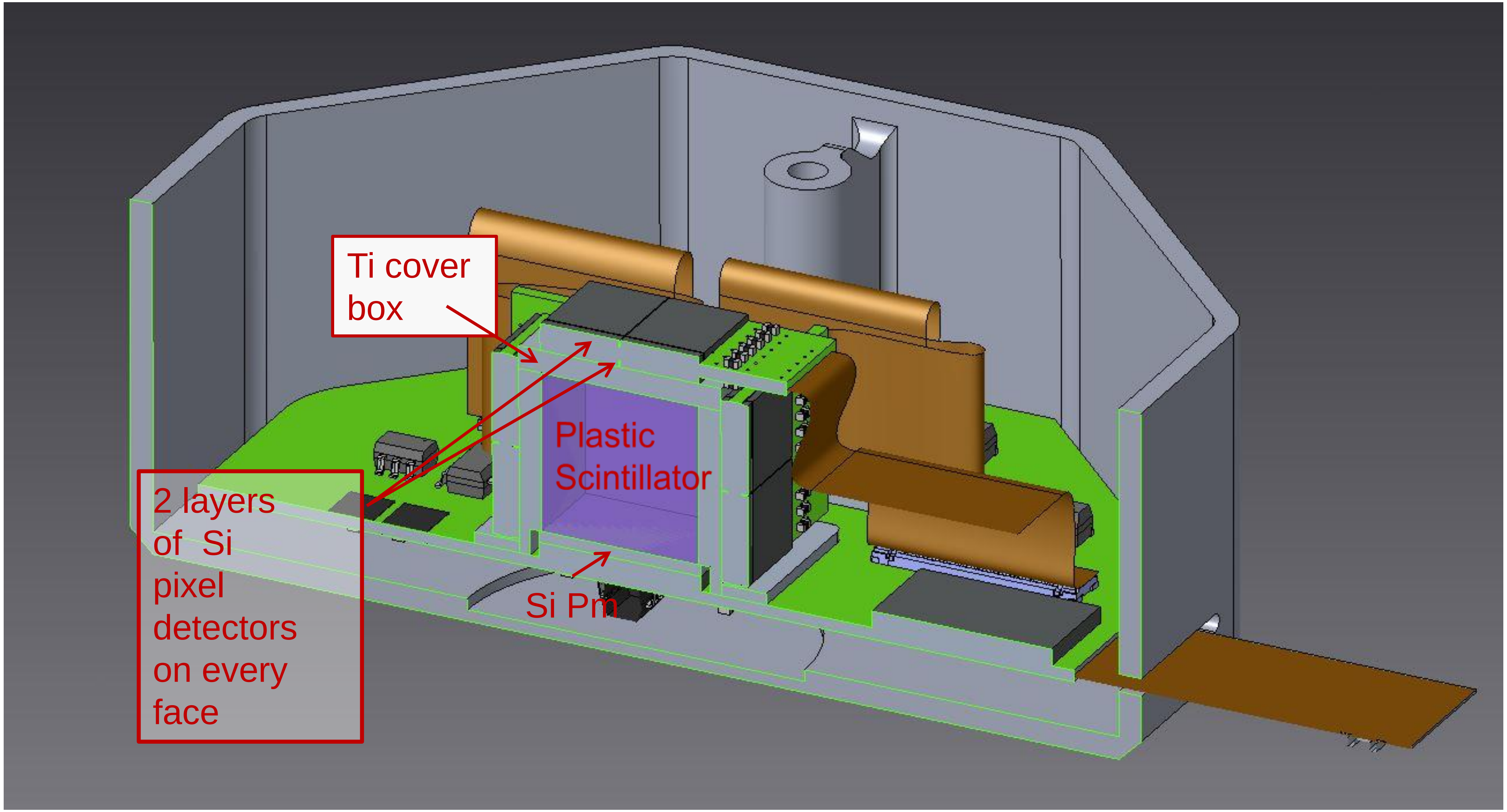
The device concept



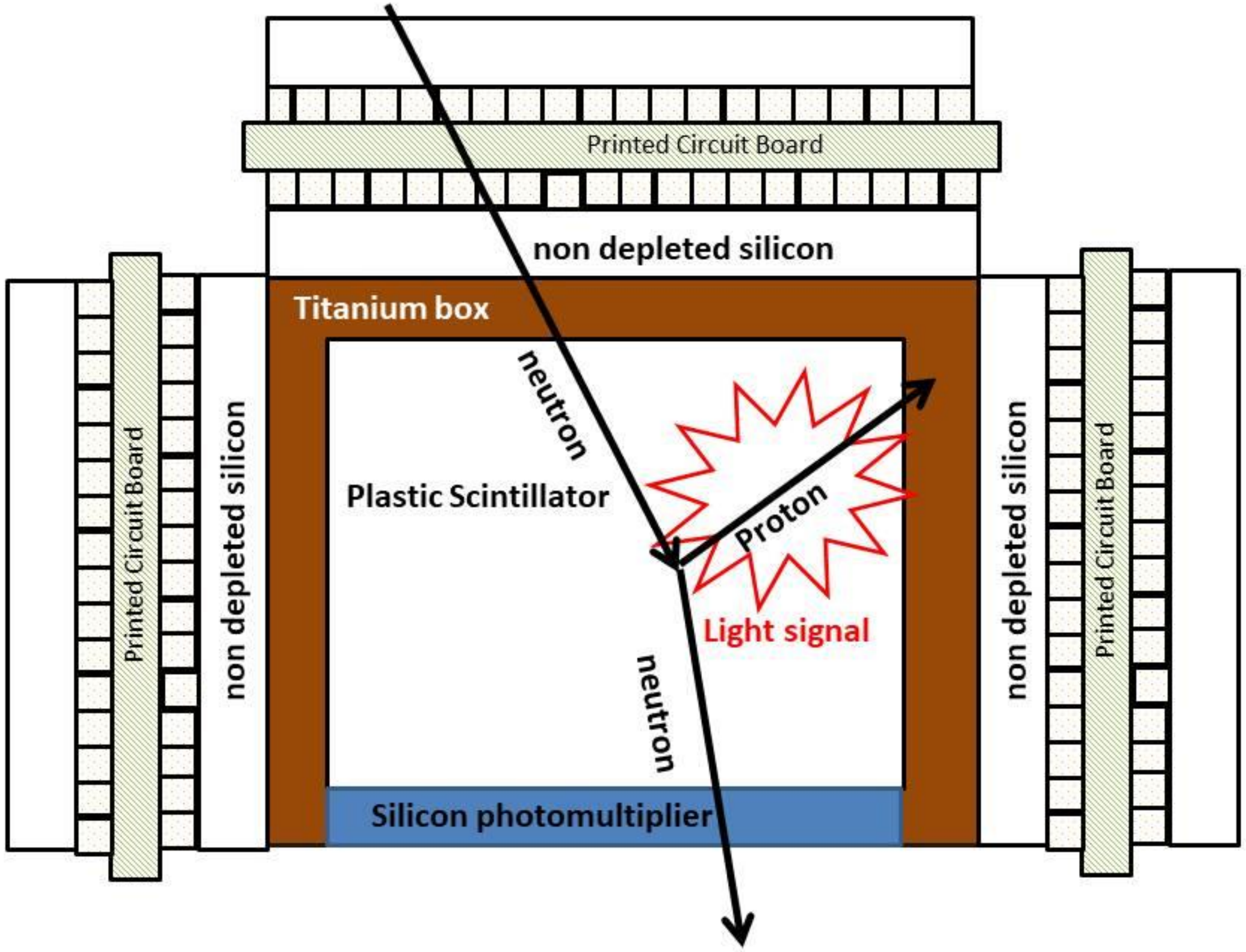
The device concept



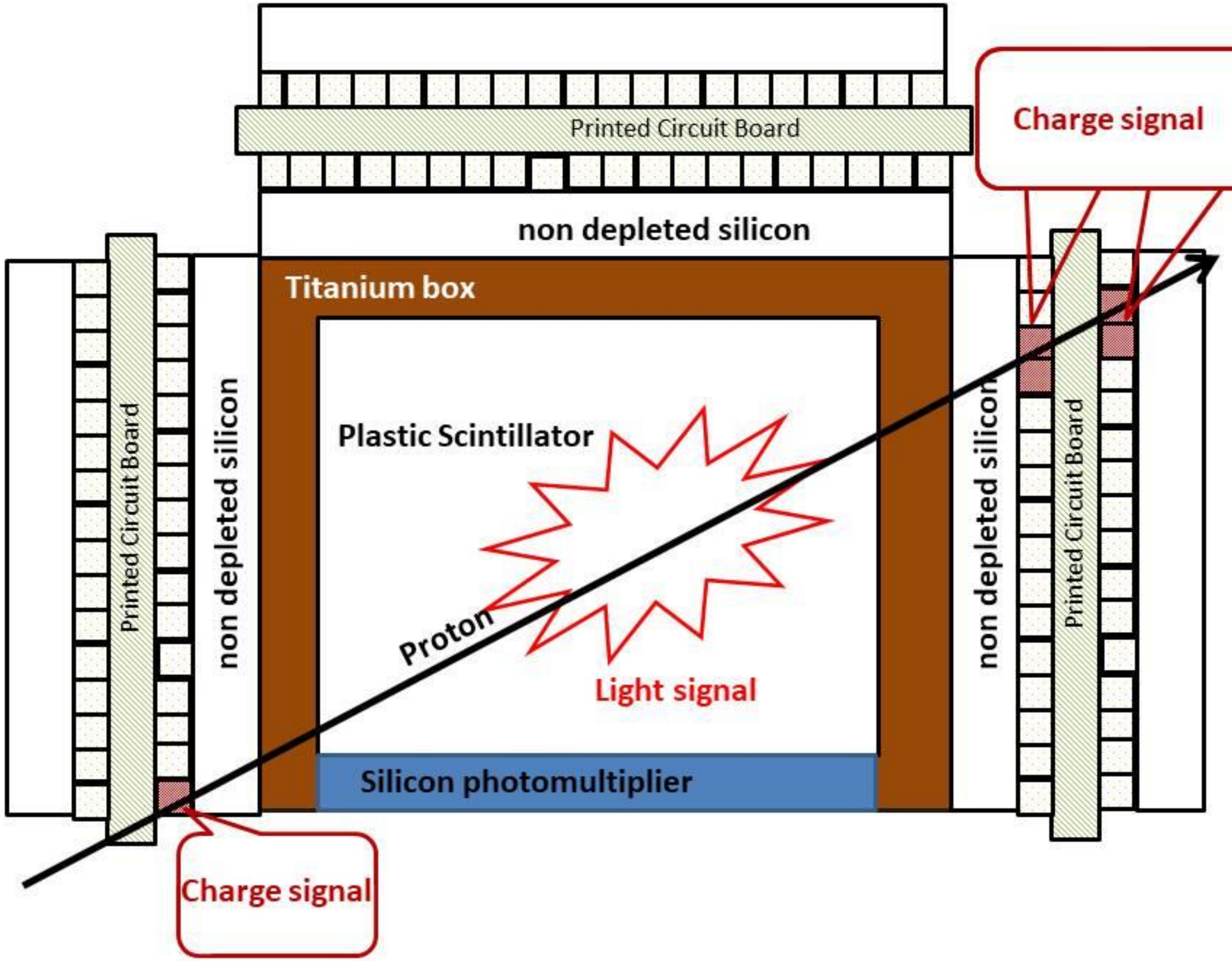
The device concept (I)



The device concept



The device concept



Charged Particles Measurement Specifications

- ✓ Detect protons from 2 to 200 MeV
- ✓ Dynamic Range for LET spectrum measurement from $5 \cdot 10^{-4}$ MeV·cm^2/mg to ≥10 MeV·cm^2/mg
- ✓ Battery operation for … 30 days

Translation:

The minimum detectable charge should come from the deposited energy in Si by minimum ionizing protons:

dE/dx 0,387 KeV/μm × **Depletion depth** 50μm × **Landau distribution** 0,7 × **Conversion to charge** = **0,598 fCb**

Design target: 0.5 fCb

(1/ρ)*dE/dx 10 MeV·cm^2/mg × **Depletion depth** 50μm × **Conversion to charge** = **5,2 pCb**

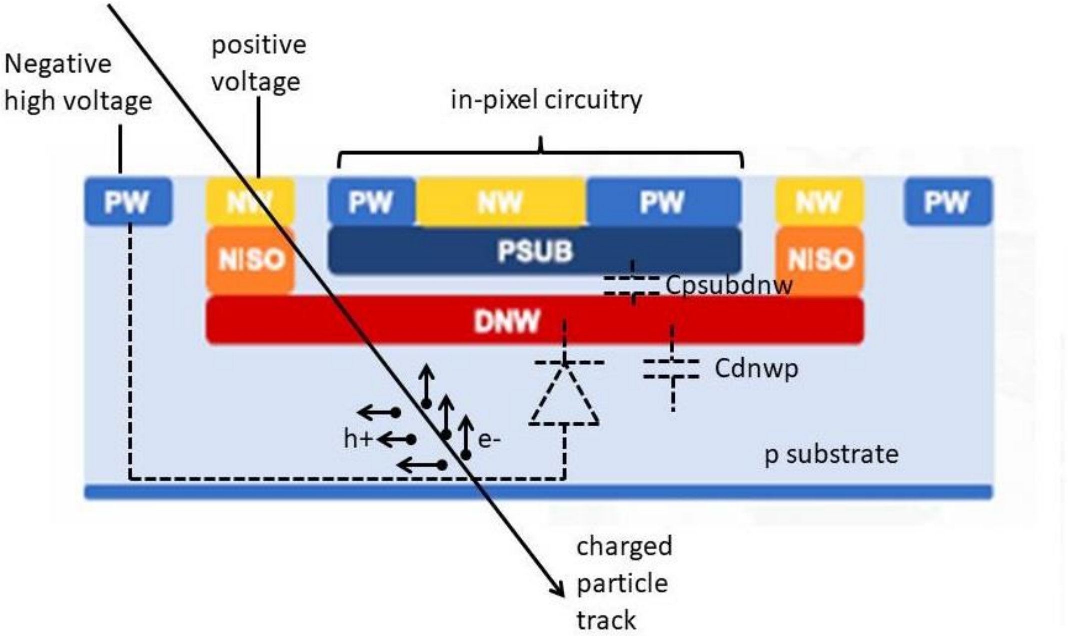
Design target: 6 pCb

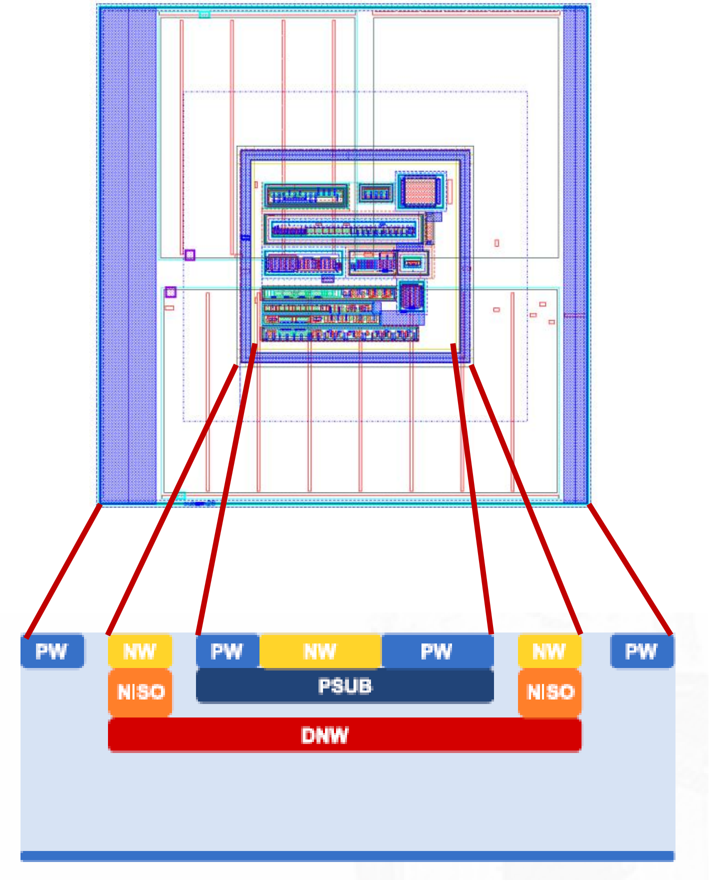
Power consumption: Even a target of 10mW/cm^2 is a big challenge

Count rate: 10000 cm^{-2} ·s^{-1} means 1 count /s for an area of 100 x 100 μm^2

Technology proposed:

Principle of operation illustrated
in the manufacturer technology chosen:

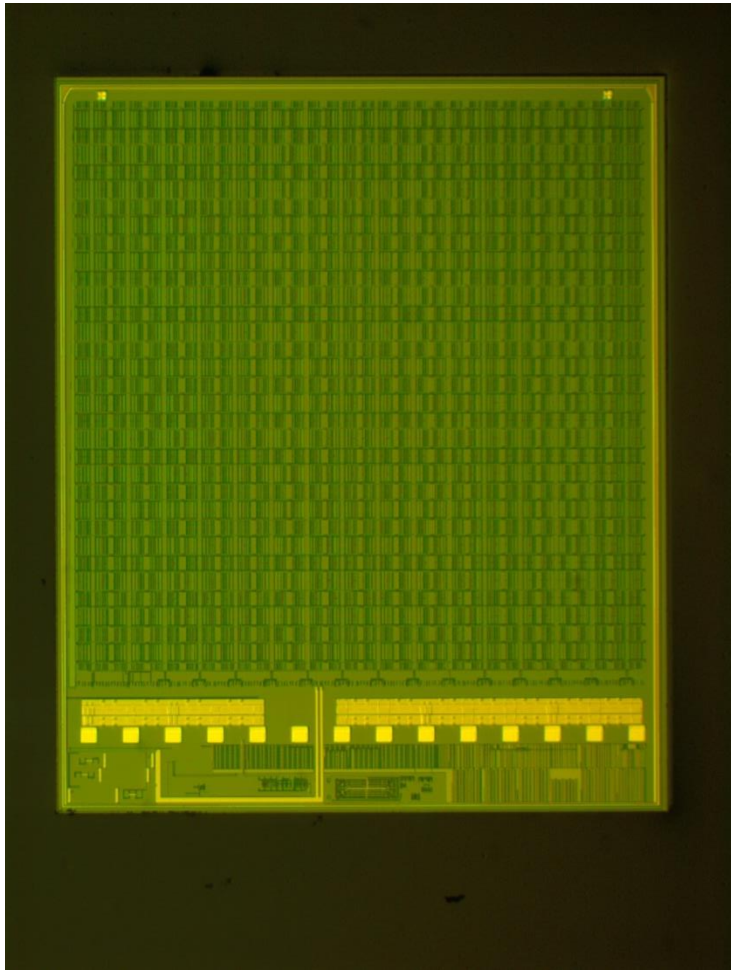




The MIDAS chip

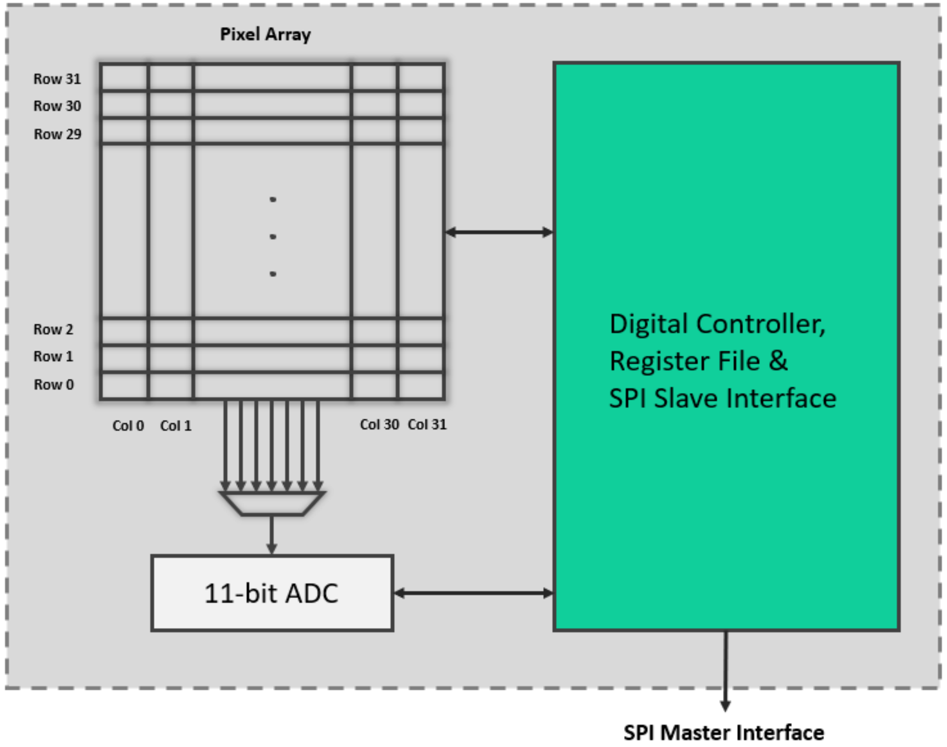
Summary of Characteristics	
Chip dimensions	4290 x 3550 um
Pixel array size	32 x 32
Pixel pitch in x	100.5um and 110.5um alternatively
Pixel pitch in y	105.91um
Charge dynamic range	0.5fCb to 6pCb
High gain - range	0.884 mV/fCb - 0.5fCb to 1.2pCb
Low gain - range	0.179 mV/fCb - 0.5fCb to 6pCb
Power supply	1.8V
Power consumption	<10mW
Readout mode	*Normal*: only hit pixels are read *Full array*: all pixels are read *Single pixel*: a chosen pixel is read
Digitization	11 bits on chip SAR ADC
Readout interface	SPI
Readout time per pixel	600 ns with 12 MHz clock

Die photo

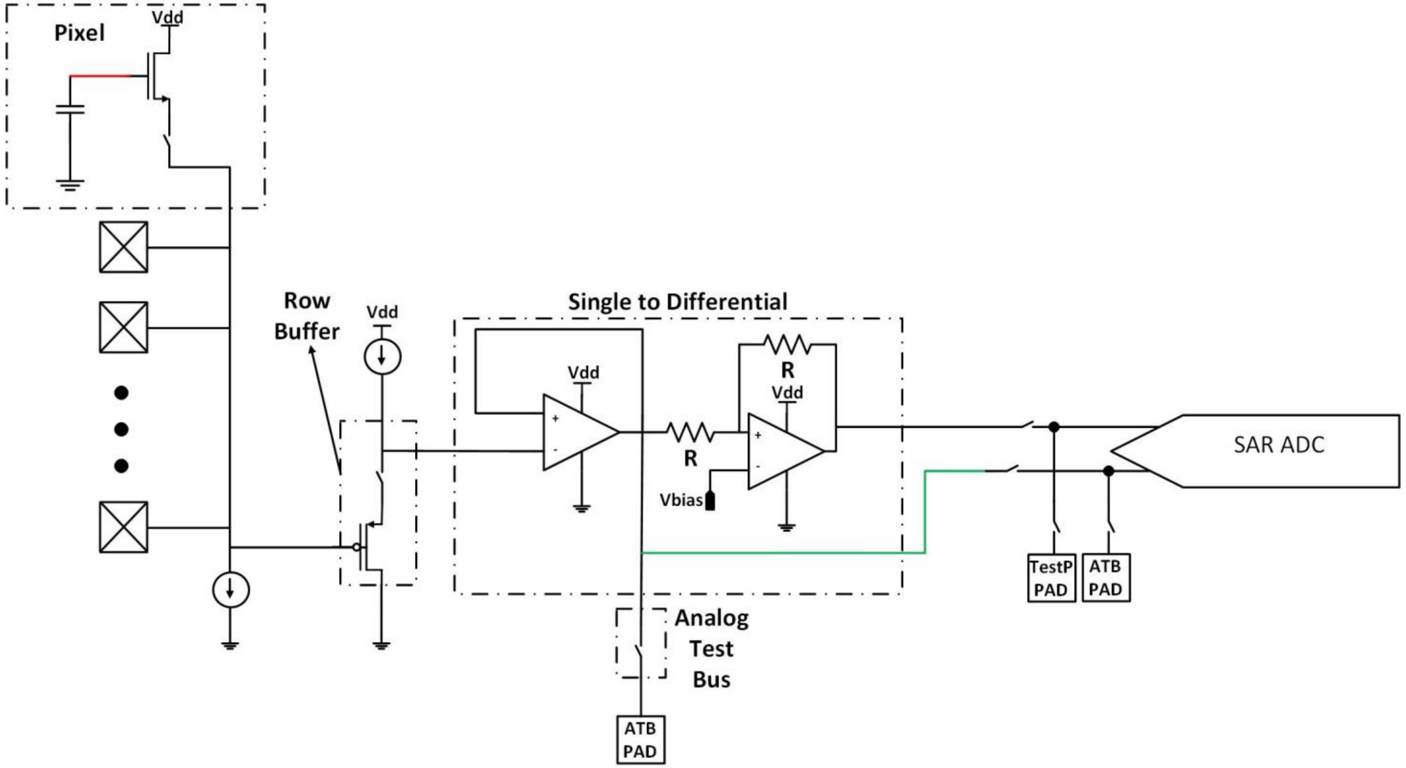


Architecture

Architecture-block diagram

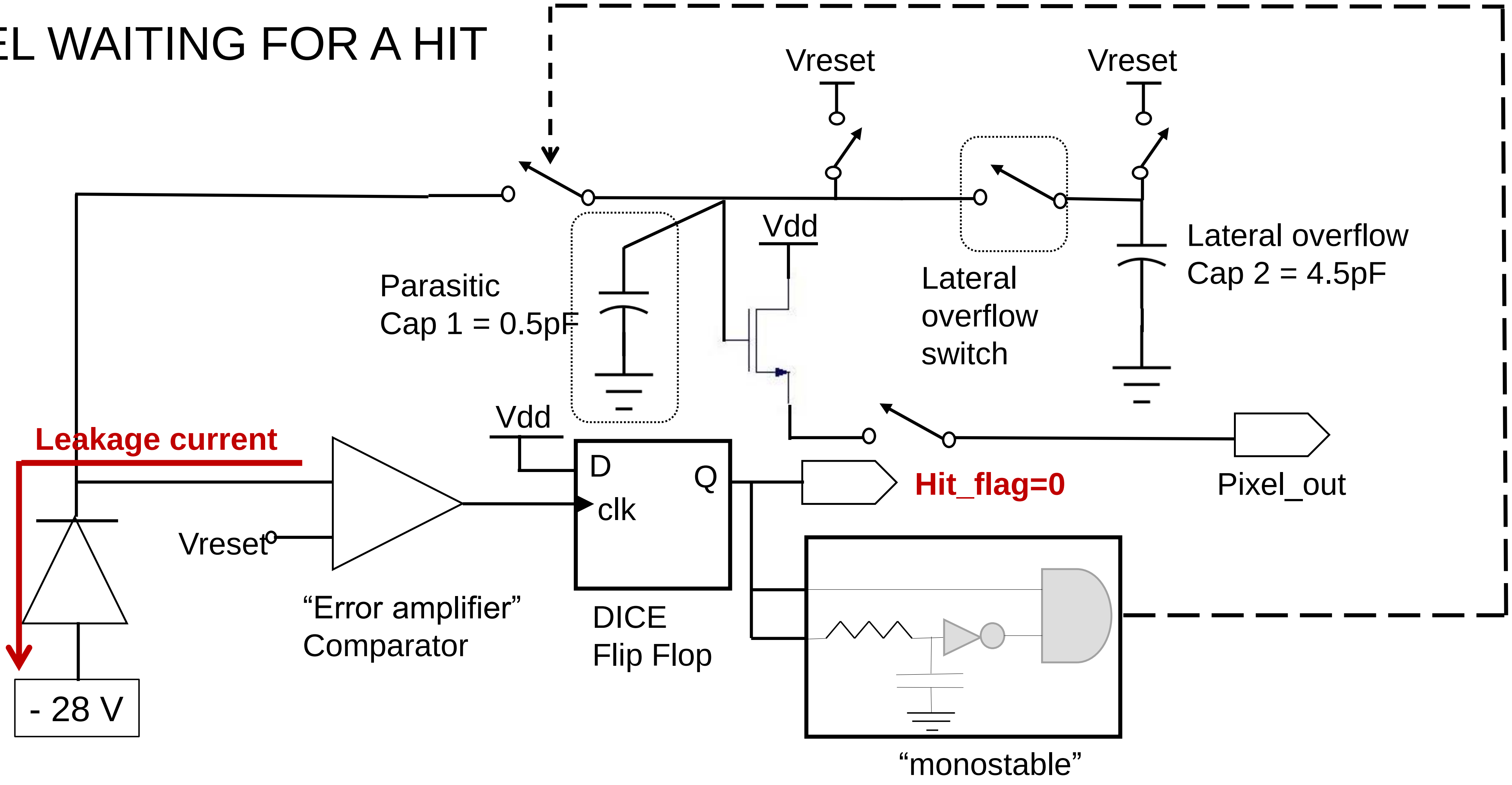


Signal readout chain



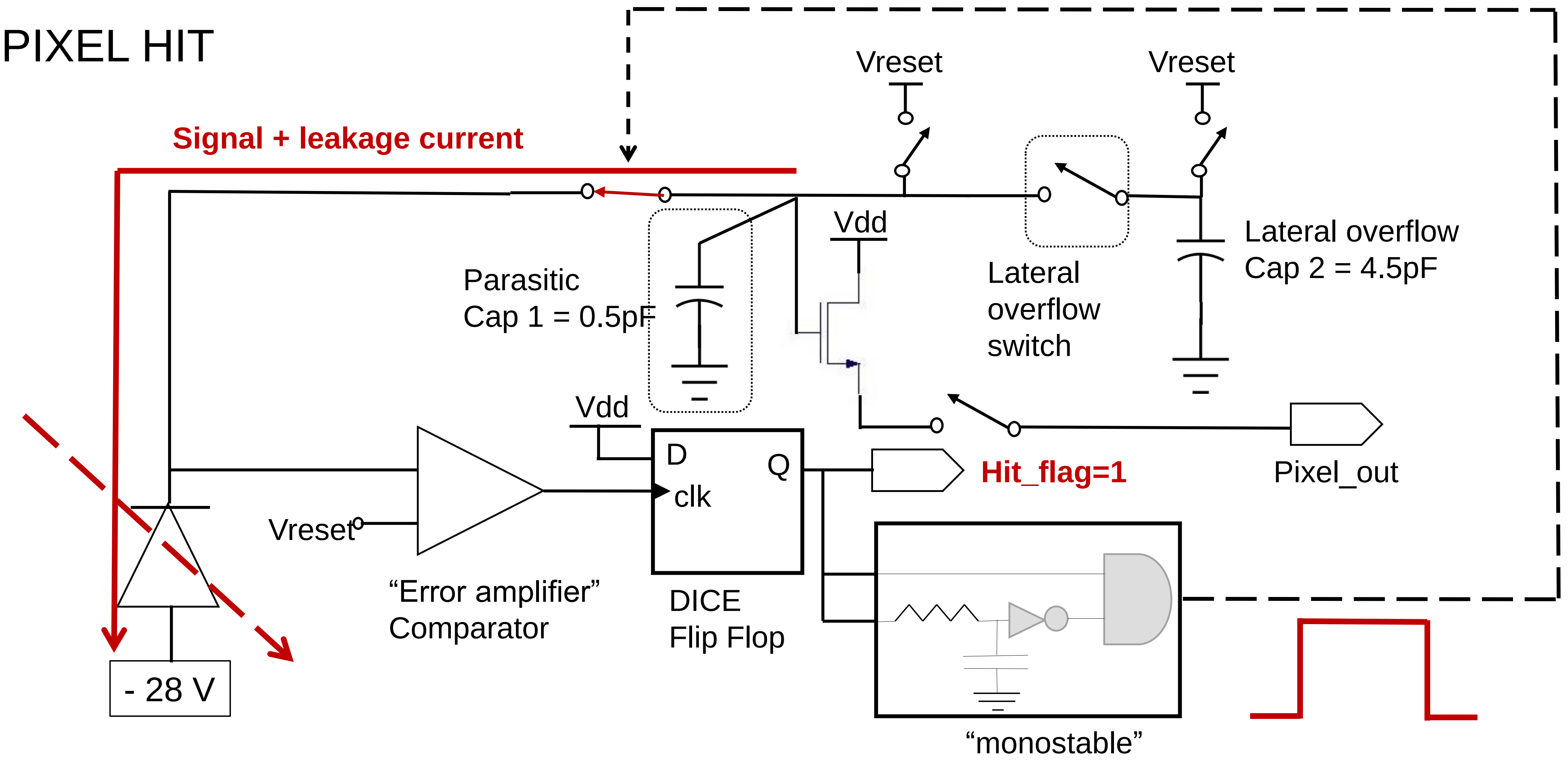
Pixel operation explained

PIXEL WAITING FOR A HIT



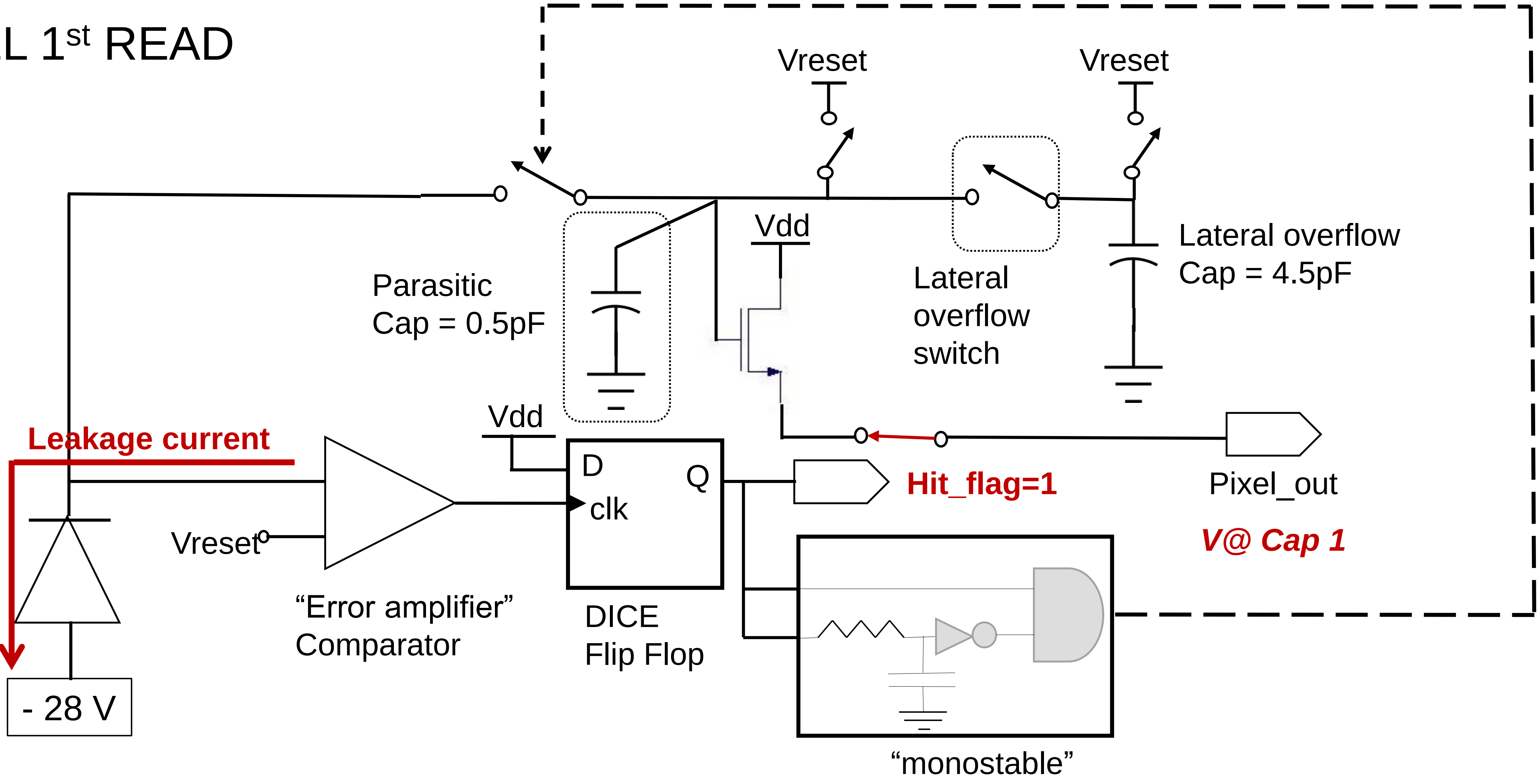
Pixel operation explained

PIXEL HIT



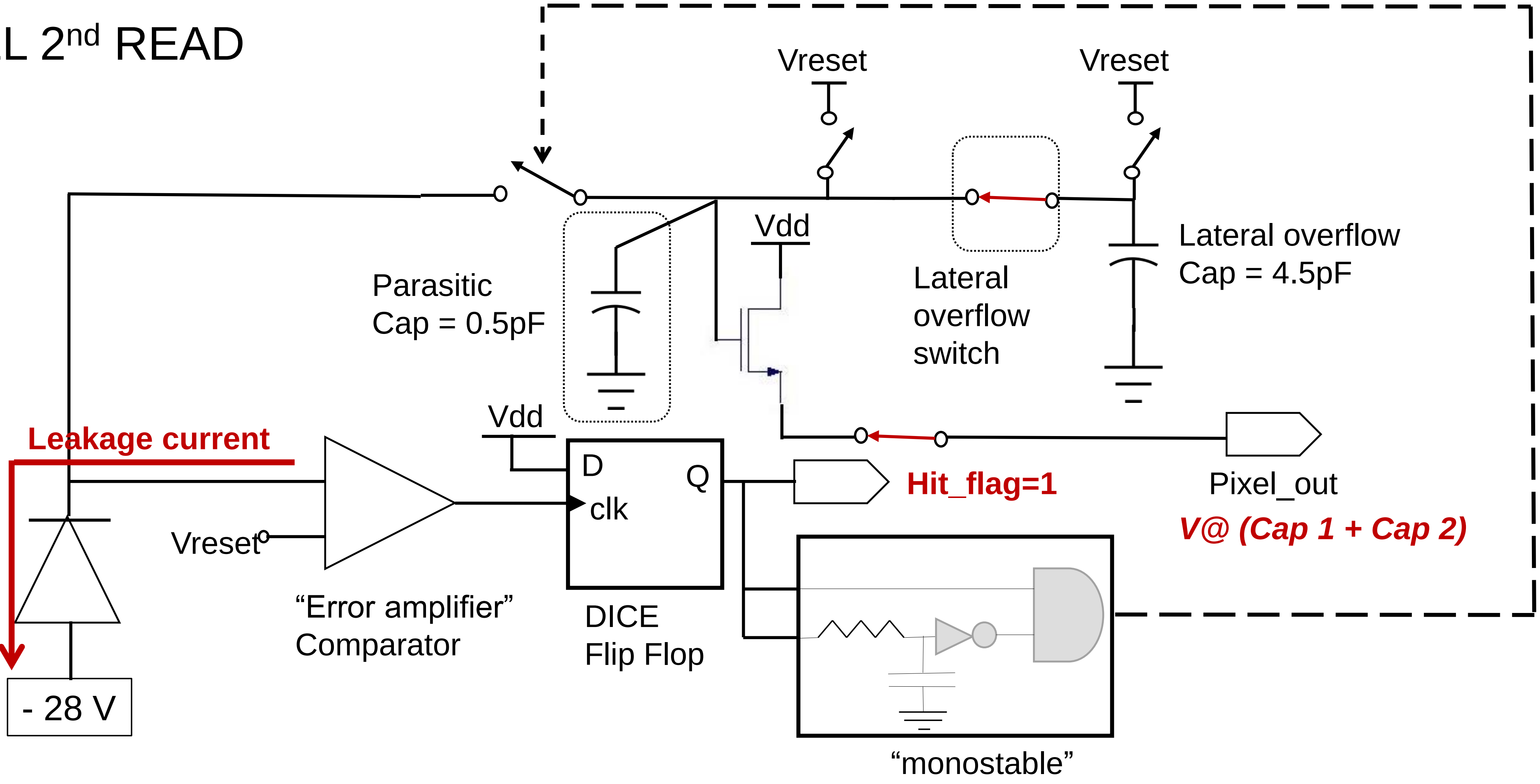
Pixel operation explained

PIXEL 1st READ



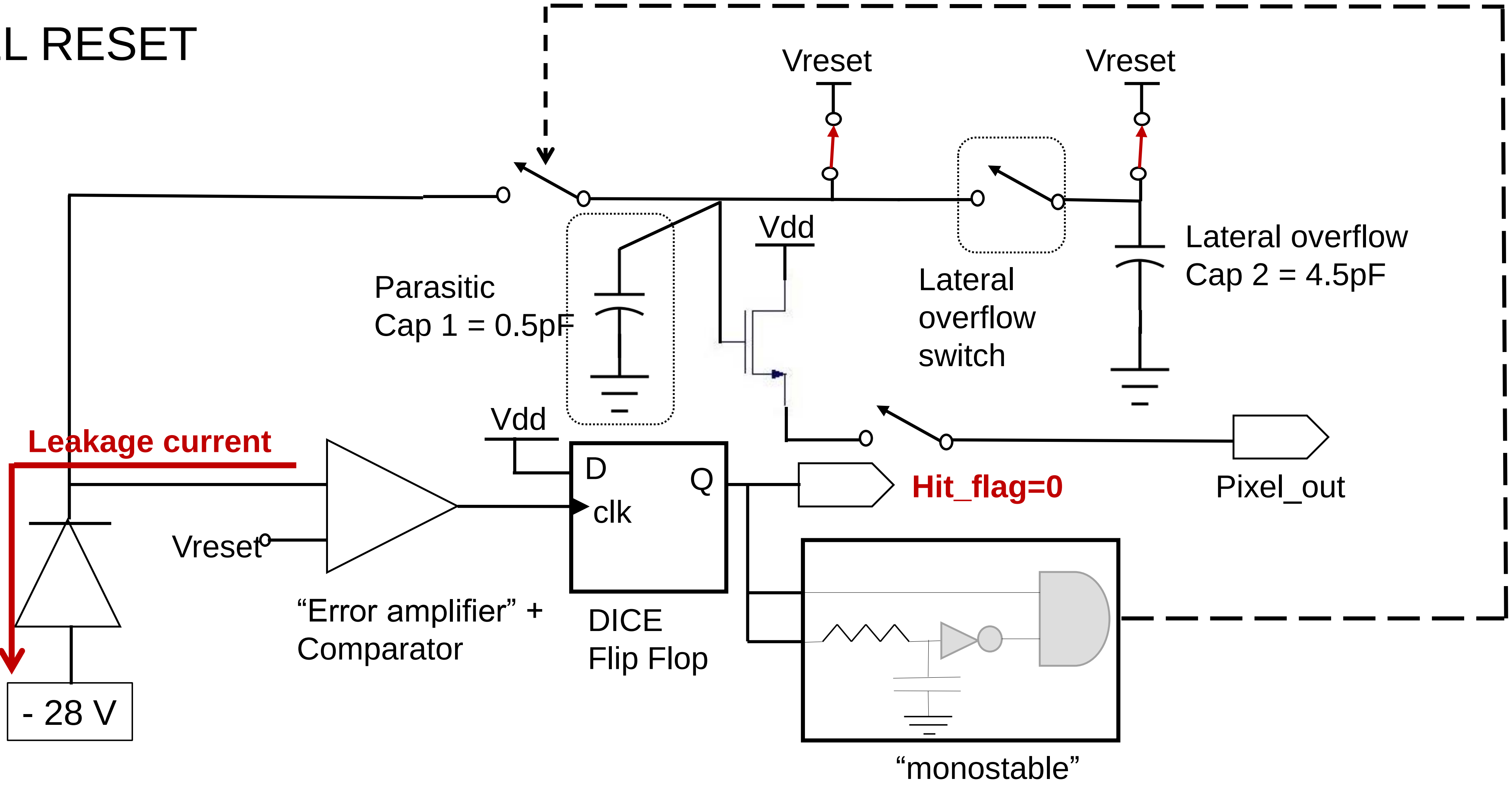
Pixel operation explained

PIXEL 2nd READ

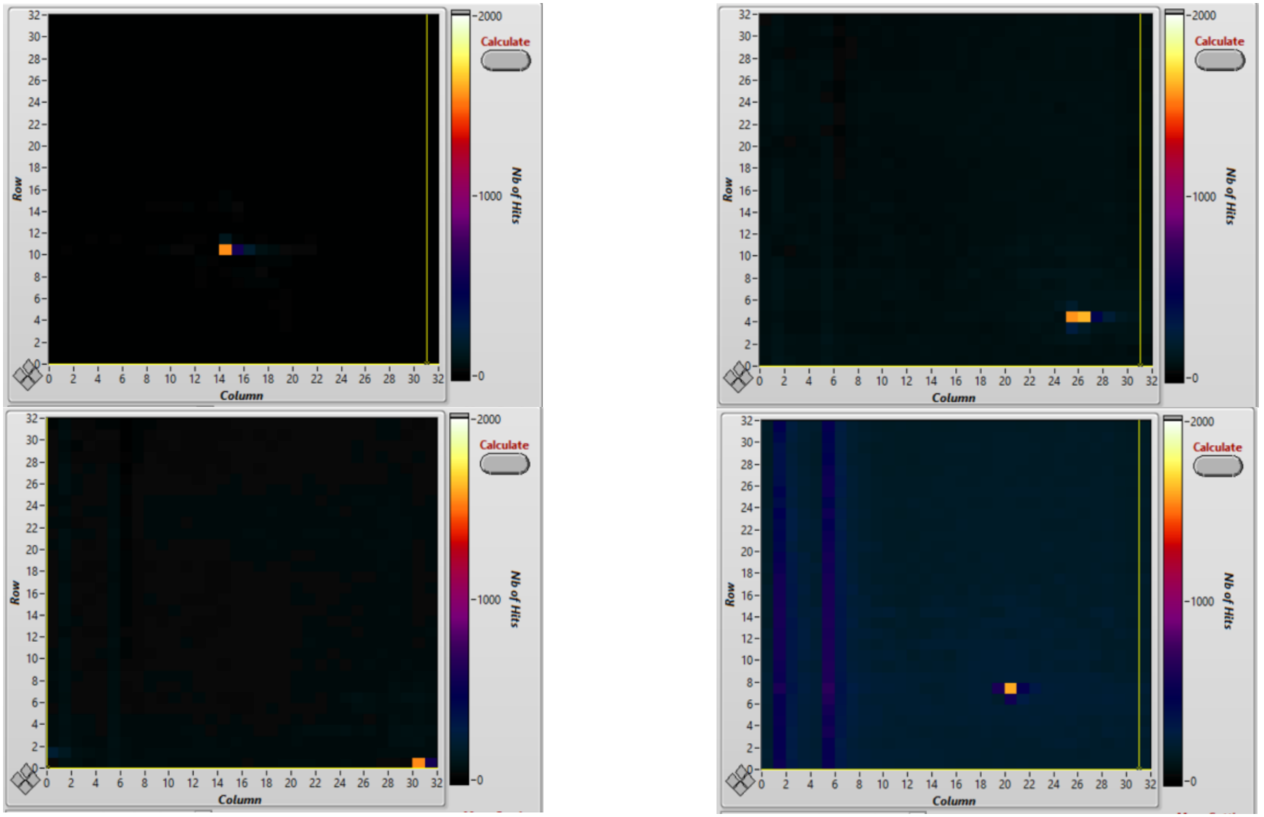


Pixel operation explained

PIXEL RESET

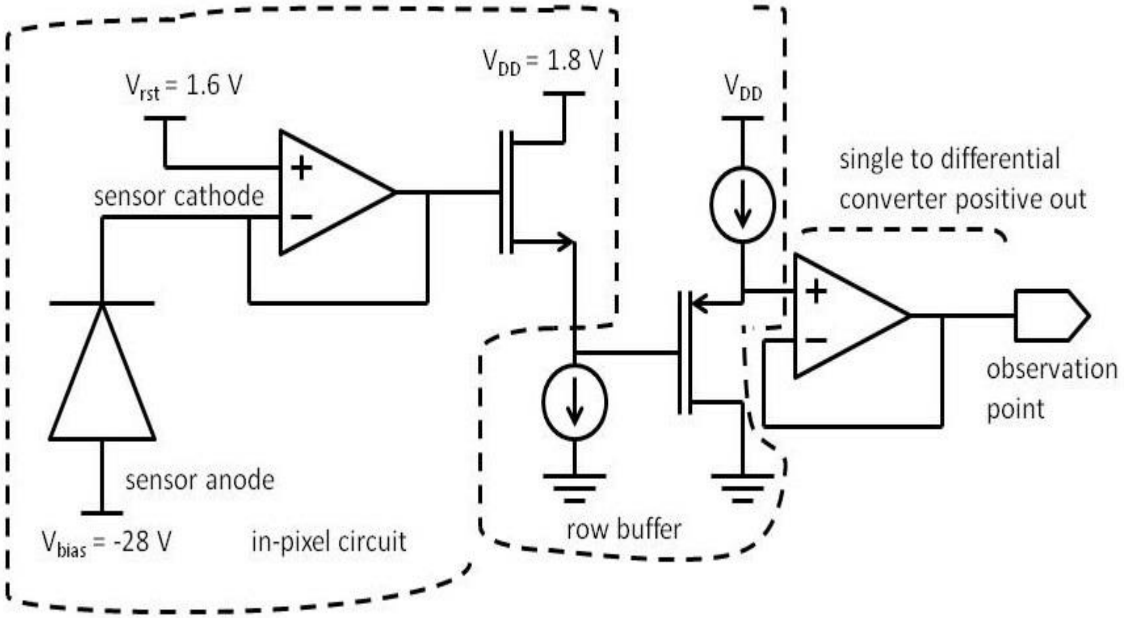


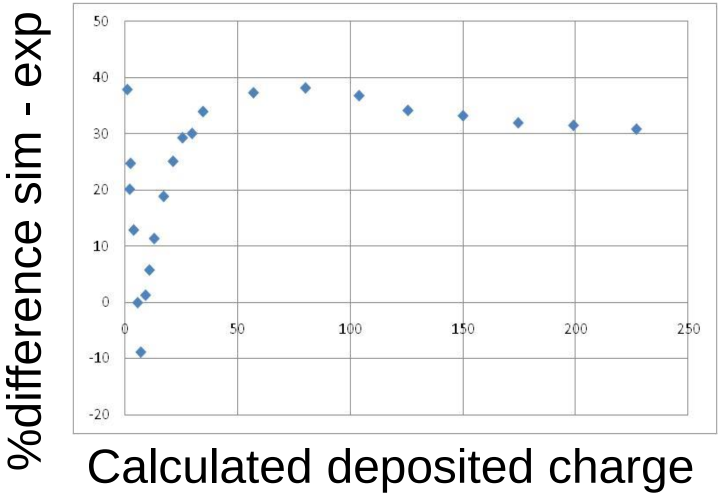
First measurements

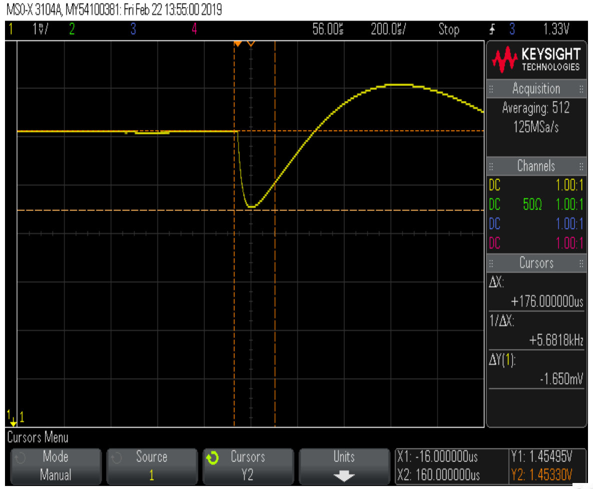


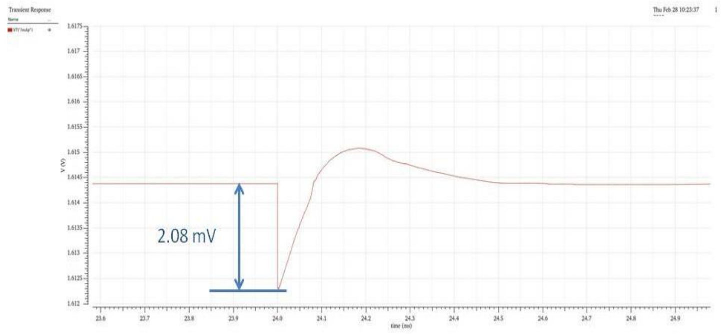
The x-y axes are the pixels and the colour scale is the difference of ADC values of the pixel output with illumination from the ADC value without illumination. Non illuminated pixels give a 0 difference. The bottom right figure shows a vertical zone pattern which appears right after HV is applied

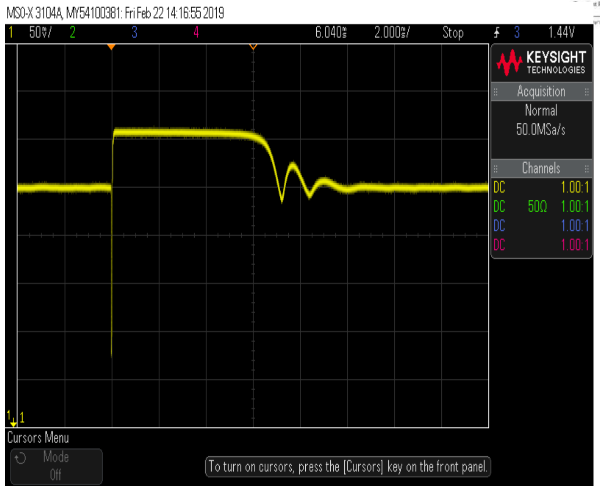
Test of the in-pixel error amplifier-comparator with a laser source

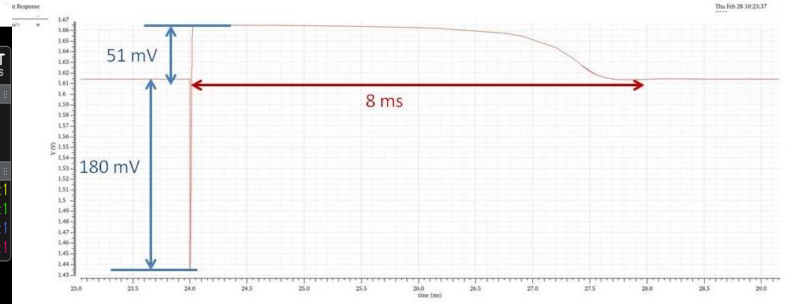












Conclusions-Perspectives

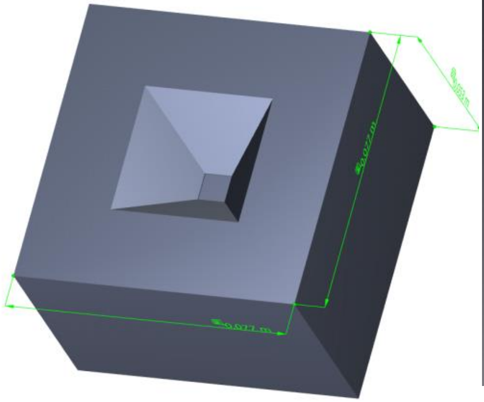
•The first prototype of high dynamic range depleted monolithic active pixel sensors for measuring energy deposition from Galactic Cosmic Rays and Solar Energetic particles has been manufactured.

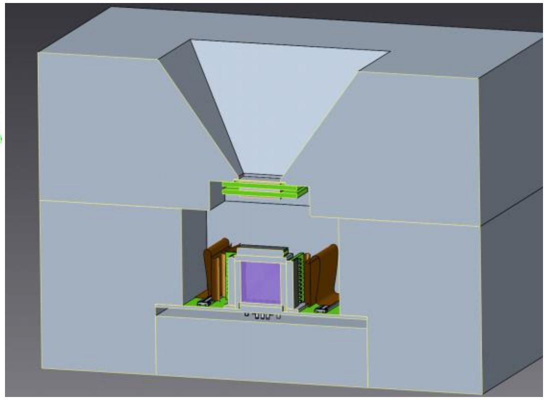
•Measurements with laser pulses have proven that the in-pixel error amplifier – comparator works as designed

•Measurements with test beams are pending

•A new version with incremental improvements is designed

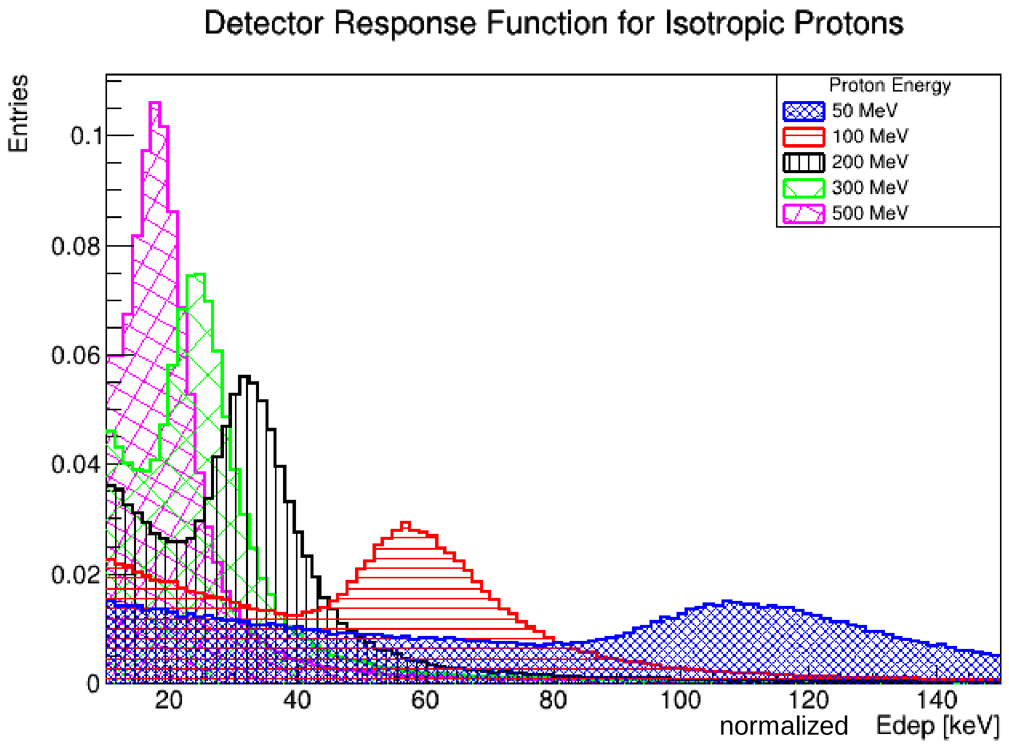
• Depleted monolithic active pixel sensors can be used for compact dosimeters or radiation monitors in space. Simulation results show that particle discrimination and energy determination can be achieved. We have proposed also the development of a radiation monitor for Galileo satellites:

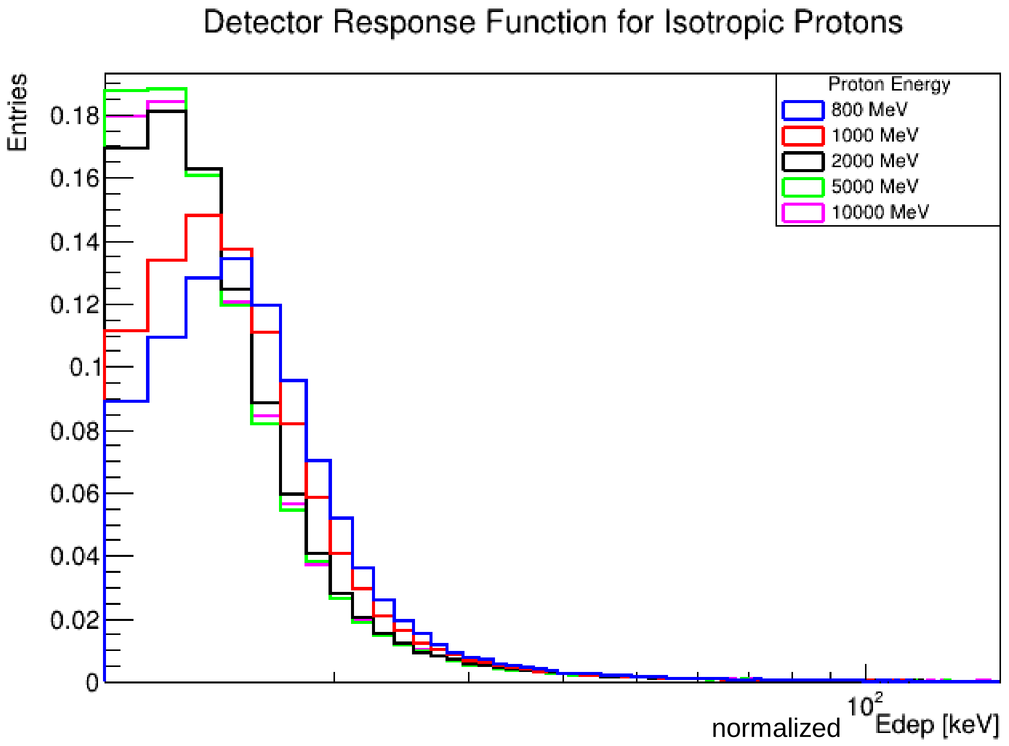




BACKUP SLIDES

Response Function for Protons

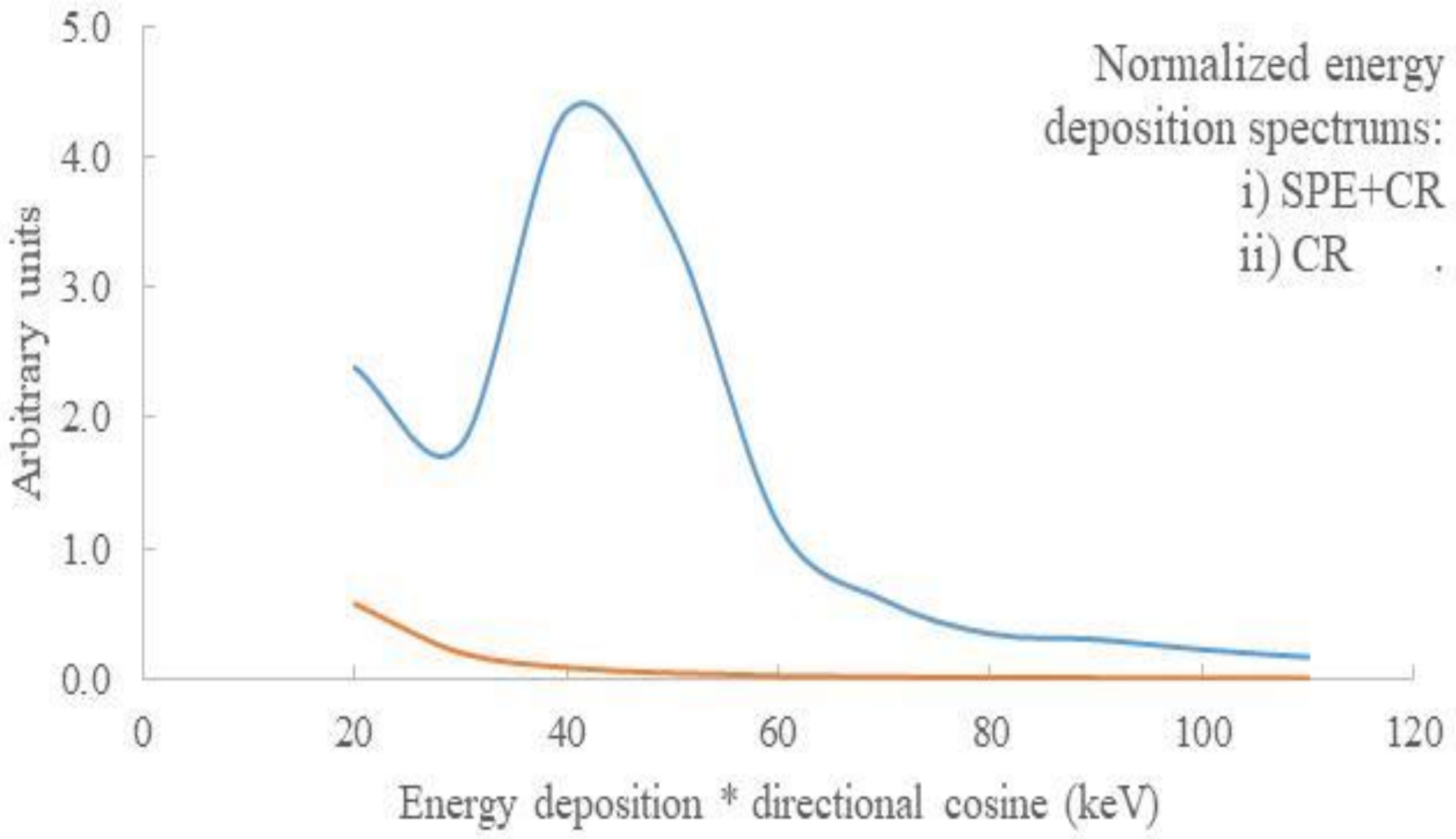




✓Protons with energy higher than 600 MeV give almost identical energy deposition distributions onto the Silicon Pixels. The MIDAS detector can only count the protons with energies higher than 600 MeV.

✓Even if the MIDAS dosimeter cannot distinguish energies higher than 600MeV, the resulting uncertainty in the estimation of the effective dose equivalent is lower than 10% in the case of the Cosmic ray energy spectrums and negligible in the case of Solar Particle Events

Spectra for GCR and SEP



Discrimination and cross over between the most abundant ions in cosmic rays

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University of Cyprus

	"Normalized energy deposition" bins in keV (min – max)									
min	0	50	400	800	1000	1500	3000	6000	8000	12000
max	50	300	800	1000	1500	3000	6000	8000	10000	27000
proton	0.95	0.048	0.0002	0.00004	0.0003	0.0002	0.0001	0.00004	0.0002	0.0001
alpha	0.14	0.85	0.0005	0.0008	0	0	0.002	0	0	0.0003
^{12}C	0.002	0.0005	0.81	0.14	0.05	0.005	0	0	0	0
^{14}N	0	0.004	0.21	0.59	0.31	0.01	0	0	0	0
^{16}O	0	0	0.005	0.14	0.78	0.12	0	0	0	0.0009
^{20}Ne	0	0	0	0.005	0.03	0.94	0.03	0	0	0
^{28}Si	0	0	0	0	0	0.007	0.98	0.018	0	0
^{40}Ca	0	0	0	0	0	0	0	1	0	0
^{48}Ti	0	0	0	0	0	0	0	0	0.84	0.16
^{56}Fe	0	0	0	0	0	0	0	0	0	1