COMPREHENSIVE RADIATION MONITOR PACKAGE FOR LUNAR MISSION (**LURAD**)
Final Presentation:
contract: 4000133574/21/NL/CRS

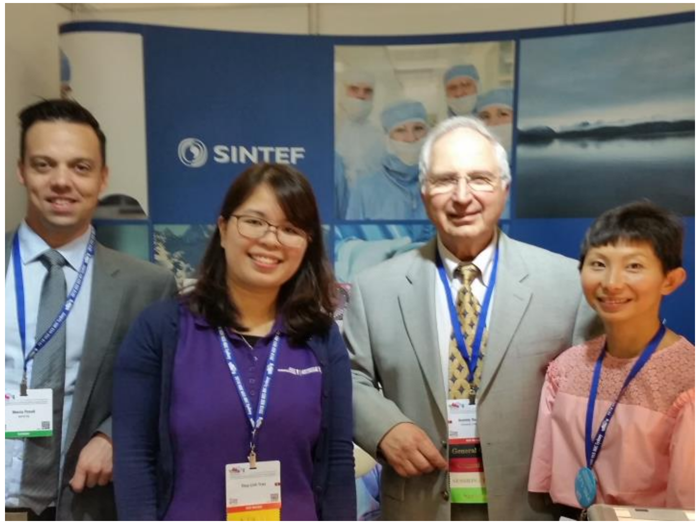
Presenter:

Haris Lambropoulos, Professor NKUA, lambrop@uoa.gr

LURAD is a collaborative effort










SINTEF

CENTRE FOR MEDICAL RADIATION PHYSICS

UNIVERSITY OF WOLLONGONG AUSTRALIA

National and Kapodistrian UNIVERSITY OF ATHENS

ADVEOS
A BEKEN COMPANY

Motivation

ESA Product Specifications for the SWE segment of the SSA system

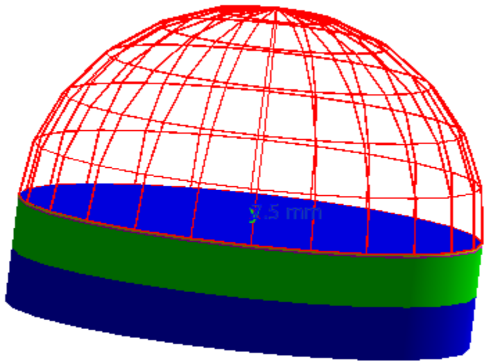
3.2.6 L1-002-M: High Energy >10 MeV/nuc Ions in Interplanetary Medium - Measurement

PRODUCT	High Energy >10 MeV/nuc Ions in Interplanetary Medium - Measurement
Product Code	L1-002-M
Input Data required	
Data to be provided and associated units	ion flux in cm^-2s^-1sr^-1(MeV/nuc)^-1
Dynamic Range	10^8 (min./max. vary with energy and species)
Physical Range	Threshold of 5 channels, goal of 10+ channels, logarithmically spaced in energy ranging from 10 MeV/nuc to 5 GeV/nuc. Goal of 2 PI steradians (hemisphere) coverage with resolution of 20 degree half-angle cones. Threshold of single cone of minimum 20 deg half-angle.
Spatial range	L1 or GEO
	SWE-CRD-GEN-1705
Justification of the requirements	A factor in a wide range of single-event related effects and biological effects. In addition, there may be special sensitivity of some equipment (e.g. X-ray detectors) to low energy ions (500 keV to 1 MeV).
Comment	Regarding species coverage the goal is Z = 2 - 92 with a threshold of Z = 2 - 28.

- ❑ Powerful GCR detectors AMS-02 and PAMELA cannot measure the <1 GeV spectrum of GCR because they are in LEO
- ❑ Albedo particles energy spectrum and composition is sensitive to the details of regolith composition.

ESA AO/1-10319 /20/NL/CRS preliminary requirements:
Protons in the energy range from 10 MeV to 2 GeV
Heavy ions from a few MeV to 2 GeV/n
Electrons from 0.1 MeV to 20 MeV
Neutrons from thermal to fast,
Gamma rays
Dosimetry information

Lunar radiation field environment: GEANT4 simulations



Components:

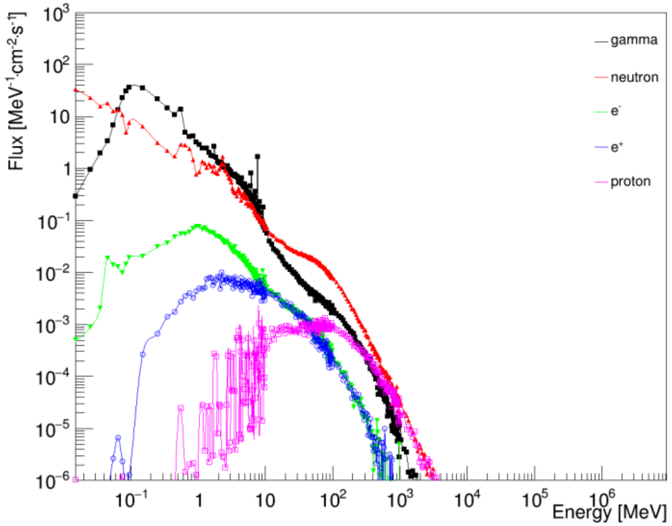
1. GCR differential flux energy spectra given by the ISO-15390 GCR model 1996.4 solar minimum at 1 AU without geomagnetic shielding (SPENVIS)
2. Lunar Albedo Field created by GEANT4 simulations

The Lunar model used in the Geant4 simulation:

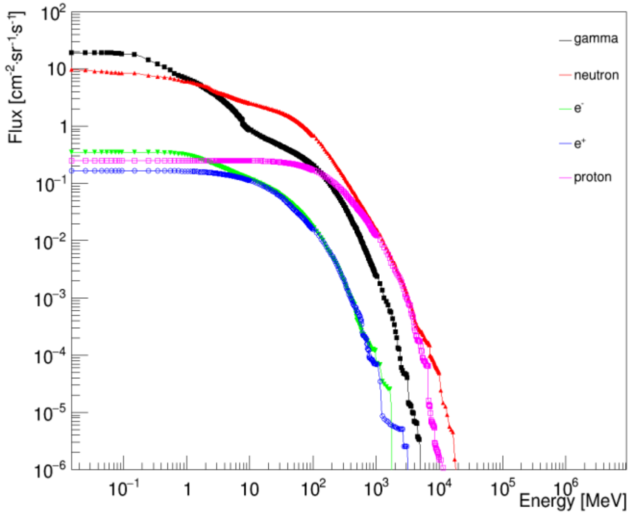
- **5 cylindrical layers with radius of *20* m. Density and composition from LUNA 16 & LUNA 20 data**
- **A hemispherical radiation source with a radius of *20* m emits particles using the cosine law**

Particle	% contribution
Gamma	65,66
Neutron	30,64
e-	1,29
Proton	0,92
e+	0,61
Deuteron	0,03
mu+	0,01
Triton	0,0057
mu-	0,005
Other	0,82

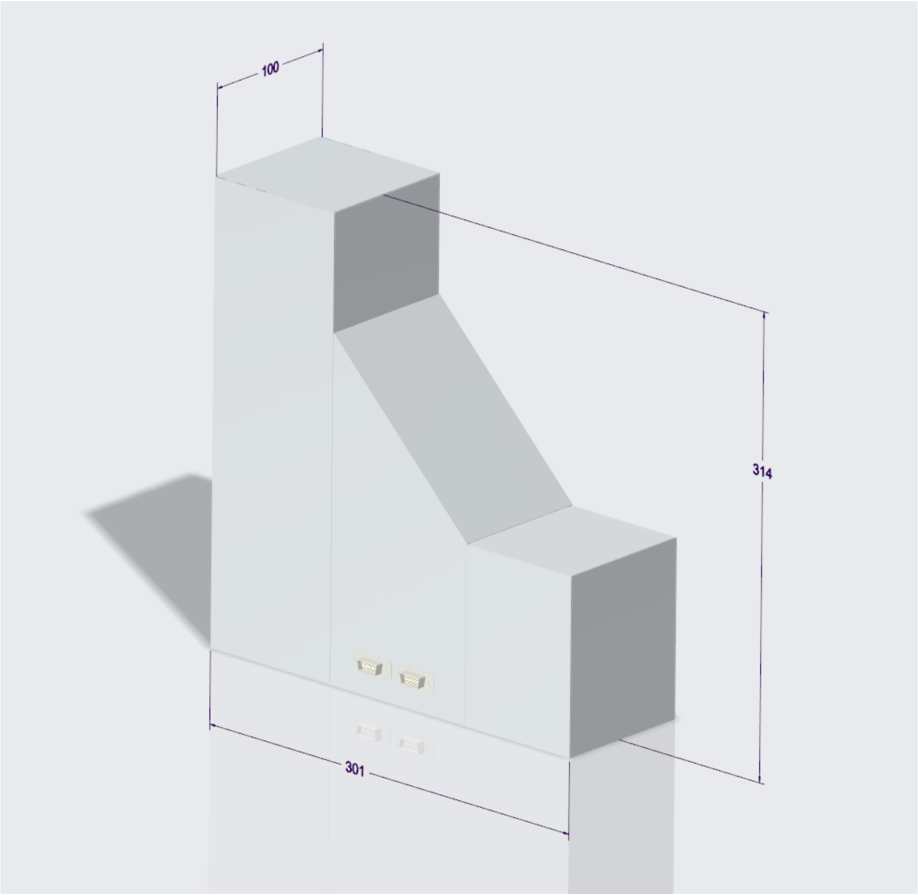
Differential energy distribution



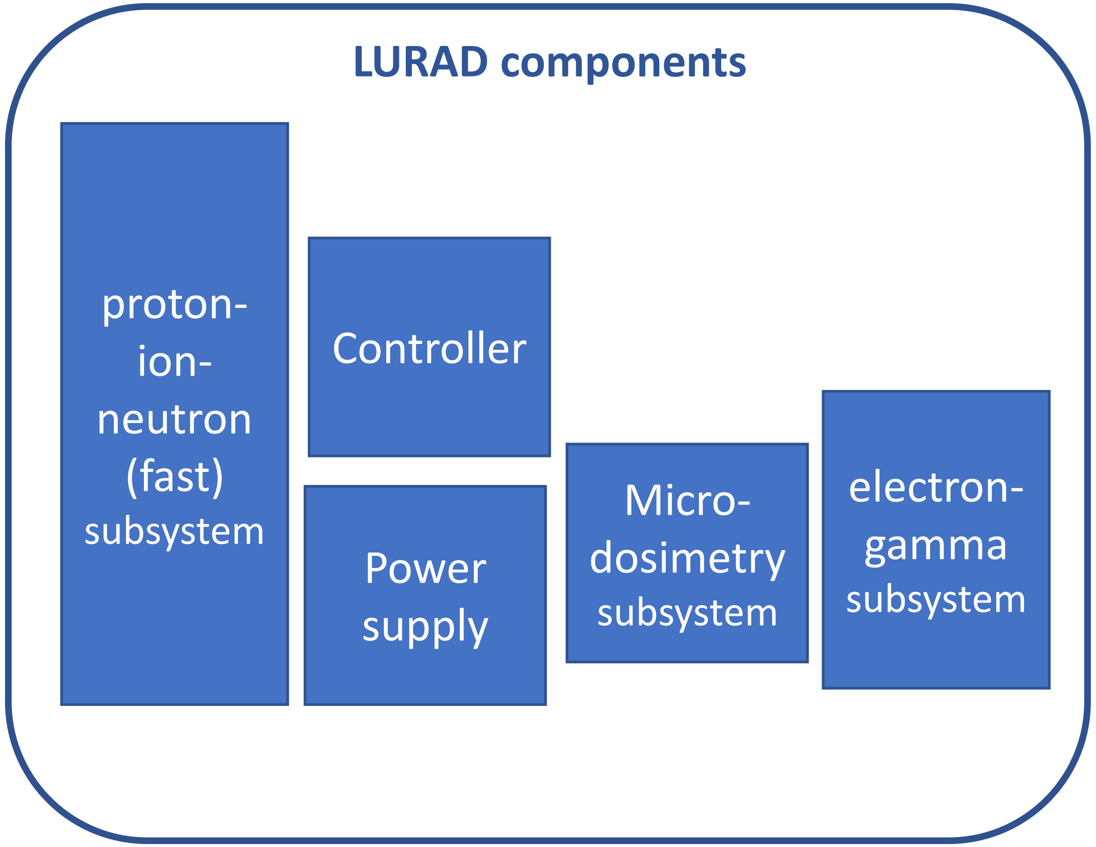
Integral energy distribution



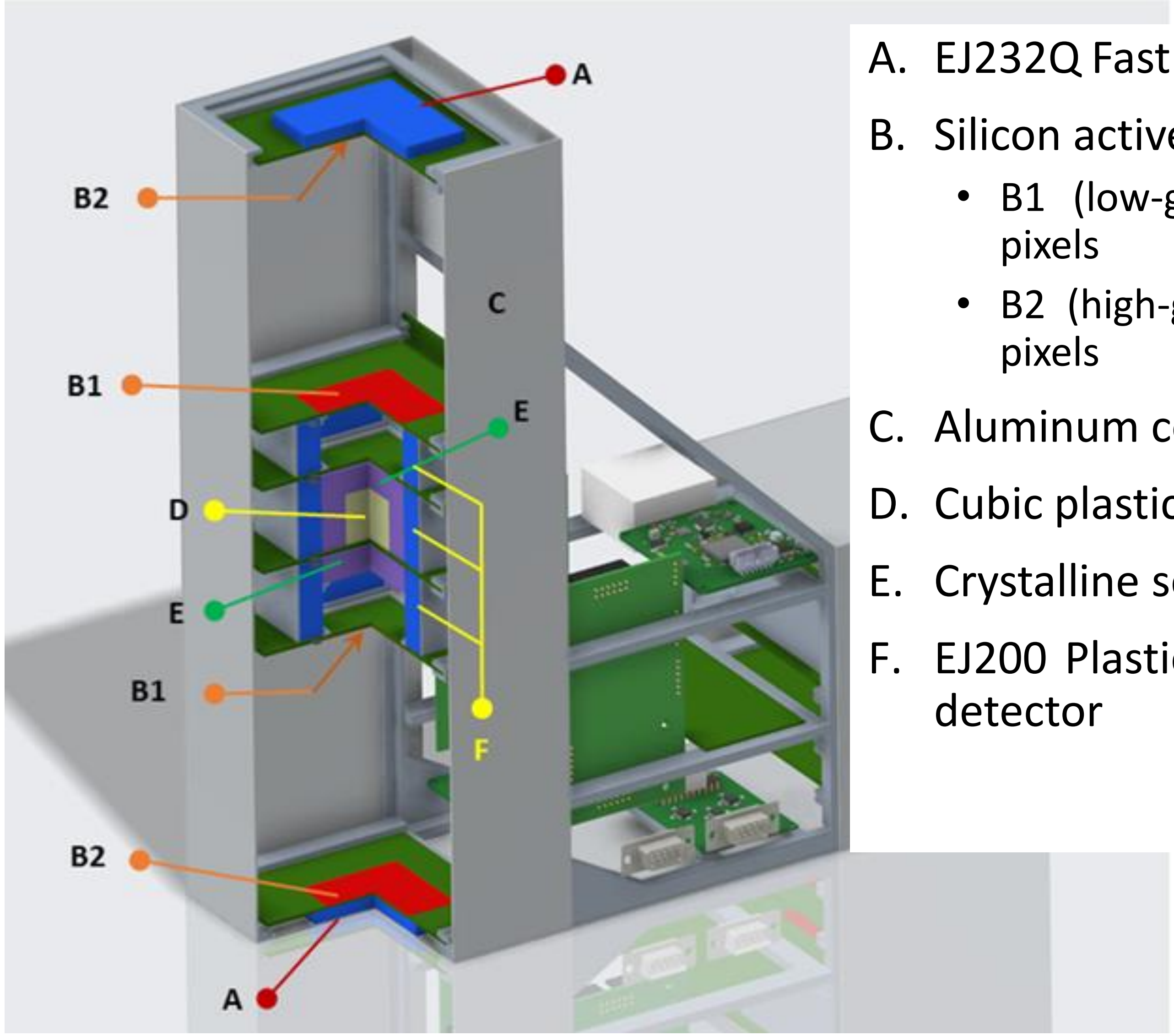
The LURAD instrument package



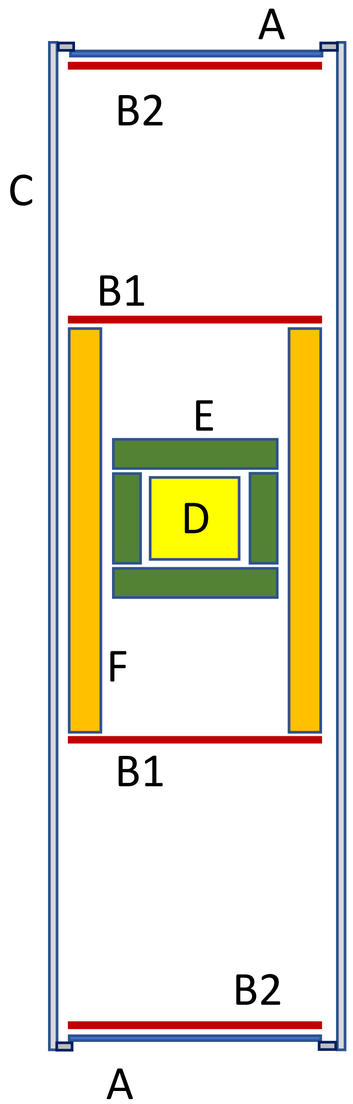
Mass ≈ 2.9 kg



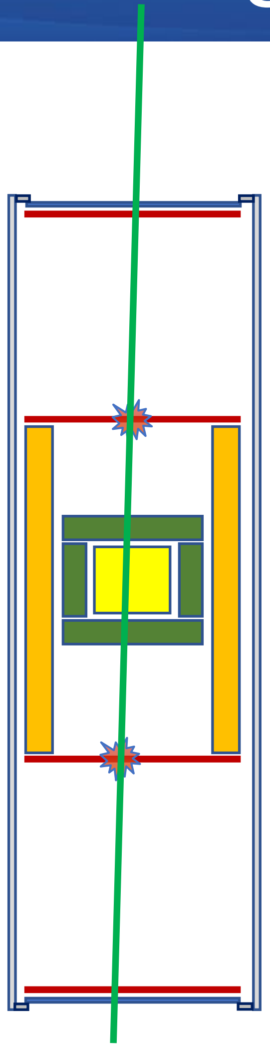
Proton – ion – fast neutron subsystem



A. EJ232Q Fast Scintillator (50x50x5 mm^3)
B. Silicon active pixel detectors
   - B1 (low-gain): 200 x 200 μm^2, 40000 pixels
   - B2 (high-gain): 100 x 100 μm^2, 160000 pixels
C. Aluminum cover
D. Cubic plastic Scintillator (EJ200)
E. Crystalline scintillator CsI(Na)
F. EJ200 Plastic scintillator anticoincidence detector



Charged Particles Identification



Criterion for charged particles selection:

(a) produce signal on one or more scintillator volumes of the central sensitive cube

(b) produce signal on both the low gain Si detectors placed above and below the central sensitive cube

(c) do not produce signal on the EJ200 anticoincidence detectors

Not used when identifying heavy ions
Eliminates the majority of the heavy ion events due to the production of delta rays that trigger the EJ200 system

Input:
Deposited energies on all sensitive volumes

GBDT for multiclass Classification
Classes:
- **Proton**
- **Alpha**
- **Electron**
- **Ion**

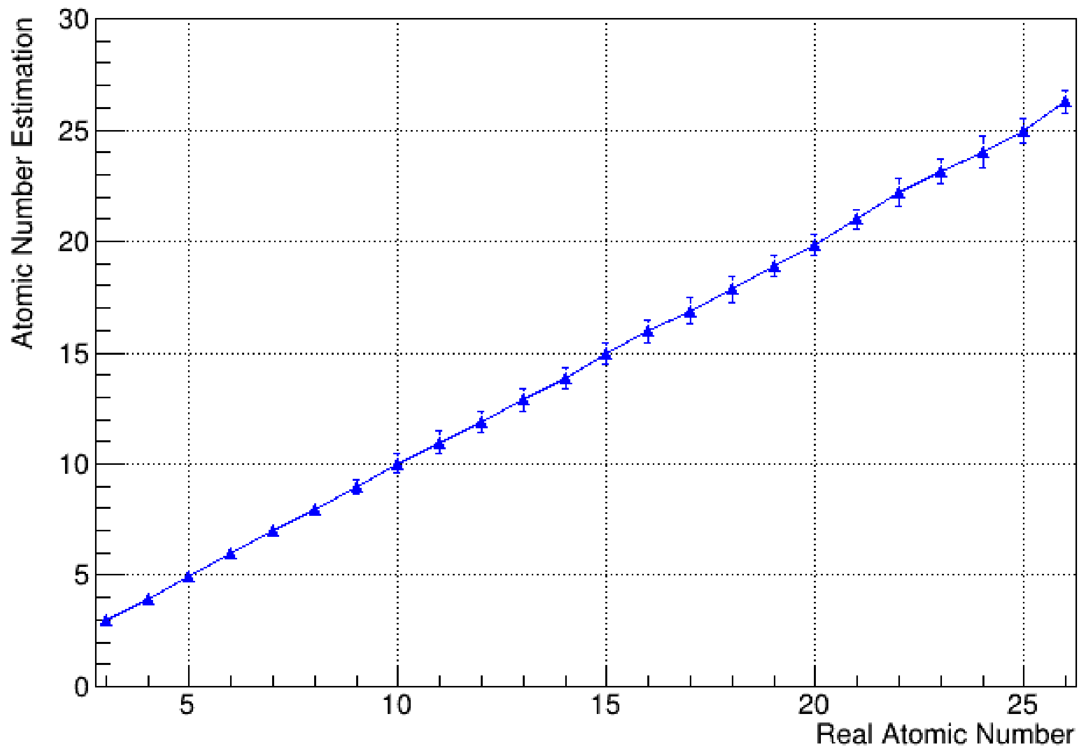
Proton Purity: 98%

Alpha Purity: 95%

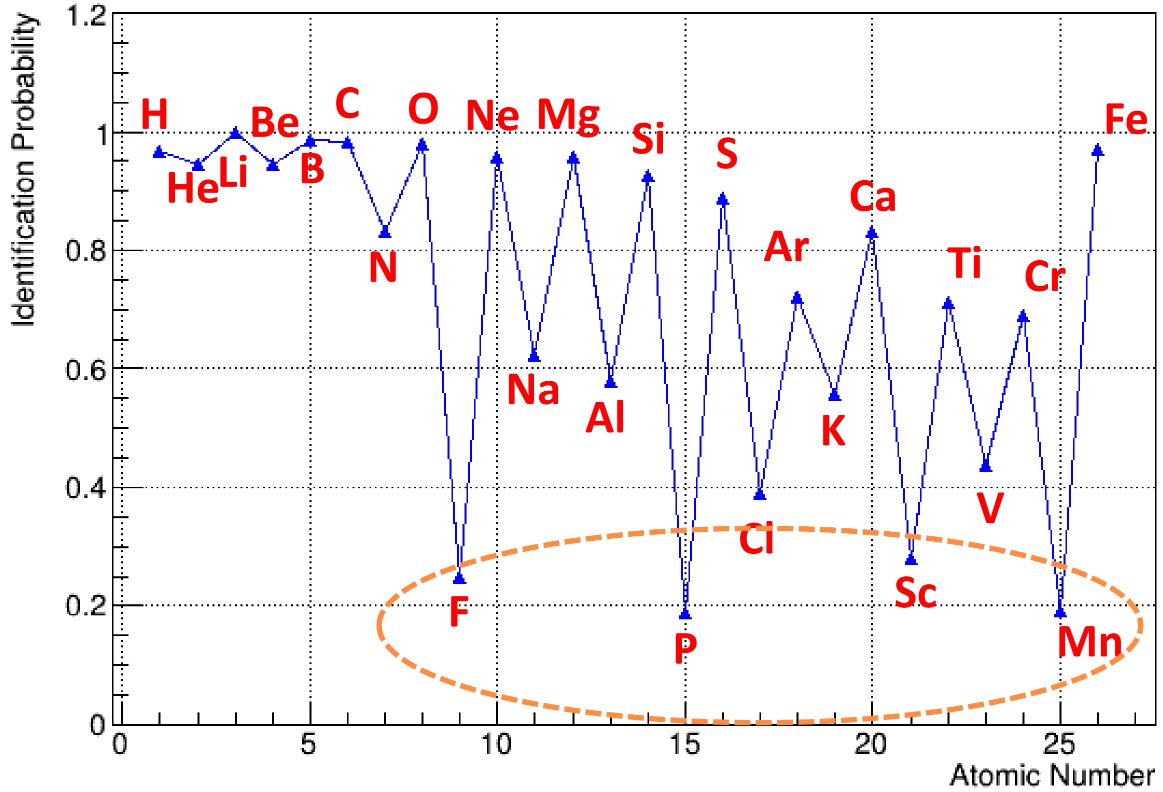
GBDT for Regression problem:
Atomic Number, Z, Estimation

Charged Particles Identification Capability

Atomic number estimation for particles with Z>2 with GBDT solving regression problem

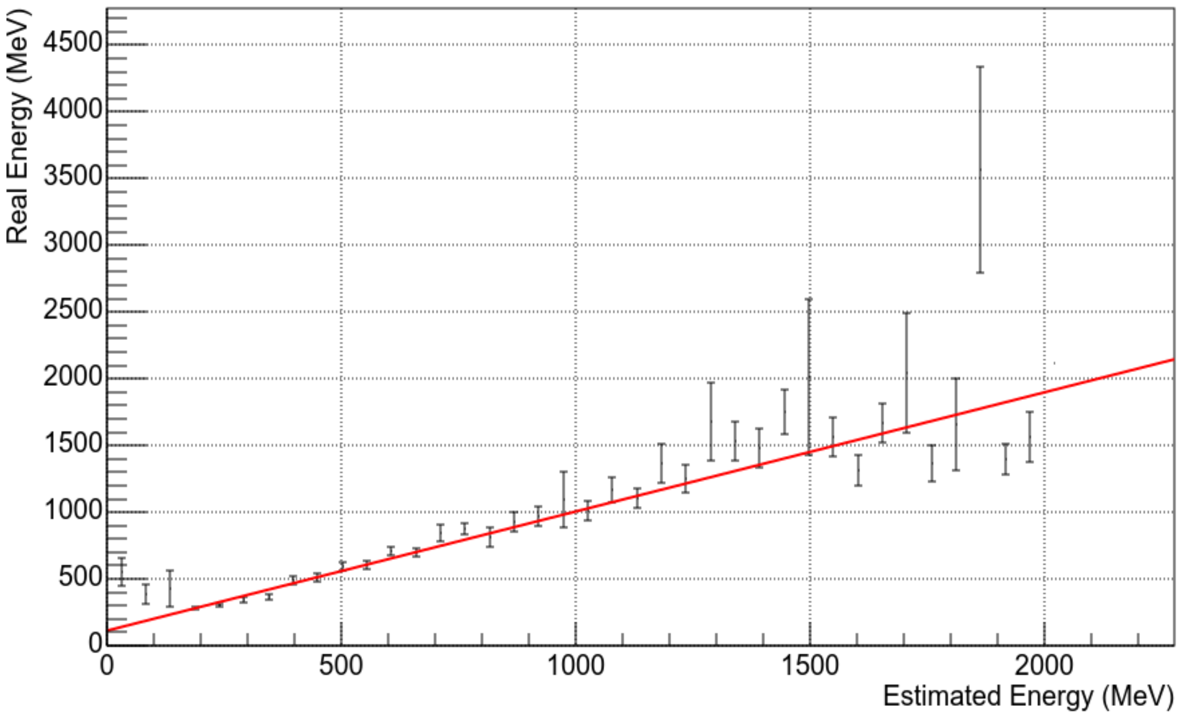


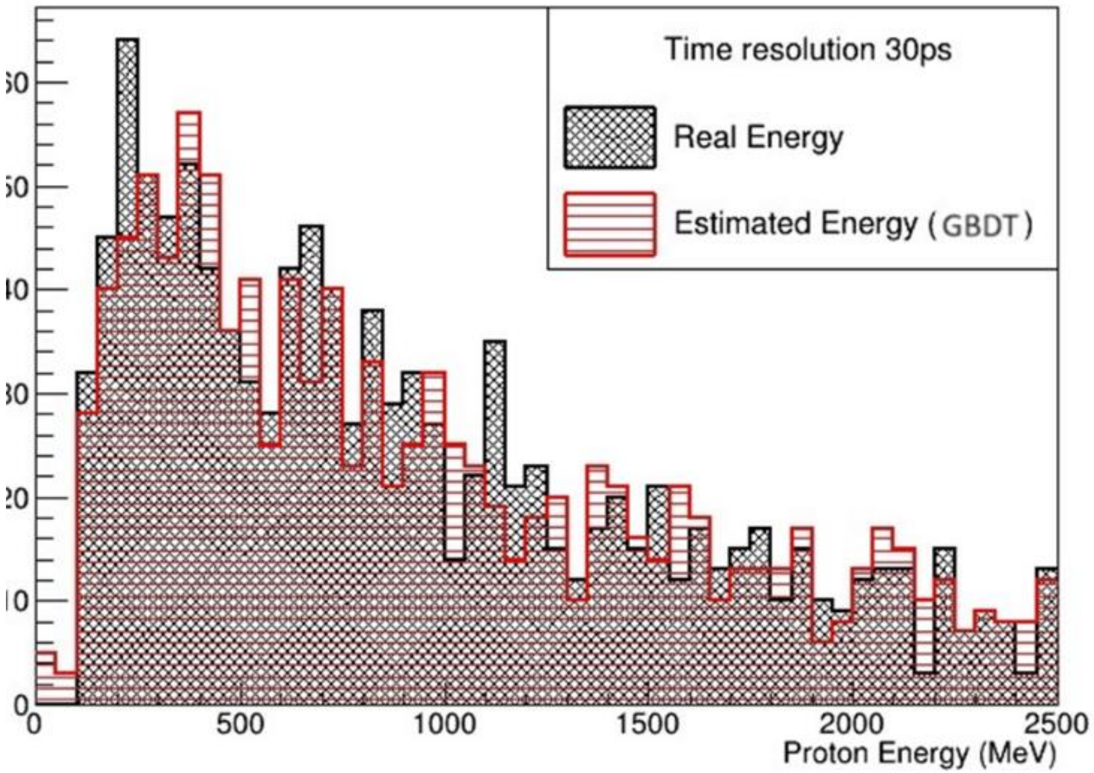
Identification considering lunar field particle composition



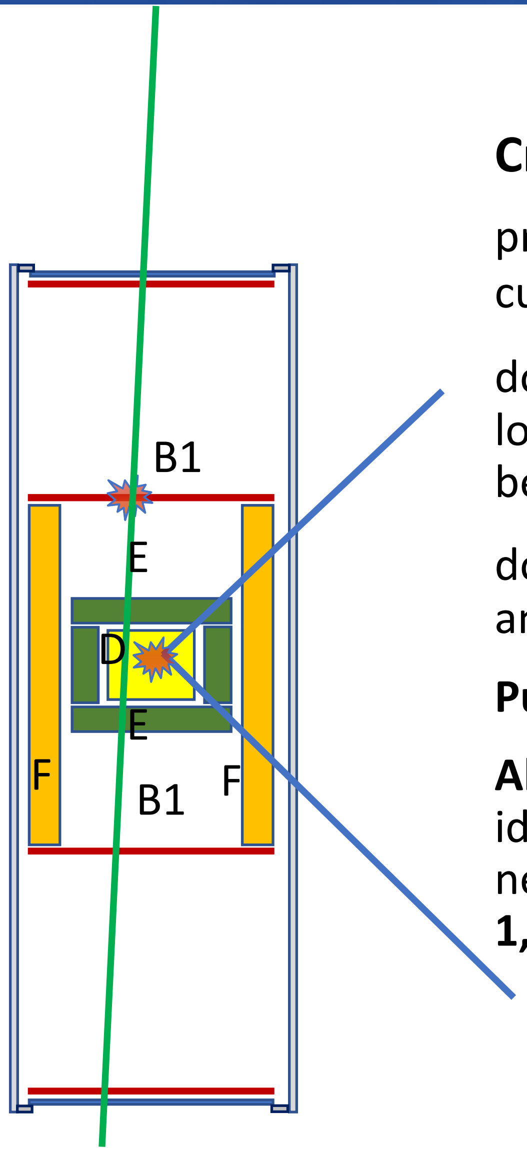
Significantly lower flux compared to neighboring ions. Misidentification of the high-flux neighboring ions as F, P, Sc, or Mn, leads to substantial contamination of the sample of these ions → Low correct identification probability

Proton kinetic energy estimation





Fast neutrons



Criterion: (Neutron Selection)

produce signal **on the central** EJ200 cube **D AND**

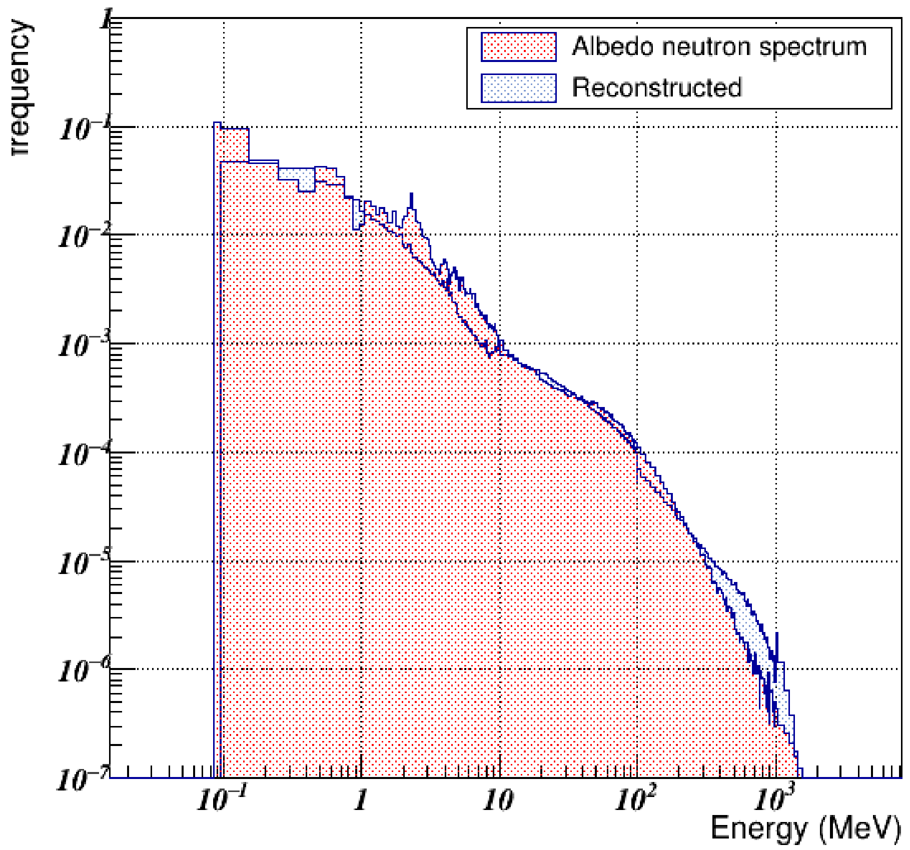
do not produce signal on the two **B1** low gain Si detectors placed above and below the central sensitive cube **AND**

do not produce signal on the **F** EJ200 anticoincidence detectors

Purity: > 75% (the rest are gammas)

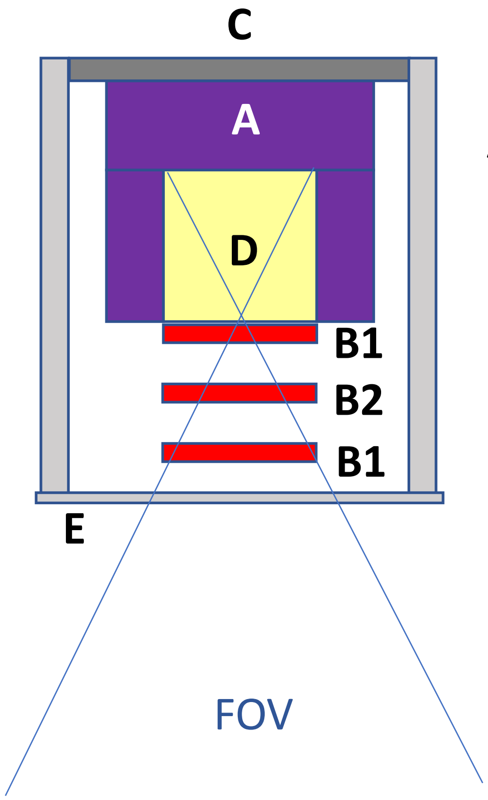
Absolute efficiency: neutrons correctly identified over the total number of neutrons impinging the detectors **is 1,26%**

neutron spectrum reconstructed from the energy depositions on the central cube compared to the real spectrum



Algorithm presented in doi:10.1029/2019SW002344

Electron – gamma subsystem



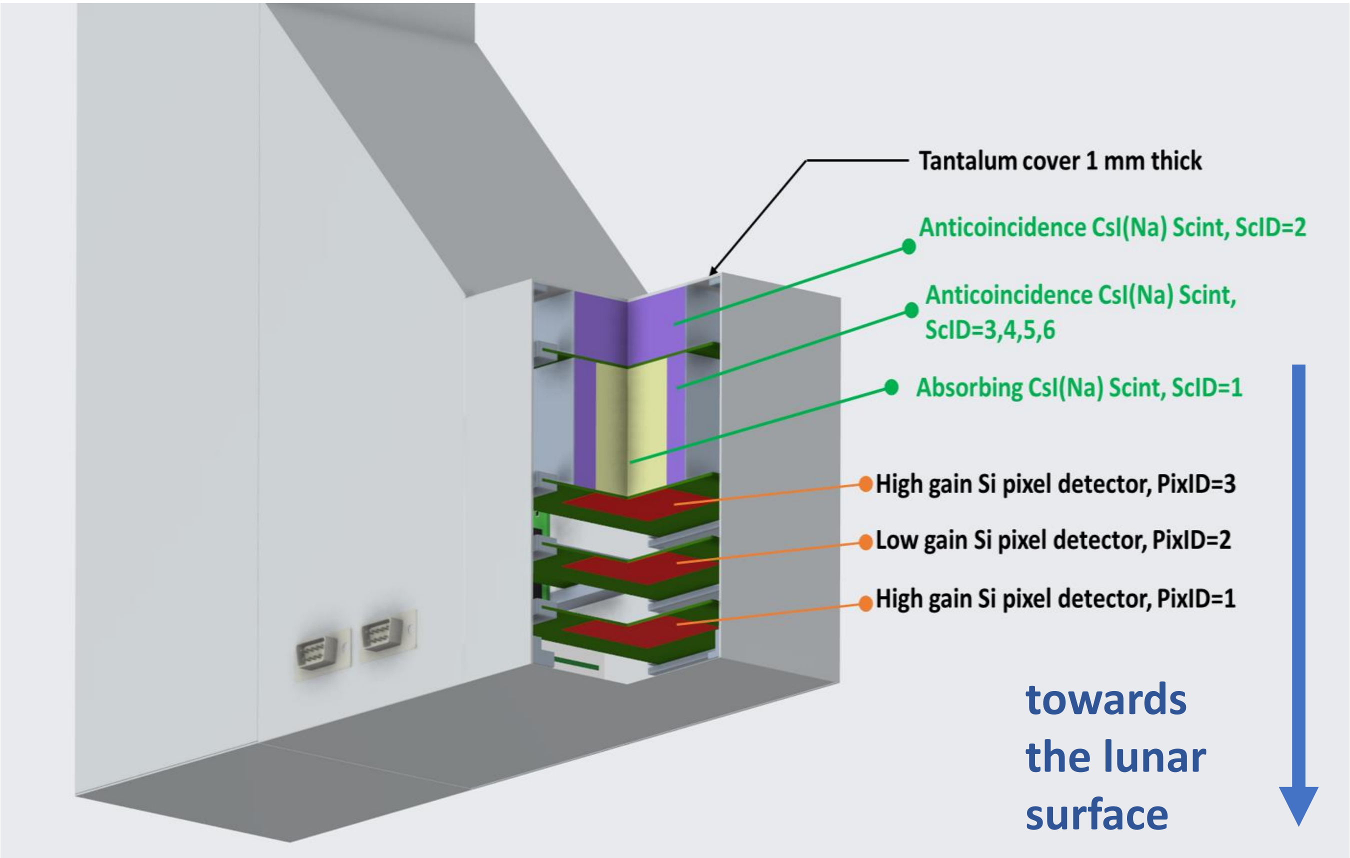
A: Anticoincidence CsI(Na)

B: Si pixel sensors

C: Tantalum sheet

D: CsI(Na) absorber

E: Aluminum enclosure



<u>Photon selection</u>

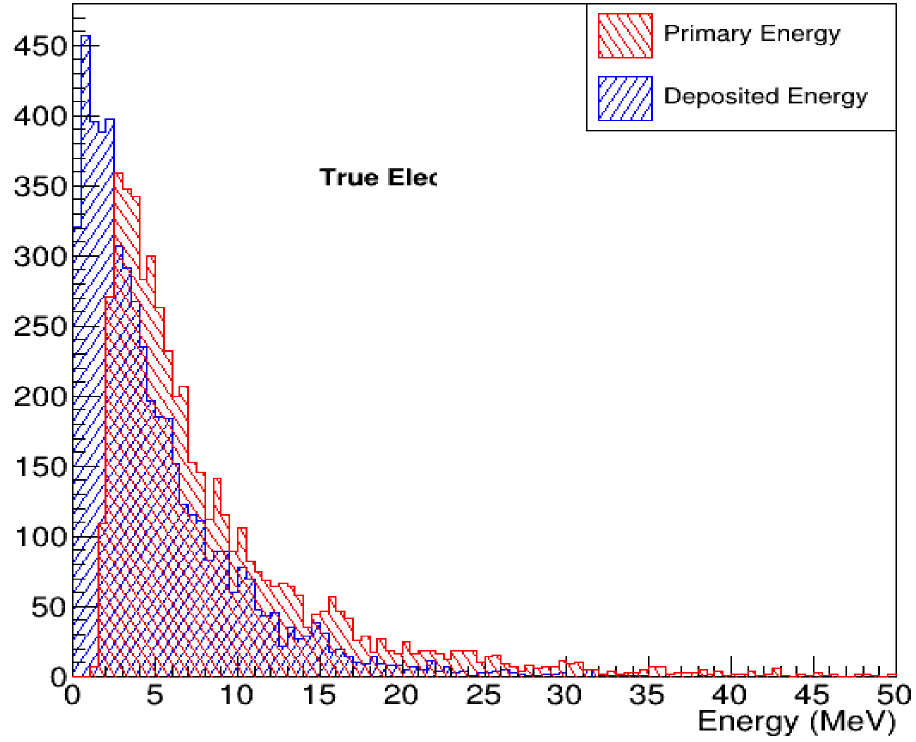
Purity: almost **93%** -- **Efficiency: 97.5%**

<u>electron</u> coming from the FOV

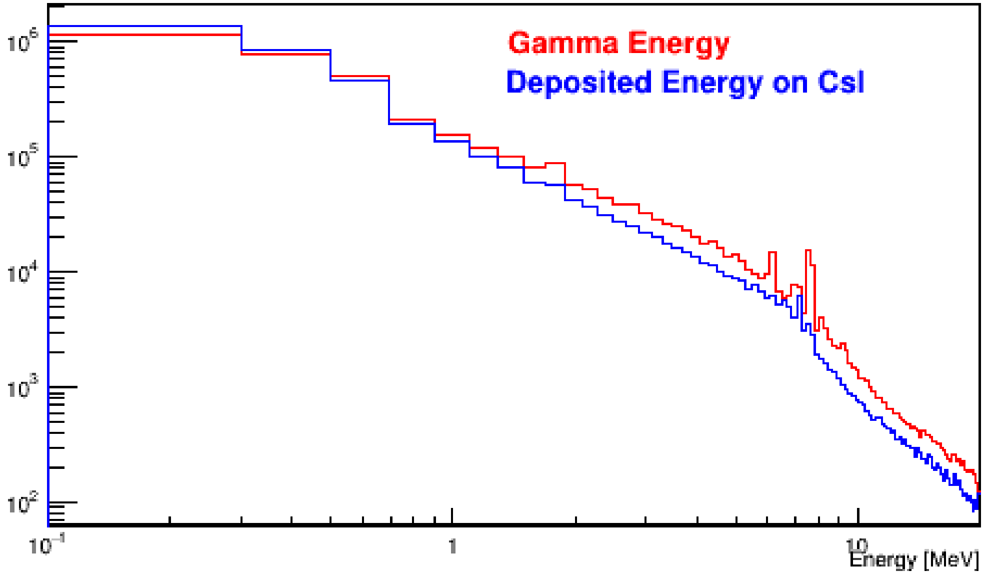
Purity: almost **83%** -- **Efficiency:** almost **66%**

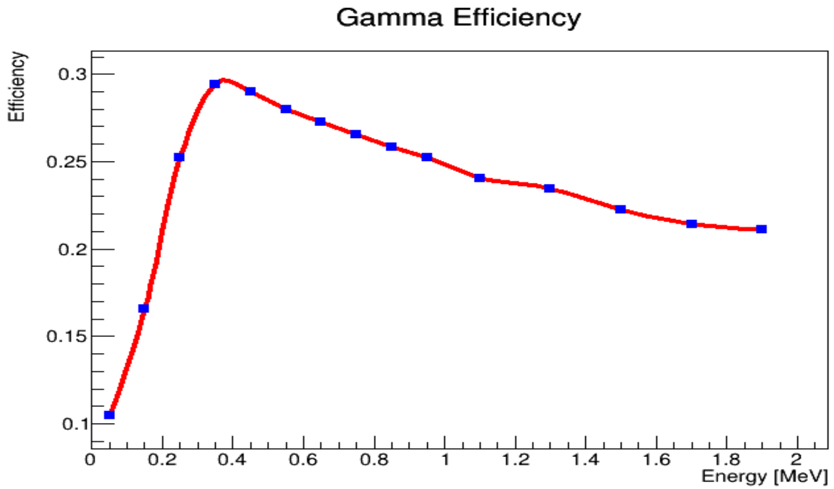
electron gamma subsystem response

Electron spectra



Gamma spectra





Effects from SEP events

From the SEPEM reference event list (www.sepem.eu/help/event_ref.html) the event with the highest daily average and peak flux occurred from Oct 19, 1989 to Nov 11, 1989.
This event has been selected as a worst-case SEP event
Proton, alpha spectra of this event reproduced with the CRÈME-96 5 min peak

Electron-gamma subsystem	
Sub-Detector	Proton and alpha Event rate (Events/s) x10^8
SciID=1	3.1
SciID=2	11.15
SciID=3	4.8
SciID=4	8.7
SciID=5	4.6
SciID=6	3.4
PixID=1	24.9
PixID=2	5.3
PixID=3	2.9

Proton-ion-fast neutron subsystem	
Sub-Detector	Proton and alpha Event rate (Events/s) x10^8
F (cumulative)	47.6
B1	10.2
B2	10.4
A	15.2
E	4.7
D	0.4

One pixel of the B2 sensor will have to cope with a mean rate of 6500 events/s.
So
Switch off everything else and keep some pixels operating will reduce dramatically rates.

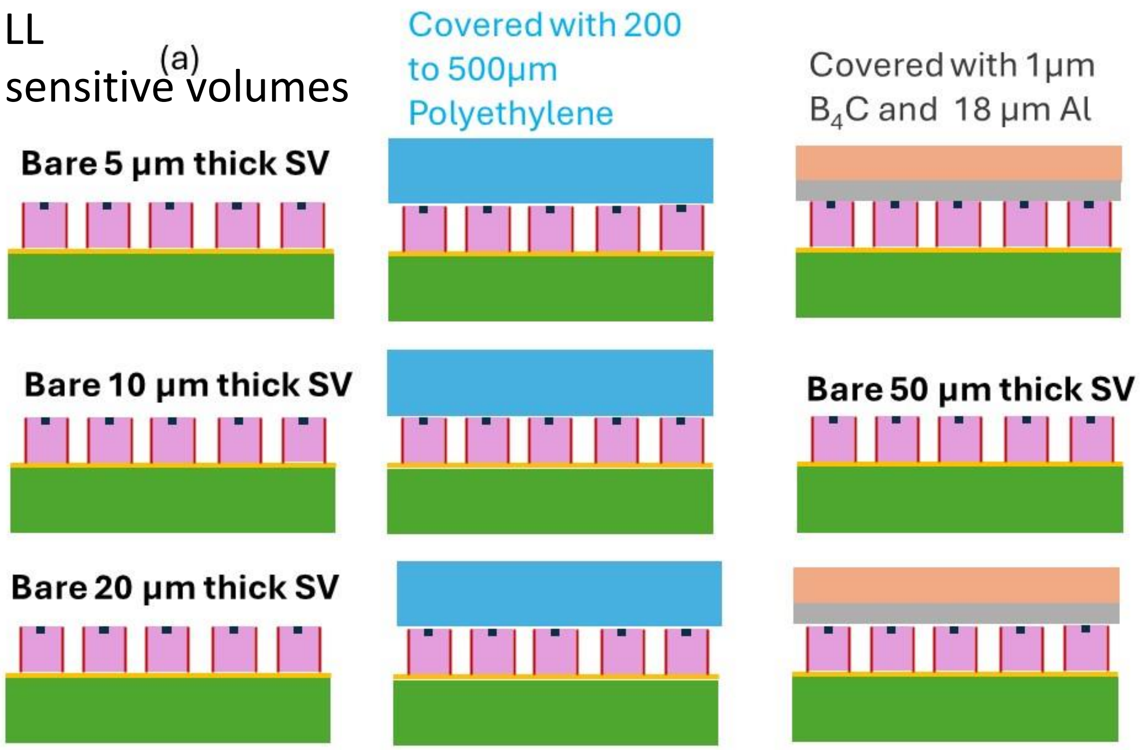
Microdosimetry subsystem CMRP-SINTEF

PBS_FULL
40 x 40 sensitive volumes (a)

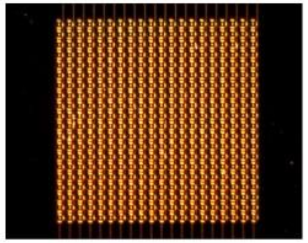
2 keV/µm to 58 MeV/µm

1 keV/µm to 29 MeV/µm

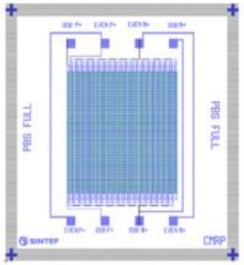
0,5 keV/µm to
14.5 MeV/µm



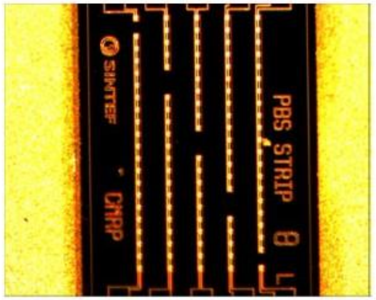
PBS_FULL
microphotograph (b)

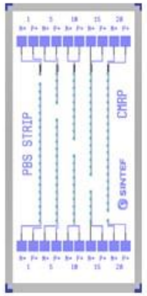


PBS_FULL
layout



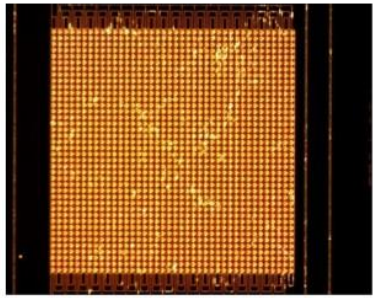
(c)

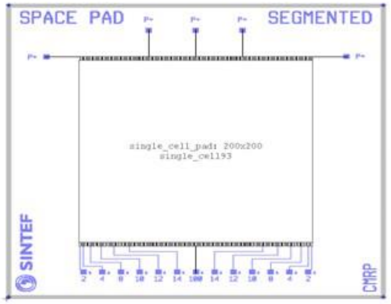




PBS_Strip
Microphotograph Layout

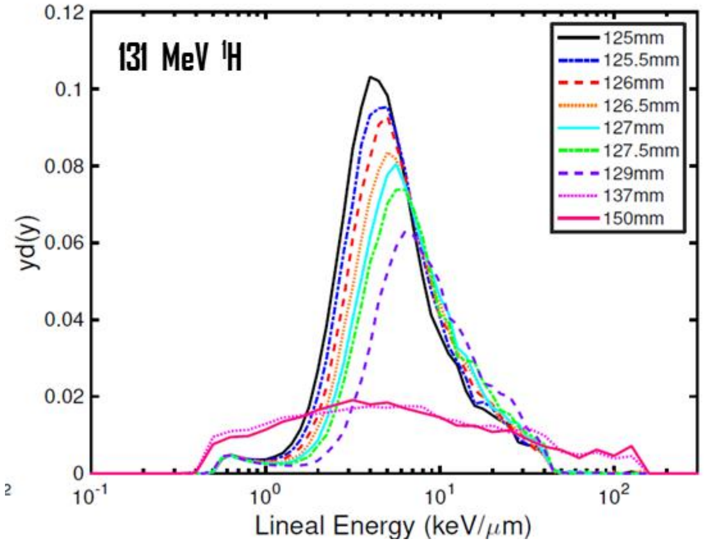
SPACEPAD
microphotograph (d)

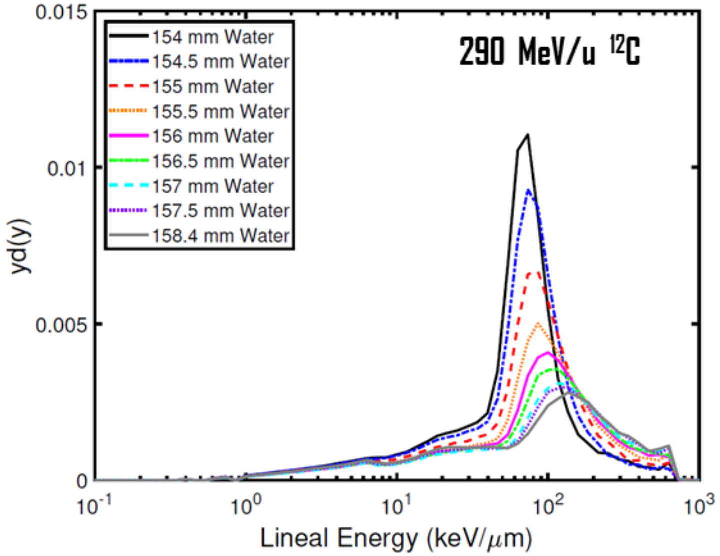


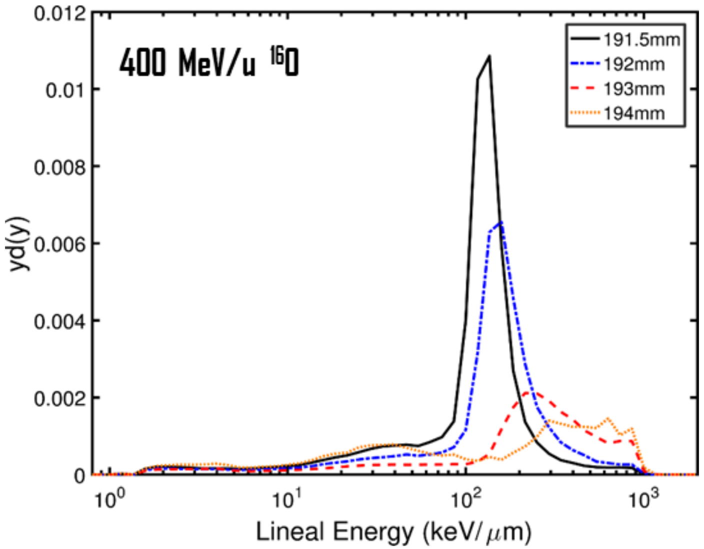


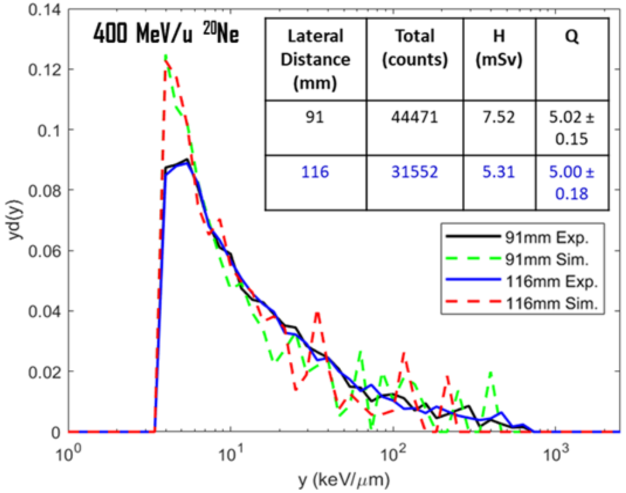
SPACEPAD
Layout
200 x 200 sensitive volumes

Microdosimetry sensors experimental validation

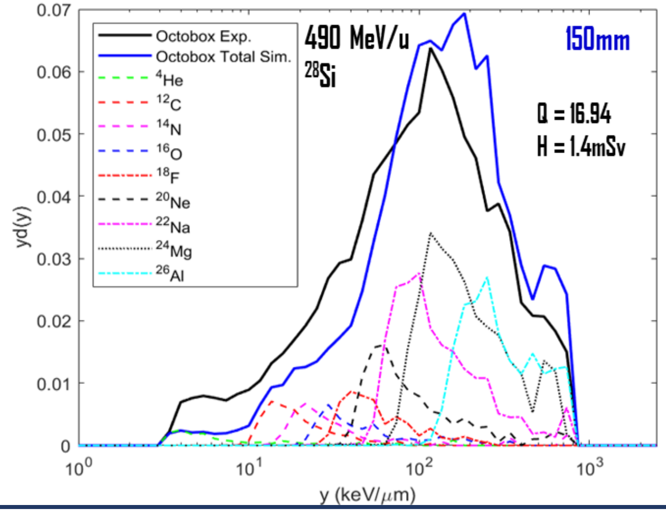


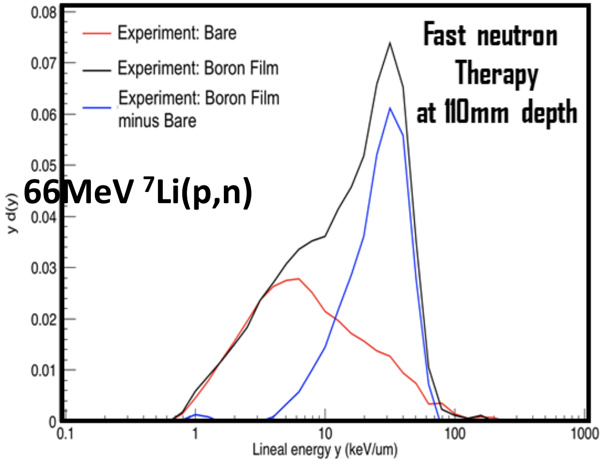




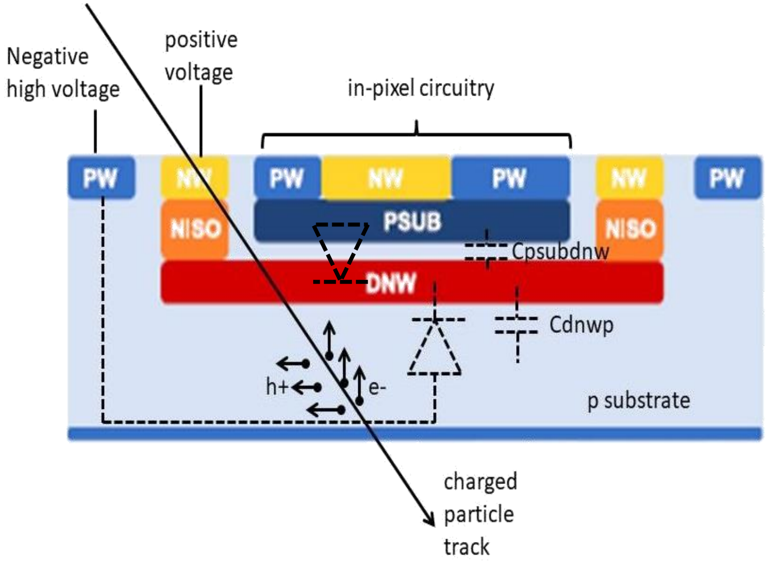


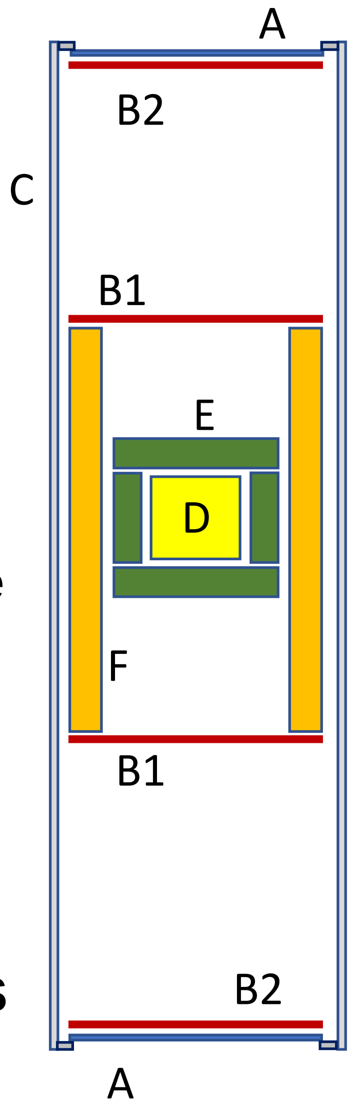
Lateral Distance (mm)	Total (counts)	H (mSv)	Q
91	44471	7.52	5.02 ± 0.15
116	31552	5.31	5.00 ± 0.18

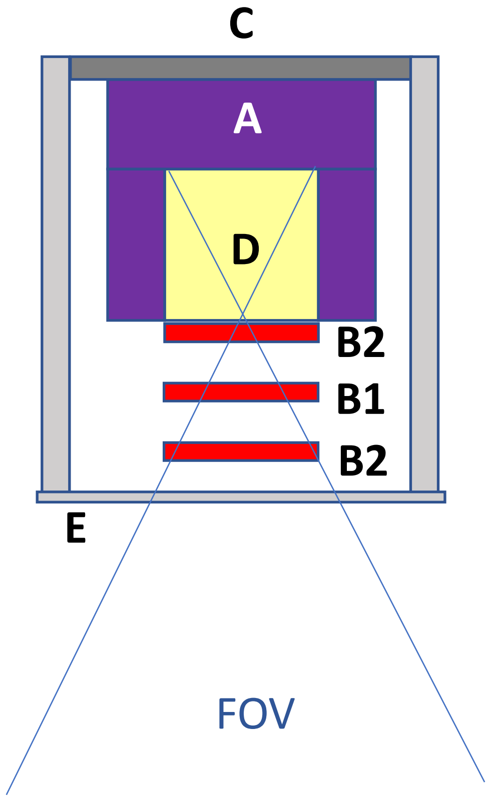




Fully Depleted Monolithic Active pixel sensors (DMAPS)







- ➢ Pixel circuits are built inside of a Deep n-well biased at a positive voltage
- ➢ Substrate is biased at a high negative voltage (–HV = -28V or more negative)
- ➢ Impinging charges are collected by the depletion region below the pixel

B1 and B2 layers have an area of 4 cm x 4 cm covered with DMAPS
B1: 40000 pixels 200 x200 μm² - B2:160000 pixels 100 x100 μm²

DMAPS for space applications

- DMAPS a “spin-in” from High Energy Physics
- Energetic particles in space environment:

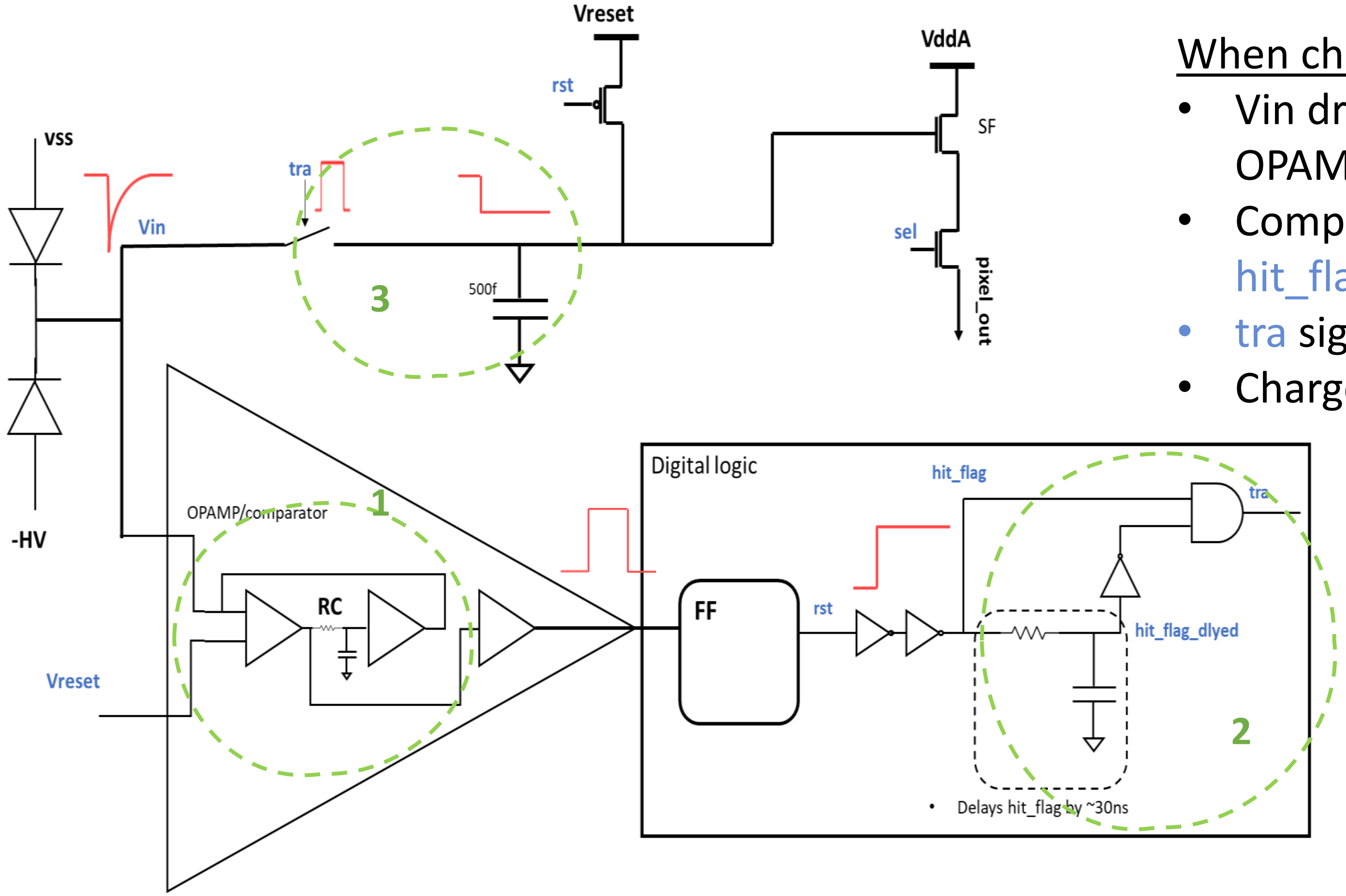
➢ Have a range of energy depositions on Si from keV to tens of MeV (not only minimum ionizing particles)

➢ For ions energy deposition is not only along the track of the particle: It has rich spatial structure

➢ The hit rate can be from 2 to 4 $cm^{-2}\cdot s^{-1}$ (GCR) to $55\cdot 10^{7}$ $cm^{-2}\cdot s^{-1}$

Power consumption minimization is obligatory.

Low gain pixel design covers 40 fC – 9 pC



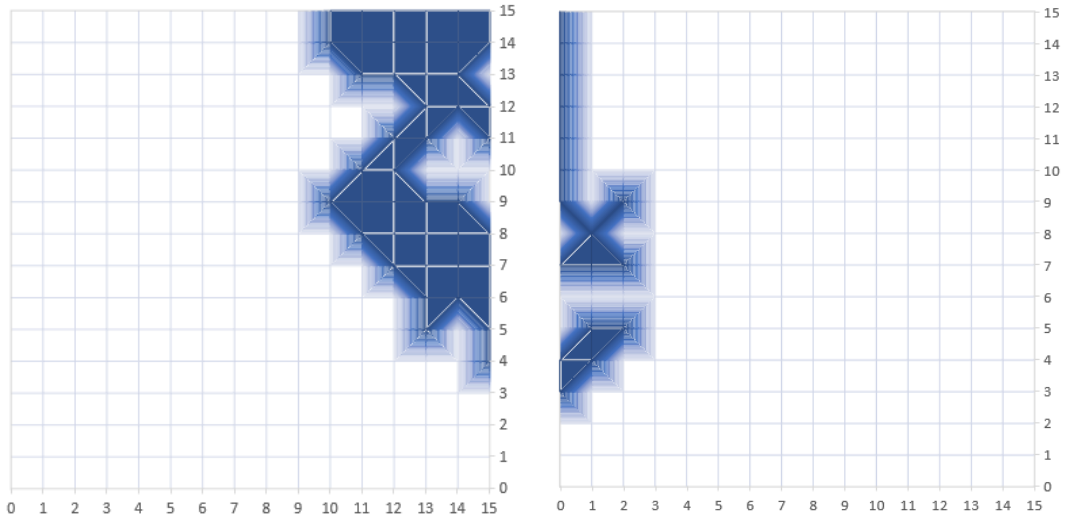
When charge Q_{in} hits the pixel:

- Vin drops abruptly and is slowly returned to Vreset by OPAMP loop[1]
- Comparator flips: rst transistor is turned off and hit_flag signal is raised
- tra signal is generated locally as shown[2]
- Charge is transferred to a 500f capacitor[3]

Low gain characterization

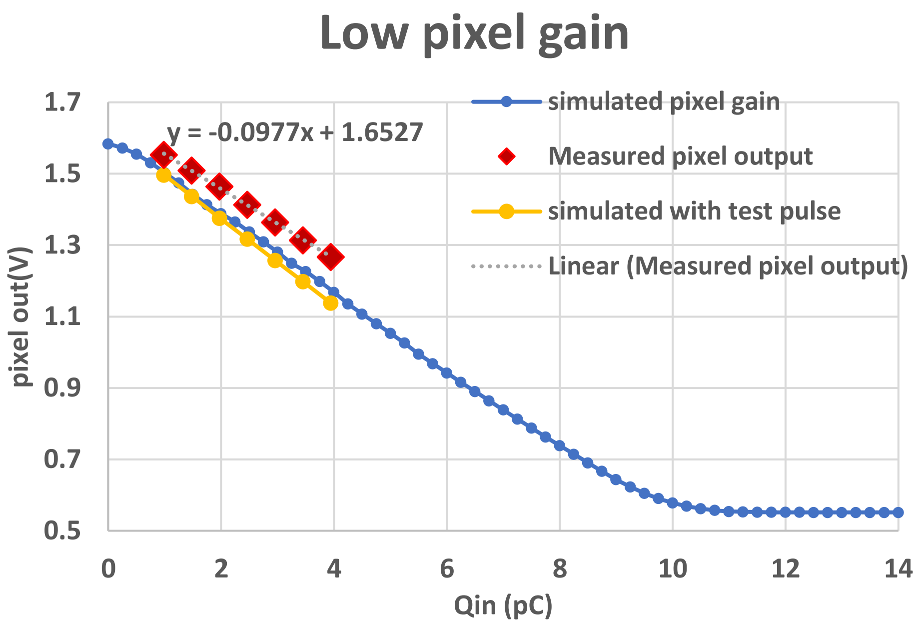
Low gain sensor response to light:

- ➢ Illuminating the sensor with a diffused laser locally from the top
- ➢ Filtering false hits from the pixel array



*Laser positioned at the **top-right** corner of the array*

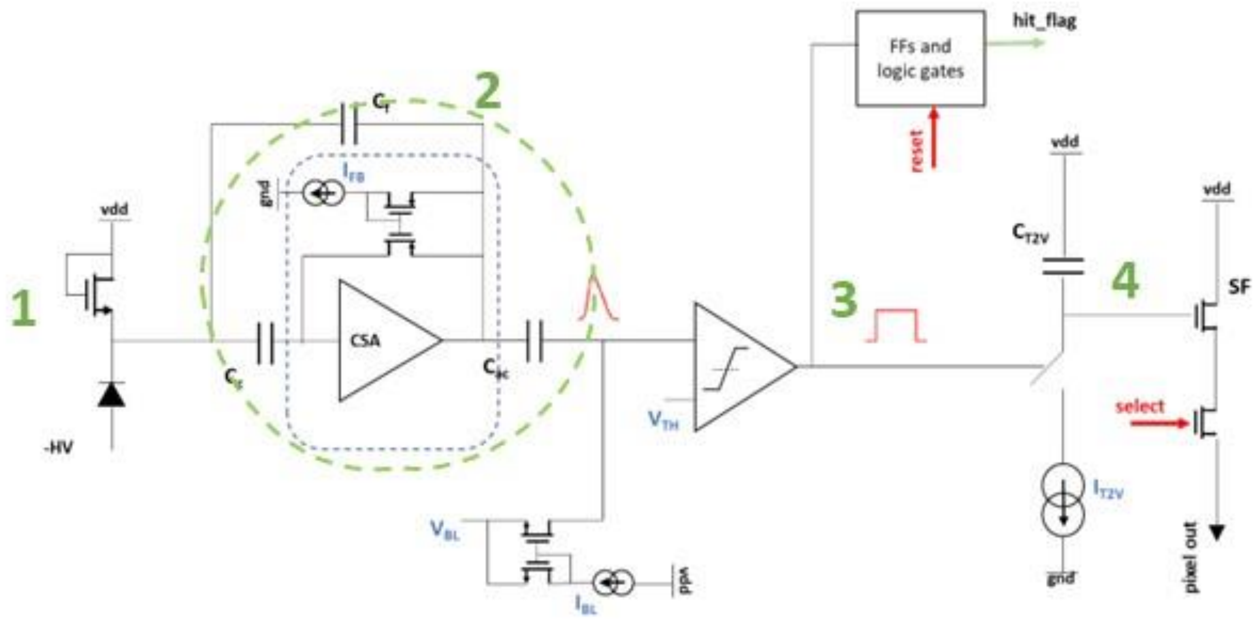
*Laser positioned at the **top-left** corner of the array*



Simulated pixel gain	109 mV/pC
Measured pixel gain	98 mV/pC

- ➢ $Q_{in} = \Delta V_{in} \cdot C_{test} \cdot \frac{C_{det}}{C_{det}+C_{test}}$
- ➢ Good agreement with simulation results
- ➢ Deviation possibly due to C_{in} value being different from what simulation predicts

High gain pixel design covers 0.5 fC – 50 fC

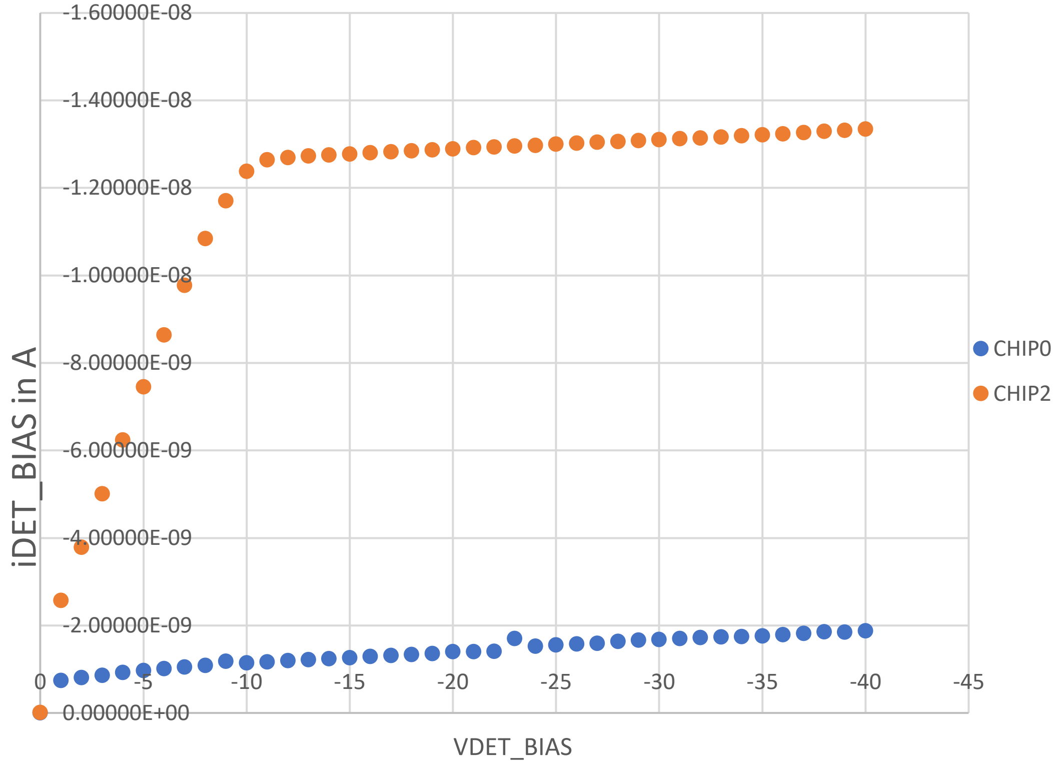


- Diode connected nmos for DNW bias 1
- Cc decouples CSA from leakage path
- CSA to integrate input charge over feedback capacitor C_f 2
- CSA output compared against threshold voltage to produce time-over-threshold pulse 3
- Comparator decoupled from CSA to allow for trimming of V_{TH}
- Comparator output used to charge C_{T2V} for time to voltage conversion 4
- Same readout as the low gain pixel

idle power consumption ≈ 7.5uA @ 1.8 V = 13.5 µW / pixel
For 16 cm^2 covered by 160000 pixels
Idle power consumption = 2.16 W
High power consumption!

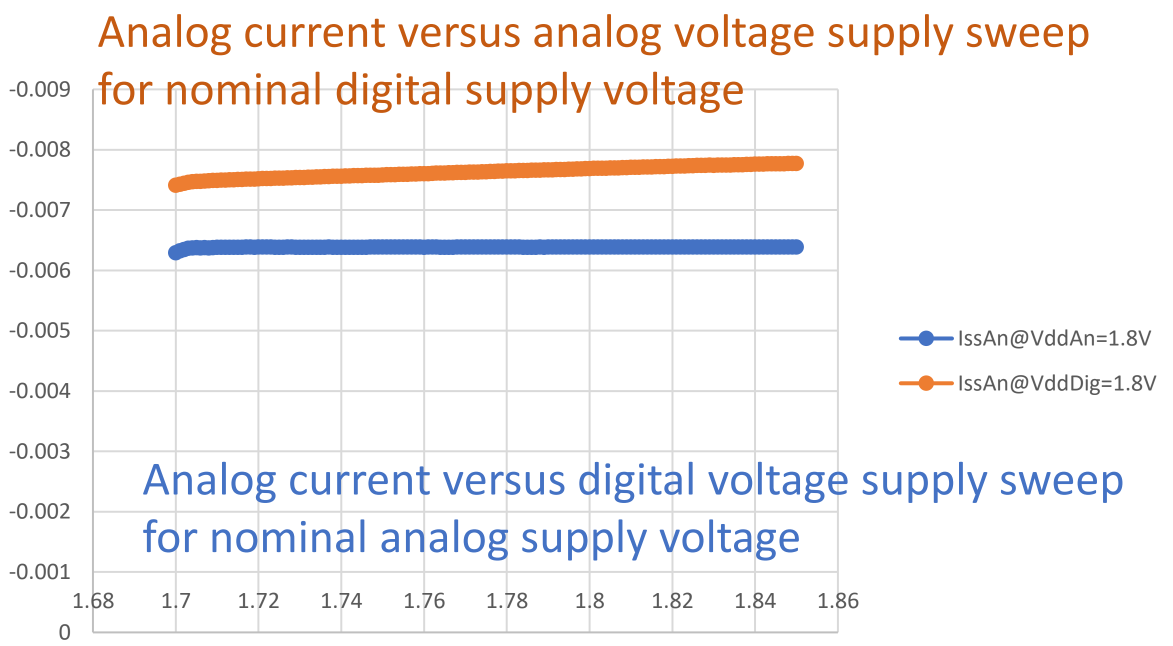
High gain sensor characterization very first measurements (to be continued)

Leakage current



Conclusion: No breakdown occurs for up to -40 V bias

"sanity checks"



No leakage between analog and digital supply domain

DMAPS for LURAD: Specifications

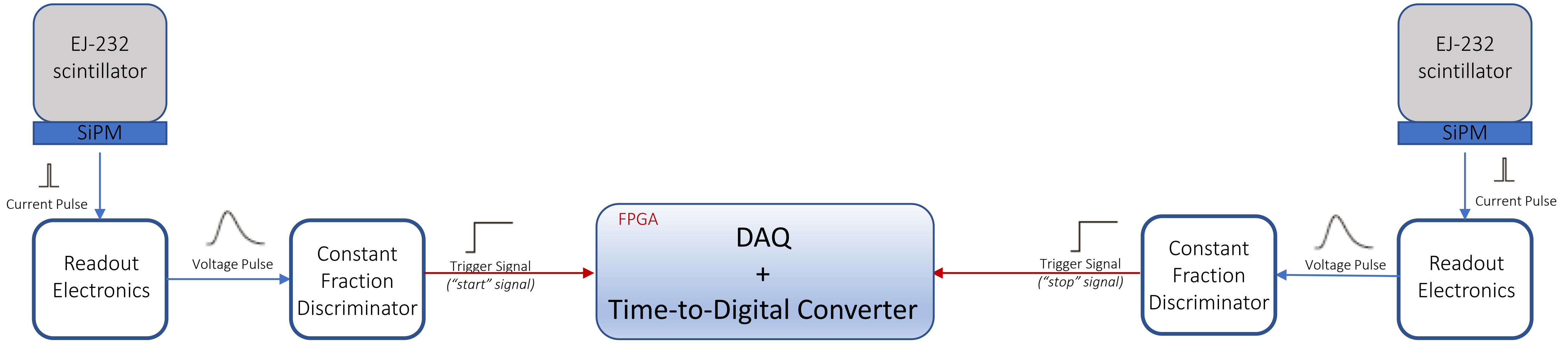
	LOW GAIN PIXEL	HIGH GAIN PIXEL
Pixel size	200x200 um^2	100x100 um^2
Charge range	40fC - 9pC	0.5fC -50fC
Gain	109 mV/pC	17.5 mV/fC (Q_{in}>3fC) 120 mV/fC (Q_{in}<3fC)
Idle power consumption	35nA/pixel	7.5uA/pixel
Noise charge	1.5fC	200aC
Digitization	Embedded SAR ADC 11 bits @ 10 MHz	
Communication	SPI @ 10 MHz	
Readout mode	Only hit pixels/all pixels/specific pixel	

No charge amplifier !
idle power consumption ≈ 35nA @ 1.8 V = 63 nW/pixel
For 16 cm^2 covered by 40000 pixels
idle power consumption = 2.52 mW
A very low power figure !!!

idle power consumption ≈ 7.5uA @ 1.8 V = 13.5 µW / pixel
For 16 cm^2 covered by 160000 pixels
Idle power consumption = 2.16 W
High power consumption!

- Low gain and High gain sensors combined cover a dynamic range from 0.5fC to 9pC
- Common top-level architecture and read-out circuitry for the two sensors

Time of Flight



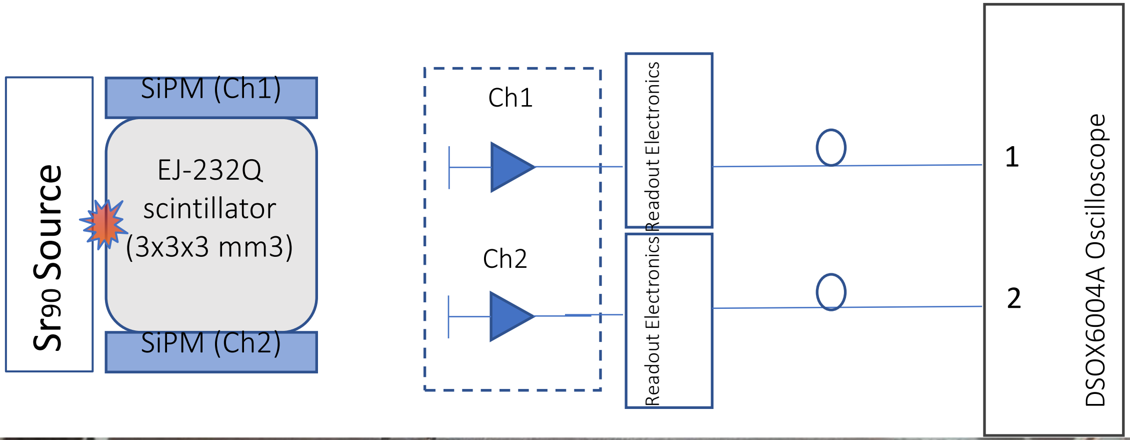
ToF Specifications:

- Distance between 2 detectors = 30cm
- Time of Flight measurement duration up to 2ns
- Resolution better (lower) or equal to 30ps

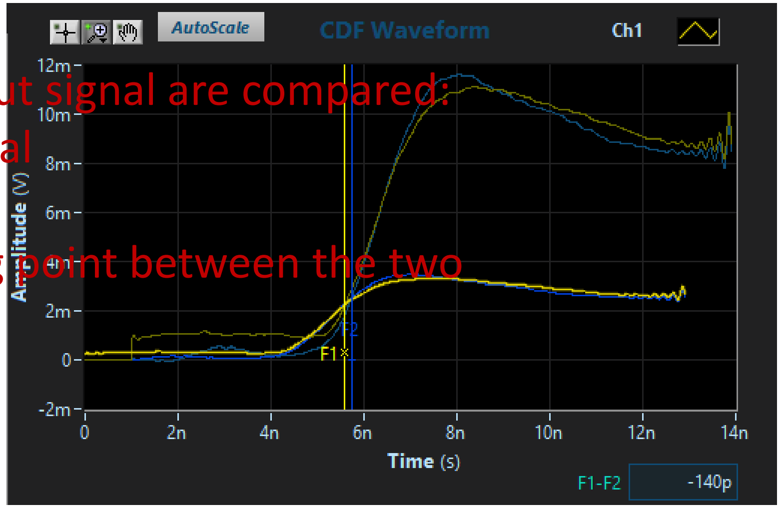
Development Strategy:

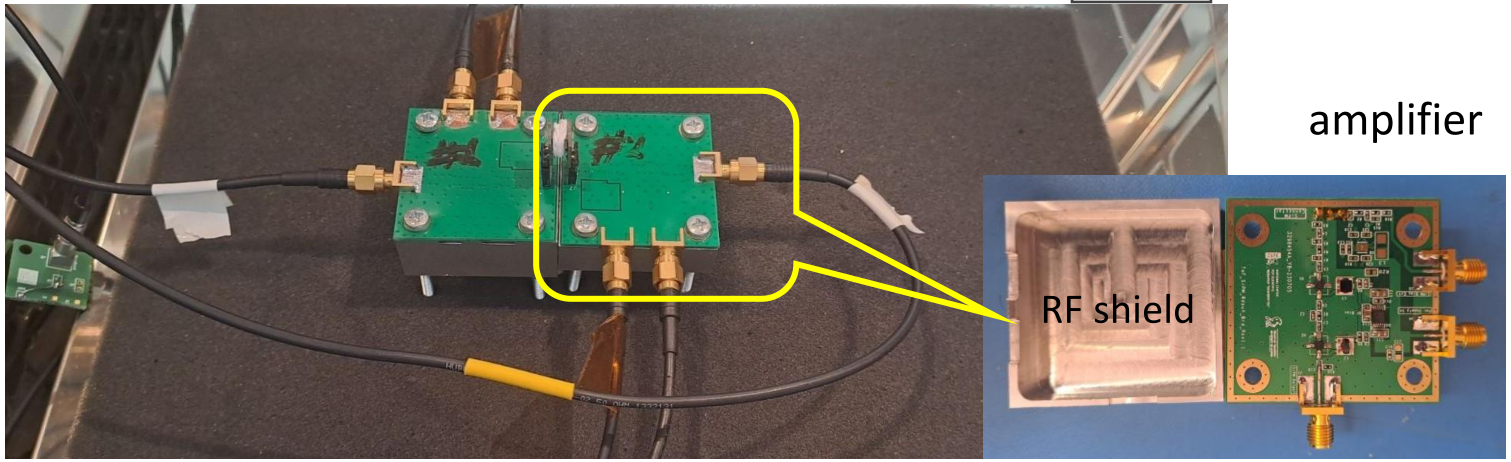
- Construct a "reference detector with a small scintillator (time resolution around 10 ps)
- Characterize the 5 cm x 5 cm x 5 mm scintillator with the aid of the reference detector
- Construct the final detector system and characterize with beams

Reference time of flight detector

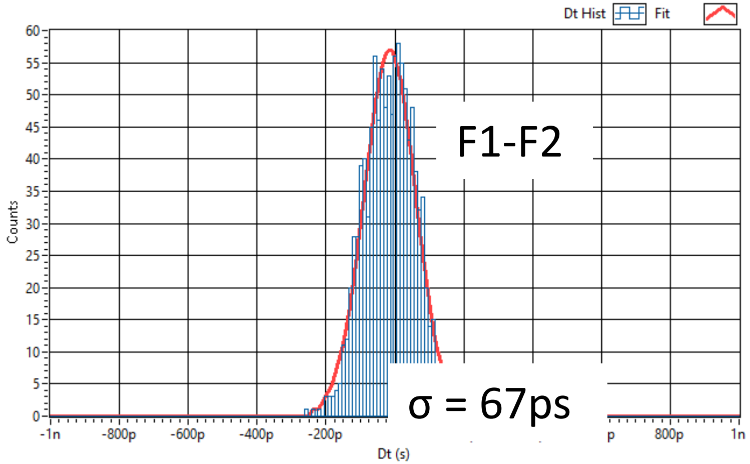


Two copies of the input signal are compared:
Attenuated input signal
Delayed input signal
Timing of the crossing point between the two signals is constant





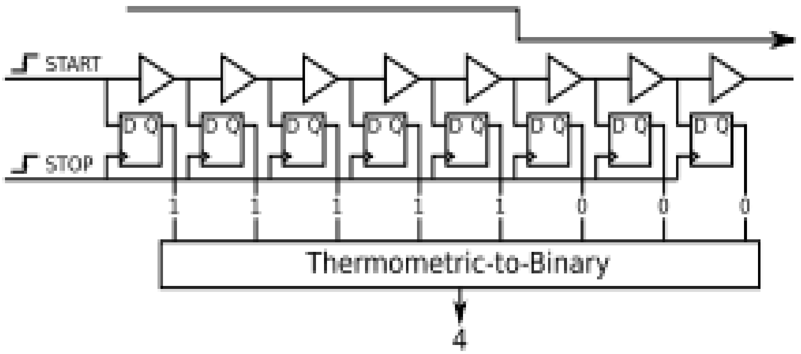
amplifier

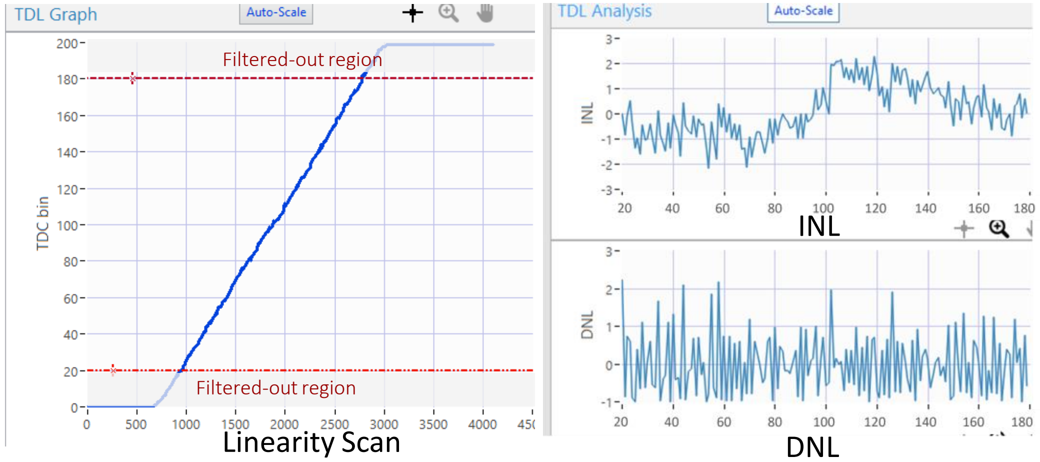


Dt (F1-F2) Histogram

Time to digital Converter + Constant Fraction Discriminator

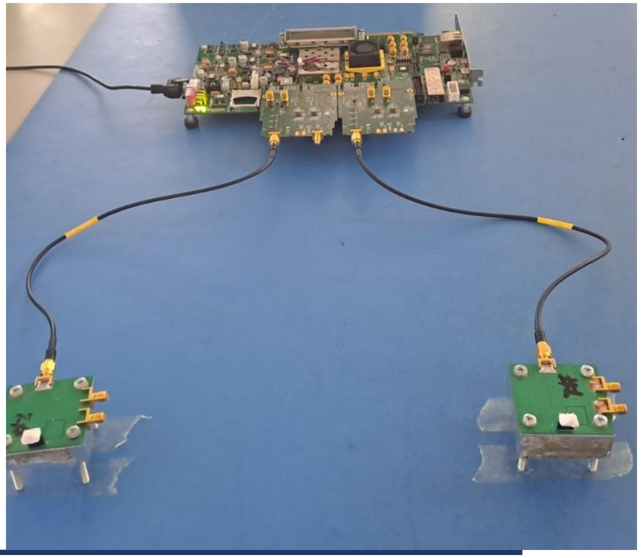
Time-to-Digital Converter (TDC) based on Multiple Tapped-Delay-Line (TDL)



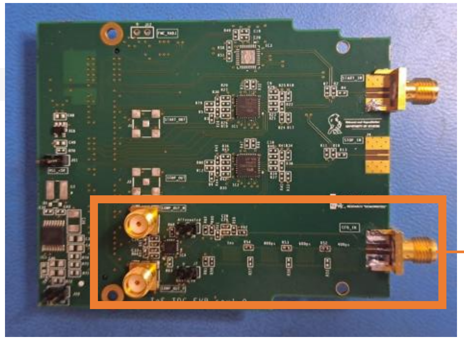


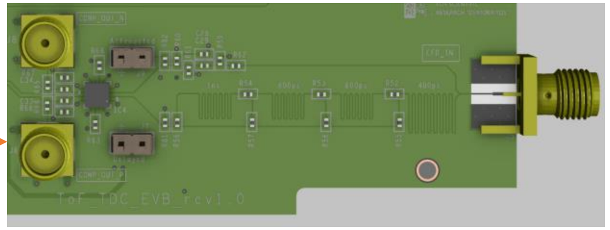
- VHDL implementation in Xilinx 7-series FPGA, taking advantage of the device built-in primitives
- CARRY4 primitive used as the basic delay element

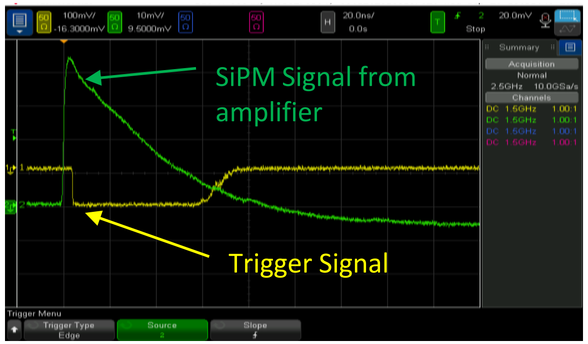
INL +/- 2.3, DNL +/-2.2 (LSB=11.5ps)
Target : TDC real resolution below 10 ps



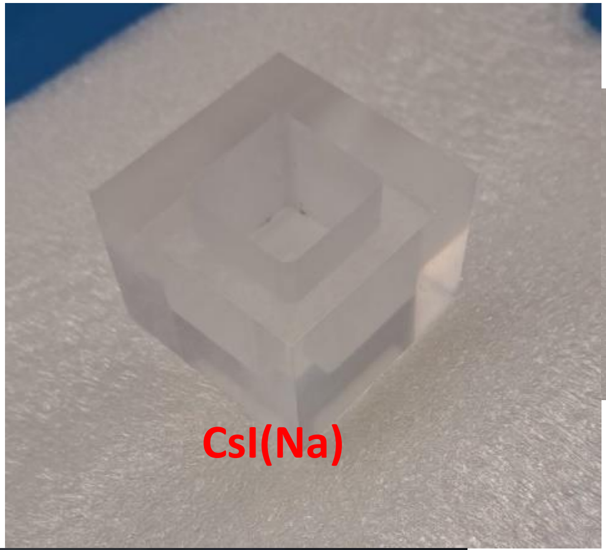
Constant fraction discriminator hardware implementation

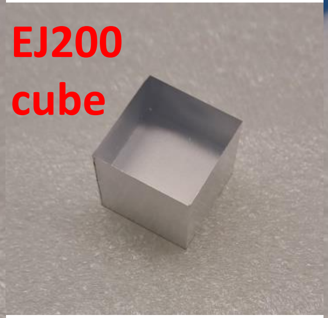


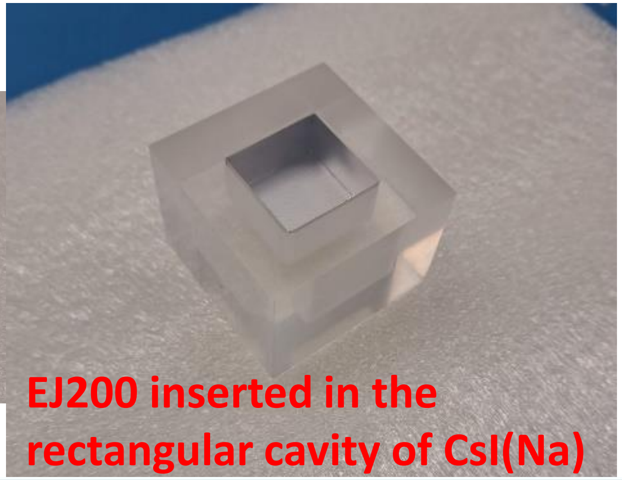


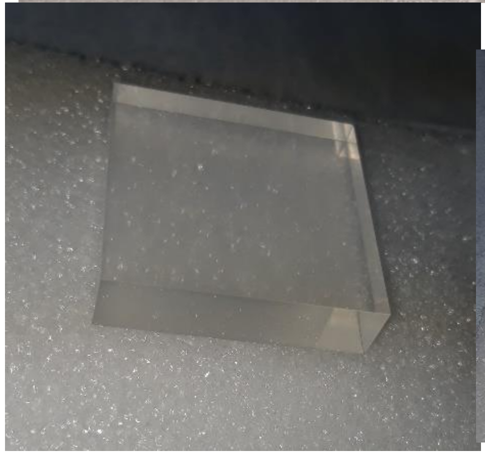


Scintllators + SiPMs cube



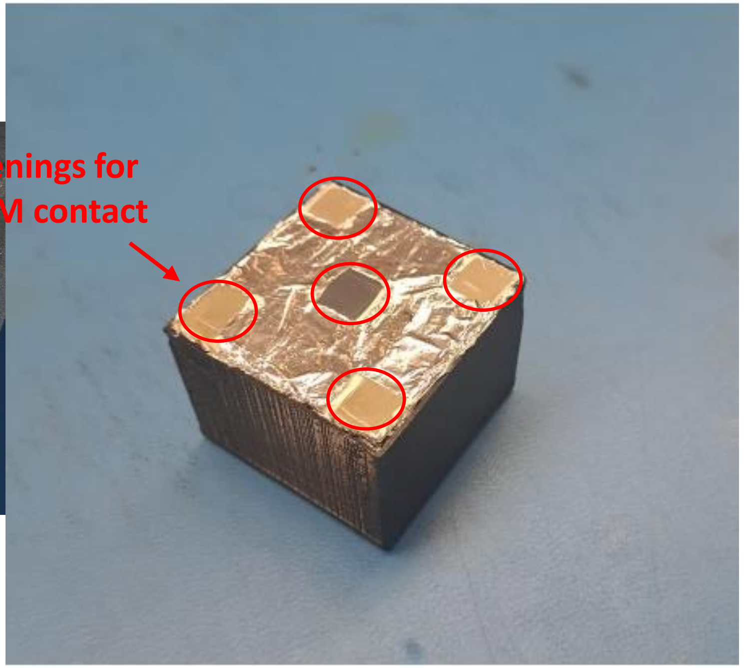


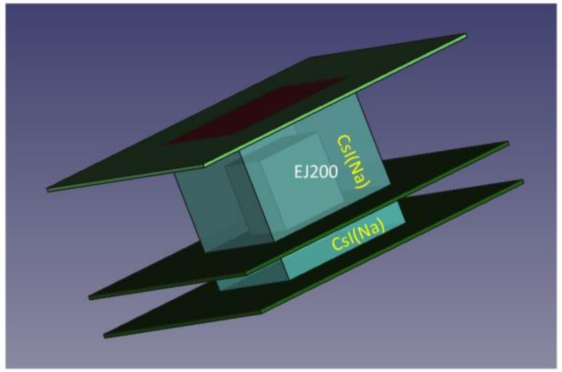




Bottom CsI(Na) plate

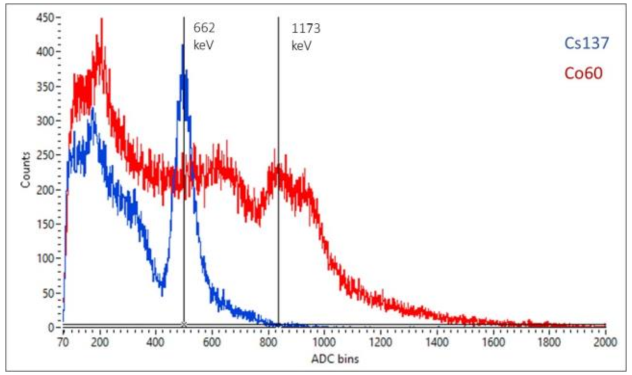
Covered with Teflon

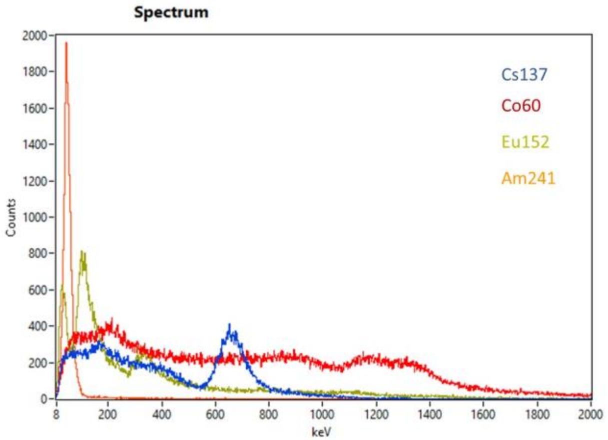




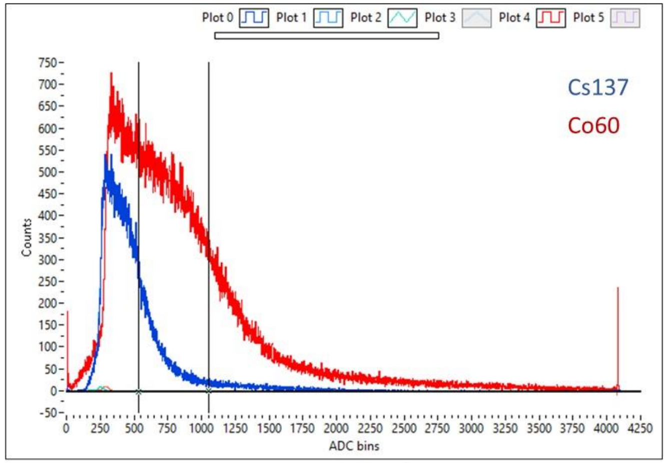
First results with Scintillators and SiPMs

Gamma ray spectra measurements using the SiPM connected to



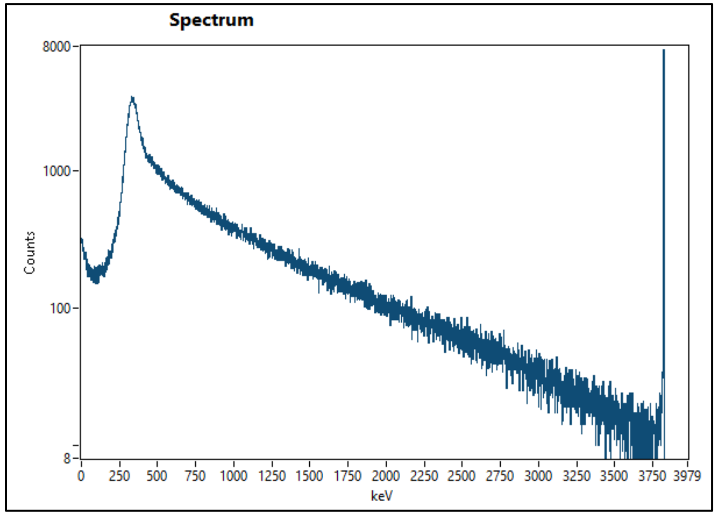


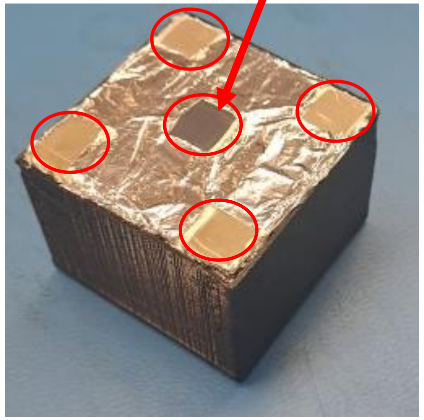
Gamma ray spectra measurements and



Spectrum – ADC bins

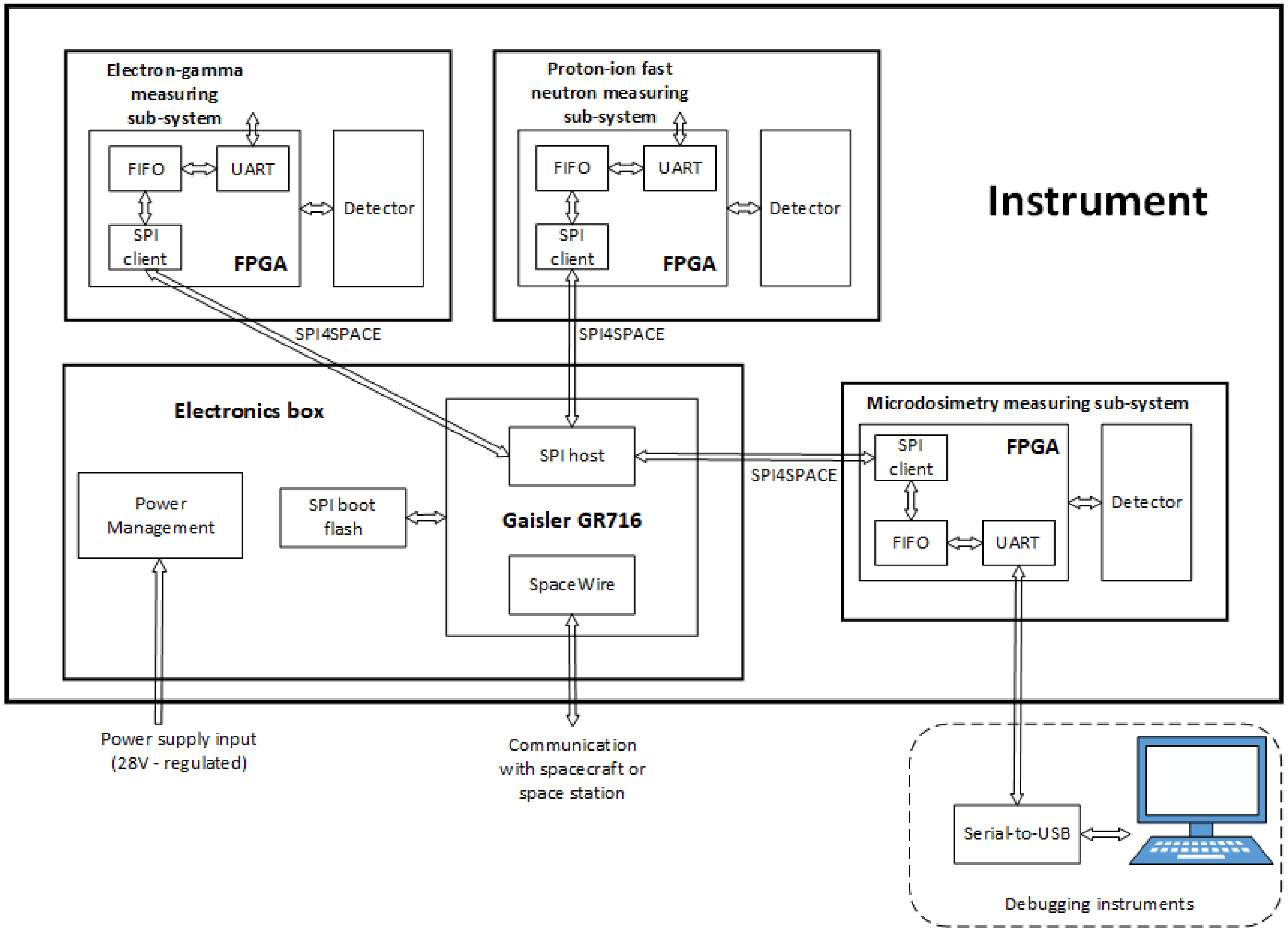
Spectrum of signals from AmBe neutrons using the SiPM (plastic EJ200)



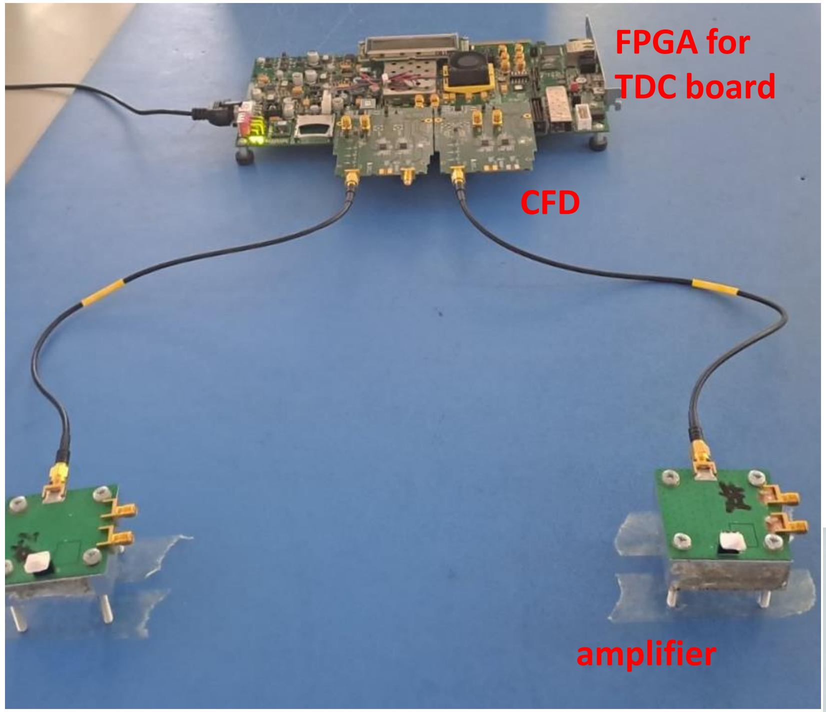


Conclusion from all measurements: More SiPMs are needed to improve light collection.

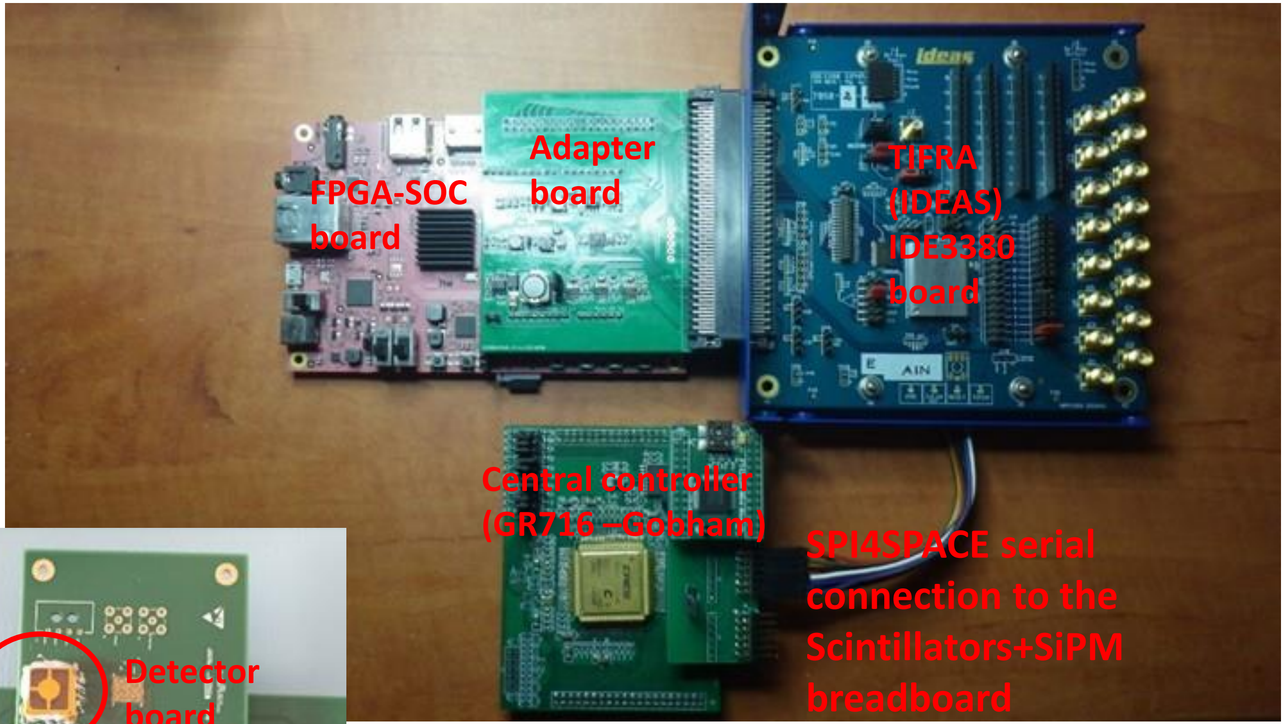
LURAD system electronics block diagram

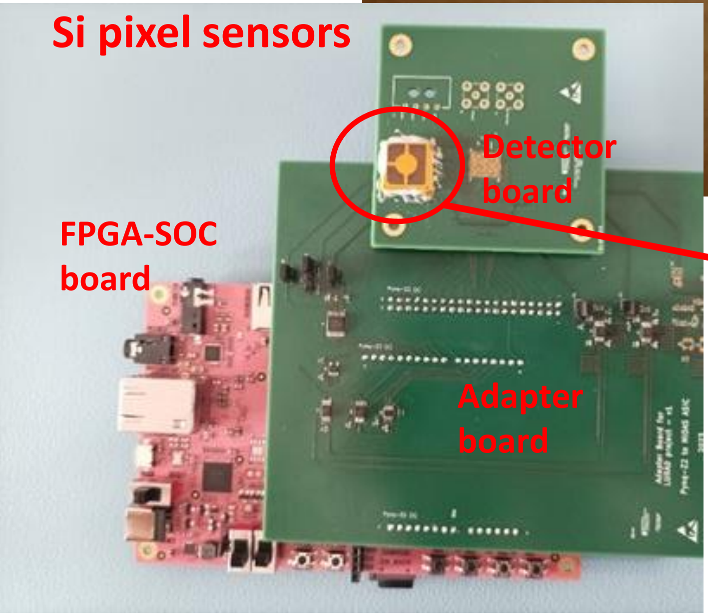


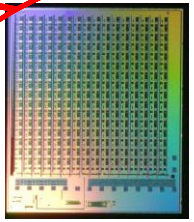
Breadboards:

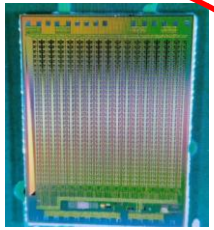


Time-of-flight









low gain — high gain

Recapitulation

Simulated Measurement Capabilities. LURAD in the lunar radiation field will:

- ✓ Identify charged particles with Z=1 to Z=26 or higher
- ✓ Measure kinetic energy of protons and ions from <40 MeV/n up to 2 GeV/n
- ✓ Identify fast neutrons and measure their kinetic energy from 0.1-0.2 MeV up to >200 MeV
- ✓ Discriminate electrons + positrons from gammas
- ✓ Measure energy spectra of electrons + positrons from <1 MeV to 20 MeV
- ✓ Measure energy spectra of gammas from 100 keV to 10 MeV
- ✓ Provide early warnings for SEP events

Verified with experiments

- ✓ Provide microdosimetric measurements with ions in LET(Si) range from 0.2 keV/µm to 80000 keV/µm

- Final Comments

Parts of the work have not been presented here. (e.g. The work for SPI4SPACE implementation)

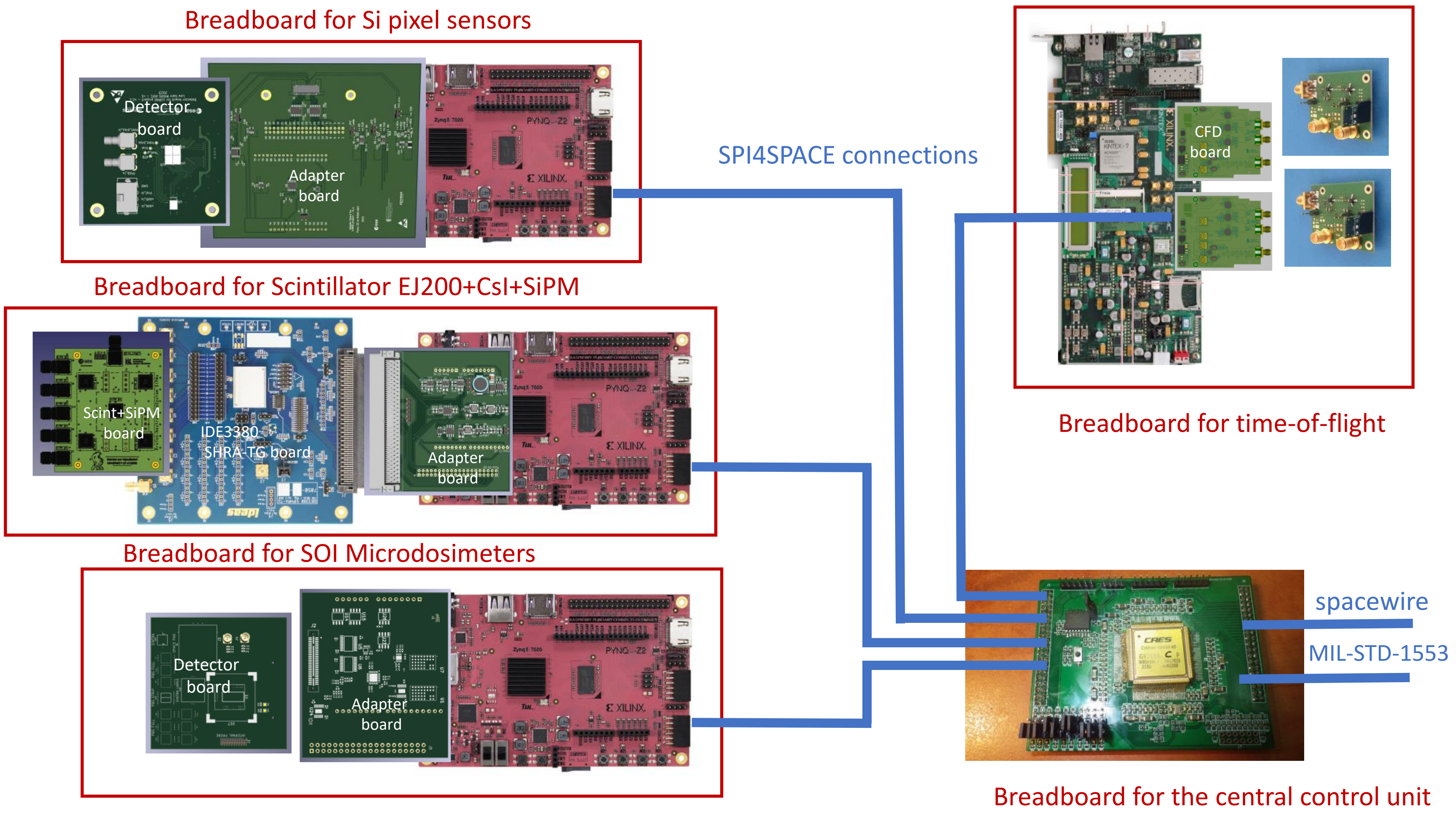
R&D for LURAD is at a very interesting phase:

- **A considerable experience for the development of the DMAPS sensors has been acquired. Design optimization will continue by examining closely the spatial distribution of energy deposition in the pixels and the transport of the charge produced.**
- **The minimization of the time resolution of the "reference detector" is pending as well as the construction and characterization of the actual time-of-flight system**
- **The construction of a new scintillator+SiPM cube and continuation of characterization with beams and radioactive sources.**

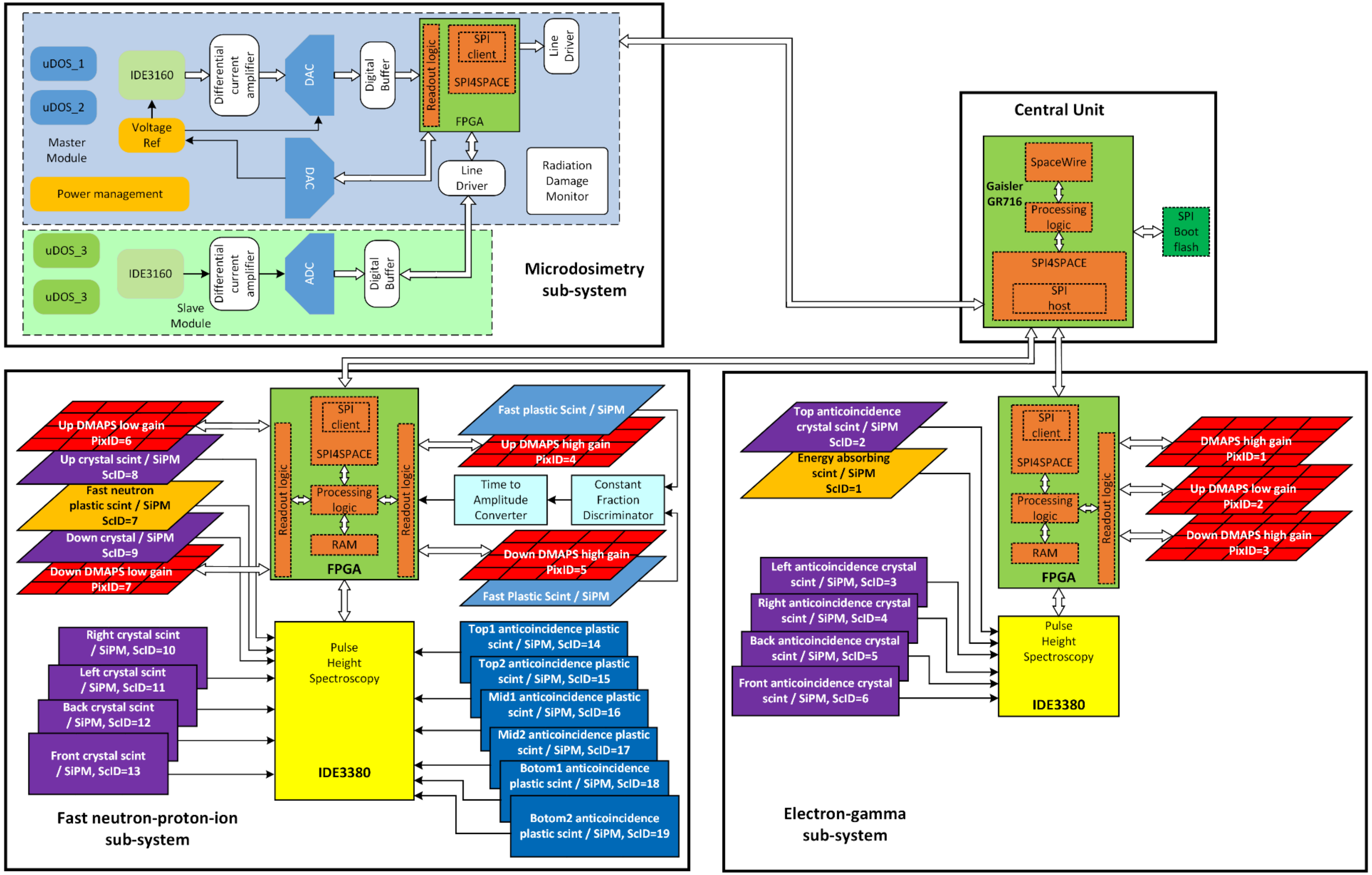
Thanks to Giovanni Santin for support and amazing collaboration!

BACKUP SLIDES

LURAD breadboards

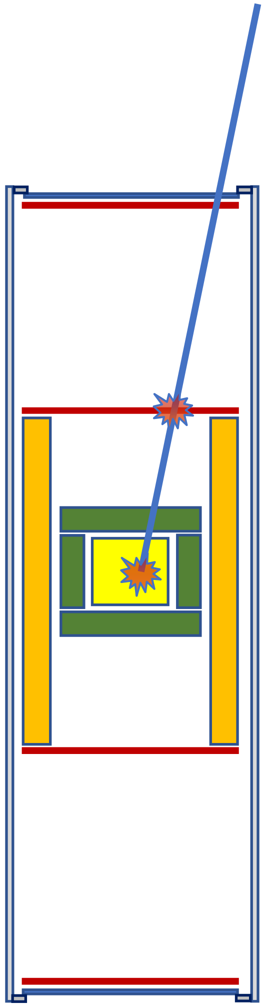


LURAD system block diagram



How to select low – medium –high energy charged particles

40 MeV <$E_{kinetic}$ ≤ 150 MeV

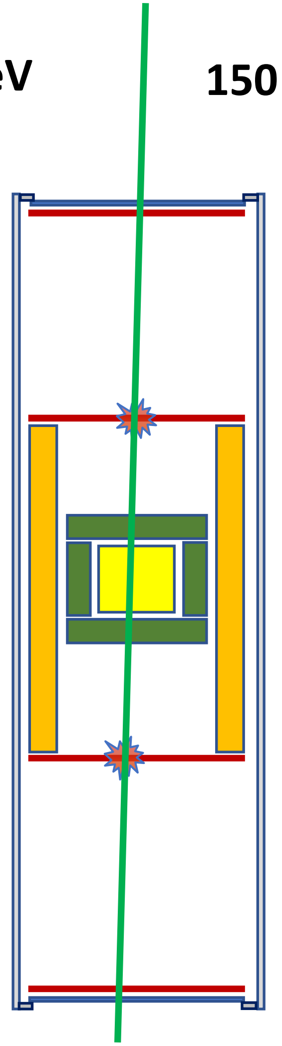


produce signal on one or more scintillator volumes of the central sensitive cube with Edep ≥ 40 MeV;

produce signal on only one of the two low gain Si detectors placed above and below the central sensitive cube

do not produce signal on the EJ200 anticoincidence detectors

150 MeV < $E_{kinetic}$ ≤ 500 MeV

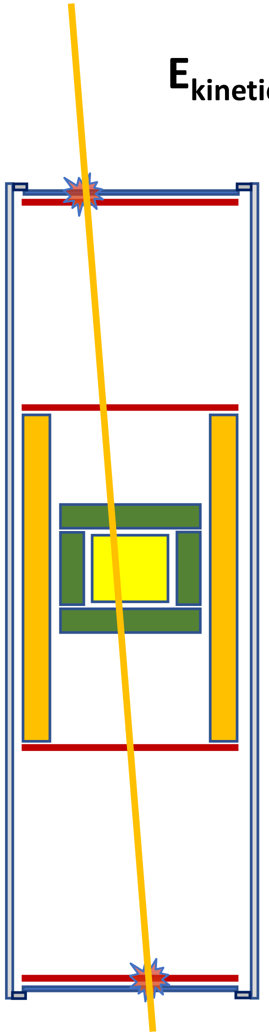


produce signal on one or more scintillator volumes of the central sensitive cube;

produce signal on both the low gain Si detectors placed above and below the central sensitive cube

do not produce signal on the EJ200 anticoincidence detectors

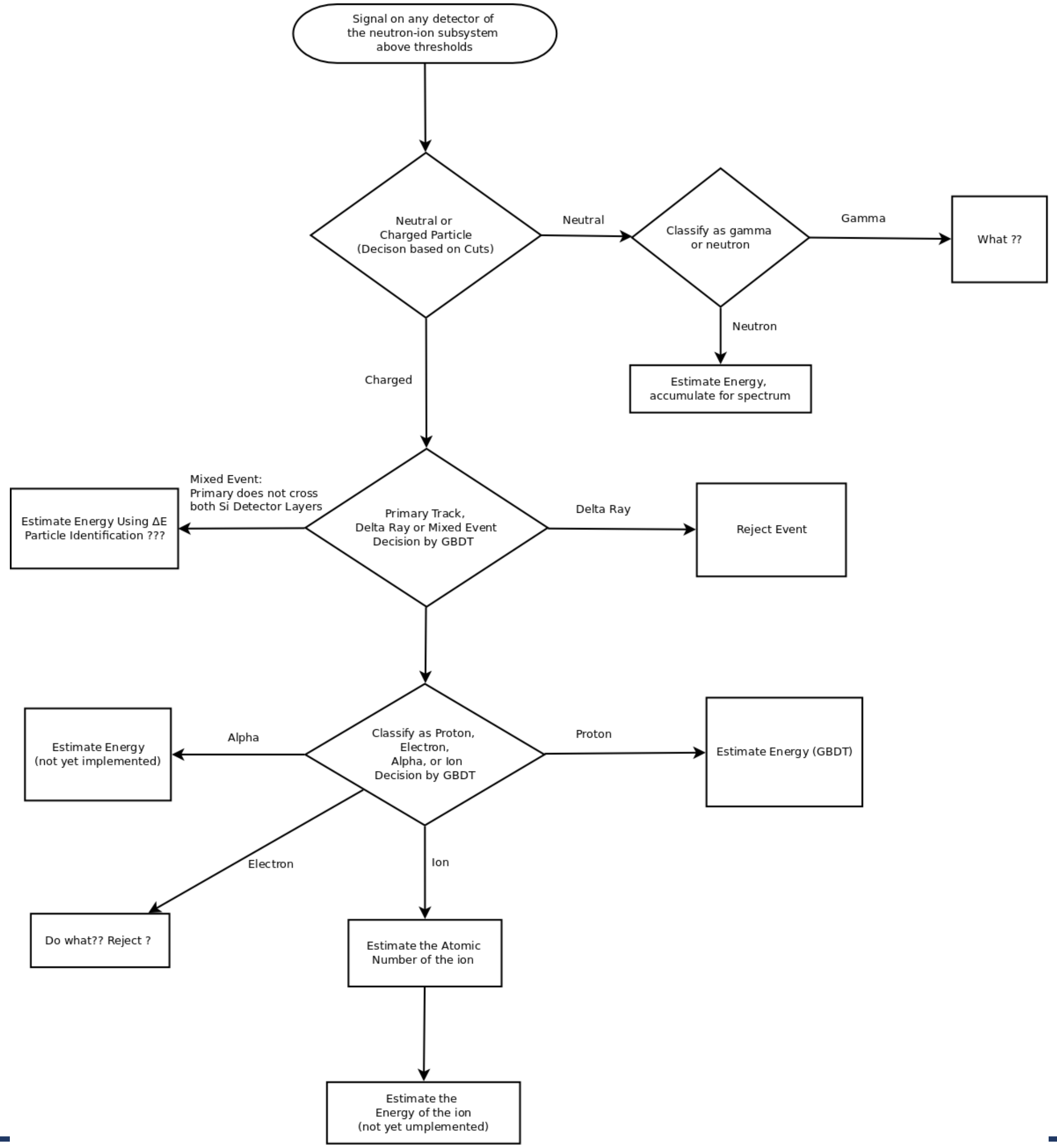
$E_{kinetic}$ > 500 MeV



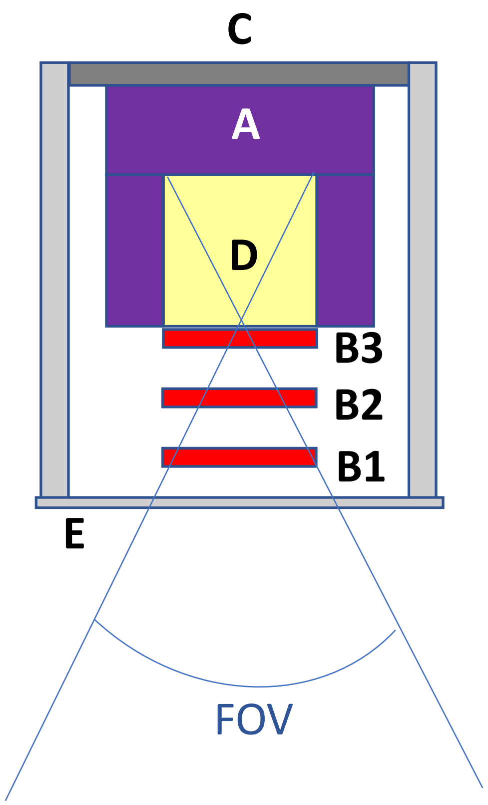
produce signal on both fast scintillators

do not produce signal on the EJ200 anticoincidence detectors

Proton-ion-fast neutron data analysis flowchart



How to select gammas or electrons



Criterion C1: (Select photons)

If energy > 50 keV is deposited ***only*** on **D** then the event is probably a ***photon***

Purity: almost **93%** -- **Efficiency: 97.5%**

Criterion C2: (Select electrons)

If energy is deposited on B1, B2, B3 and D in coincidence **AND**

Only one energy cluster on B2 **AND**

Only one energy cluster on B3 **AND**

Energy deposition on B1 < **150 keV AND**

Energy deposition on D < **18 MeV**

Then the event is probably due to an ***electron*** coming from the FOV

Purity: almost **83%** -- **Efficiency:** almost **66%**

Comment on 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