Development of Silicon Photo-Multiplier (SiPM) Detectors for Muon Scattering Tomography

Shubhabrata Dutta, Saikat Ghosh, Subhendu Das, Nayana Majumdar and Supratik Mukhopadhyay

7th International Conference on Technology & Instrumentation in Particle Physics (TIPP 2026)
2 – 6 February

Saha Institute of Nuclear Physics, Kolkata, India, A CI of Homi Bhabha National Institute

Department of Physics, Government General Degree College, Chapra, Nadia, WB

TIPP2026

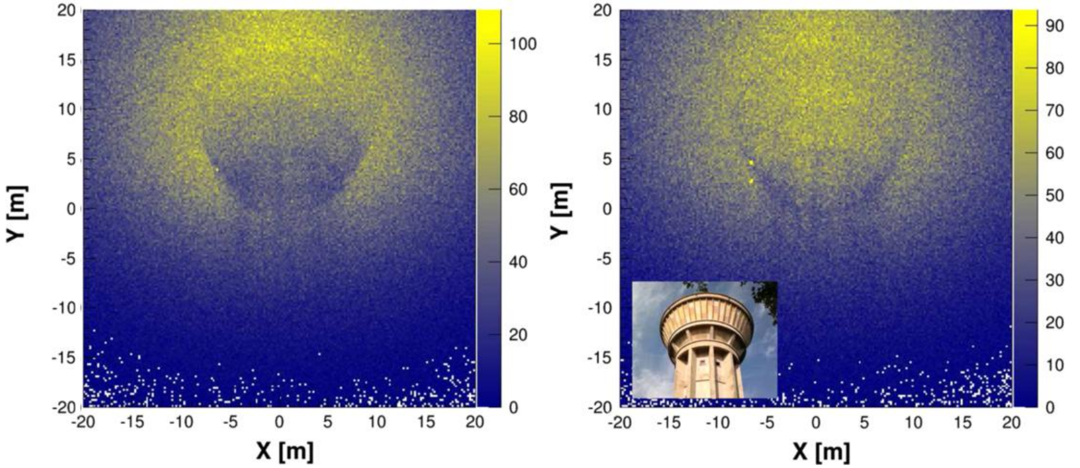
2nd February, 2026

MUON TOMOGRAPHY

- The attenuation and deviation of muons depend both on the properties of the materials crossed.
- These processes can be used in order to infer and/or image the traversed objects.
- This technology becomes a Non-Destructive Testing (NDT) technique with multiple applications.

Absorption muography

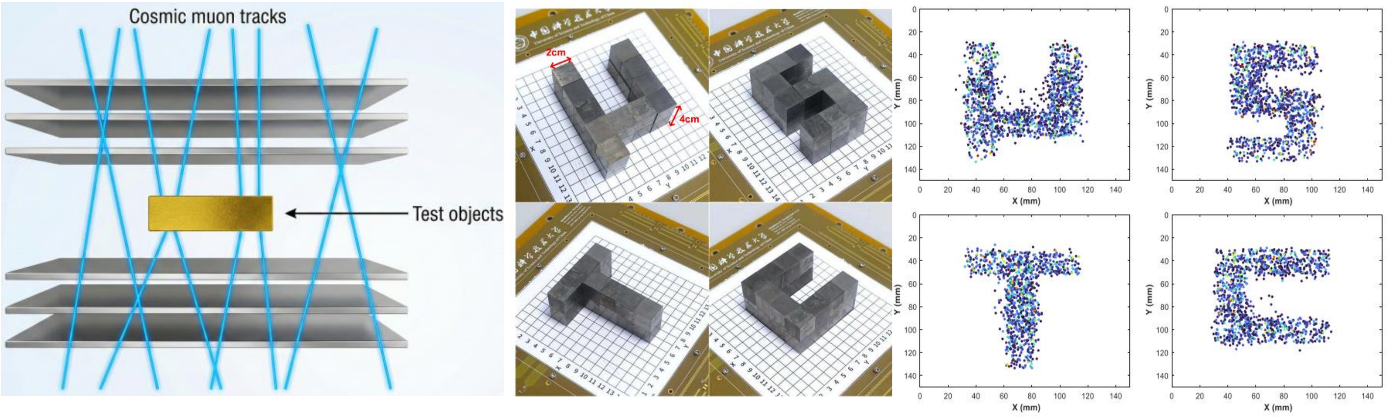
- Muon flux measured vs direction (attenuation)
- One single detector needed
- Need large object + long exposure times
- Typical applications: geology, volcanology, etc



S. Bouteille *et al.*, "A Micromegas-based telescope for muon tomography: The WatTo experiment doi.org/10.1016/j.nima.2016.08.002

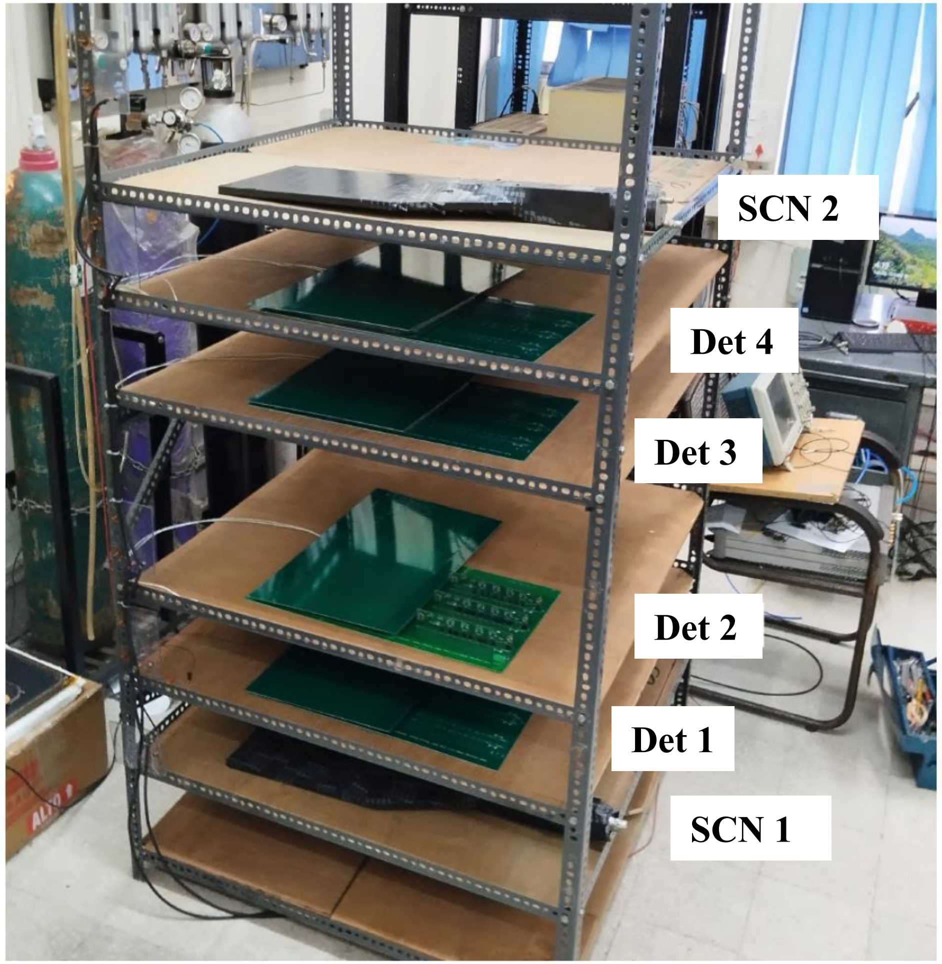
Scattering muography

- Muon angular deviation (scattering)
- Two layer of detectors needed
- Small-medium size objects + short exposure times
- Typical applications: border security, nuclear, etc

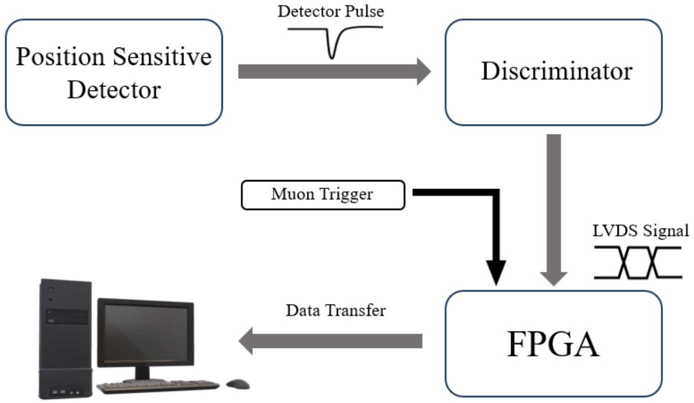


Y. Wang *et al.*, "A High Spatial Resolution Muon Tomography Prototype System Based on Micromegas Detector", doi: 10.1109/TNS.2021.3137415.

MUON TOMOGRAPHY SETUP



- A muon scattering tomography setup is currently under construction.
- High readout granularity requires a substantial number of individual readout channels.
- To cover an area of 30×30 cm^2 240 strips of 1 cm strip size is required.
- Multi-channel Data AcQuisition (DAQ) system for acquiring two-dimensional position information (X,Y) of muon events.
- FPGA-based systems have emerged as optimal solutions.



POSITION SENSITIVE DETECTORS

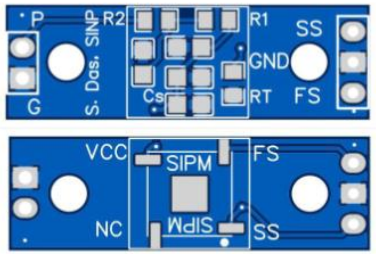
- We want to explore the possibilities of using several types of MPGDs as well as scintillator detector.
- Also trying to build a scintillator-SiPM detector prototype, which will be compatible with the existing DAQ setup.

Why Scintillator ?

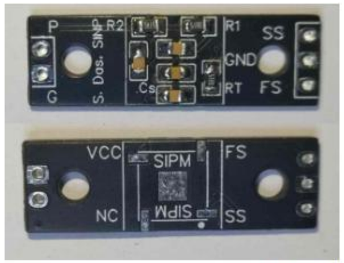
- **Lower Voltage Requirements:** Operates at low voltages unlike gaseous detectors requiring high voltage (kV range).
- **Compactness:** Small, lightweight, and ideal for portable or space-constrained setups.
- **Operational Simplicity**: No need for gas handling systems or constant monitoring.
- **Robustness:** Resistant to environmental changes and mechanical stress, Reliable across various conditions
- **Scalability:** Easily scalable for large-area detection.

DETECTOR PROTOTYPE

- Scintillator-SiPM strip type detector.
- Fabricated using material available in our lab.
- Can be used as a detector layer in muon stack.

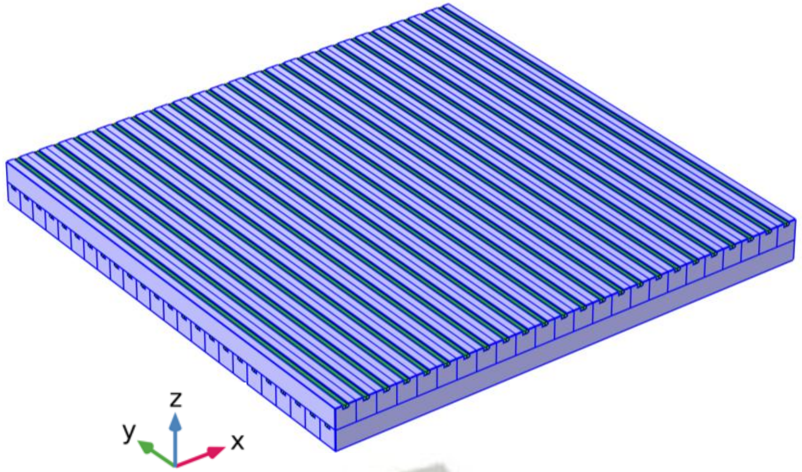


(a) Schematic of PCB



(b) PCB with placed components(without SIPM)

Detector layer with an array of strips



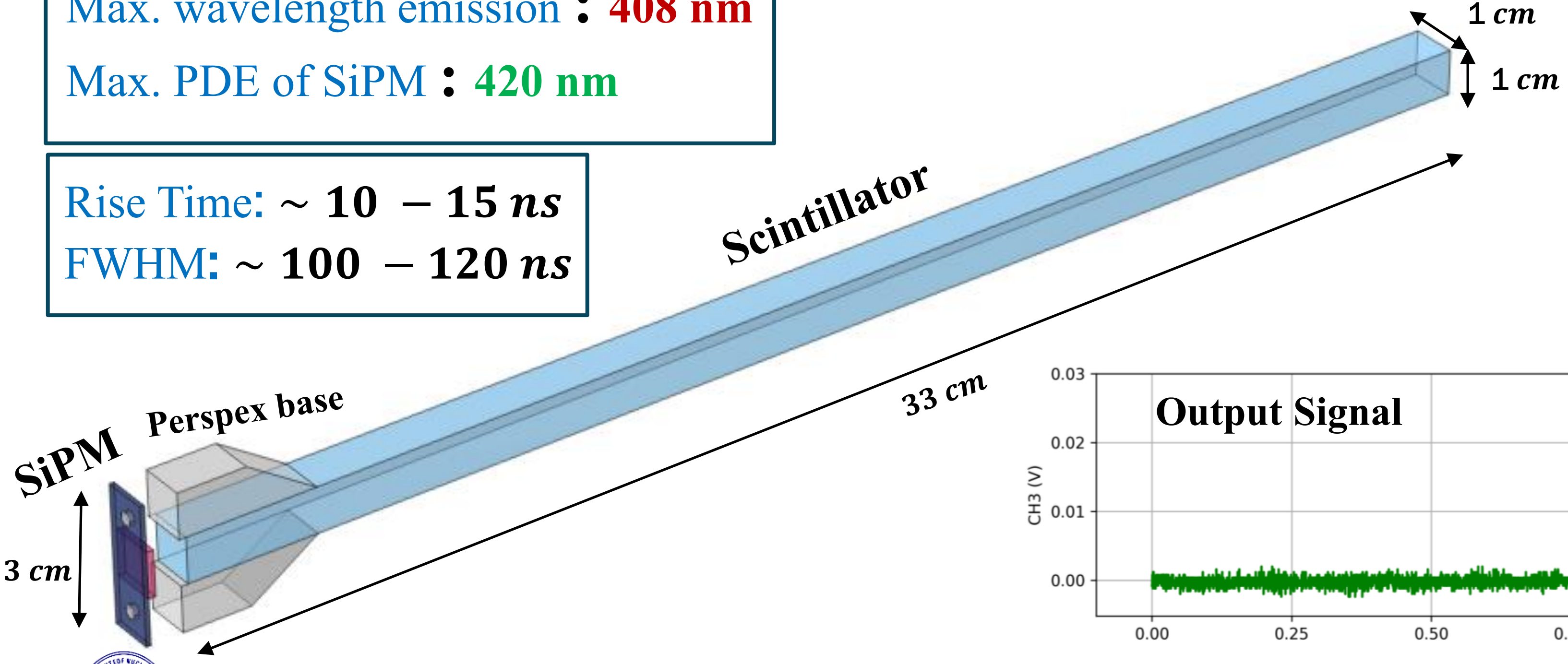
Scintillator Material : BC 404

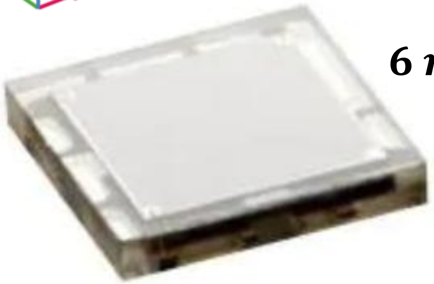
Max. wavelength emission : 408 nm

Max. PDE of SiPM : 420 nm

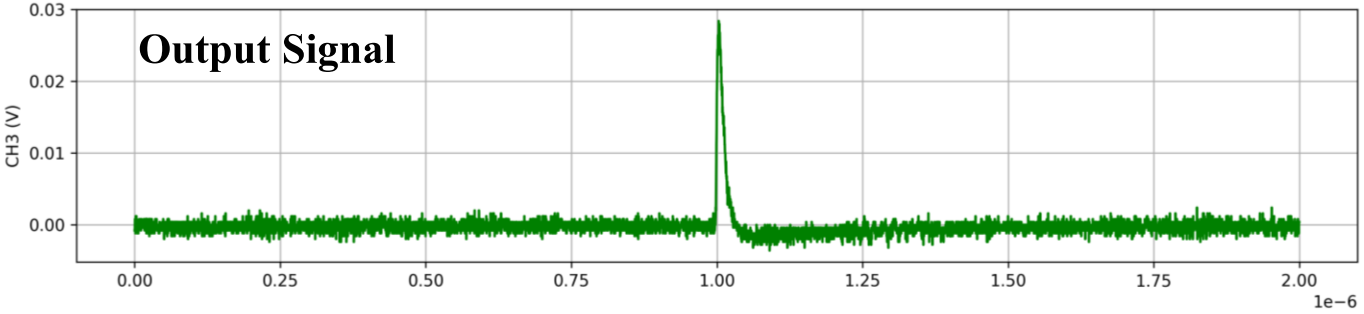
Rise Time: $\sim 10 - 15\ ns$

FWHM: $\sim 100 - 120\ ns$

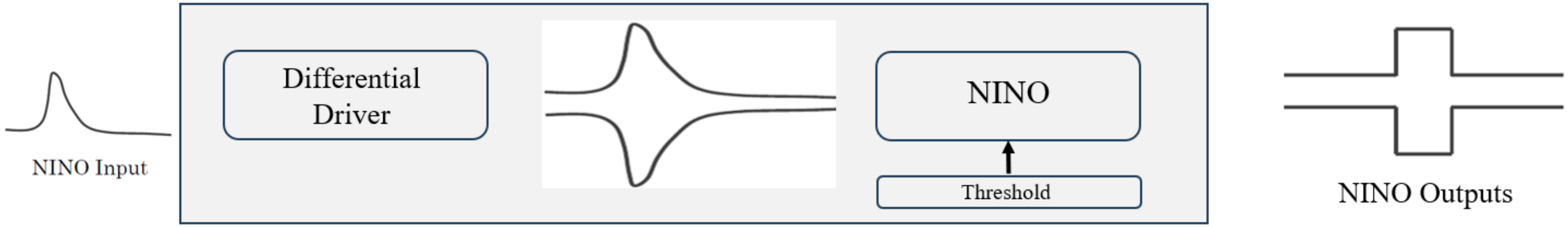




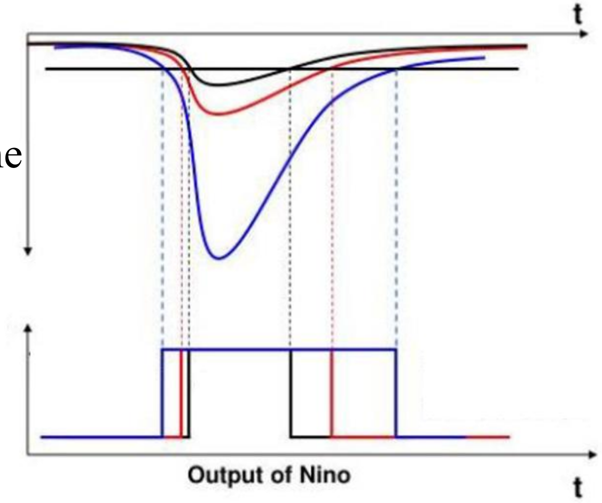
MICROFC-60035-SMT-TR [1]

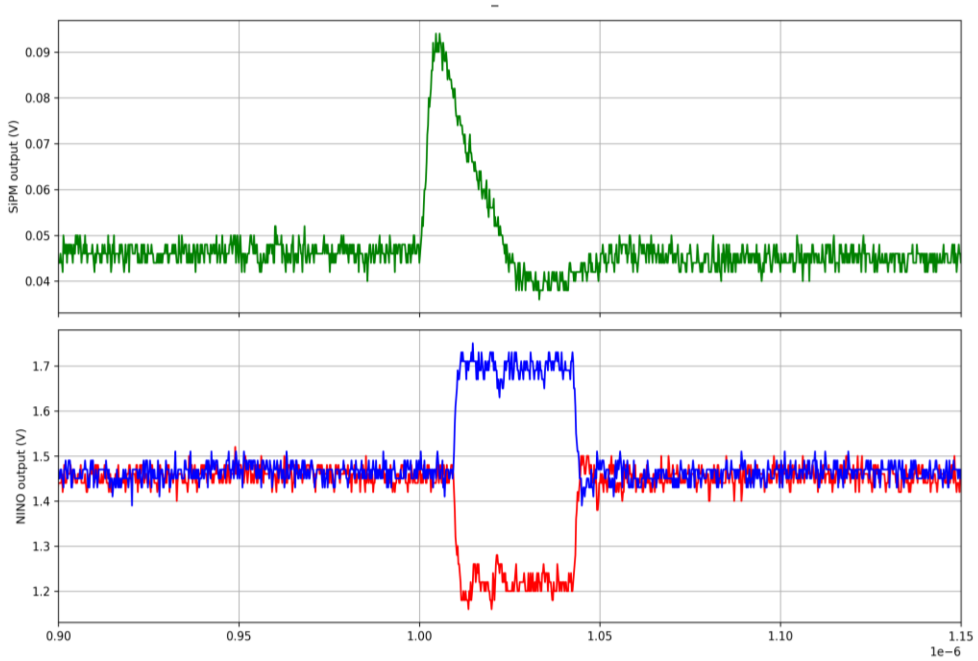


FRONT-END ELECTRONICS (FEE), NINO ASIC



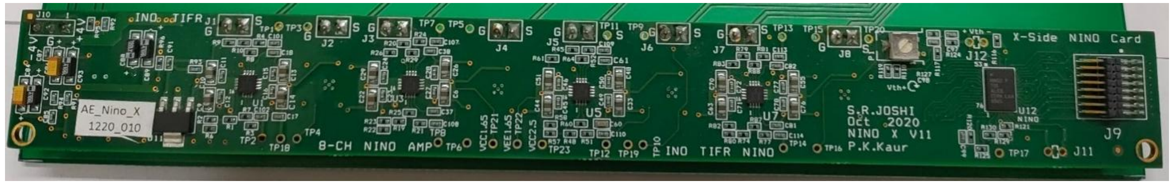
- Time over threshold (TOT) related to charge.
- Developed for Time-of-Flight (TOF) array of the ALICE experiment
- Adjustable threshold level of ***10 - 100 fC*** .
- 1 NINO board accommodate 8 channels





NINO output for SiPM signal

NINO ASIC[2]



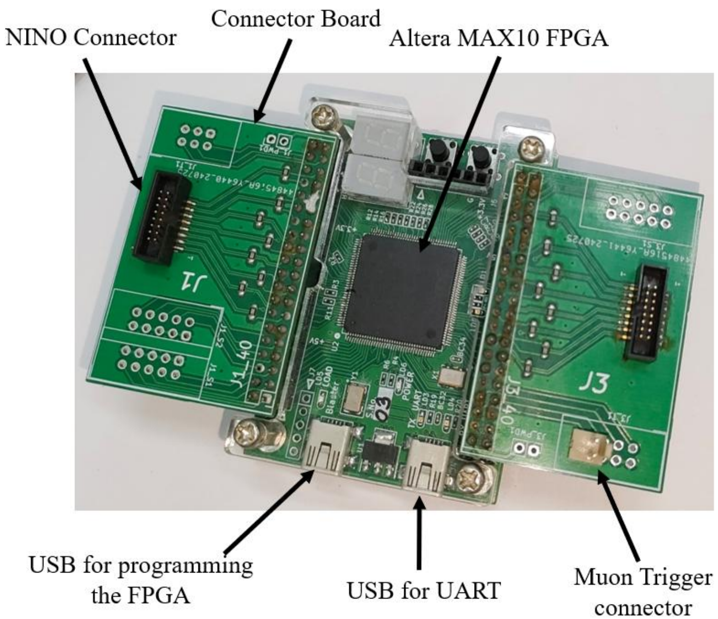
NINO Board *(Designed by INO Collaboration [3])*

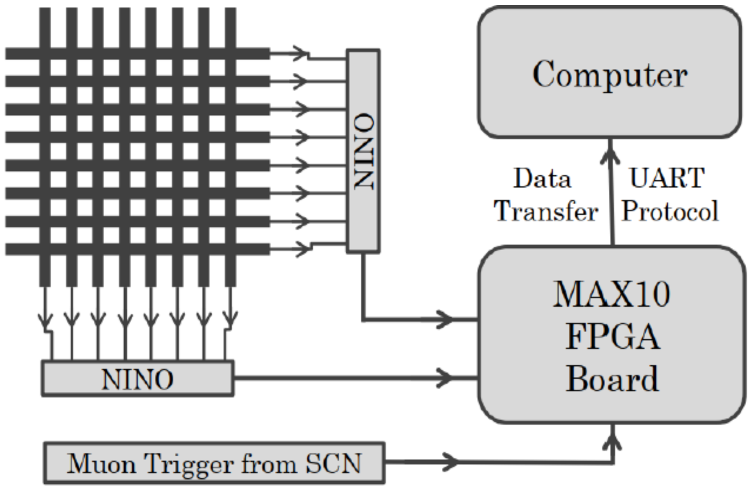
BACK-END ELECTRONICS (BEE), FPGA

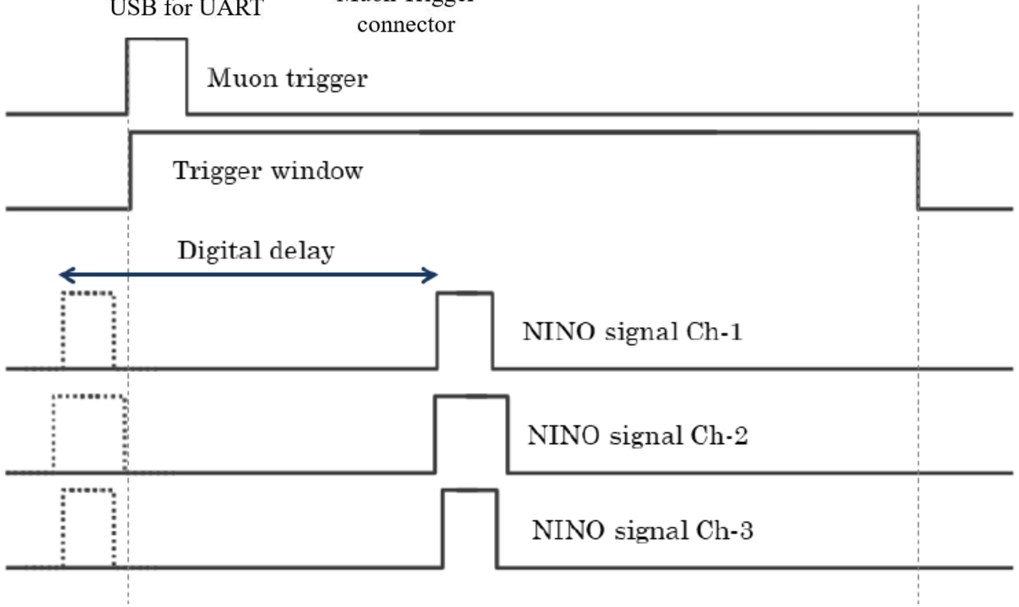
- Programmable, High speed
- Large number of I/O pins
- Logic gates with programmable interconnection.
- Direct acquisition of LVDS signals
- Low cost and easy to get

Altera MAX-10 FPGA:

- 2000 Logic elements (LEs).
- 50 MHz on board clock.
- 108 Kbits embedded memory,
- 101 FPGA I/O pins.
- Two 40-pin GPIO headers.
- 1 FPGA can handle 16 individual channels





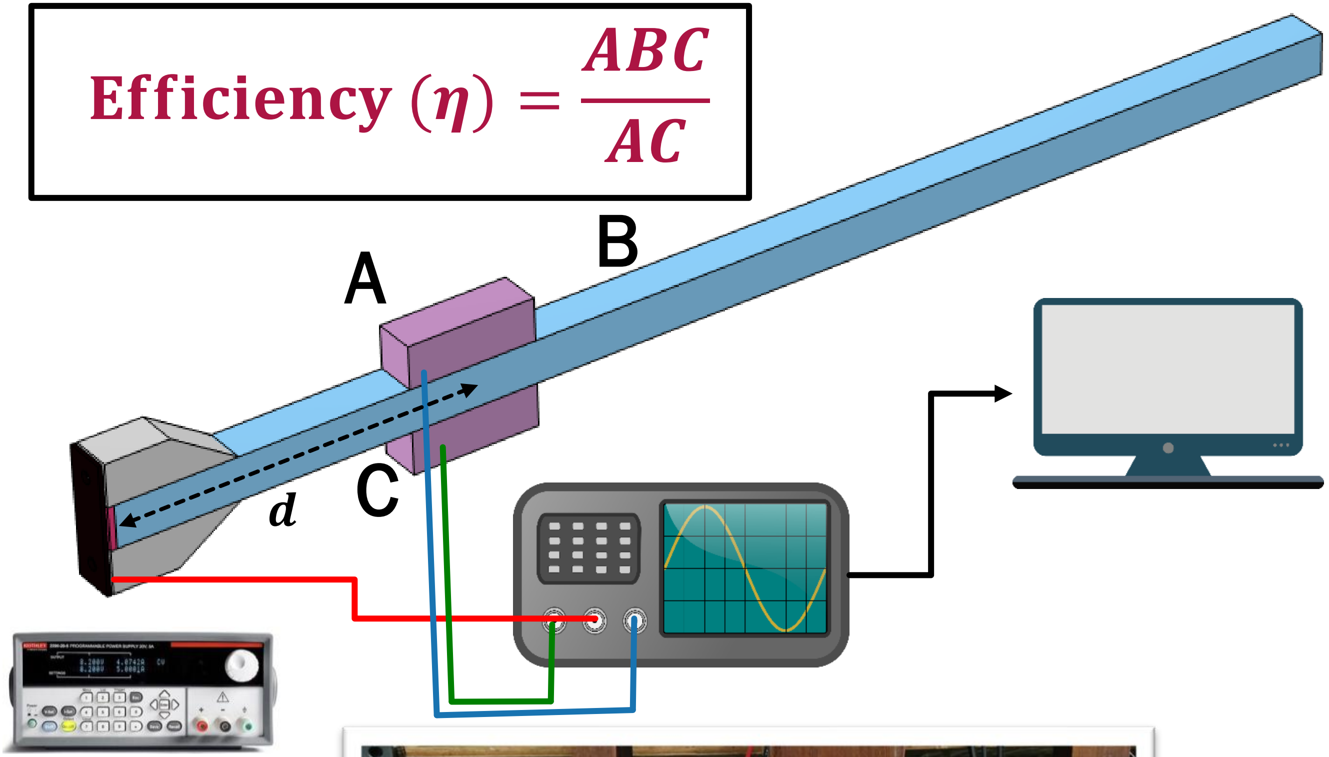


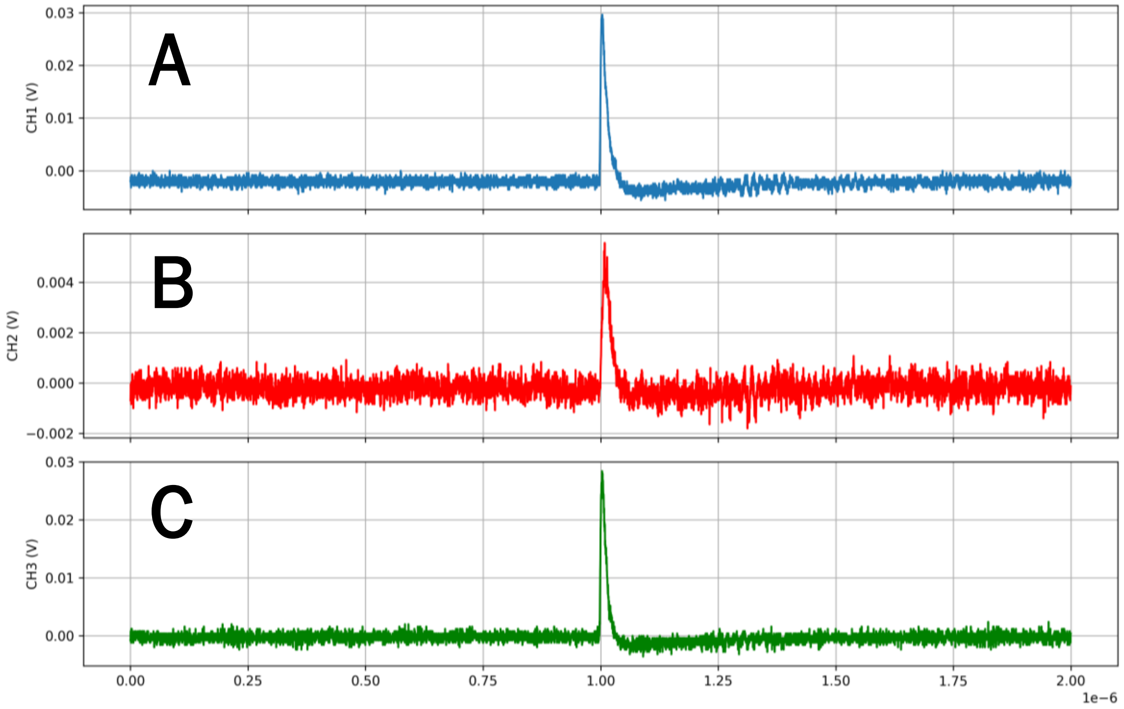
The development board is designed by TIFR for XII SERB EHEP School, 2019 [Link].
Interfacing has been done in our lab using the GPIO headers

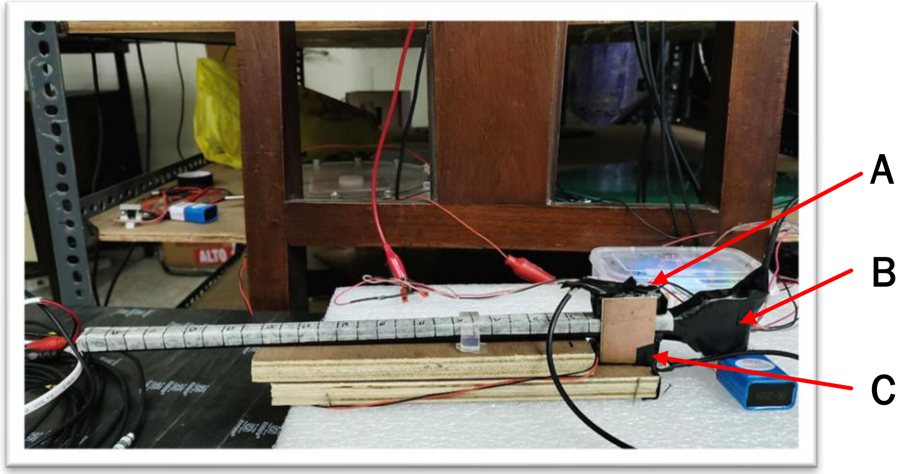
EFFICIENCY STUDY

- To measure the efficiency two small ***3 cm x 1 cm x 1cm*** detector has been used.
- Variation in detection efficiency w.r.t. SiPM distance (***d***) need to be known for optimal detector length selection

$$\text{Efficiency}\ (\eta) = \frac{ABC}{AC}$$







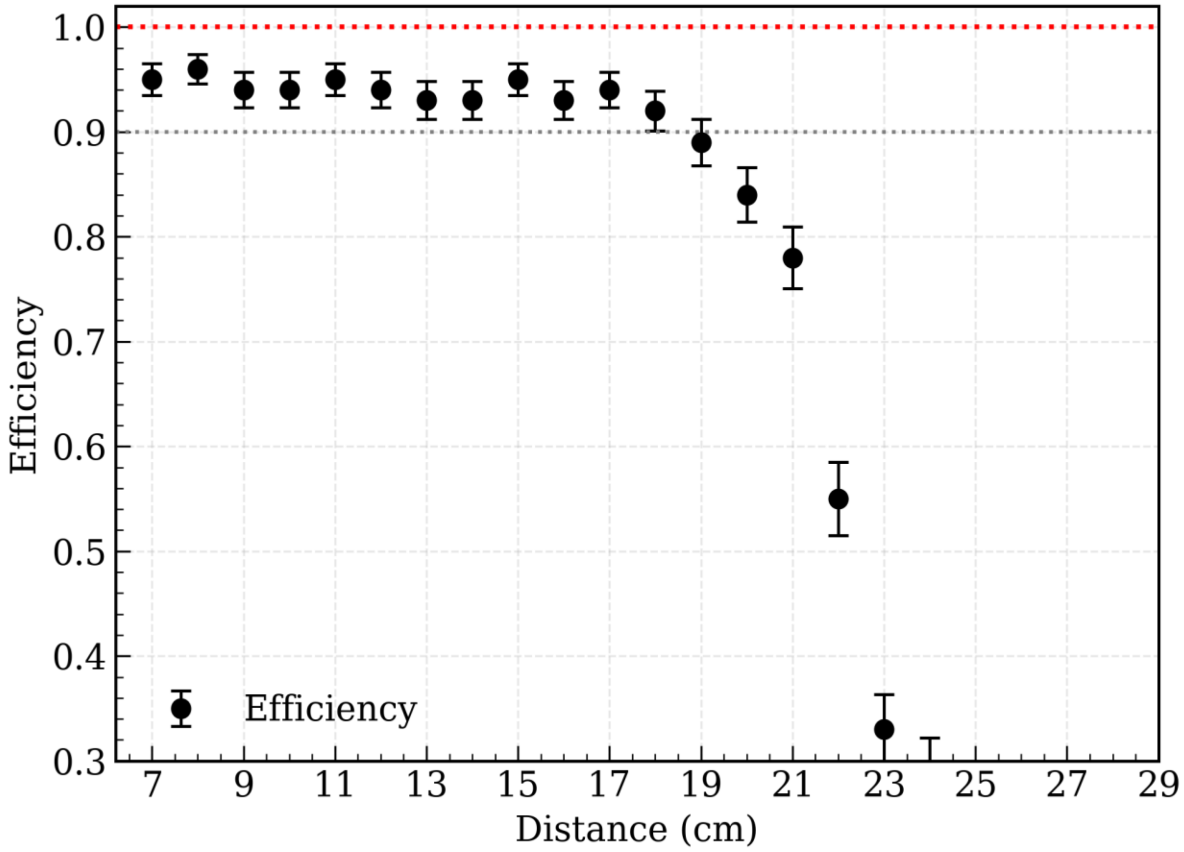
EFFICIENCY RESULT

Observations:

- Efficiency is close to ~95% when the muon passes close to the SiPM.
- As the interaction point moves away, efficiency slowly degrades.
- After ~20 cm, efficiency falls rapidly, reaching very low values.
- Optimal usable length ≈ 18 cm

Conclusion:

Without any light-guiding, the practical strip length is limited to about *18 cm*

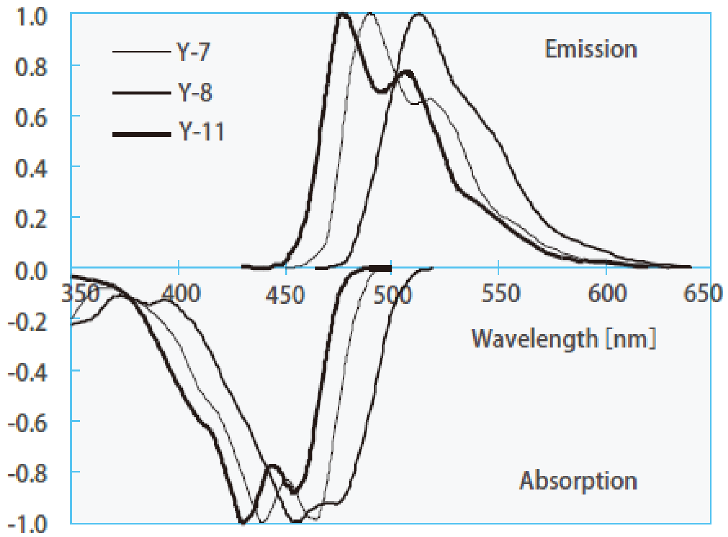


INCLUSION OF WLS FIBER AND REFLECTIVE PAINT

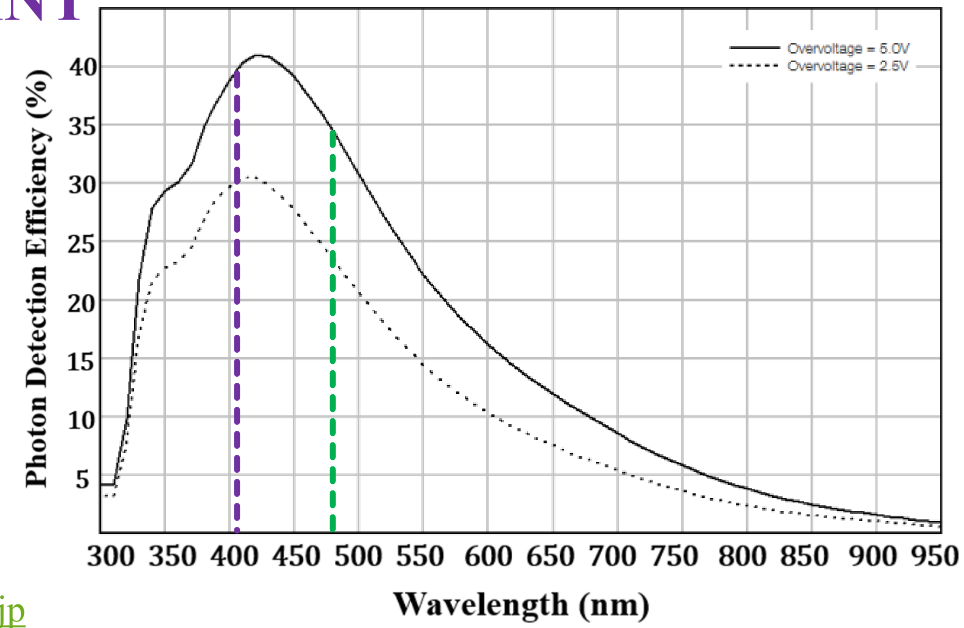
Reflective Coating: TiO_2
WLS Fiber: Kuraray Y-11

Blue to Green Shifter with Long Attenuation Length and High Light Yield

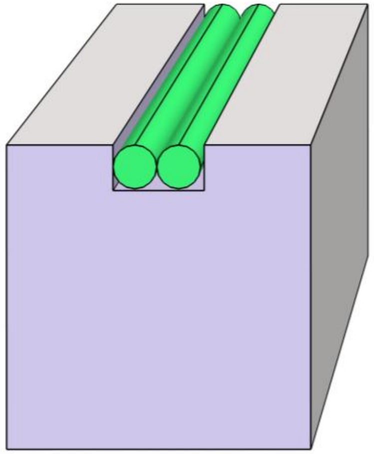
Fiber Diameter: ~ $1.44\ mm$
Peak Emission: $476\ nm$
Att. Length: $> 3.5\ m$

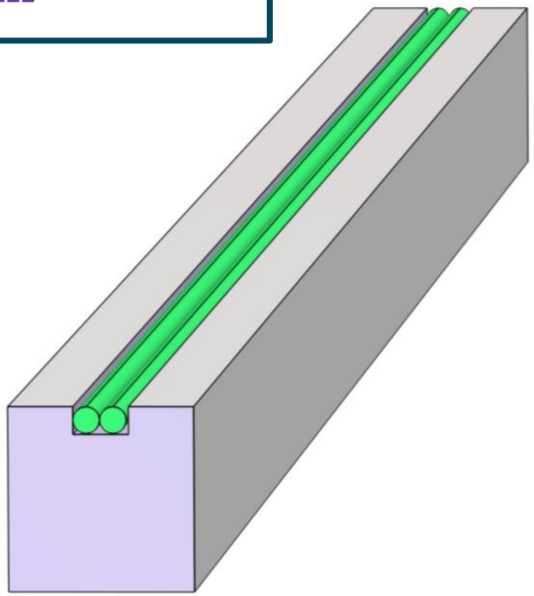


Ref. kuraraypsf.jp



Ref. luxiumsolutions.com



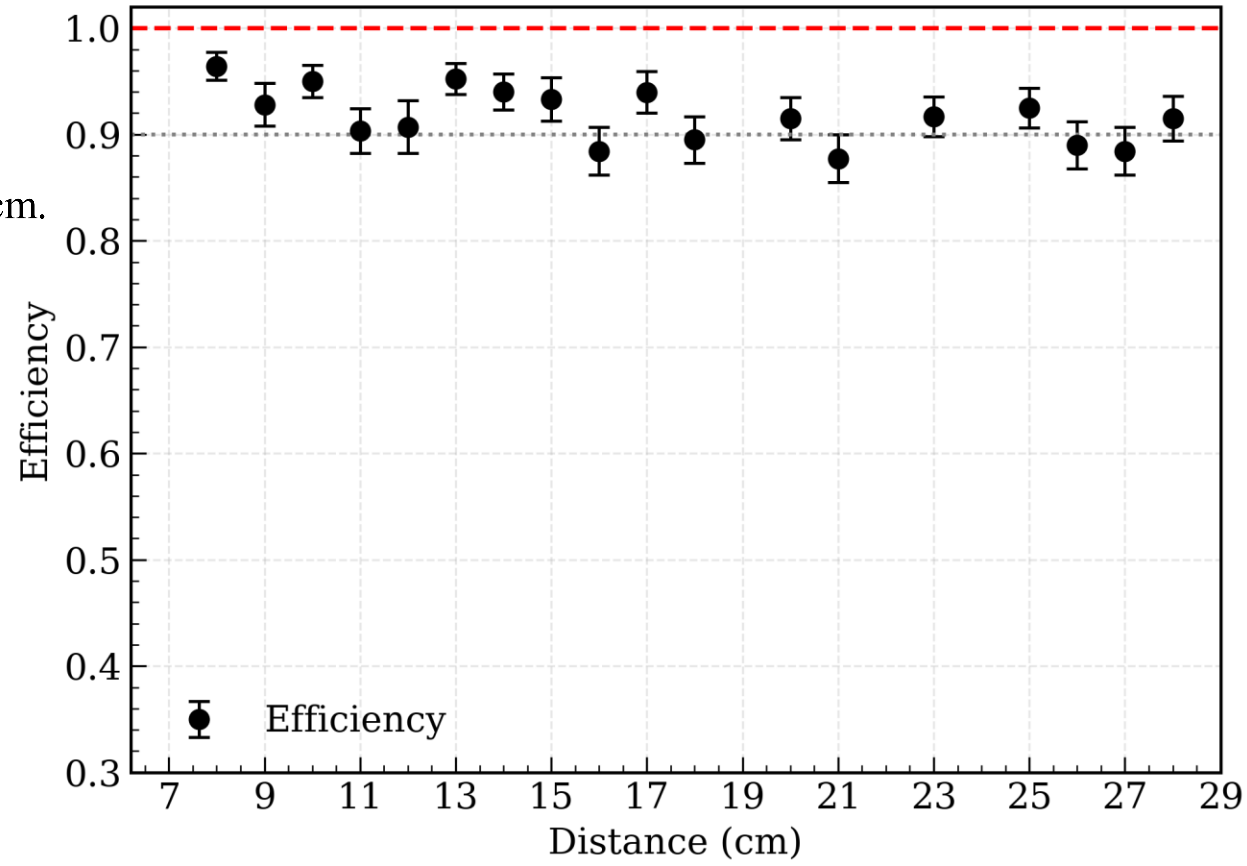


IMPROVEMENT IN EFFICIENCY

Observations:

- No sharp efficiency drop
- Unlike the previous case, there is no catastrophic fall beyond 20 cm.
- Efficiency remains high across the full strip
- **Around *~90%* efficiency even at large distances**
- Small fluctuations along the strip
- Maybe due to the non-uniform optical coupling between

  the fiber and the scintillator



FUTURE OUTLOOK

- Optimization Steps to address the fluctuation as well as increase the efficiency :
  - Trying with a different type of grooving.
  - Using Optical cement for better photon coupling.
- Build a detector layer combining a number of these prototypes.
- Finally, using it in the muon stack.

REFERENCES

[1] Silicon Photomultipliers (SiPM), Low-Noise, Blue-Sensitive, C-Series SiPM Sensors.

[2] F Anghinolfi et al. "*NINO: An ultrafast low-power front-end amplifier discriminator for the time-of-flight detector in the ALICE experiment*", IEEE Transactions On Nuclear Science 51 (2004), p. 1974

[3] Puneet Kanwar Kaur et al. "*Development of Fast, Low Power 8-Channel Amplifier-Discriminator Board for the RPCs*", Springer Proceedings in Physics 203 (2018), p. 571

[4] Sridhar Tripathy et al. "*Precise tracking of cosmic muons using the Time-over-Threshold property of NINO ASICs*", Journal of Instrumentation 15 (2020), p. C11013

[5] *"Particle Tracking with Gaseous Detectors and Development of Related Readouts"* Thesis by Subhendu Das

ACKNOWLEDGEMENT

- The Organisers of TIPP 2026

  – for giving the opportunity to present our work.

- Prof. Gobinda Majumder and Team, TIFR

  – for providing the necessary materials for testing.

- Group Mates at SINP: Subhendu Das, Tanay Dey and Saikat Ghosh.

  – for their continuous help and encouragement.

- SINP, HBNI, DAE

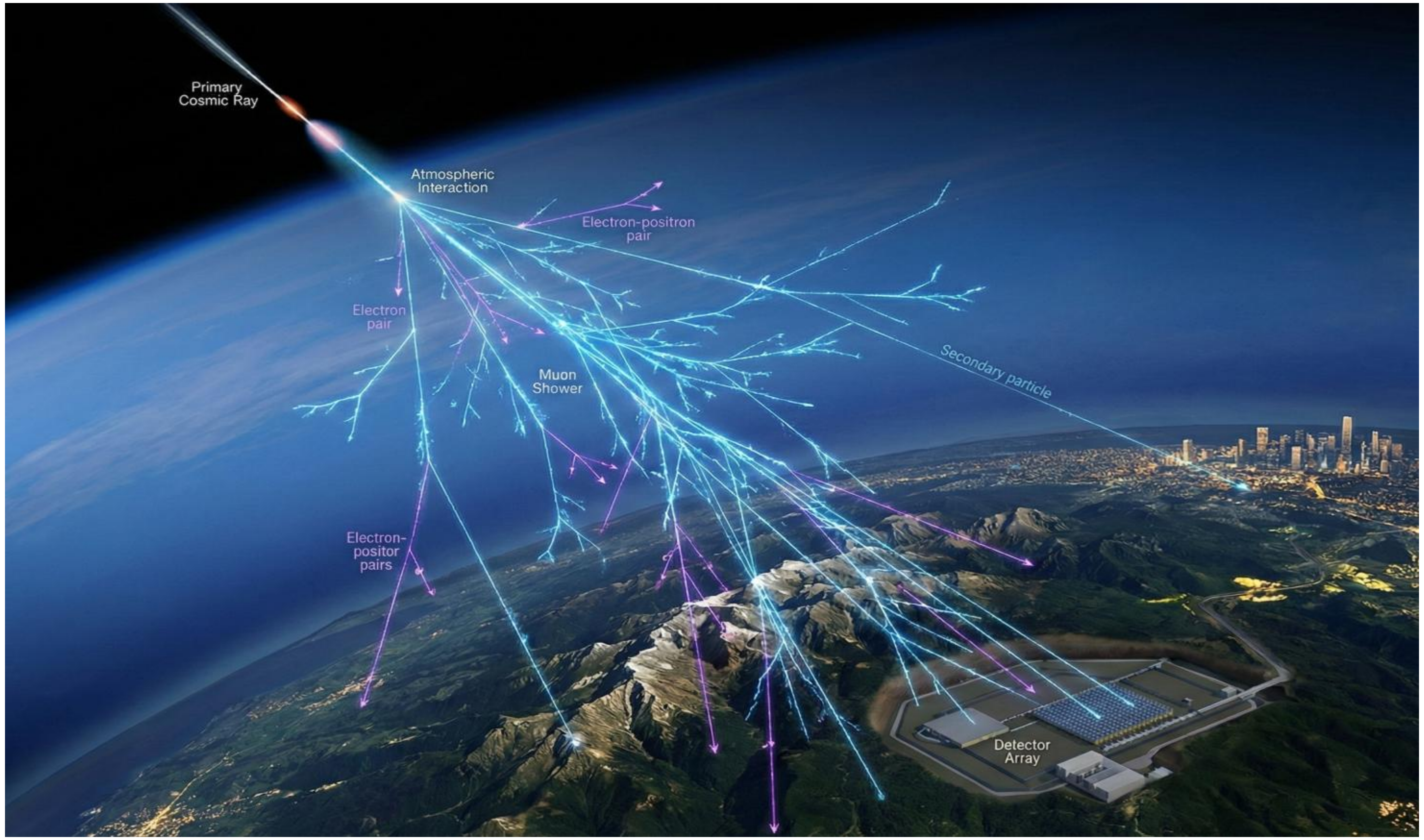
  – for providing the necessary funding and equipment support throughout this work.

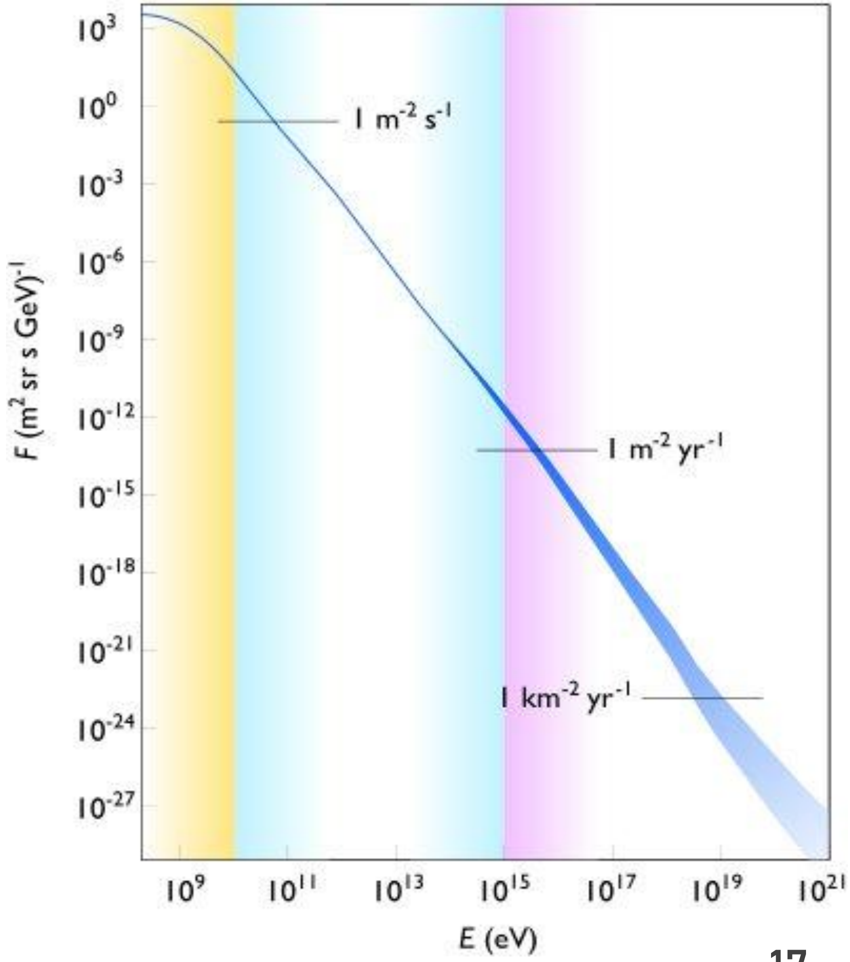
Thank You

Backup Slides

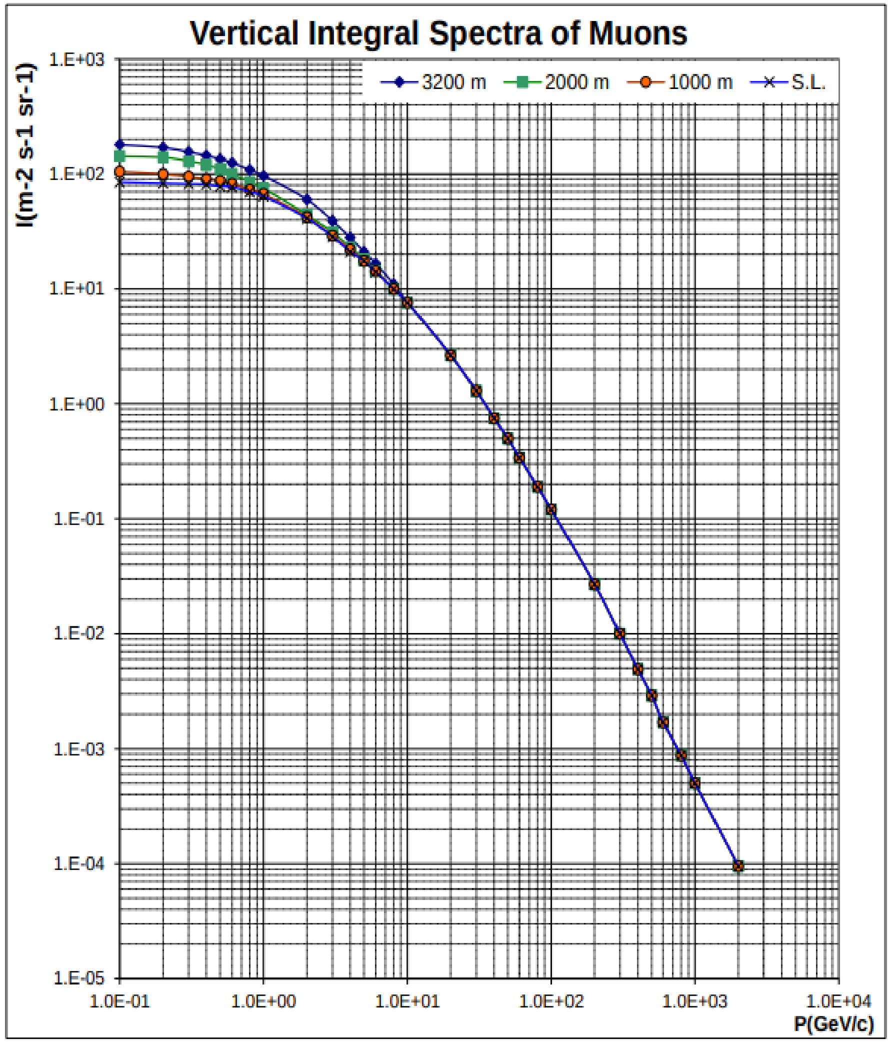
COSMIC RAYS: ORIGIN AND COMPOSITION

- Constant flux of high energy particles bombarding the Earth from outer space.
- Composed mainly by protons (98%), alpha particles (~2%), and other particles (< 0.1%).
- Cosmic rays are the most energectic particles observed so far.



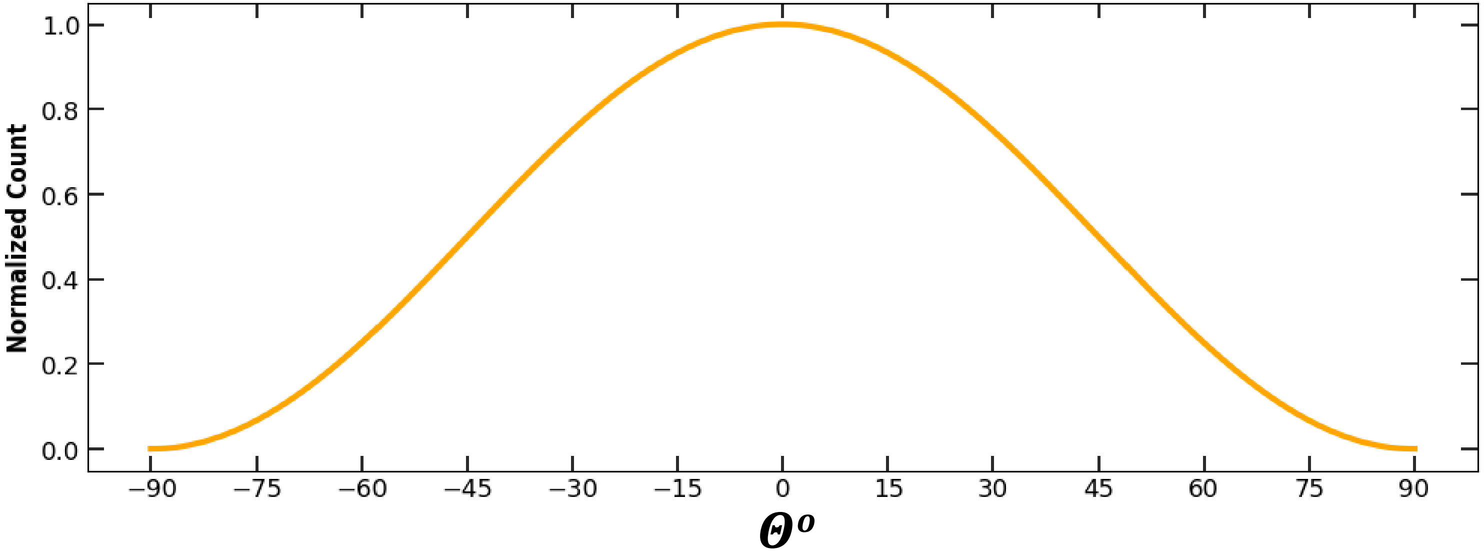


COSMIC MUONS: FLUX, ENERGY SPECTRUM



- Muons are generated mostly from pion decays in the upper layers of the atmosphere.
- The flux of muons is roughly proportional to $Cos^2(\Theta)$(angle with respect to the vertical)
- Quickly falling spectra => average of about 3 GeV when integrating to the full solid

The vertical muon flux ($\Theta = 0$) at sea level is around **70 particles $m^{-2}s^{-1}sr^{-1}$** often quoted as **1 muon $cm^{-2}min^{-1}$**.



MUON INTERACTIONS WITH MATTER

- Coulomb scattering deviates the direction of the muons when crossing matter
- Scattering angle depends also on the Z, density and size of the material
- The angular distribution of the deviation is approximately gaussian (with some longer tails)

Muon momentum

$$\sigma = \frac{13.6[\mathrm{MeV}]}{\beta c p} \sqrt{L/X_0}\left(1 + 0.038 \ln\left(L/X_0\right)\right),$$

Radiation Length

$$X_0 = \frac{A \cdot 716.4\,[\mathrm{g/cm^2}]}{\rho \cdot Z(Z+1)\,\ln\left(287/\sqrt{Z}\right)},$$

$$\sigma = \frac{13.6}{p}\sqrt{\frac{L}{X_0}}$$

p = Momentum,

β = v/c,

X_0= Radiation Length,

L= Thickness

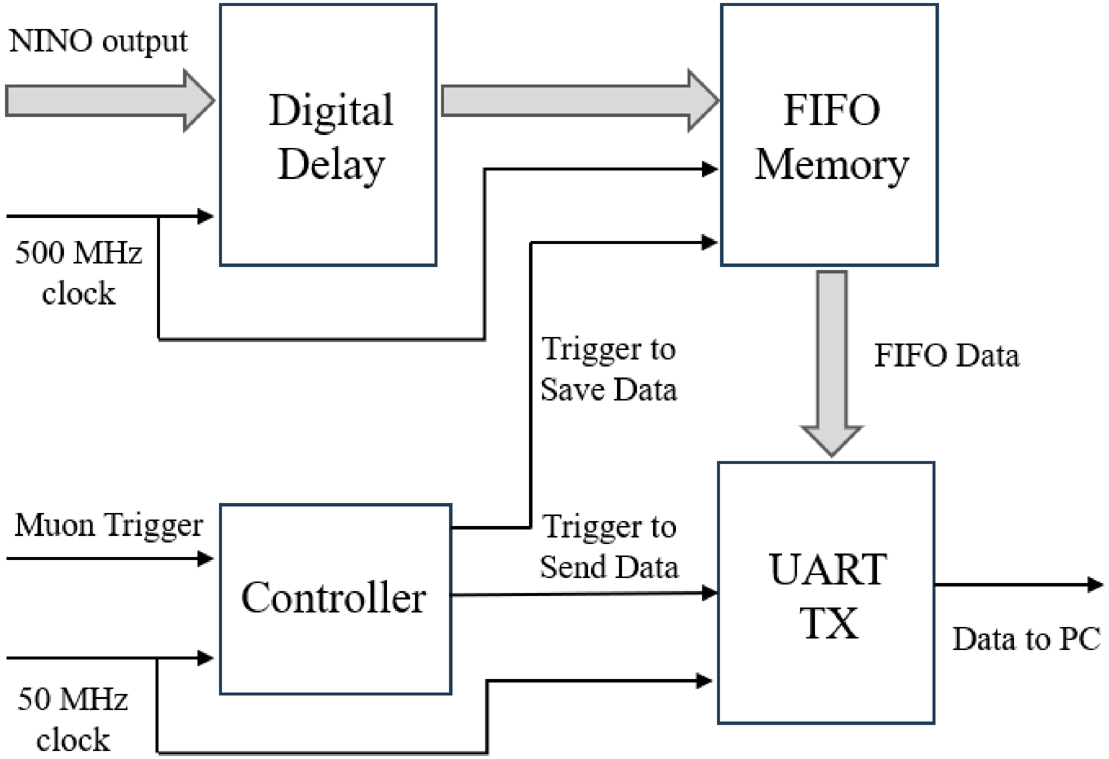
A= Atomic Mass,

Z= Atomic Number

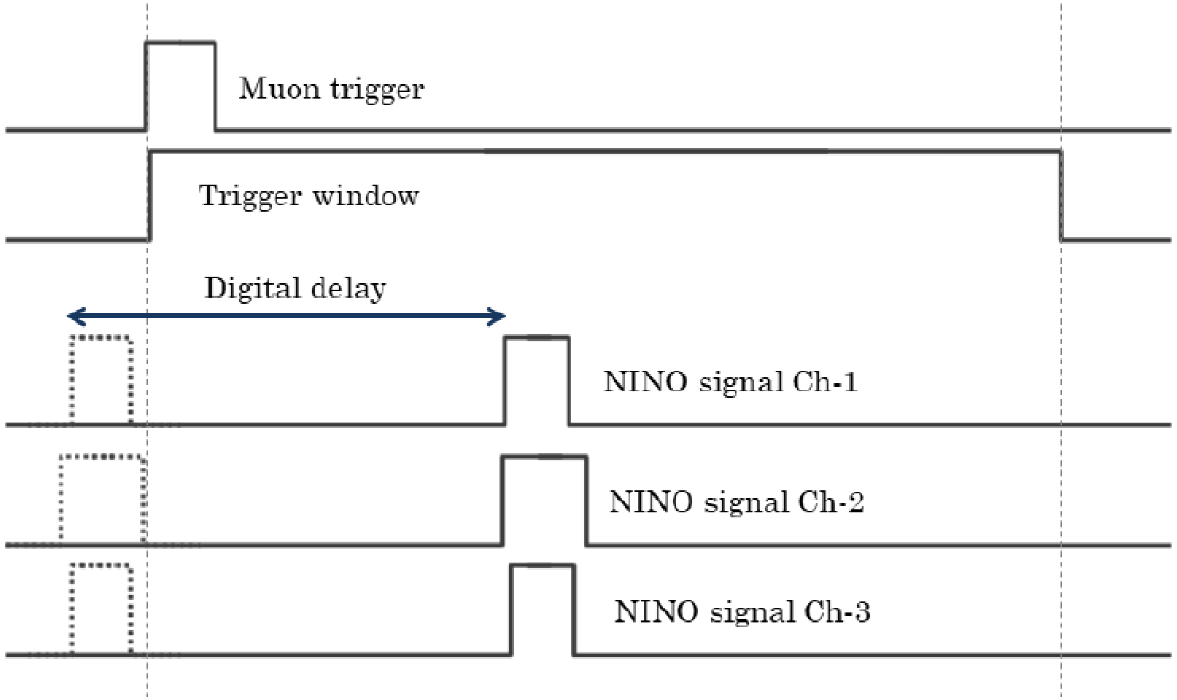
ρ = Density of material

Material	Energy (GeV)	L (cm)	σ (mrad)
Iron	1	1	10
		10	34
	10	1	1
		10	3
Lead	1	1	19
		10	64
	10	1	2
		10	6
Uranium	1	1	26
		10	88
	10	1	3
		10	9

FPGA LOGIC FOR THE SETUP

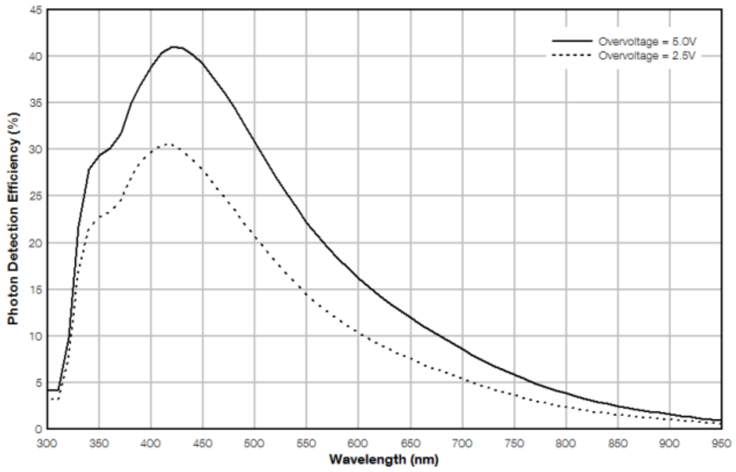


- Trigger Window : ***500 ns*** (250 bit)
- Digital Delay : ***128 ns*** (64 bit)

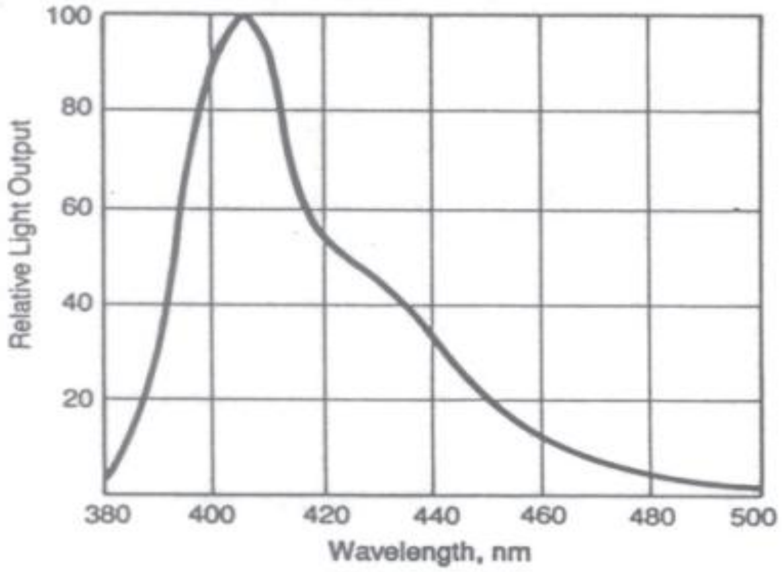


- VHDL to program the FPGAs
- Python interface for data collection.

SCINTILLATOR AND SIPM DETAILS



SiPM

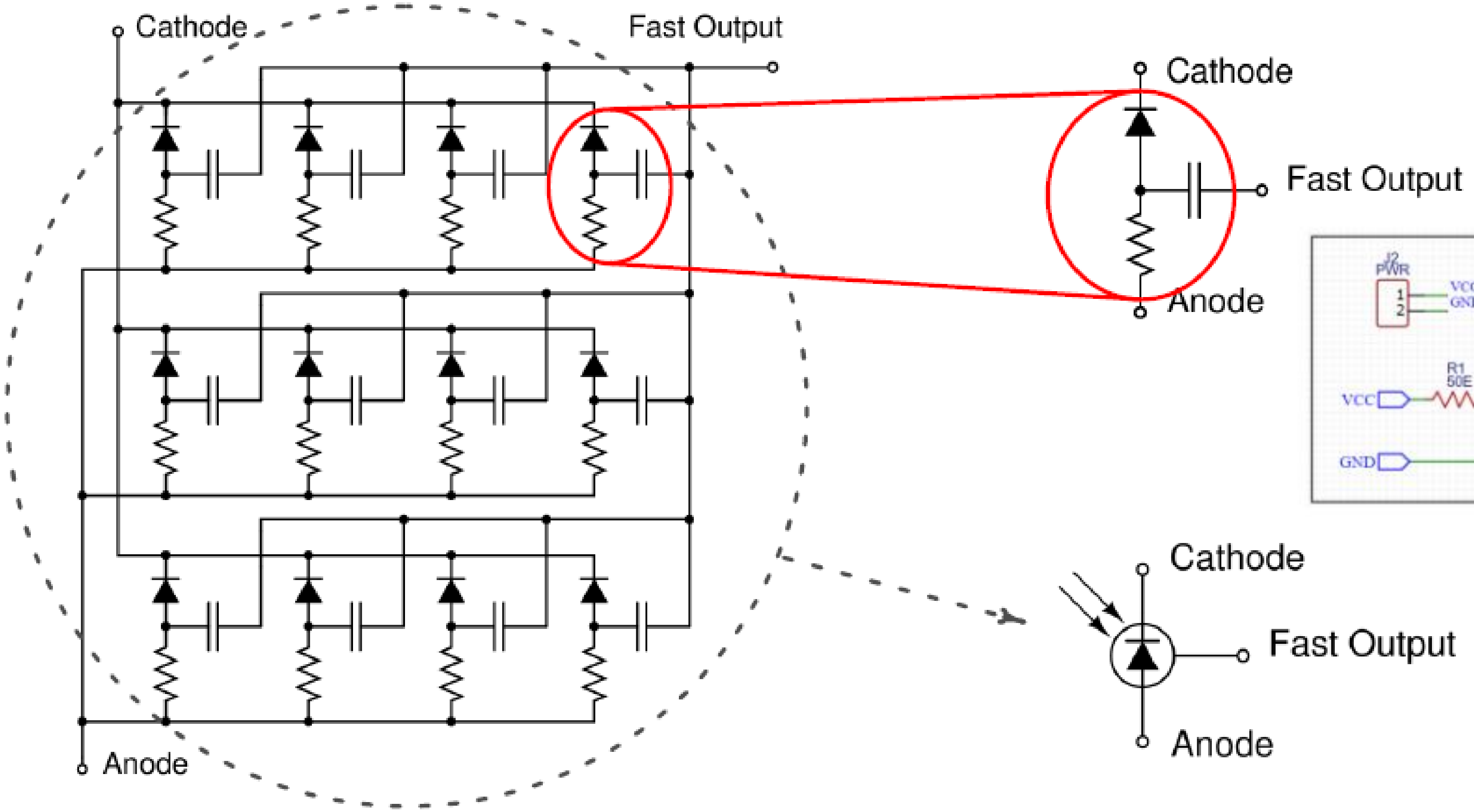


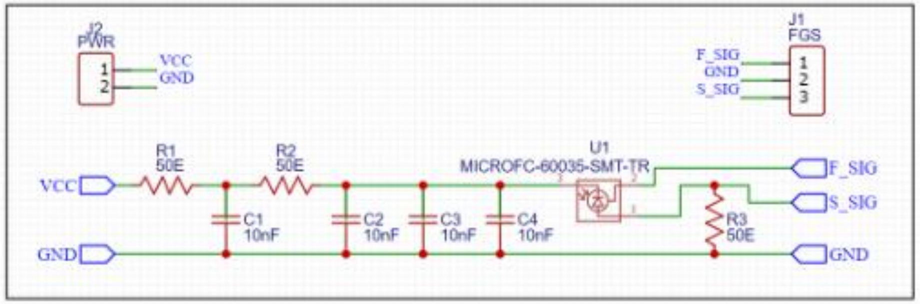
BC 404

	BC-400	BC-404	BC-408	BC-412	BC-416
Radiation Detected					
<100keV X-rays			X		
100keV to 5MeV gamma rays				X	
>5MeV gamma rays	X				
Fast neutrons				X	X
Alphas, betas	X	X	X		
Charged particles,cosmic rays, muons, protons, etc.			X	X	X
Principal Uses/Applications	general purpose	fast counting	TOF large area	large area	large area economy
Scintillation Properties					
Light Output, %Anthracene	65	68	64	60	38
Rise Time, ns	0.9	0.7	0.9	1.0	-
Decay Time (ns)	2.4	1.8	2.1	3.3	4.0
Pulse Width, FWHM, ns	2.7	2.2	~2.5	4.2	5.3
Wavelength of Max. Emission, nm	423	408	425	434	434
Light Attenuation Length, cm*	160	140	210	210	210
Bulk Light Attenuation Length, cm	250	160	380	400	400
Atomic Composition					
No. H Atoms per cc ($x10^{22}$)	5.23	5.21	5.23	5.23	5.25
No. C Atoms per cc ($x10^{22}$)	4.74	4.74	4.74	4.74	4.73
Ratio H:C Atoms	1.103	1.100	1.104	1.104	1.110
No. of Electrons per cc ($x10^{23}$)	3.37	3.37	3.37	3.37	3.37

*The typical 1/e attenuation length of a 1x20x200cm cast sheet with edges polished as measured with a bialkali photomultiplier tube coupled to one end.

SIPM DETAILS





Ref. :www.onsemi.com

PDE OF SIPM

$$PDE(\lambda, V) = \eta(\lambda) \cdot \varepsilon(V) \cdot F$$

$\eta(\lambda)$ is the quantum efficiency of silicon

$\varepsilon(V)$ is the avalanche initiation probability

F is the fill factor of the device

Ref. :www.onsemi.com