The Plastic Scintillator Detector of HERD experiment

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Outline

- The role of the HERD PSD
- The layout
- Prototype and test
- Conclusion

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Xi'an Institute of Optical and Precision Mechanics, CAS (XIOPM)
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Shandong University (SDU)
Southwest Jiaotong University (SWJTU)
Purple Mountain Observatory, CAS (PMO)
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Yunnan Observatories (YNAO)
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ICCUB – Barcelona
IFAE – Barcelona

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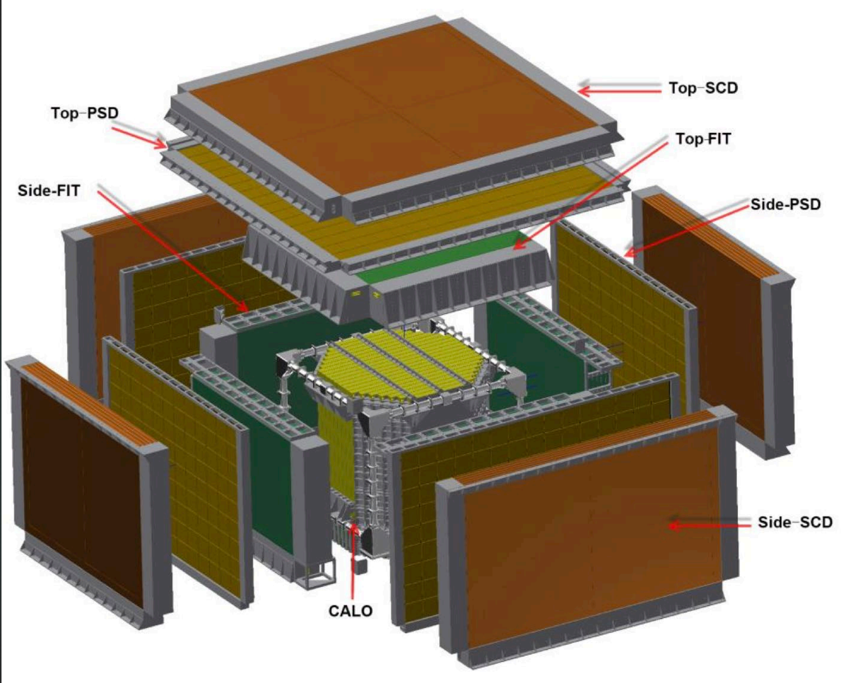
The **High Energy cosmic-Radiation Detection** (HERD) facility is an international space mission based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** that will measure the cosmic ray flux up to the knee region, search for indirect signal of dark matter and monitor the full gamma-ray sky



SCD	Charge Reconstruction
PSD	Charge Reconstruction γ Identification
FIT	Trajectory Reconstruction Charge Identification
CALO	Energy Reconstruction e/p Discrimination
TRD	Calibration of CALO response for TeV protons

Main requirements

	γ	e	p, nuclei
Energy Range	>100MeV	10 GeV 100 TeV	30 GeV 3 PeV
Energy resolution	1% @ 200 GeV	1% @ 200 GeV	20% @ 100 GeV -1 PeV
Effective Geometric Factor	>0.2 m^2sr @ 200 GeV	>3 m^2sr @ 200 GeV	>2 m^2sr @ 100 TeV

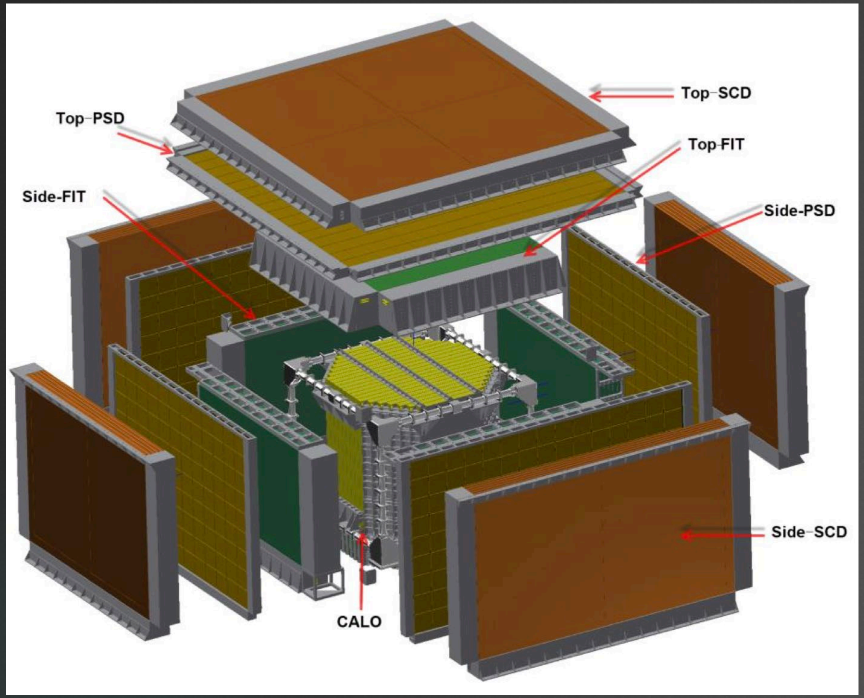
The PSD will have **different tasks** to accomplish in HERD

- It will be used in the trigger logic as VETO detector for charged particles when γ **selection** is needed
- It will be used as charge measurement detector for **nuclei identification** (energy loss $\propto Z^2$)
- It will provide timing information (1ns resolution) that will help in **track reconstruction** and **backscattered particle rejection**

In order to fulfill all these task there are strong **requirements**:

- high efficiency in charged particles detection (>99,8%)
- high dynamic range to identify nuclei at least up to iron
- Charge resolution <30%
- highly segmented design to reduce the self VETO due to back scattered charged particles and to provide useful timing information

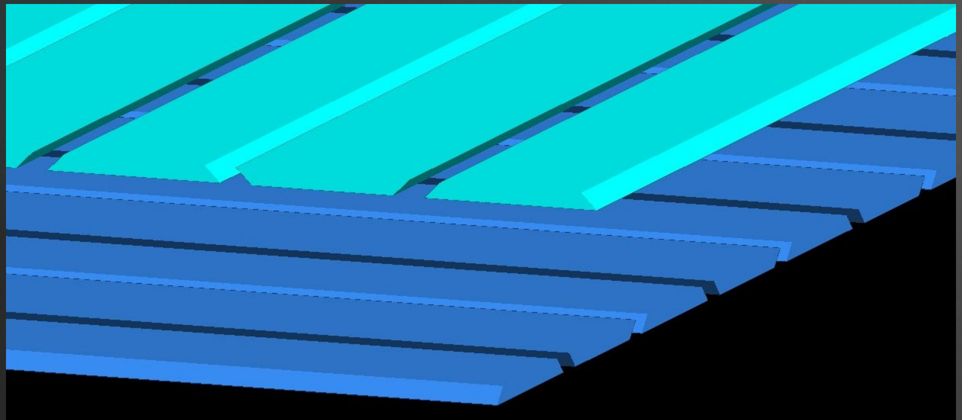
Mechanical Design



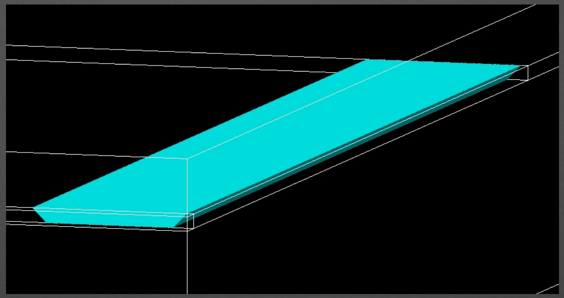
1 TOP plane and 4 SIDE plane
SCD and PSD will share the same mechanical structure

Dimensions:
- TOP 180x180 cm^2
- SIDE 170x95 cm^2

Each plane is composed of two layers to increase the **hermeticity** and so the VETO efficiency



The gap between the tiles is increased for visualization



Each layer is composed by short trapezoidal **plastic scintillating** tiles 40cm long and 5/4cm wide

TOP plane: 400 tiles
SIDE plane: 160 tiles

Total number of tiles: ~1000

Readout design of a bar

Each tile will be readout by different SiPMs in order to increase the light detection efficiency and the dynamic range for nuclei identification

- 4 SiPM (3.0x3.0mm2 – 50umcell) - **Low Z**
- 4 SiPM (1.3x1.3 mm2 – 15um cell) - **High Z**
- 2 LED for calibration
- 2 Temperature sensors
- High density coaxial cable connector for space application

LowZ SiPM

High detection efficiency for MIPS

Small dynamic range

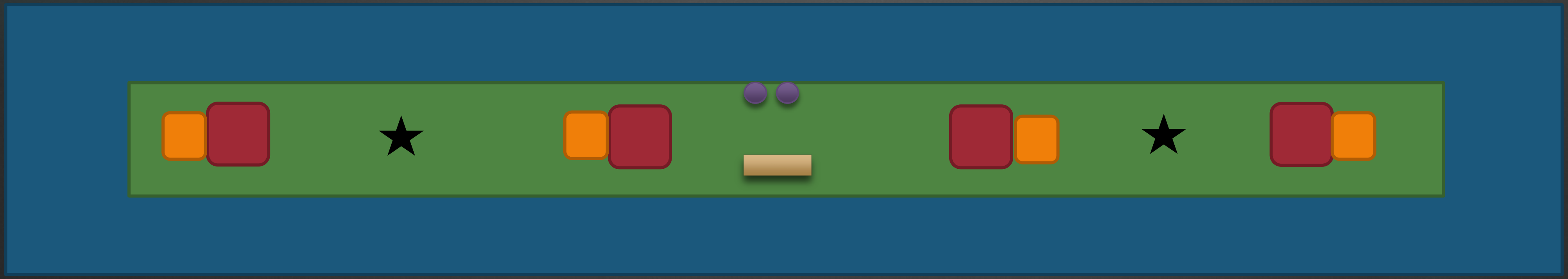
- $3x3mm^2$: Increase light collection
- 50um cell: Increase gain

HighZ SiPM

Lower detection efficiency for MIPS

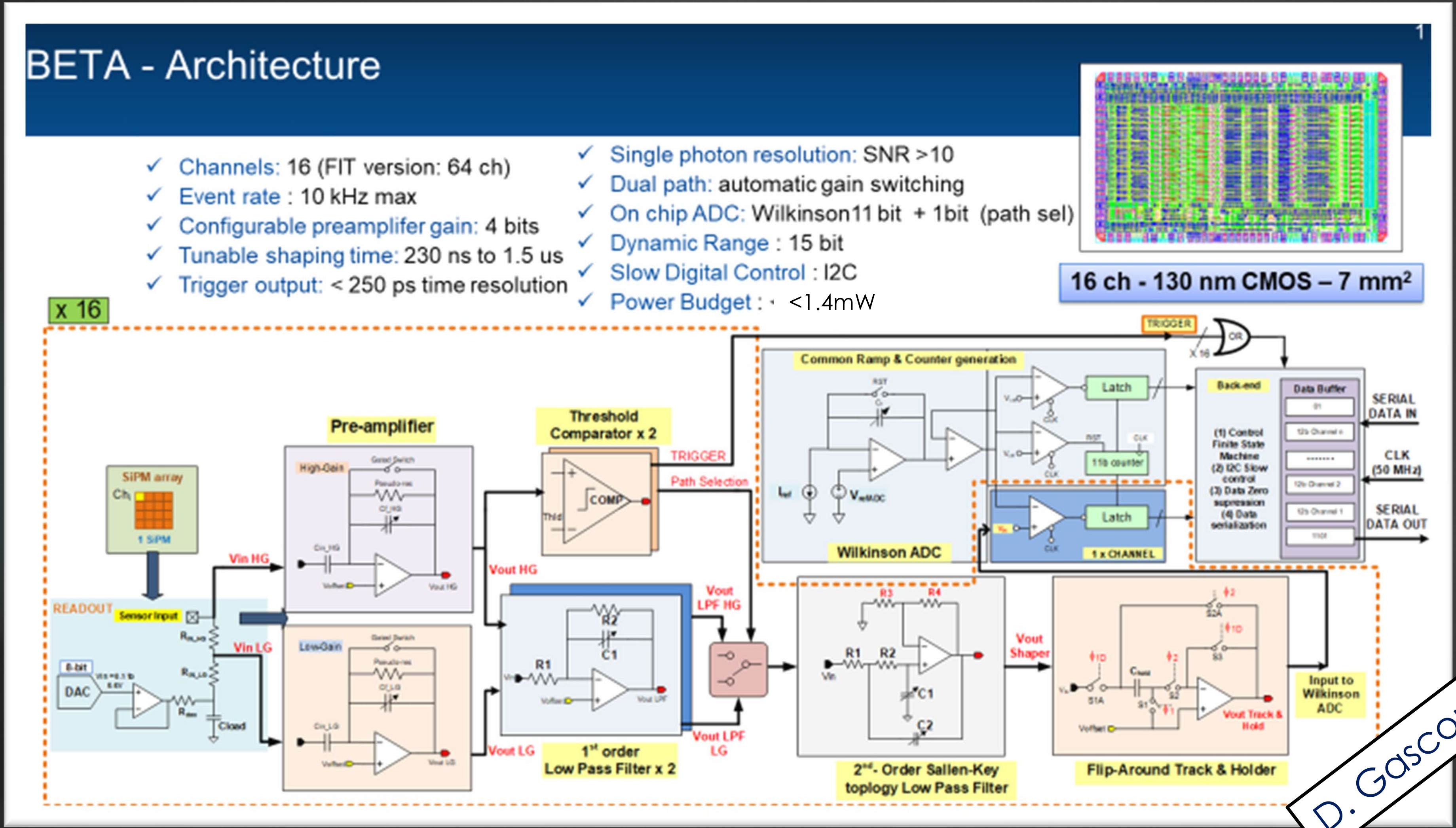
Higher dynamic range

- $1.3x1.3mm^2$: reduce collected light
- 15um cell: reduce cell saturation



Front-end β-Chip

The **ICCUB group** has designed the **β-chip** for the readout of SiPMs for both PSD and FIT in space application (**low power consumption**, **high dynamic range**)

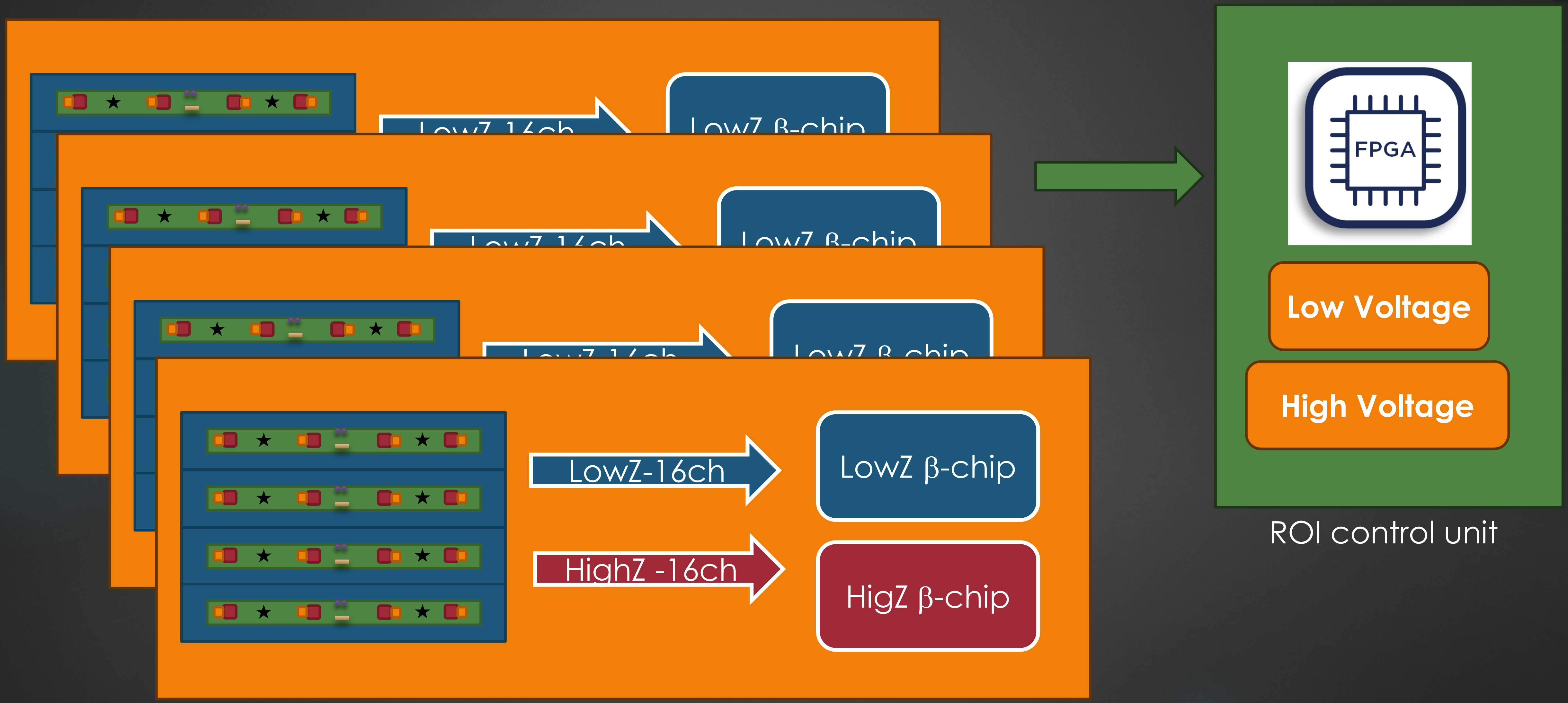


D. Gascon

Almost **500** 16-ch β-chip needed: <15W of power consumption

Readout design

4 tiles will be readout by 2 β-chip: one for LowZ and one for HighZ



Each ROI (Region of interest) control unit will be connected to 16 tiles and will provide:

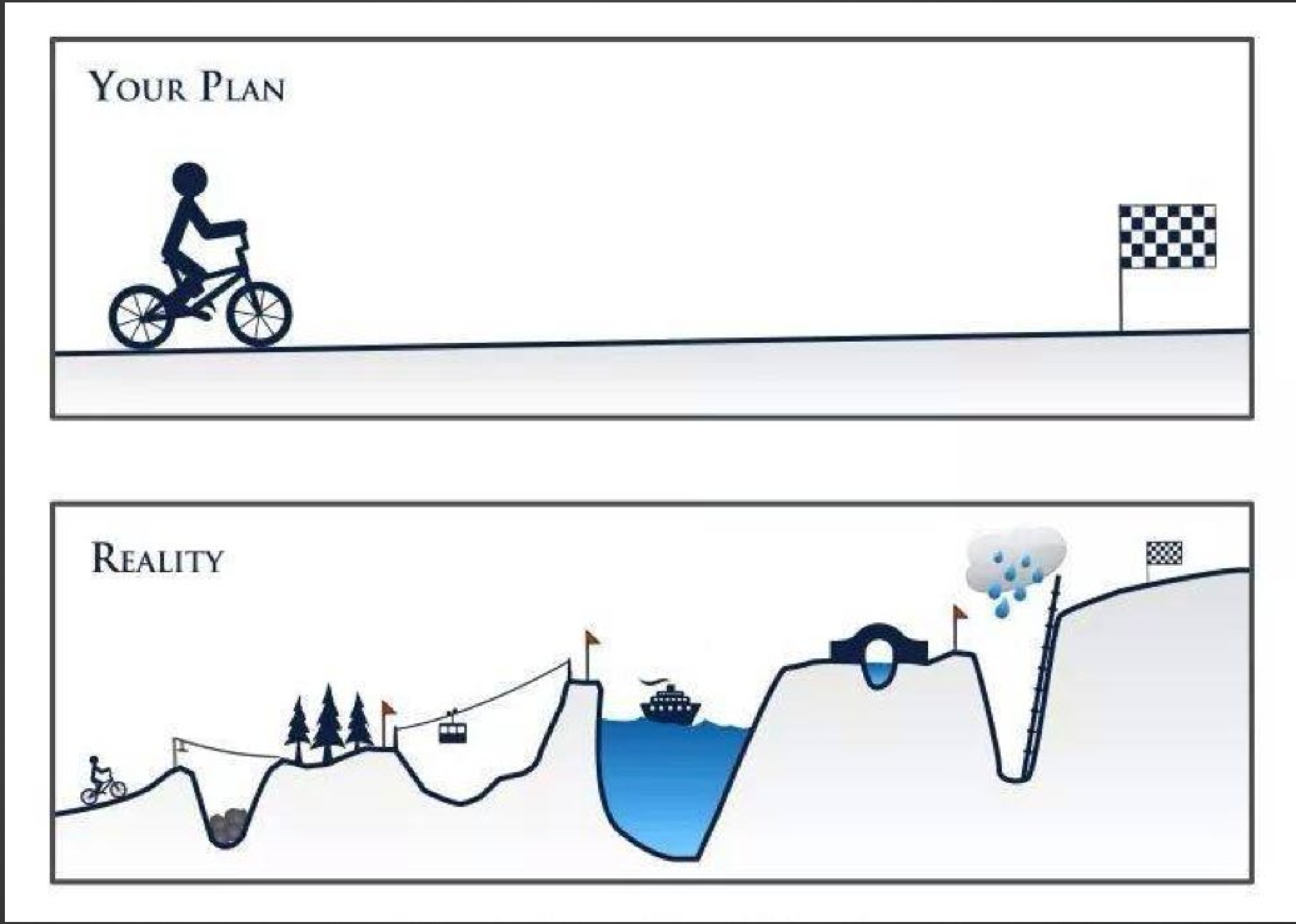
- Setting of the 8 β-chip
- Readout of the 8 β-chip
- Power supply
- Temperature monitor and active HV feedback
- LED control for calibration
- Trigger signals for VETO logic
- Time ordered fired bars identification

TOP plane **25 ROI control unit**

SIDE plane **10 ROI control unit**

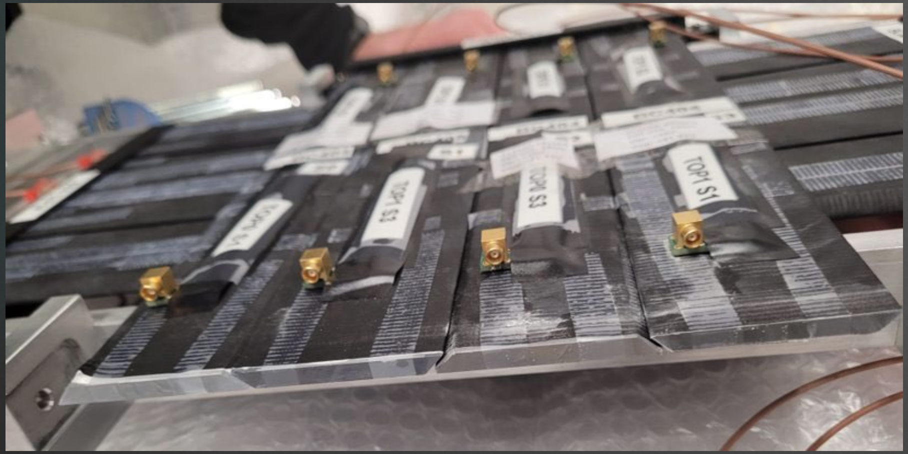
All the ROI control unit of a single plane will be connected to an FPGA that will take care of all the communications with the Main DAQ control unit

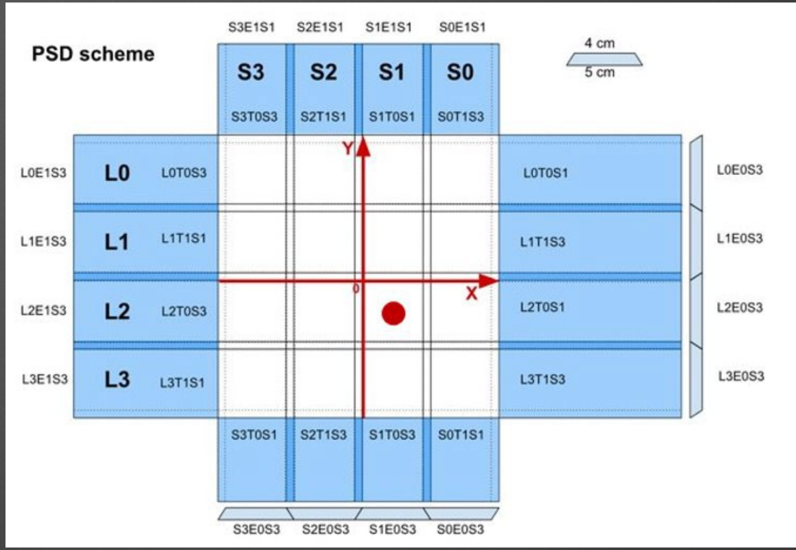
From design to prototype



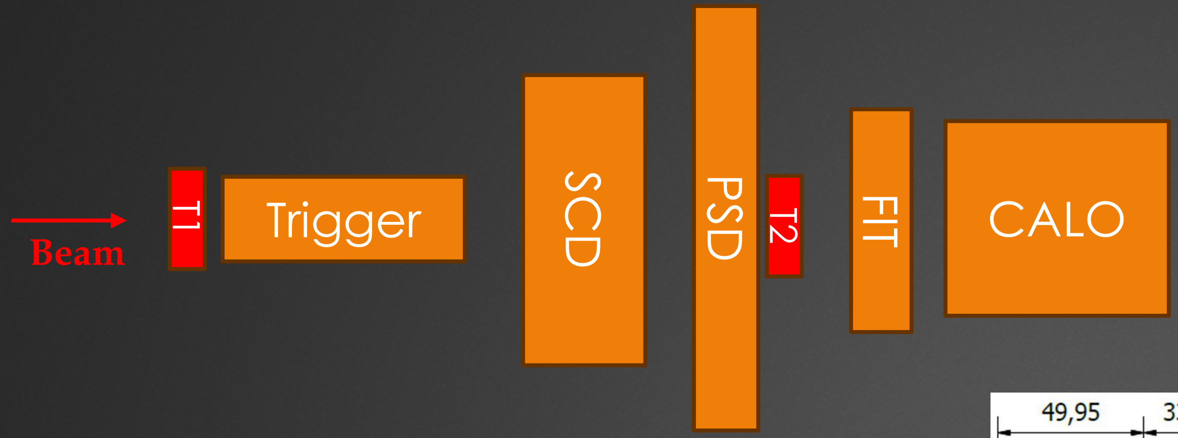
Protype and beam test

- In the last years we have done different test with small scale prototype in different labs (Bari, GSSI, Lecce and Pavia) and with both cosmic rays and radioactive sources.
- In the next slides I will focus on the 2022 test beam at CERN (PS+SPS) and 2023 beam test campaign at CNAO (Pavia)
- During these test we have tested different prototype as close as possible the PSD design. All the prototype are readout with a preliminary version of β-chip

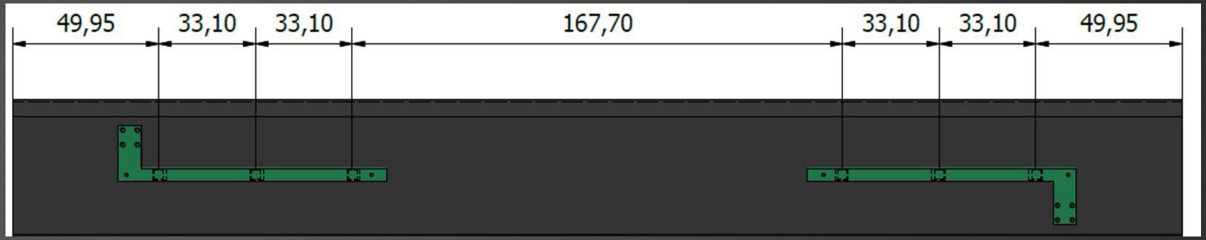




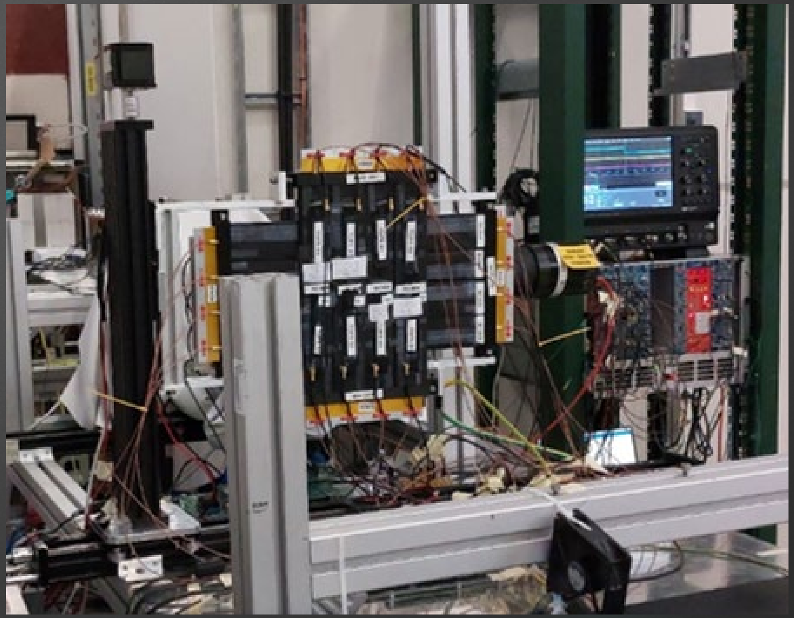
CERN 2022



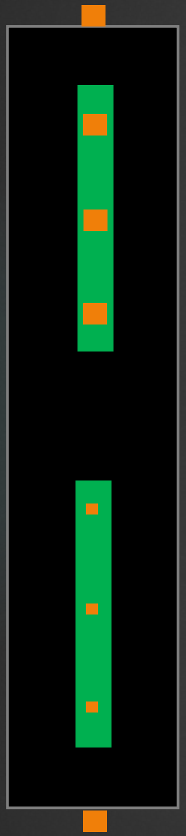
T1 and T2 are two squared plastic scintillators tiles used to monitor the beam and provide ancillary information

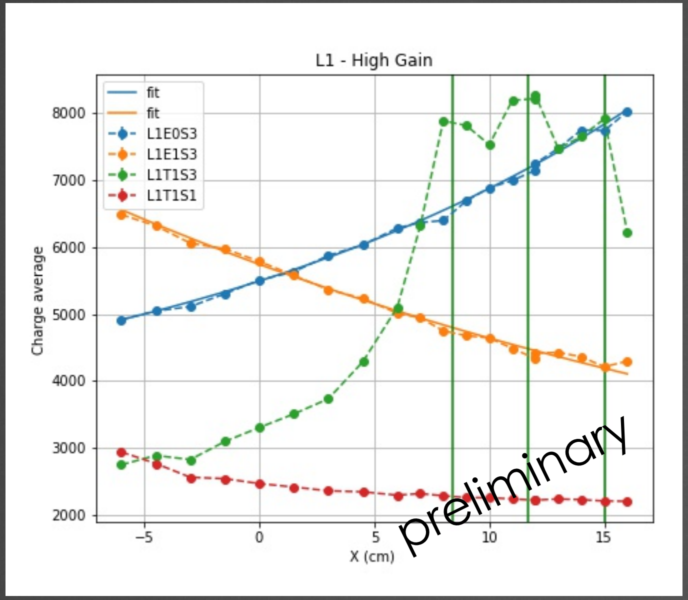


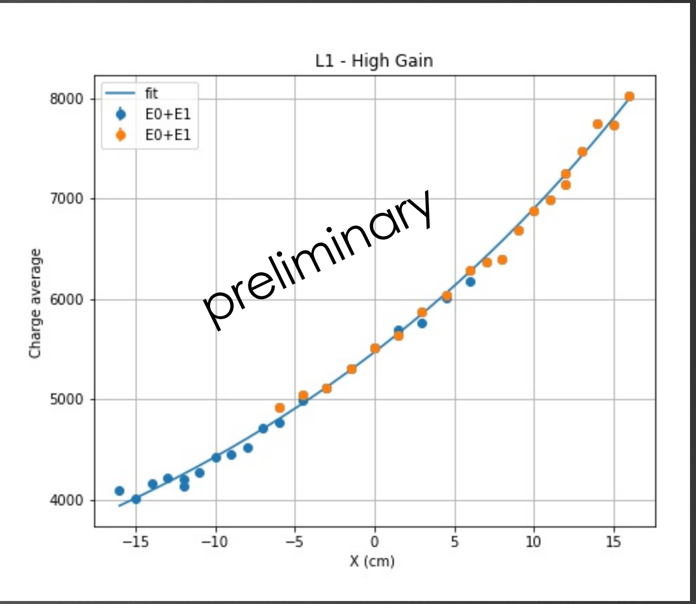
SiPM : Hamamatsu	S14160-3015	S14160-1315
Size	3x3 mm^2	1.3x1.3 mm^2
Pixel pitch	15 um	15 um
Number of pixels	39984	7284
Refractive index	1.57	1.57
Peak sensitivity wavele ngth	460 nm	460 nm
PDE	32%	32%
Vbr	38 V	38 V



- 10 GeV pions and protons
- We have tested the light collection uniformity and the attenuation length performing position scan



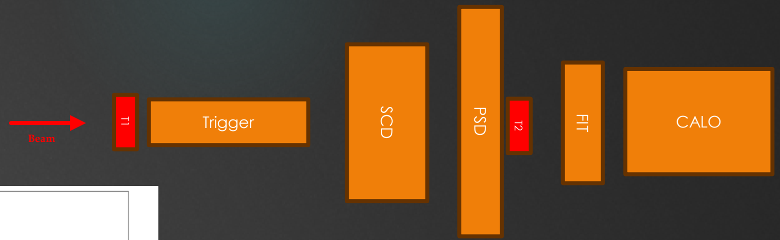


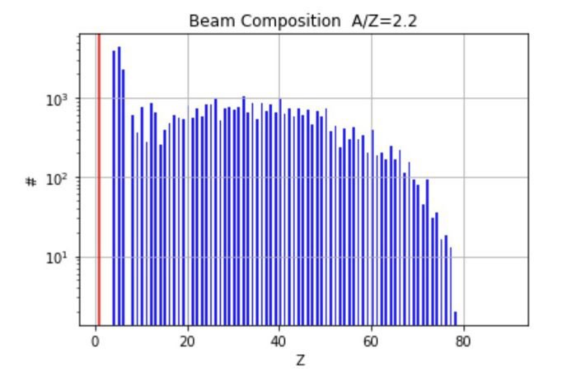


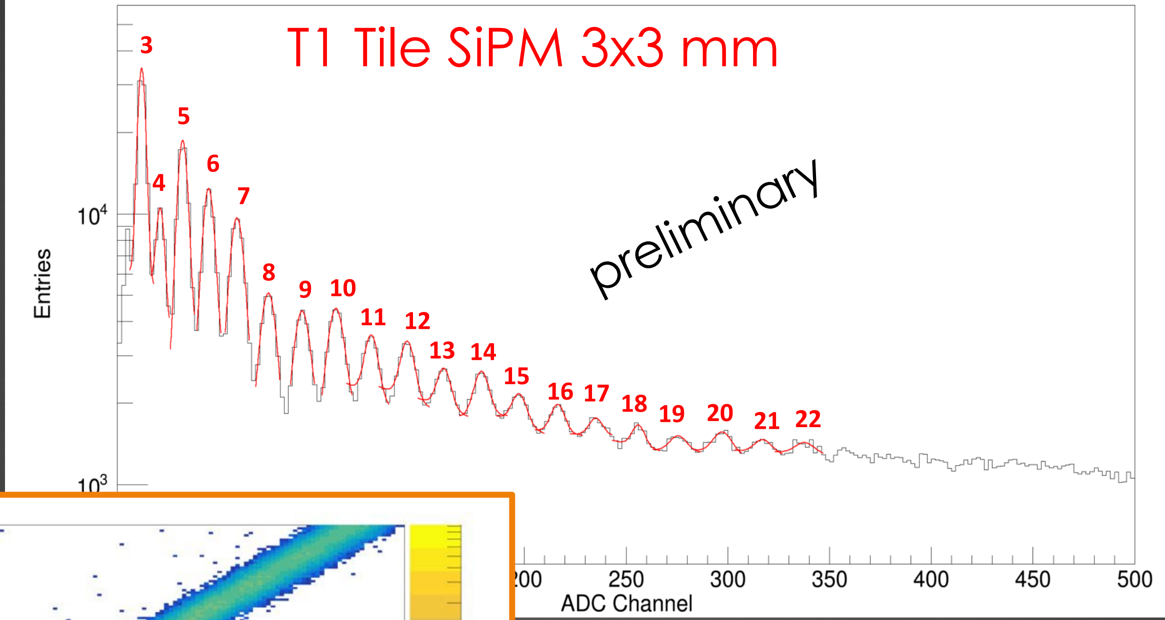
We have used the SiPM and the end of the trapezoidal tile to measure the <u>effective attenuation length</u> of the signal in trapezoidal tile: 35±0.5cm

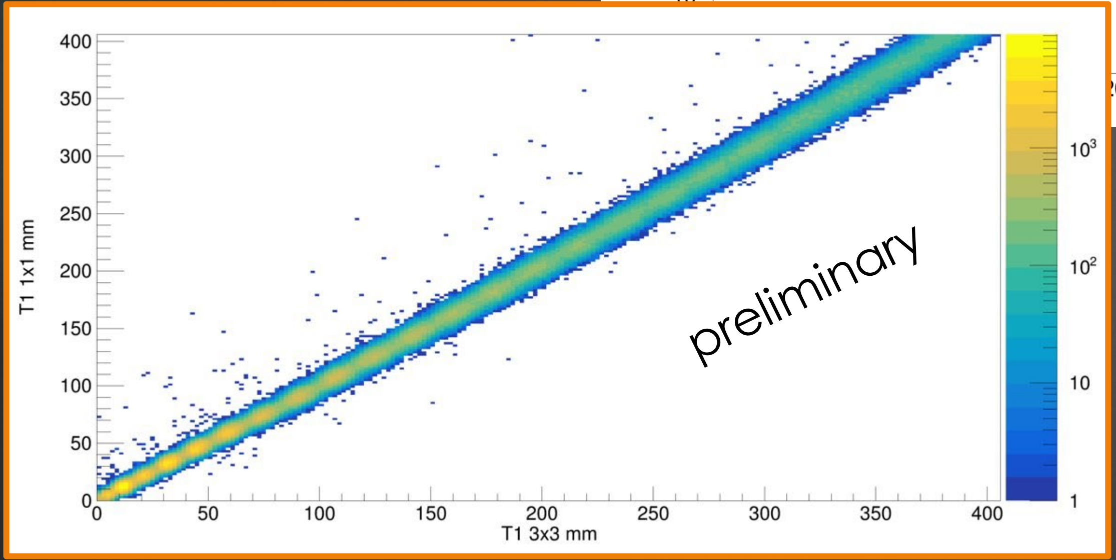
The SiPM on the top of the tile shows a great <u>light collection disuniformity</u> due to direct scintillation light

Fragments produce by **Pb on Be target @150GeV/n**





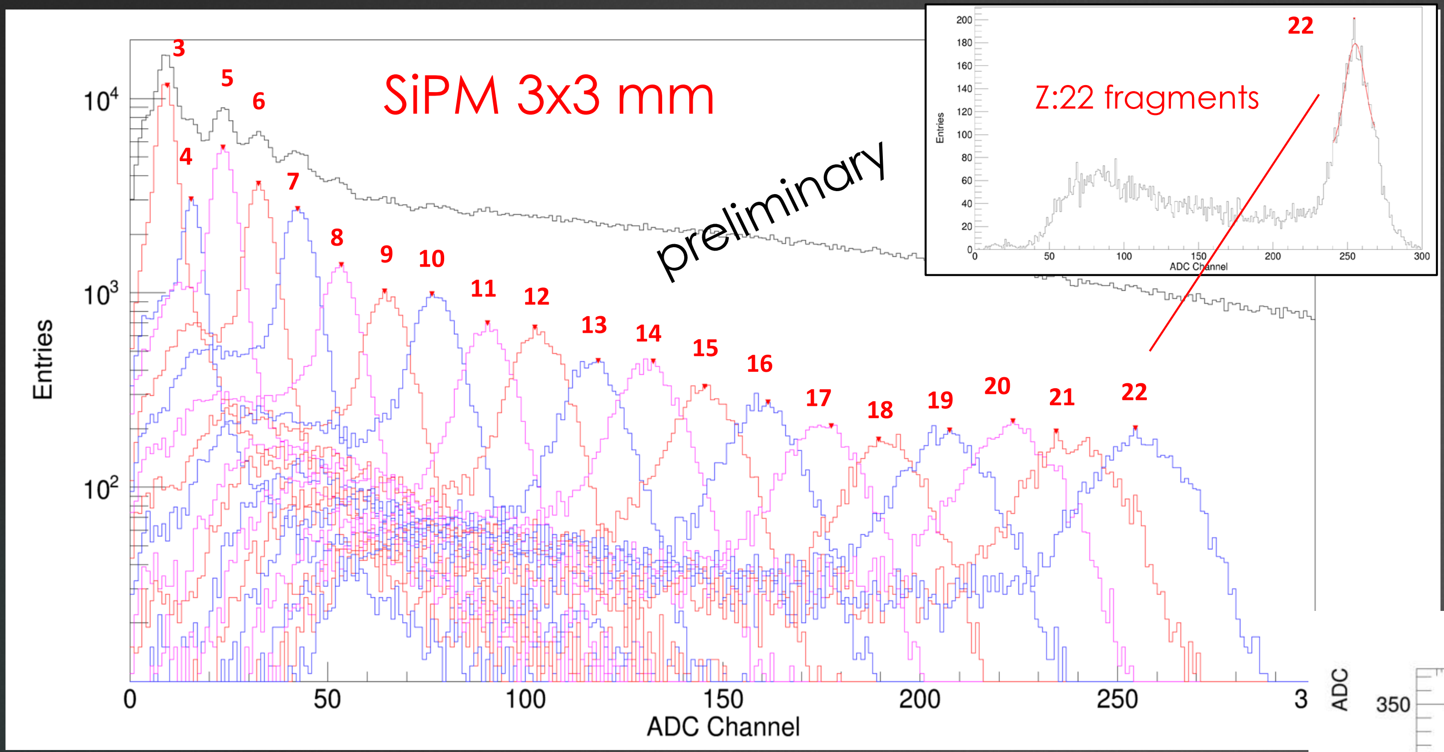


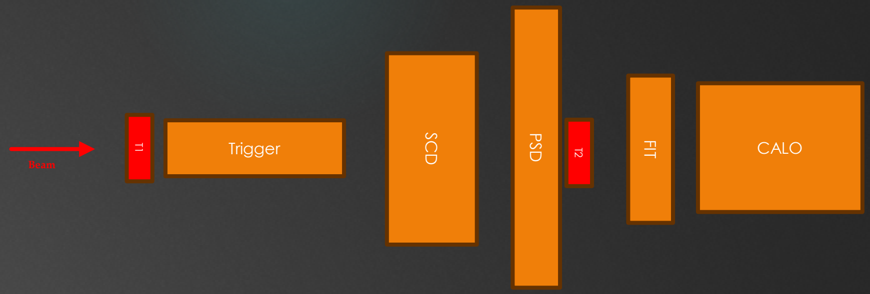


T1 is the square tile on front of all the detectors and it is not can measure the Z of incident fragments

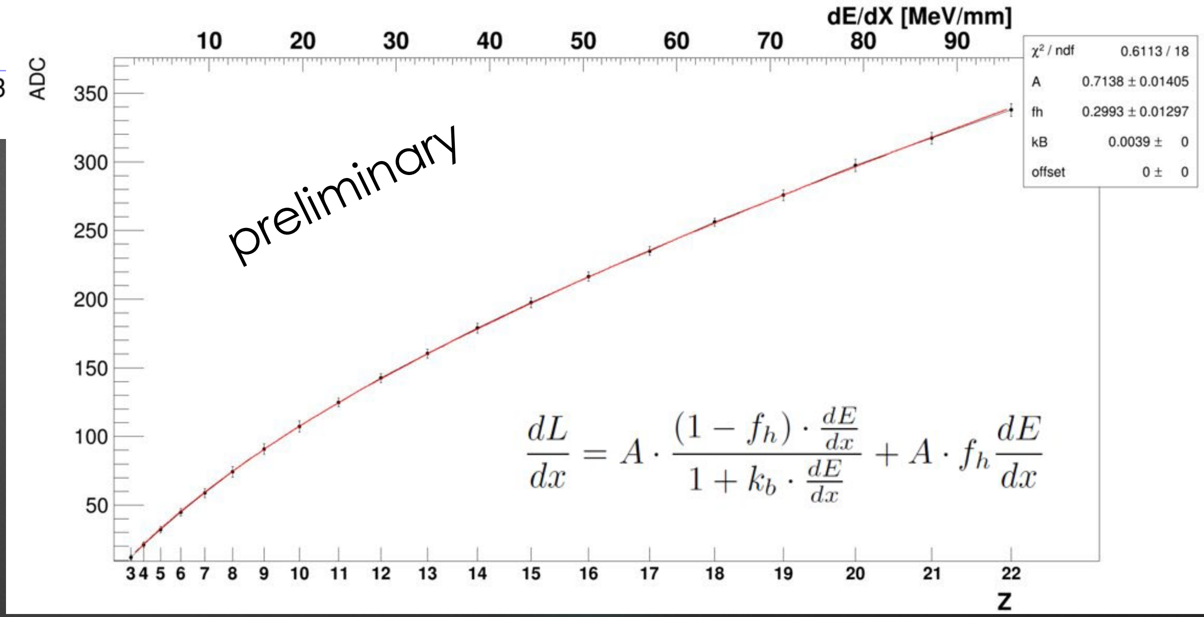
T1 is used to **identify** the Z fragments

T2 signal

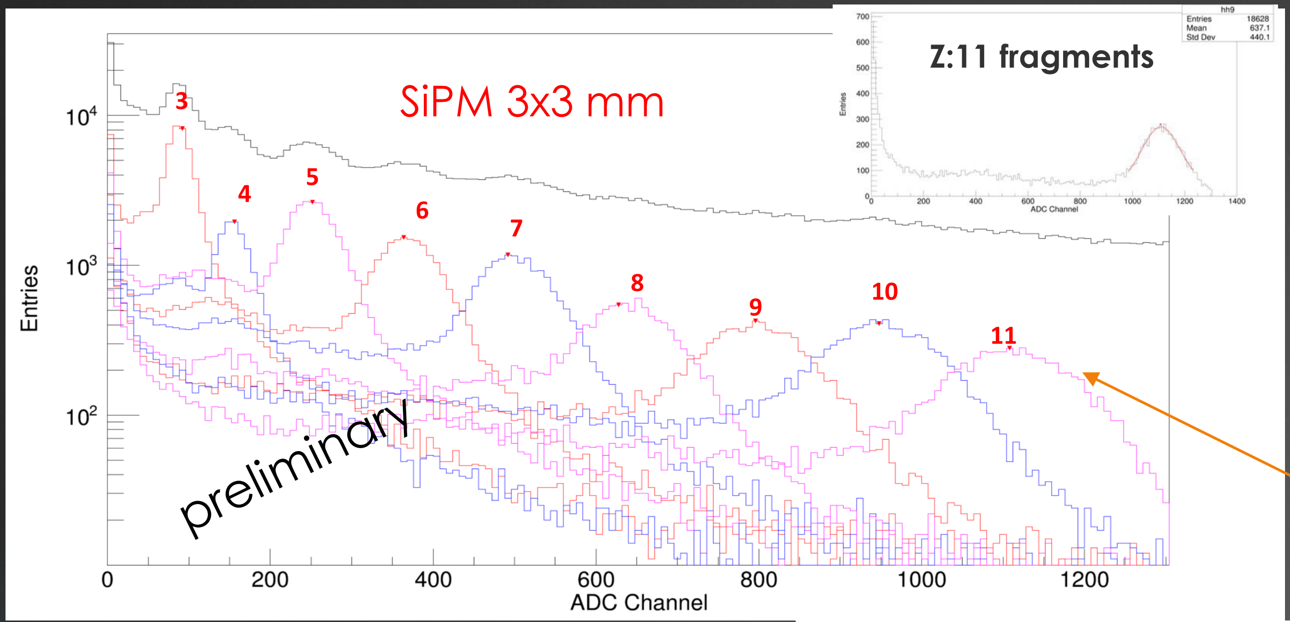


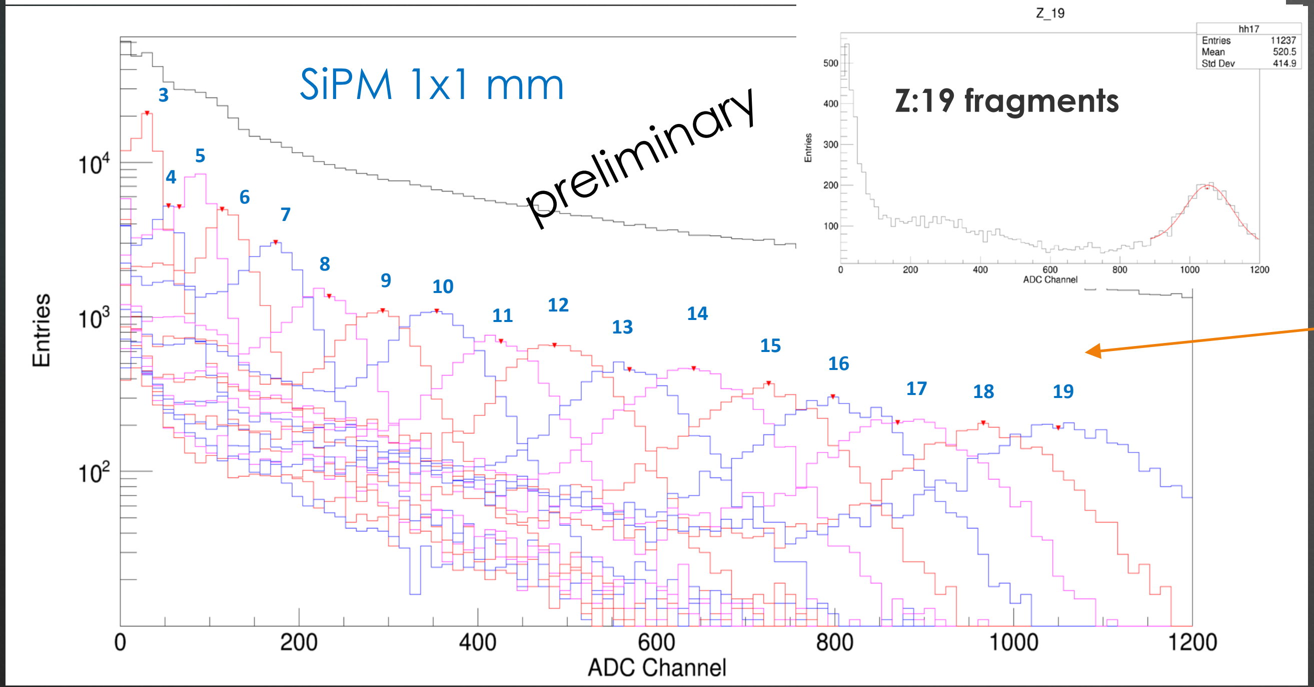


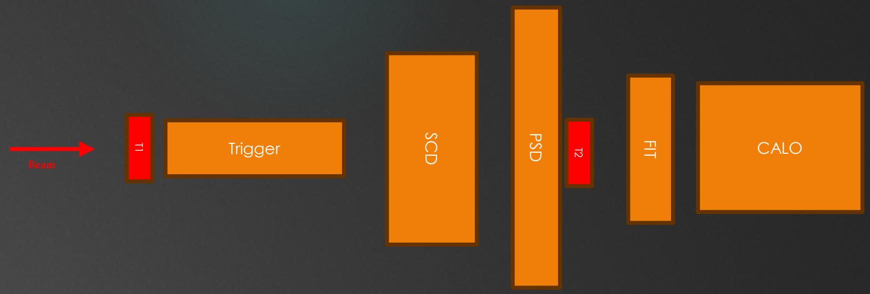
Birks saturation effect

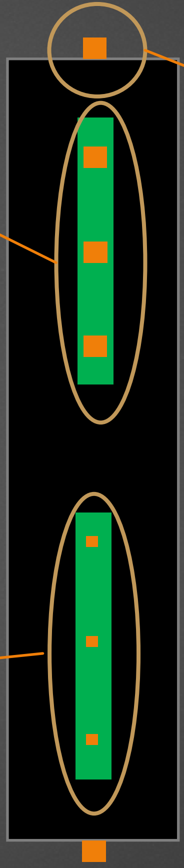


- $dE/dx \propto Z^2$;
- f_h represents the fraction of energy deposited in the halo;
- k_b is the Birks constant that depends on the material and governs the strength of the saturation;
- A is an overall gain normalization.





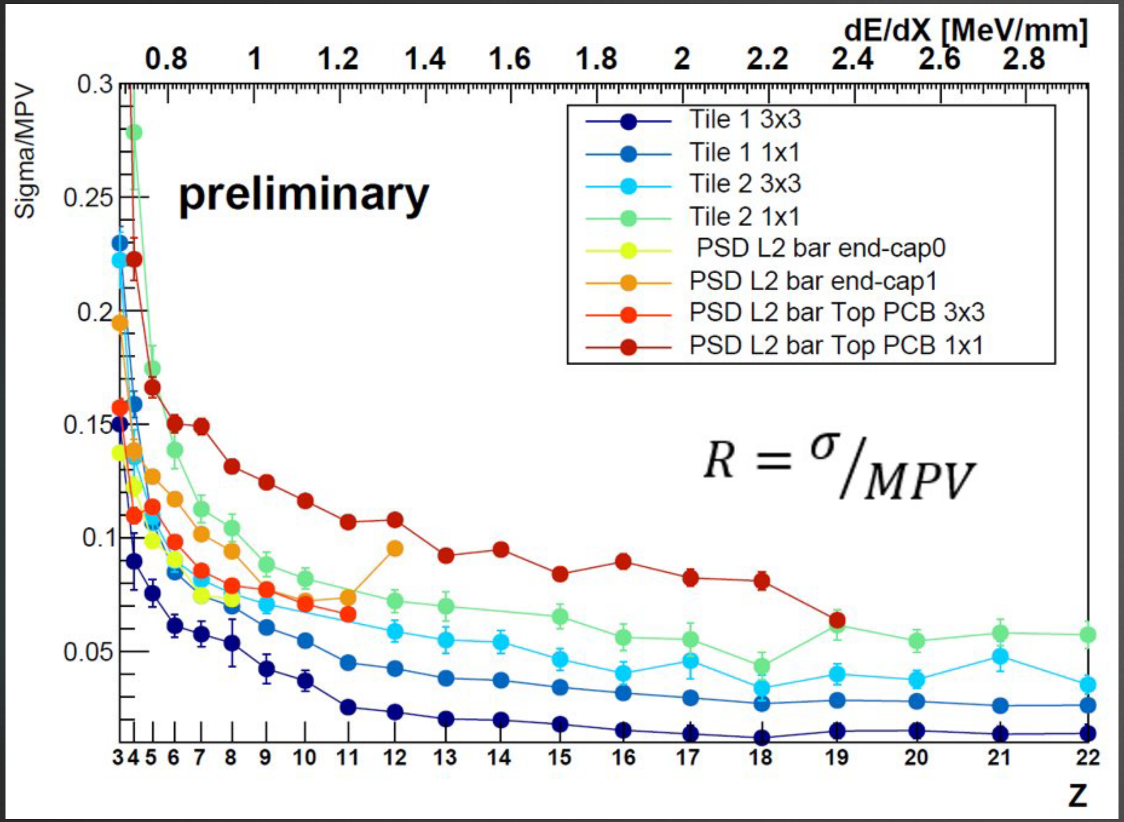




The SiPMs on the end of the trapezoidal tile collect too much light and the readout chain saturate at Z=8

Small SiPM collect less light, and this allow a higher dynamic range

The charge resolution is obtained by fitting the peaks corresponding to the different Z particles with a Gaussian function

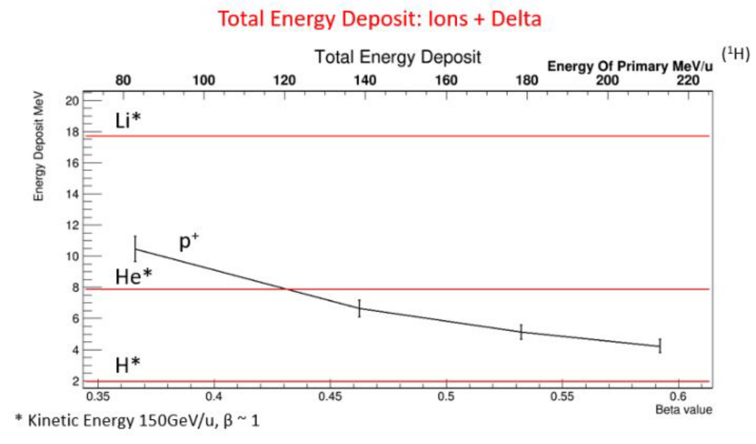


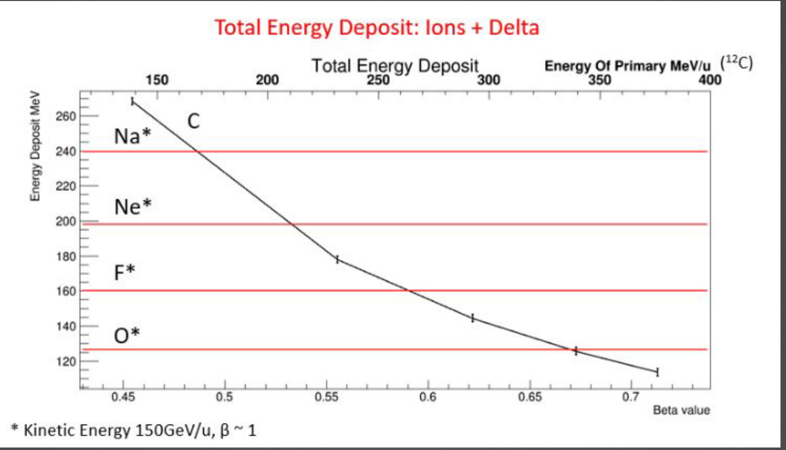
- The best charge resolution is obtained with square tile T1 since it is the first along the beam and it is not affected by ions fragmentations
- The trapezoidal tile readout on the TOP side with $3x3mm^2$ SiPM has a resolution better than **10% (Z<11)**
- The trapezoidal tile readout on the TOP side with $1x1mm^2$ SiPM has a resolution better than **15% (Z<19)**
- The charge resolution could improve in a setup with less material in front of the PSD and with the new version of β-chip

CNAO 2023

CNAO is an Italian canter for hadrontherapy

It has an experimental area with **p** and **C** beam accelerated up to **few hundred MeV** that can be used to mimic high Z particle due to higher energy loss





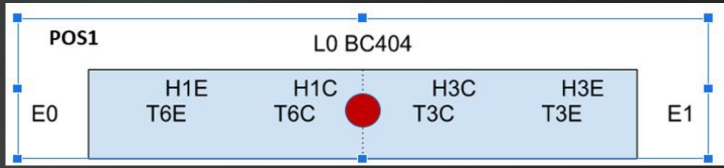
In 2023 we have done two test at CNAO with a prototype closer to the final PSD design

We have tested a single trapezoidal tile equipped with different SiPMs

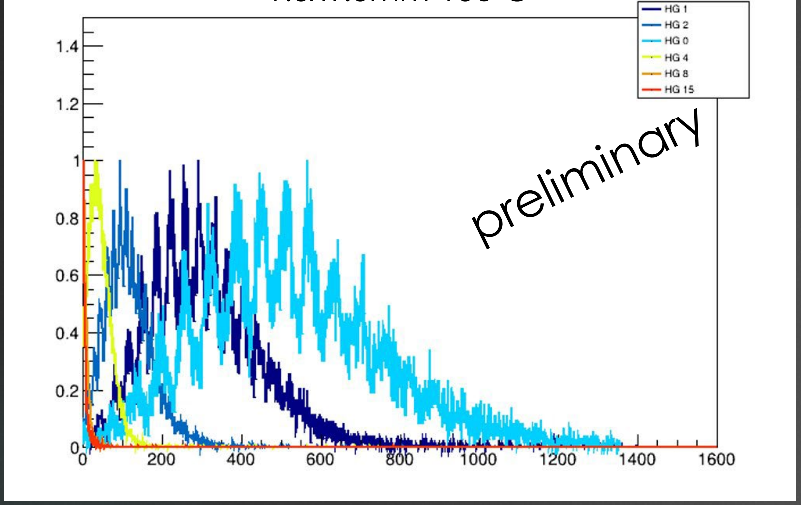
- S14160-3050HS (3.0x3.0mm2 – 50umcell)
- S14160-6050HS (6.0x6.0mm2 – 50umcell)
- S14160-1315PE (1.3x1.3 mm2 – 15um cell)
- S14160-3015PE (3.0x3.0 mm2 – 15um cell)

The analysis are still ongoing

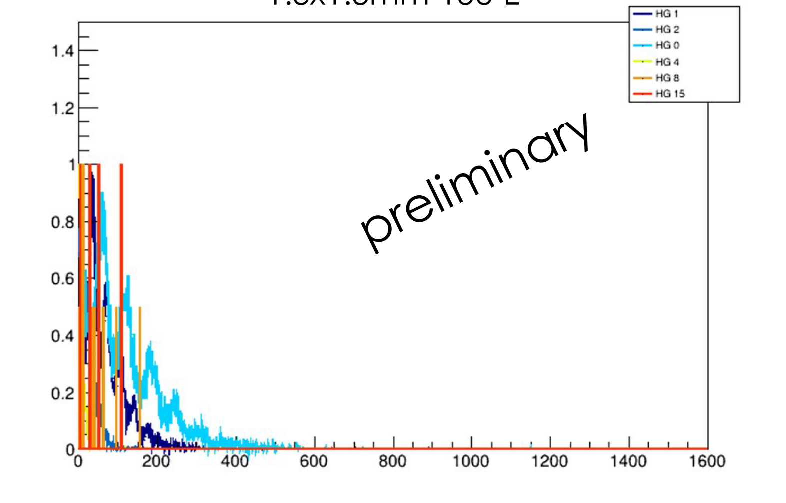
p @ 228.57 MeV



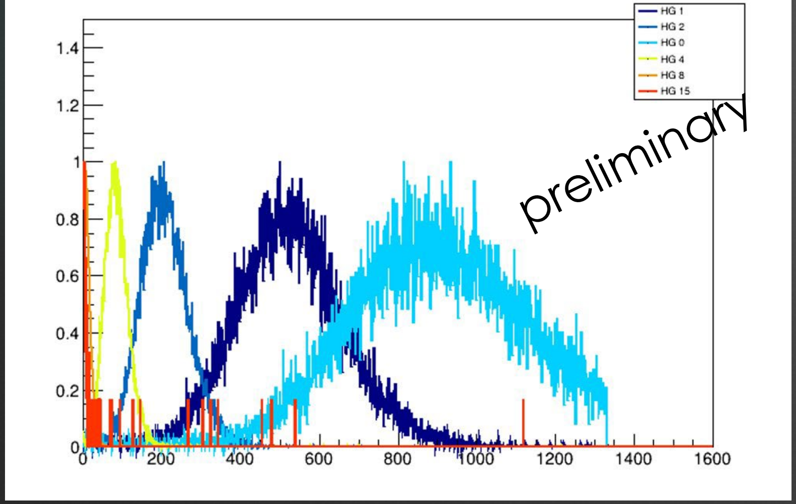
1.3x1.3mm 15u C



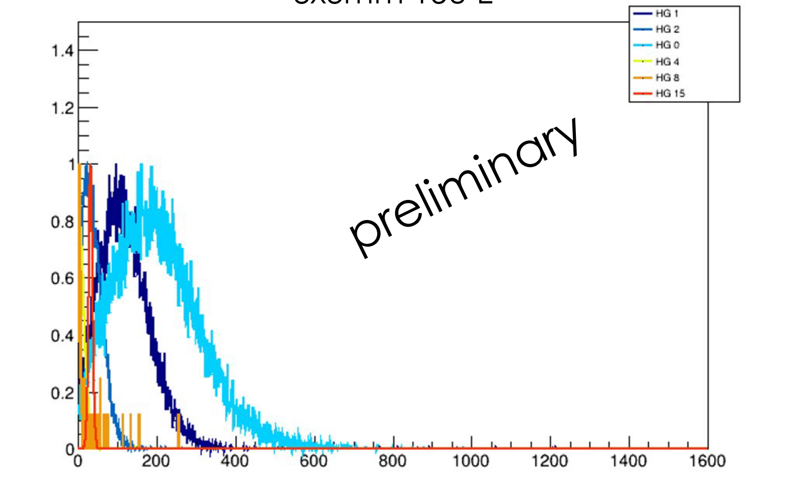
1.3x1.3mm 15u E



3x3mm 15u C



3x3mm 15u E



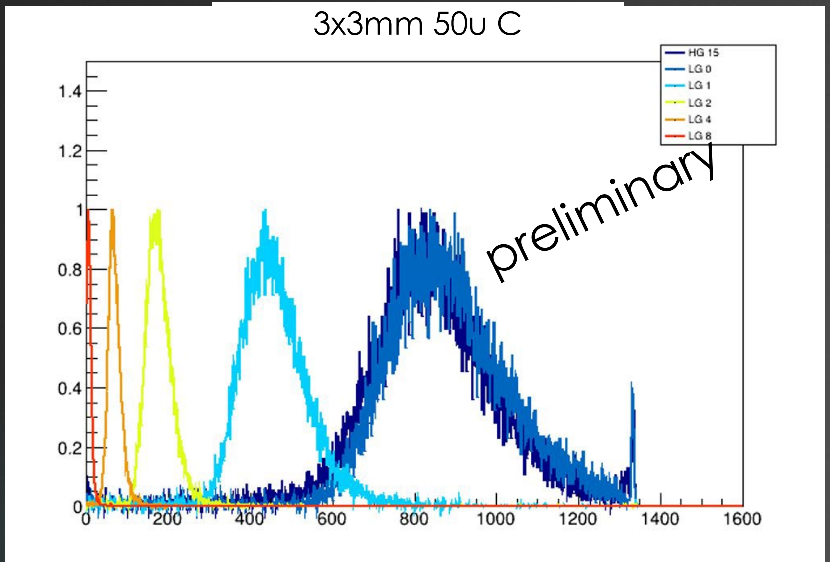
Plot at different gain for 15um cell SiPM

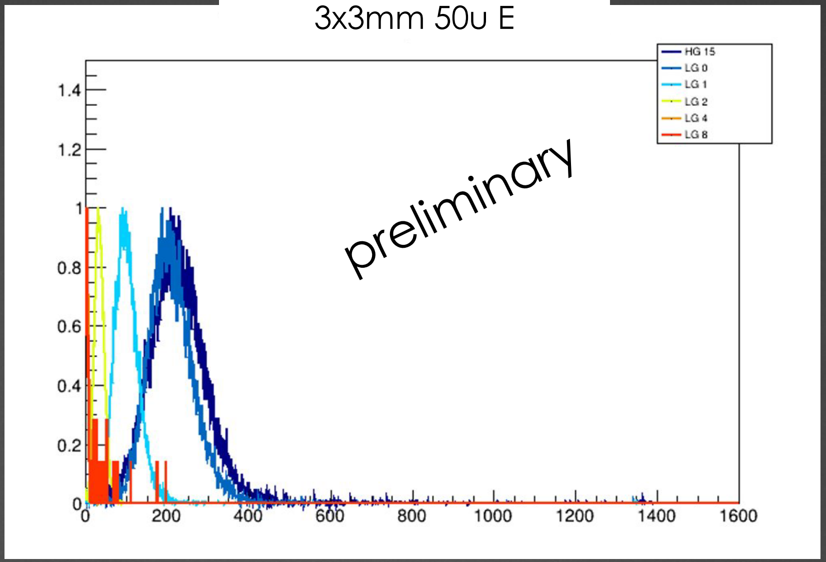
This kind of SiPM have an intrinsic gain that is probably too low for a good MIP detection if the particle cross the bar far from the SiPM

For this reason, we have also 50um cell size SiPM that have a higher intrinsic gain

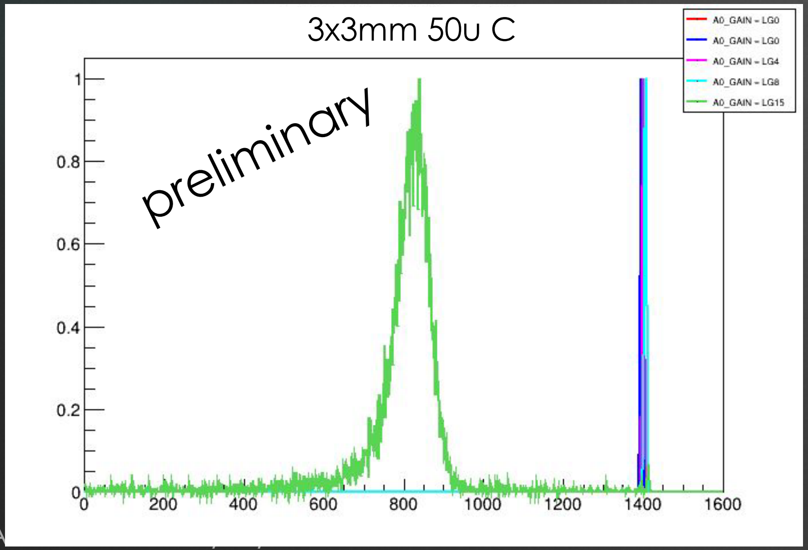
The analysis are still ongoing

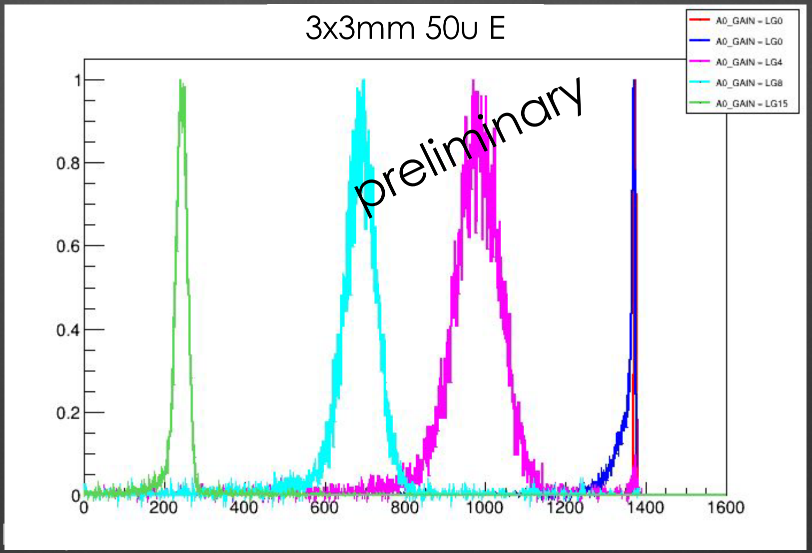
p @ 228.57 MeV

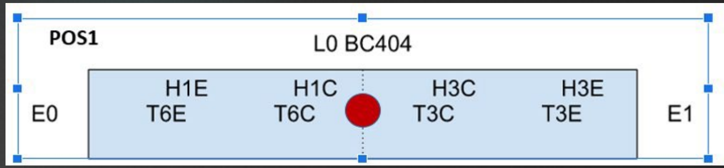




C @ 259.75 MeV







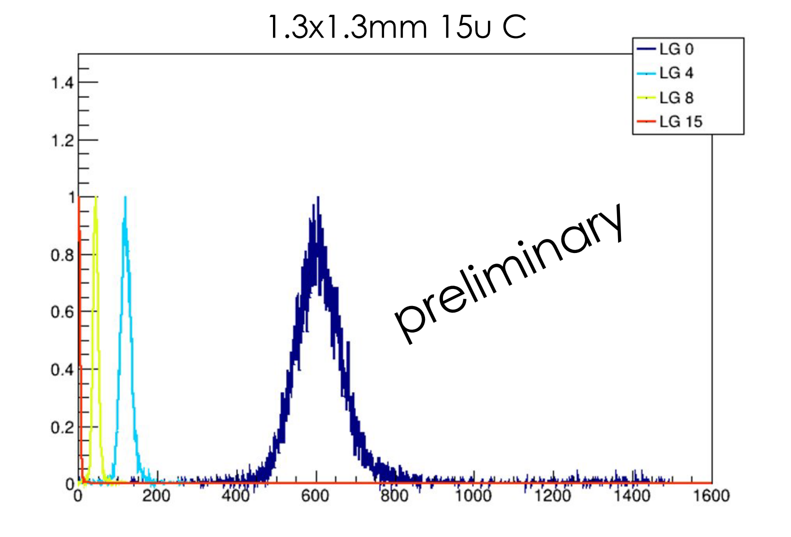
Plot at different gain for 50um cell SiPM

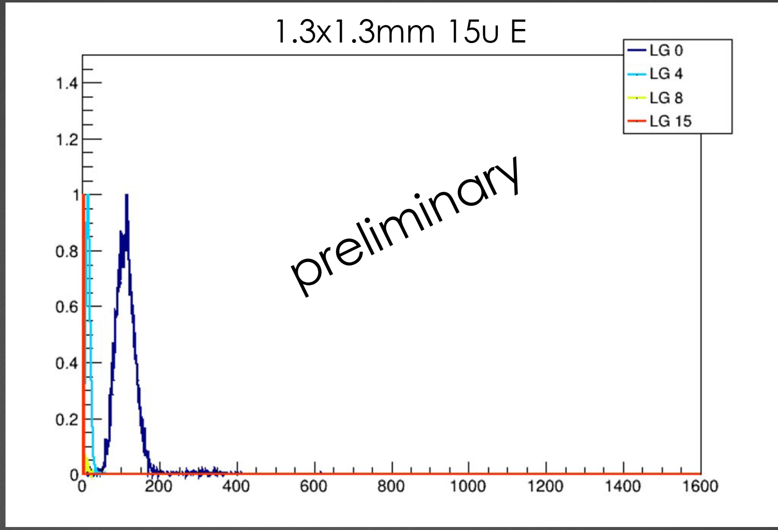
This kind of SiPM have a higher intrinsic gain and the signal is high enough to guarantee a very high efficiency of MIP detection even with a threshold at 1/3MIP

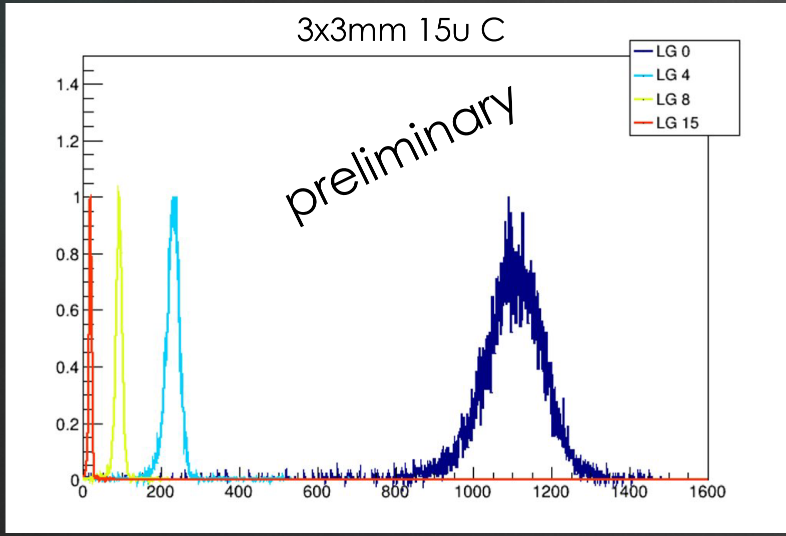
On the other side they are not very useful for High Z particle detection because of saturation of readout chain

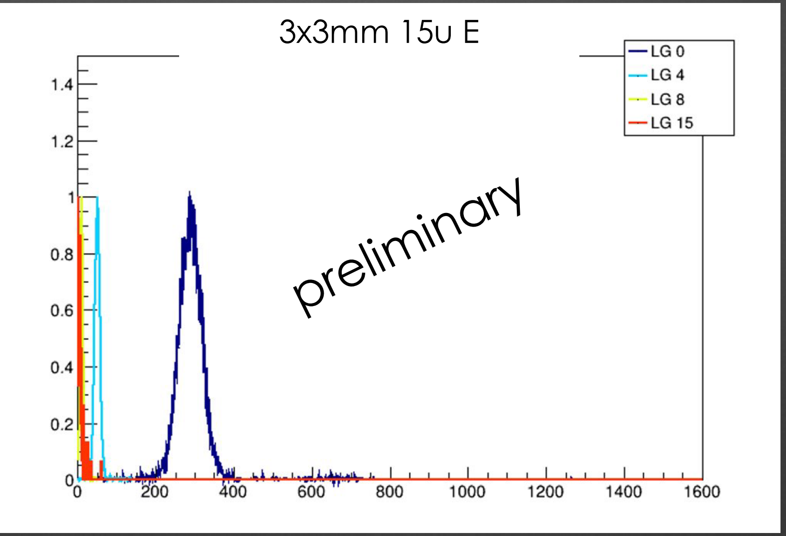
The analysis are still ongoing

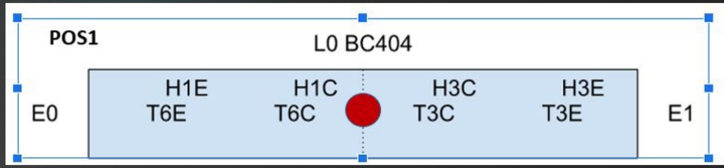
C @ 259.75 MeV





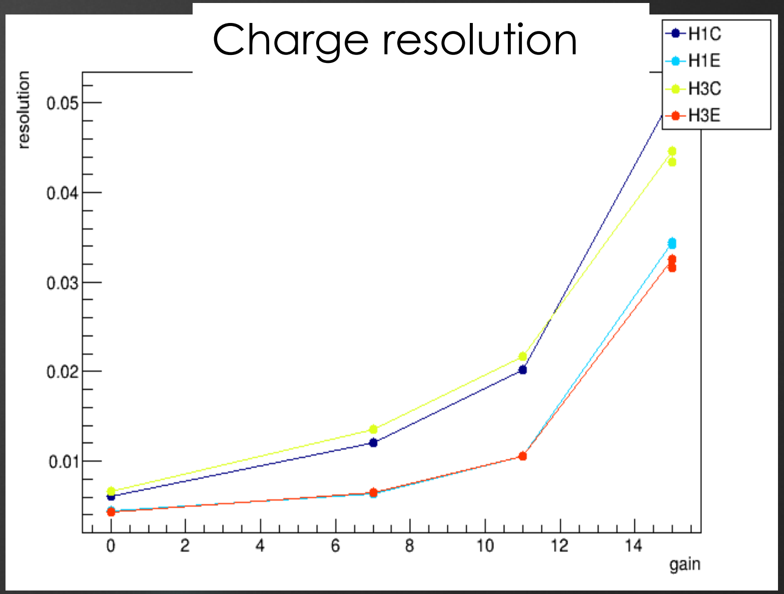






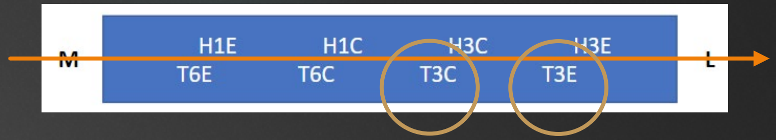
Plot at different log gain for 15um cell SiPM

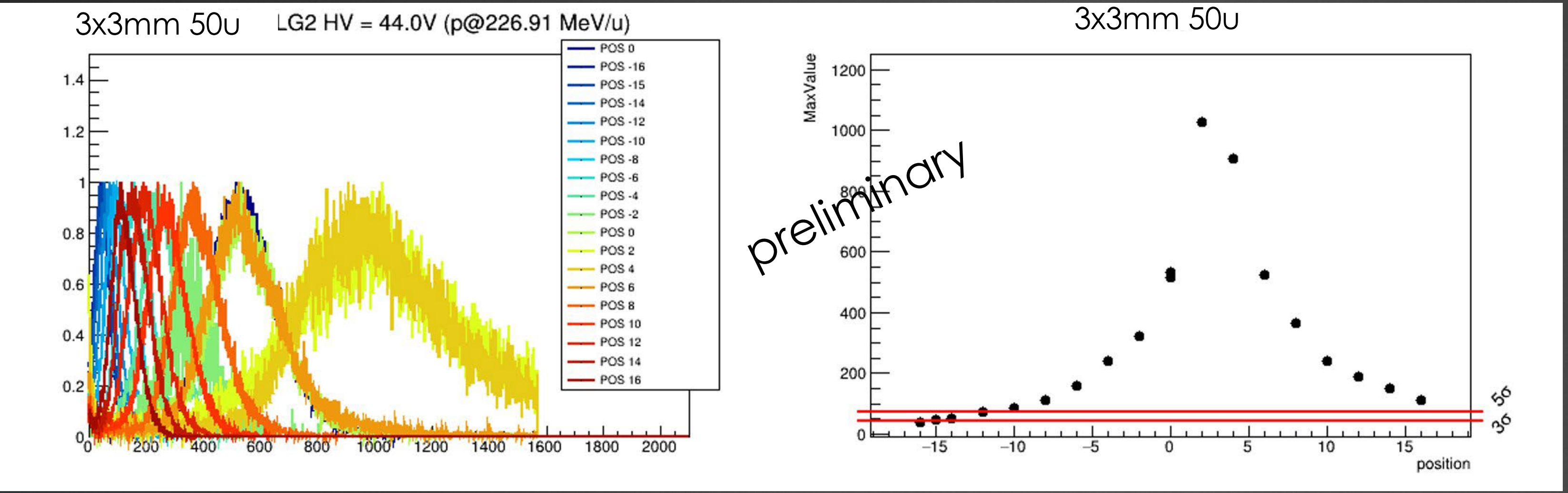
For high Z particles the intrinsic low gain is useful to increase the dynamic range and allow detection up to iron

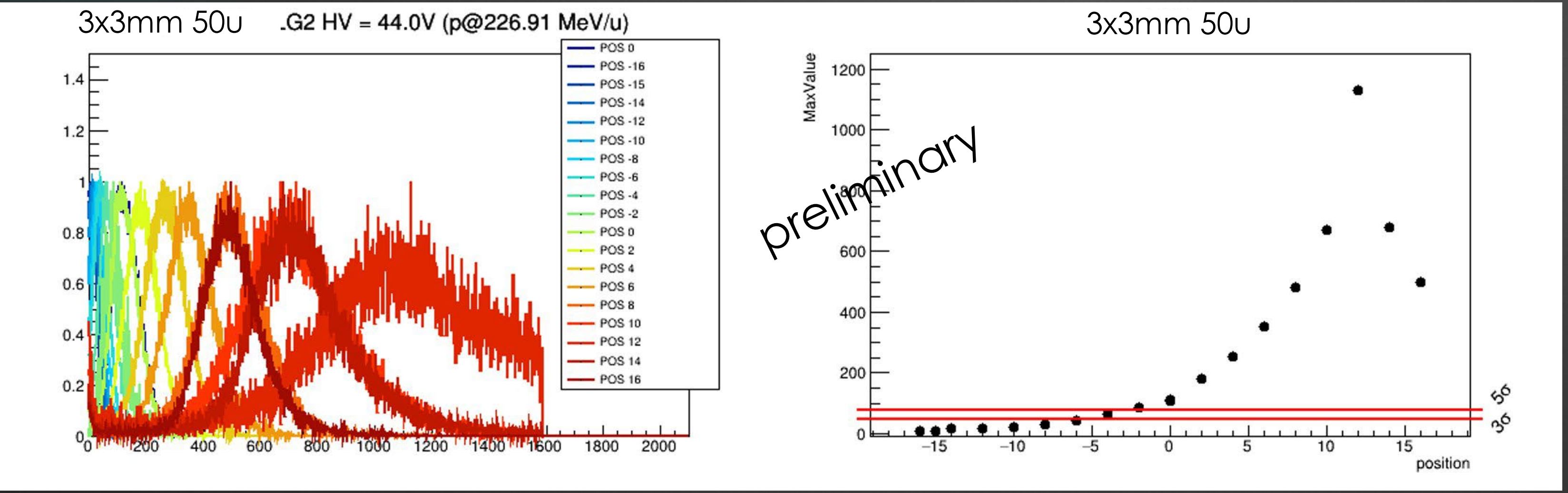


The analysis are still ongoing

We have performed a position scan to study the light collection uniformity at fixed gain for 50um cell SiPM







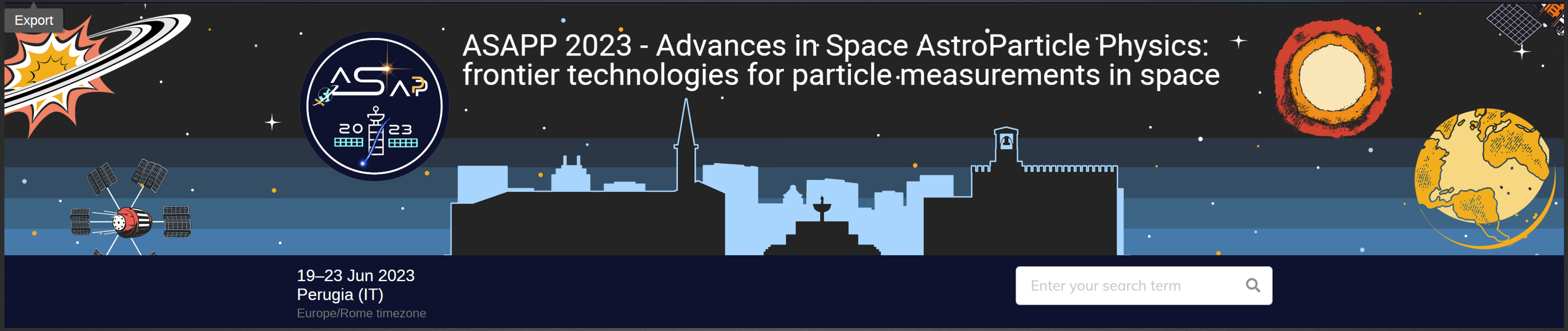
As expected, there is a great disuniformity in light collection due to scintillation light that reach the SiPM without any reflection inside the trapezoidal tile

Moreover, if the beam hit directly the SiPM there is an extra signal due to ionization in the silicon that usually saturate the readout chain

During flight data taking it is mandatory to have a tracking system that allow us to know the particle trajectory in order to **correct** the light collection disuniformity

On going activities

- We have a design for the PSD that according to our studies will allow us to reach all the targets
- We still miss some details regarding the mechanical structure and the readout overall architecture
- We have built and test prototypes that have provided very useful information to improve the design
- We will do another long beam test in September/October 2023 at CERN both at PS and SPS with a new prototype very close to the final design, with the new version of the β-chip and a readout logic very similar to the final one that allow us to check deeply all the design parameters
- In 2024 we plan to build a full-scale prototype of one SIDE plane of PSD fully equipped (INFN-ASI agreement)
- We are testing also different kinds of SiPMs produce by FBK according to our specification (RadHard, Low Cross Talk, Low HV) that should improve the overall performances of the PSD

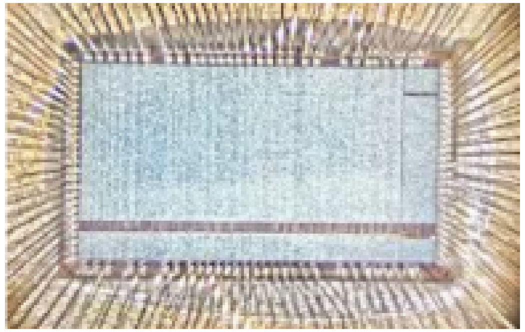


Thanks for your attention

Backup slide

Summary

- Single photon resolution: SNR >5 for 10 µm microcells (> 10 for 50 µm)
- High dynamic range: >15 bits (no saturation for > 3800 firing cells)
- Maximum event rate: 10 kHz with ADC @ 50 MHz (20 kHz @ 100 MHz)
- Tuneability: preamp gain and feedback resistor, shaping time, etc
- Trigger discriminator: time resolution < 200 ps rms (100 ps rms TBC)



First version of BETA chip

16 ch - 130 nm CMOS – 7 mm^2

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Summary

- Two final version planned:
  - 16 ch for trigger/VETO detectors
    - 16 disc. outputs and serial ADC output
    - < 1.5 mW/ch (timing optimized)
  - 64 ch for fiber tracker and large detectors
    - Single trigger and serial ADC outputs
    - < 1 mW/ch

BETA16R2:

- Under evaluation
- Preliminary results: ok
- Radiation tolerant: preparing radiation qualification (Q3 2023)

BETA64R1:

- Finalizing design
- Submission expected for Q3 or Q4 2023

First BETA16R2 have been sent to Bari and IFAEE.
Test we will start soon.

Preamp - High Gain & Low gain configuration

- The peaking voltage of the output voltage is linear with increasing values of the amplifier gain A_V for both HG and LG preamplifiers.
- The maximum achievable high gain is limited by the amplifier saturation voltage.
- Tuneable gain by changing the Cf value from 0.1pF to 2pF with a total of 10 configurations.

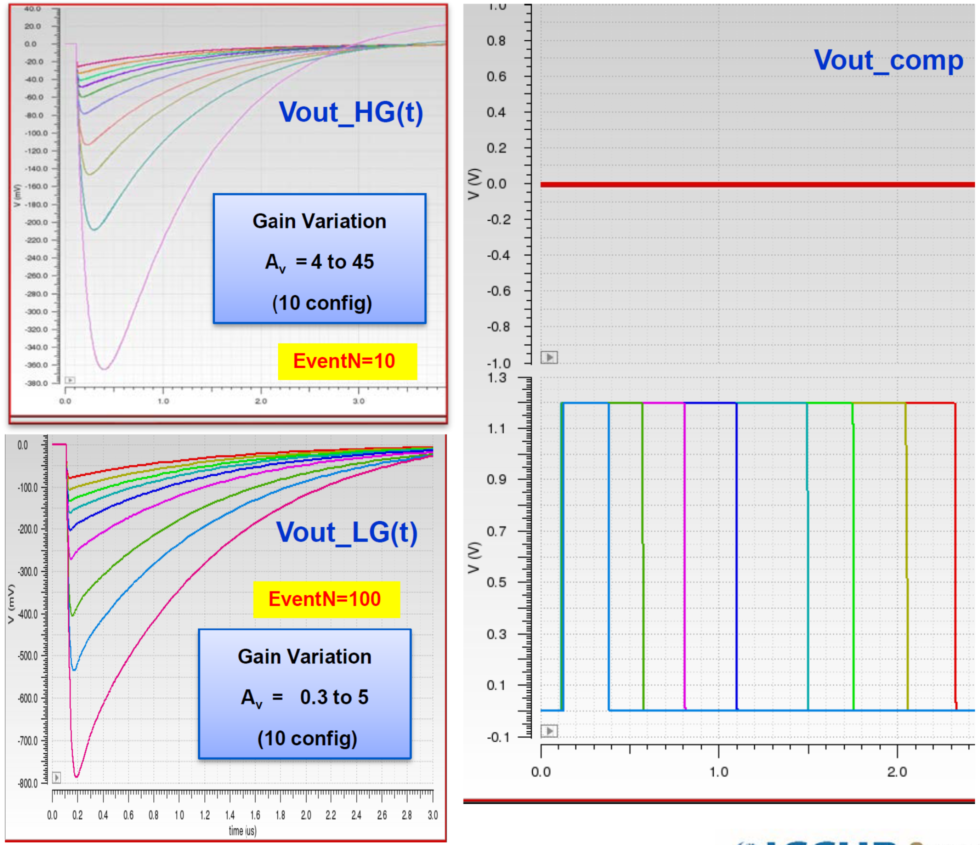
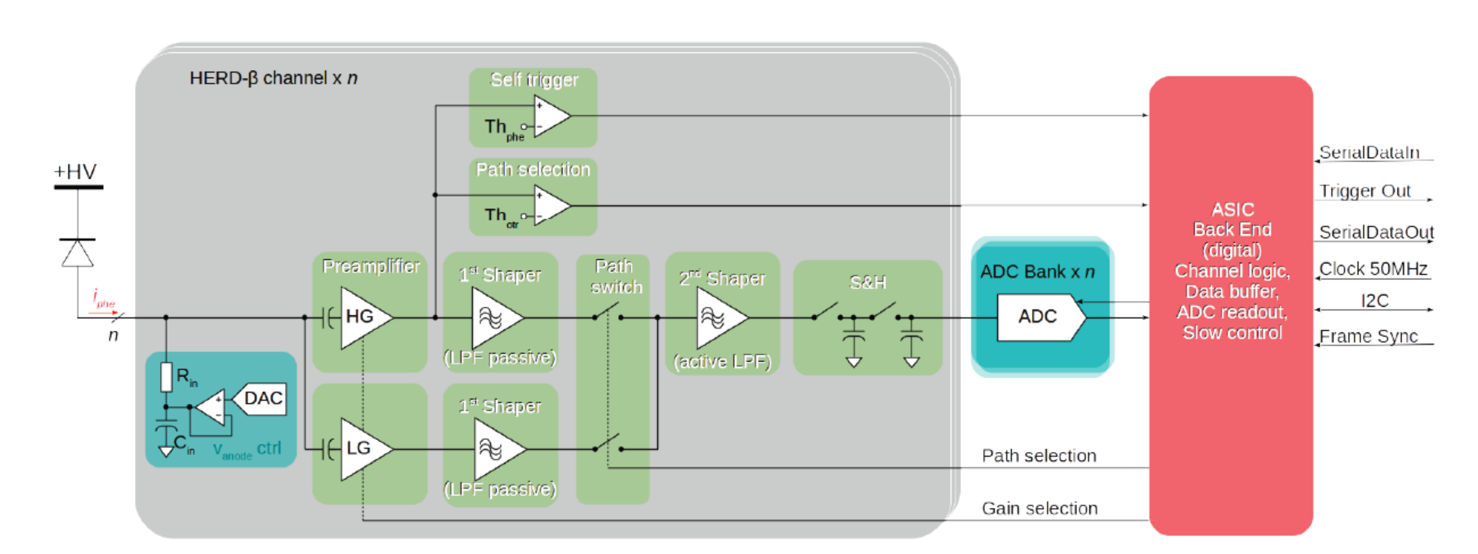


Table 1: Preamplifier Gain as function of feedback capacitance registers.

4-bit Dcap_CH_(HG or LG)_Cf	Cf	HG preamplifier gain (linear)	Cf	LG preamplifier gain (linear)
Default	125 fF	40.00	200 fF	3.72
0000	125 fF	40.00	200 fF	3.72
0001	250 fF	23.86	400 fF	1.97
0010	375 fF	16.95	600 fF	1.33
0011	500 fF	13.00	800 fF	1.00
0100	625 fF	10.64	1000 fF	0.81
0101	750 fF	8.95	1200 fF	0.67
0110	875 fF	7.73	1400 fF	0.58
0111	1000 fF	6.82	1600 fF	0.50
1000	1125 fF	6.05	1800 fF	0.45
1001	1250 fF	5.55	2000 fF	0.40
1010	1375 fF	5.00	2200 fF	0.36
1011	1500 fF	4.64	2400 fF	0.33
1100	1625 fF	4.27	2600 fF	0.30
1101	1750 fF	3.95	2800 fF	0.28
1110	1875 fF	3.73	3000 fF	0.26
1111	2000 fF	3.45	3200 fF	0.24

Electronic readout

The core of the electronic readout is the BetaChip ASIC



*Block diagram of the Betachip ASIC**

Channels x ASIC	16
Input rate	1 kHz (max recommanded)
Power drow	0.5 mW/ch
Dynamic range	12 bits

**Taken from datasheet:*

Beta ASIC :

- Multichannel signal amplification (16 channel)
- Multigain (16 level x 2 gain paths: High and Low gain)
- Low power consumption (Space application)
- Large dynamic range (auto switch between low and high gain)
- Digitalized output (12 bit ADC)

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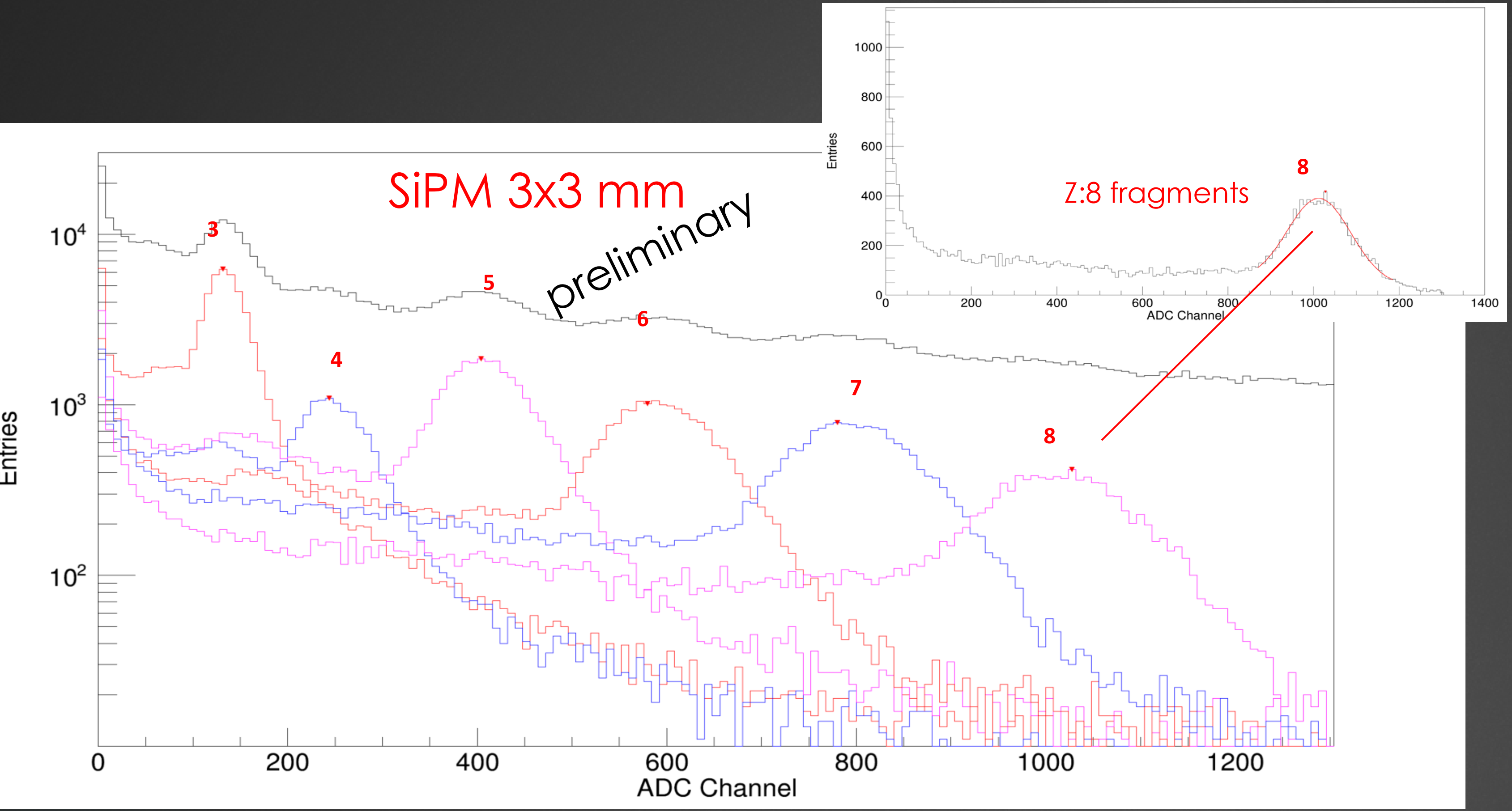
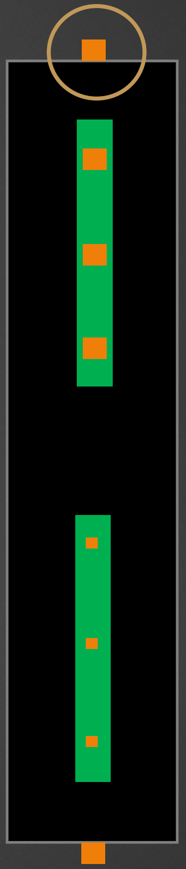
EXCELENCIA MARÍA DE MAEZTU 2020-2023

*Designed by Institute of Cosmos Sciences of the University of Barcelona (ICCUB)


SiPM 3x3 mm
preliminary
Entries
ADC Channel
3
4
5
6
7
8
Z:8 fragments
8



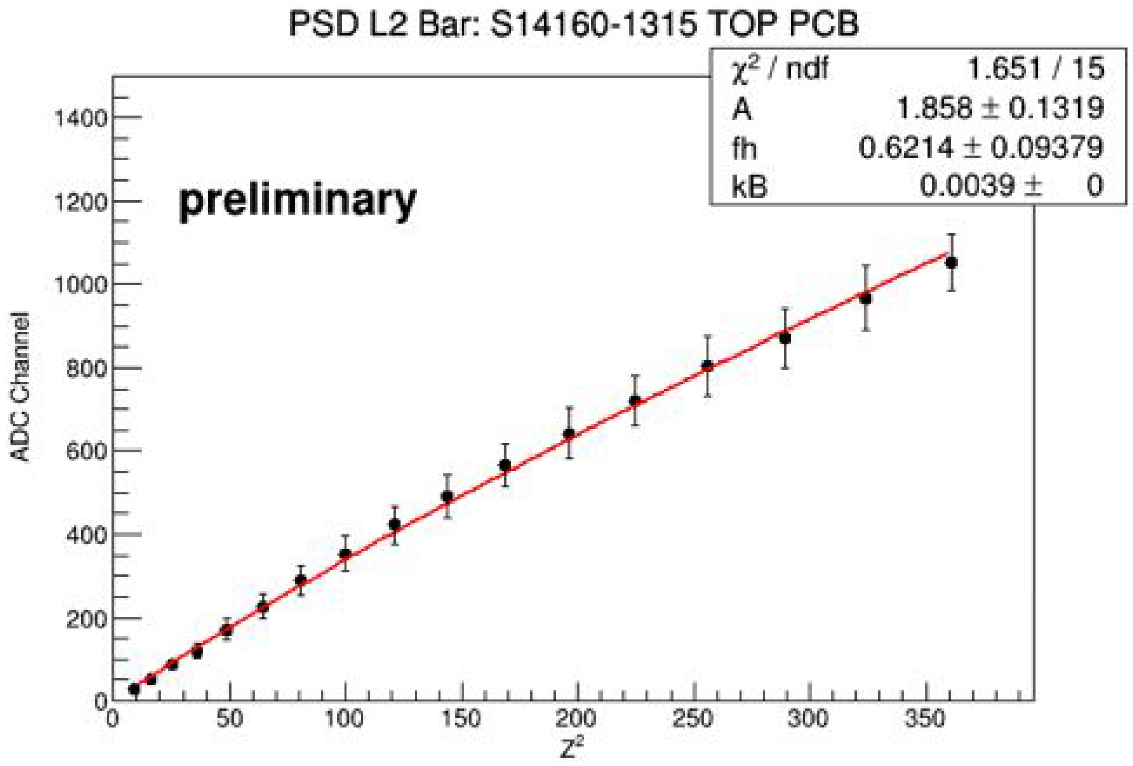
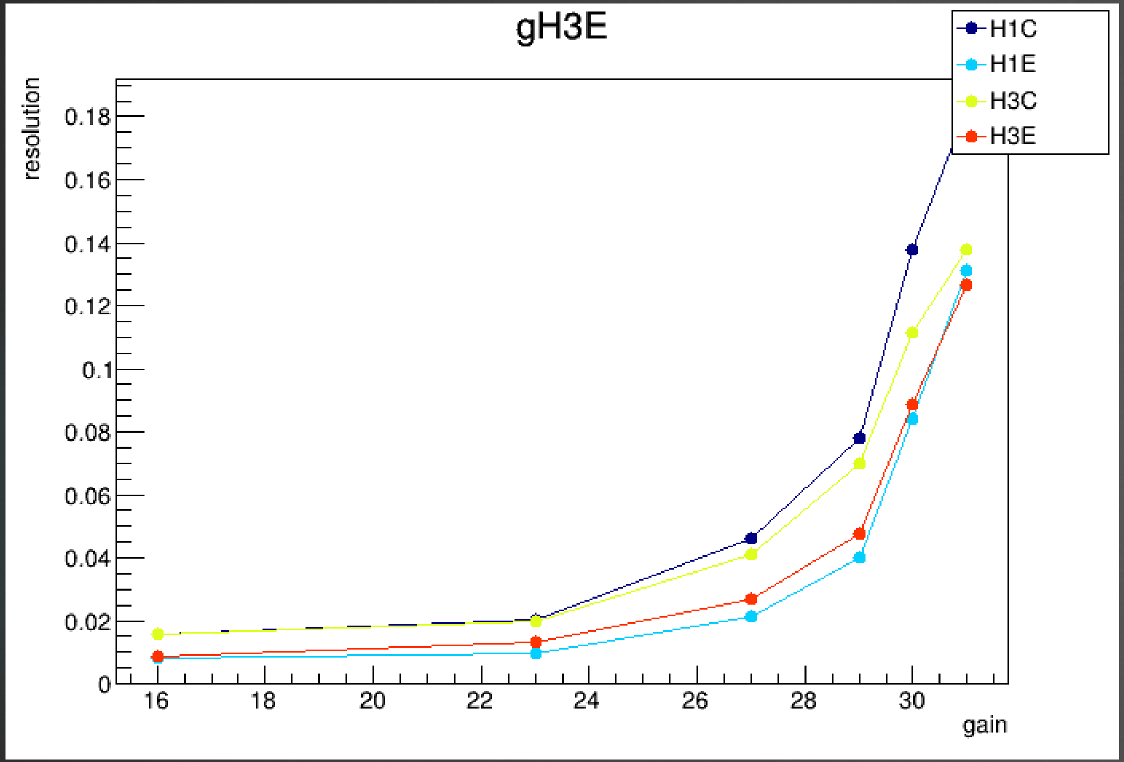
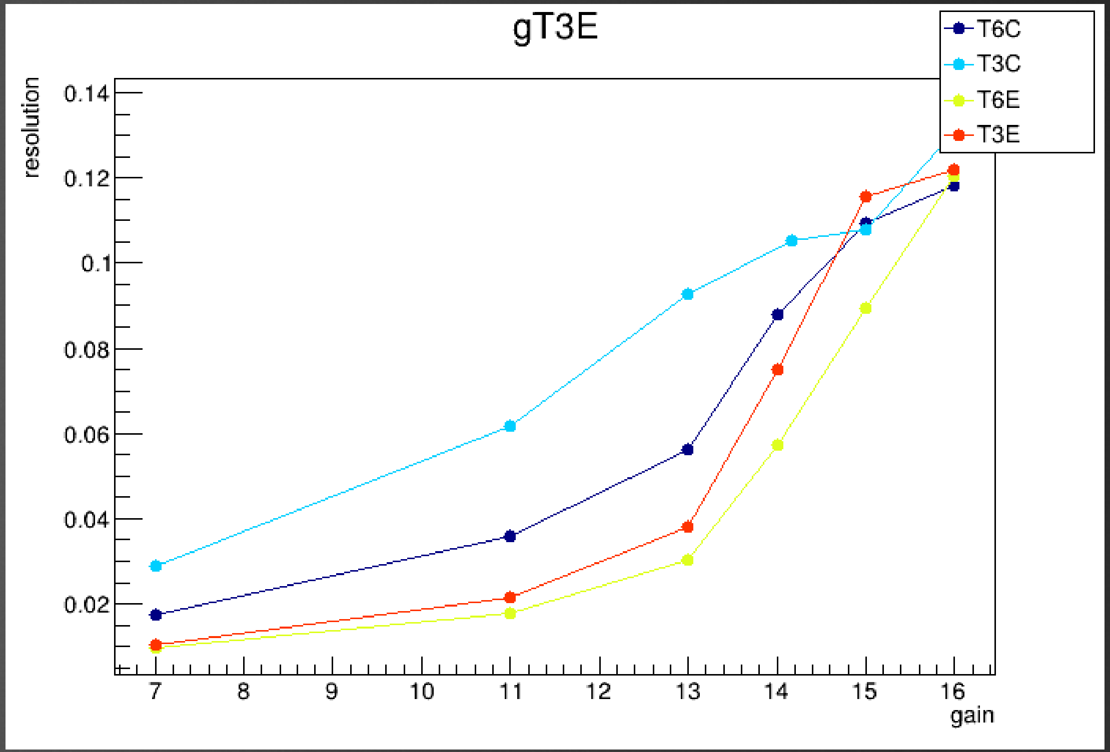


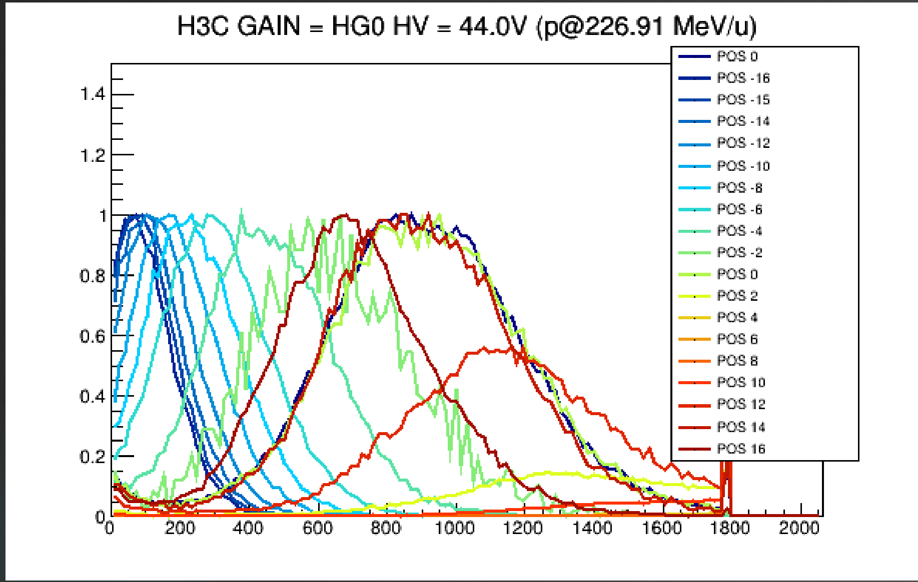
Figure X Mean ADC channels as a function of the Z^2 of the different primary ions from the selected signals of the TOP S1 SiPM for the L2 tile. The red line represents the best-fit curves obtained using the Birks's formula (1) (CITE birks).

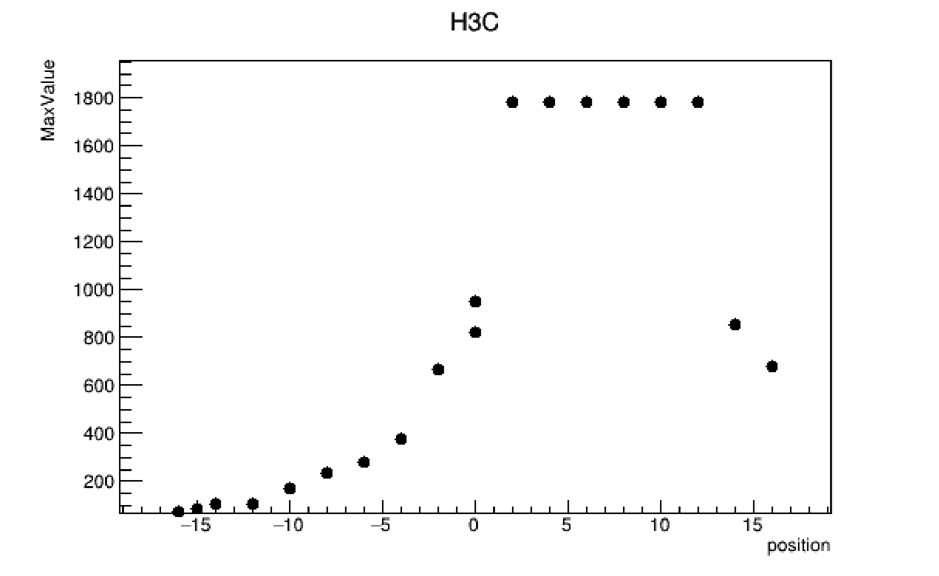
Charge resolution with protons @228.57MeV

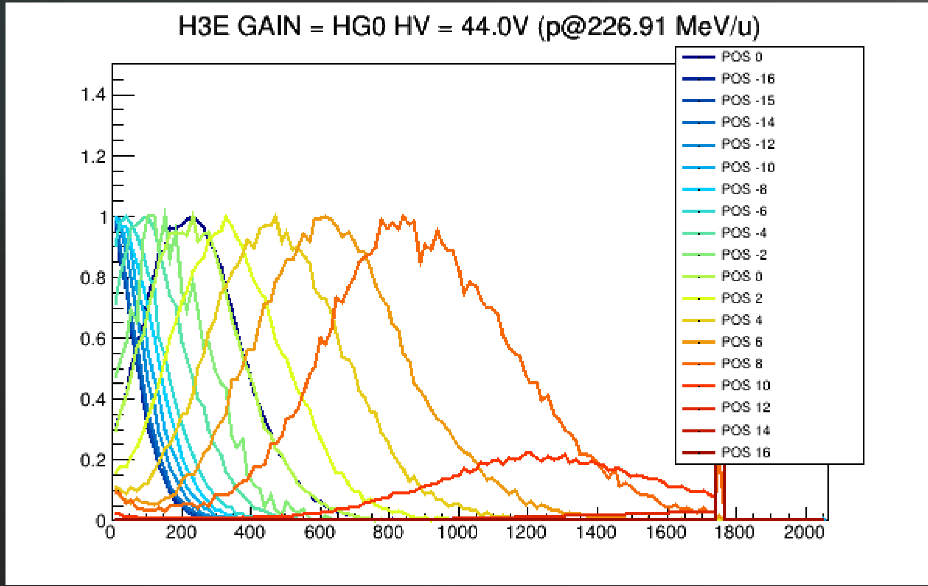


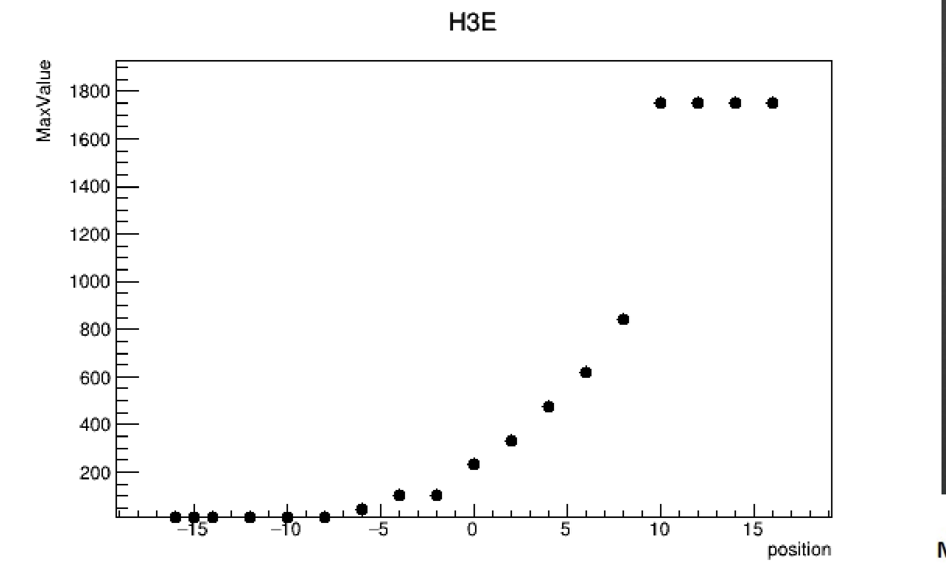


Scan Position: p@226.91 MeV - HAM Data

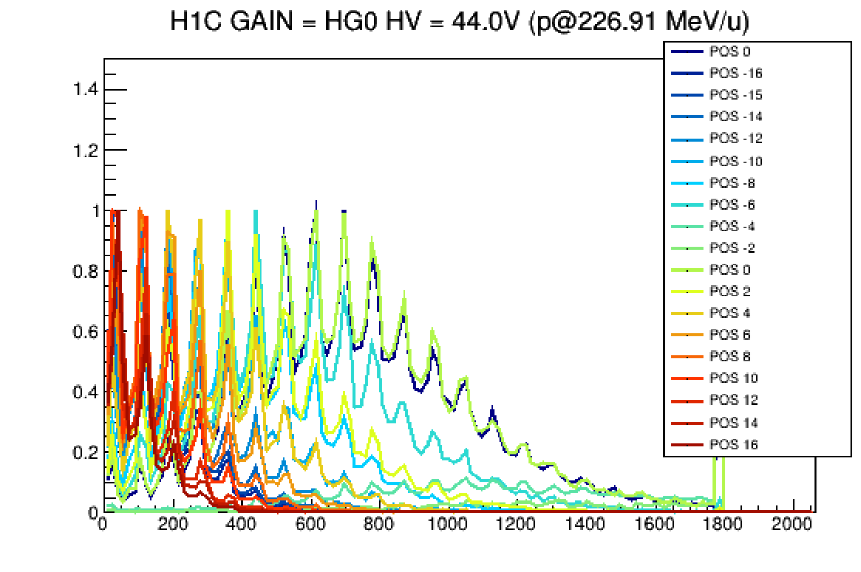


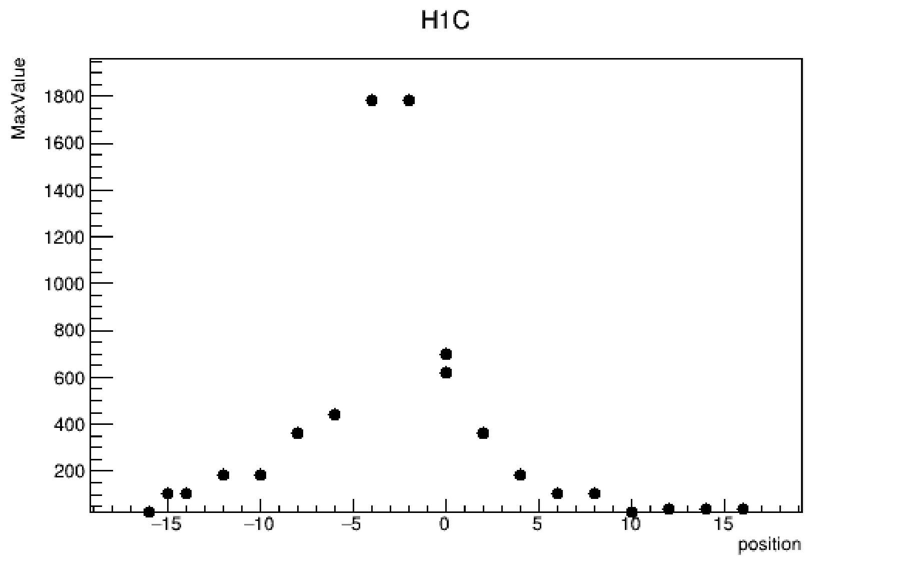


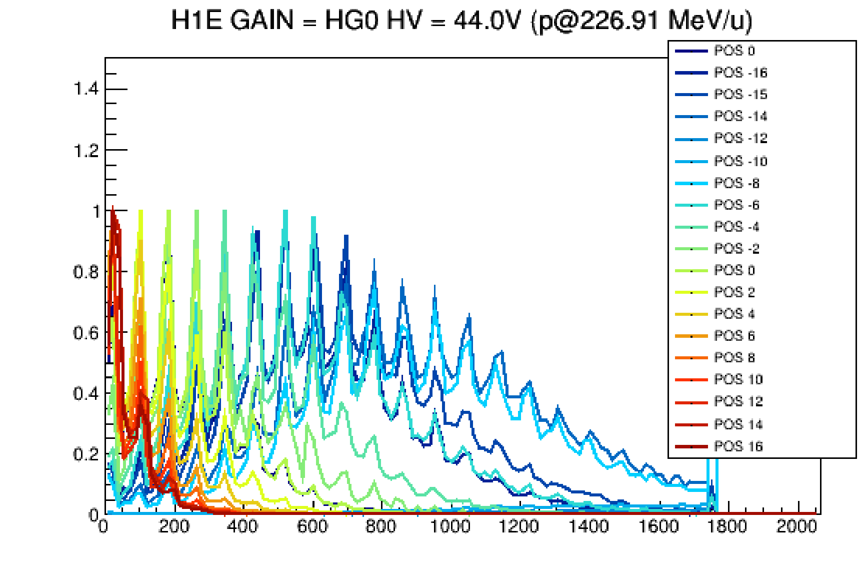


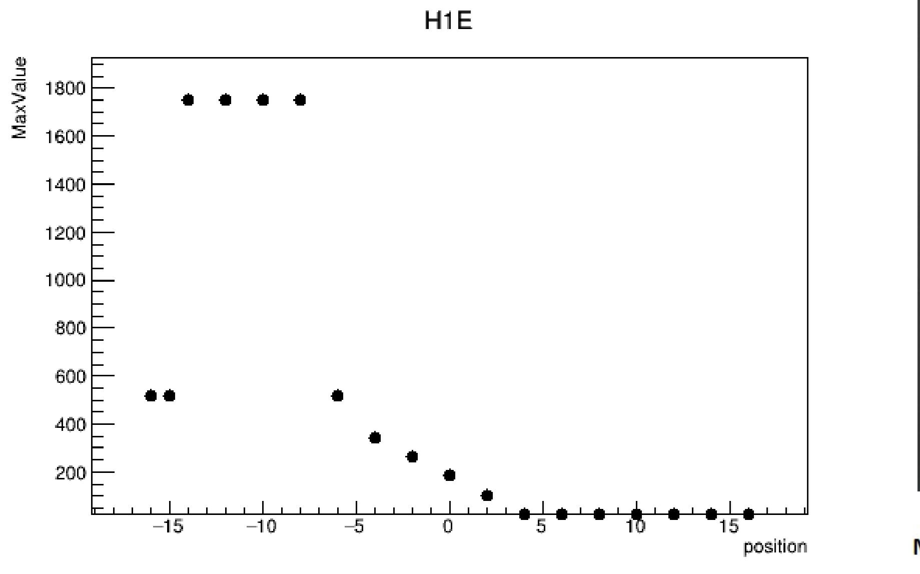


Scan Position: p@226.91 MeV - HAM Data

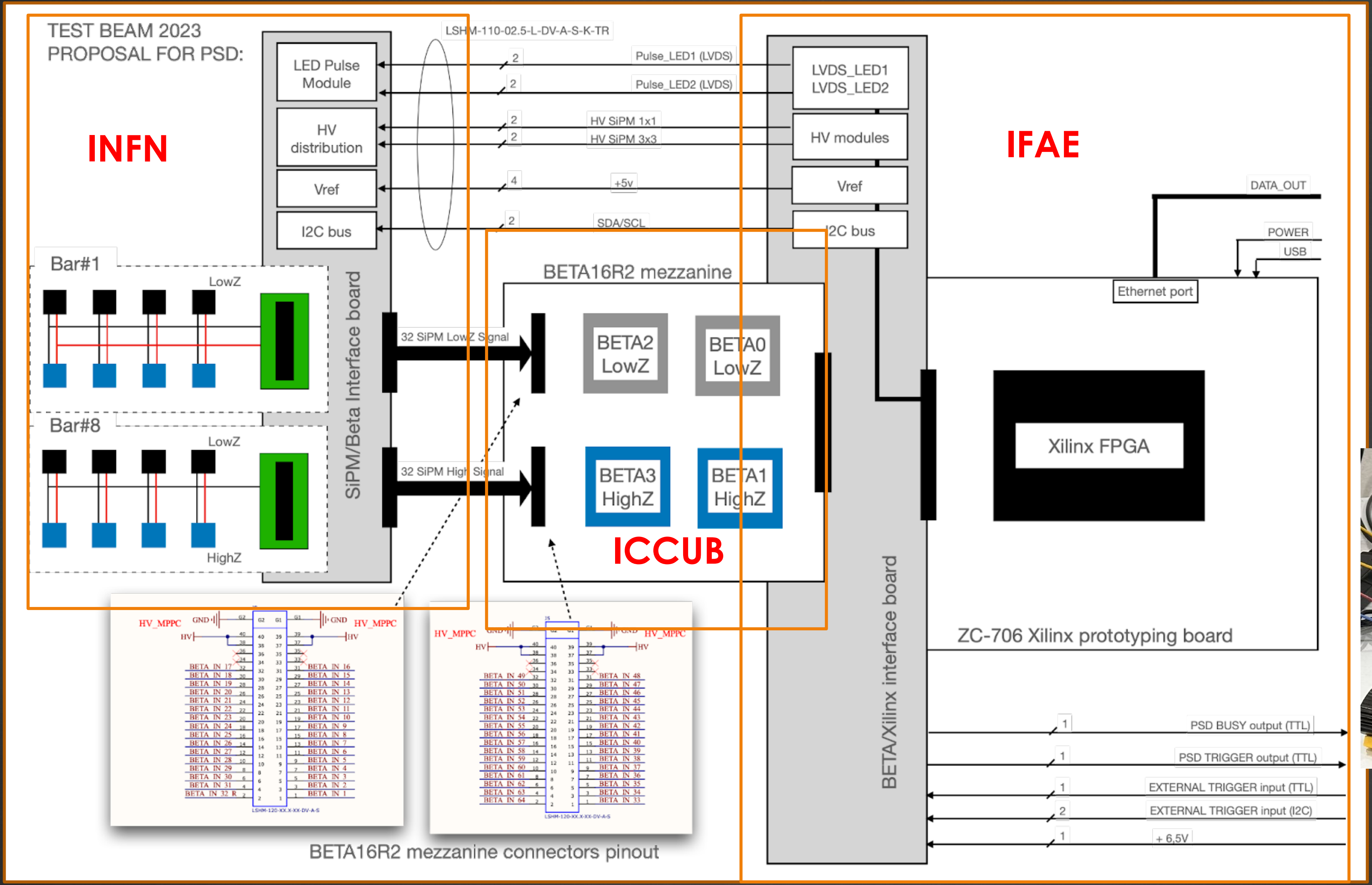








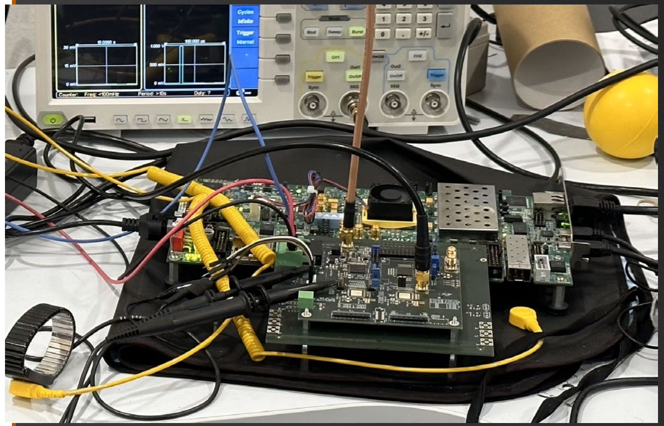
Next Beam test



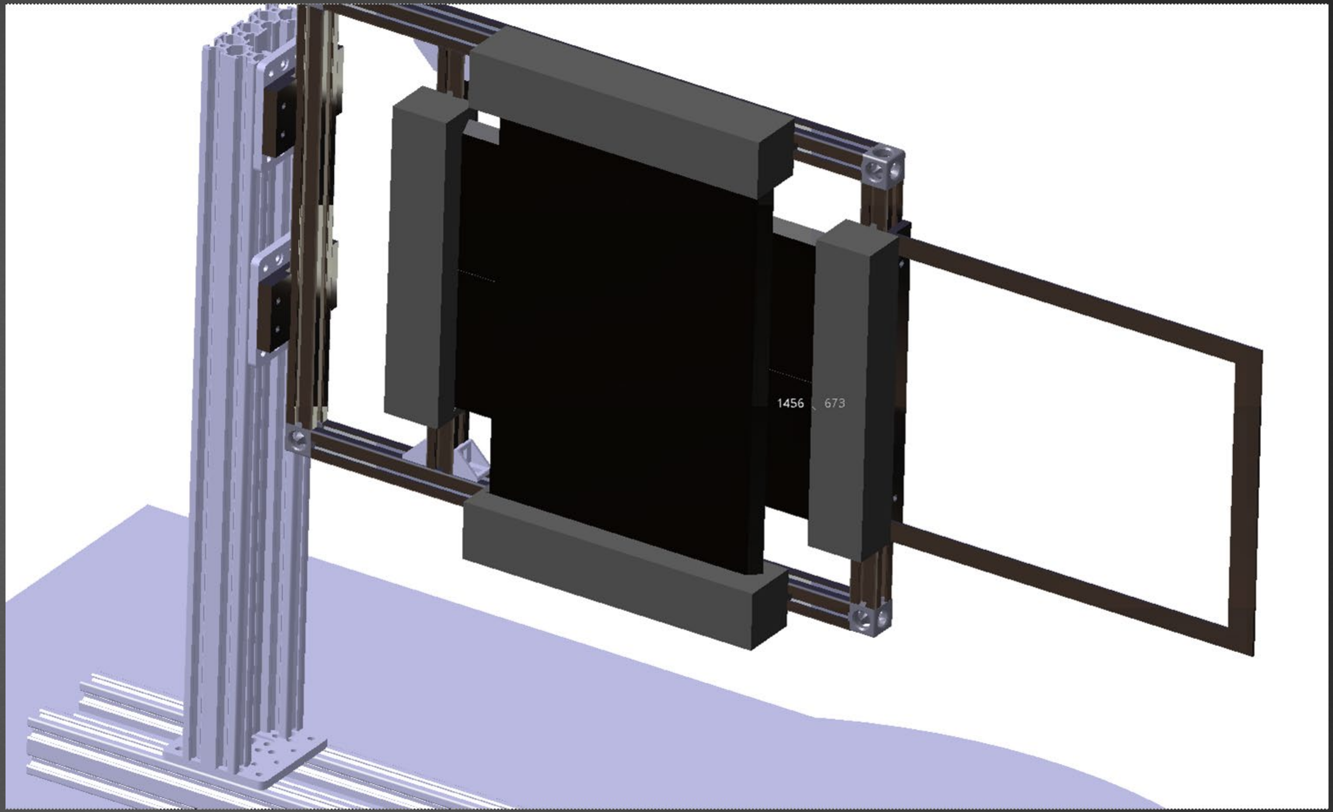
FPGA firmware almost done

Interface PCB designed

Test we will start soon



Next Beam test



We have all the scintillating bars and all the needed mechanics.
We are designing the control units for the X-Y stages.
We need to define the last details of the mechanics.