Highly-granular Silicon-Tungsten electromagnetic calorimeters
- Introduction and instruction for practical exercise

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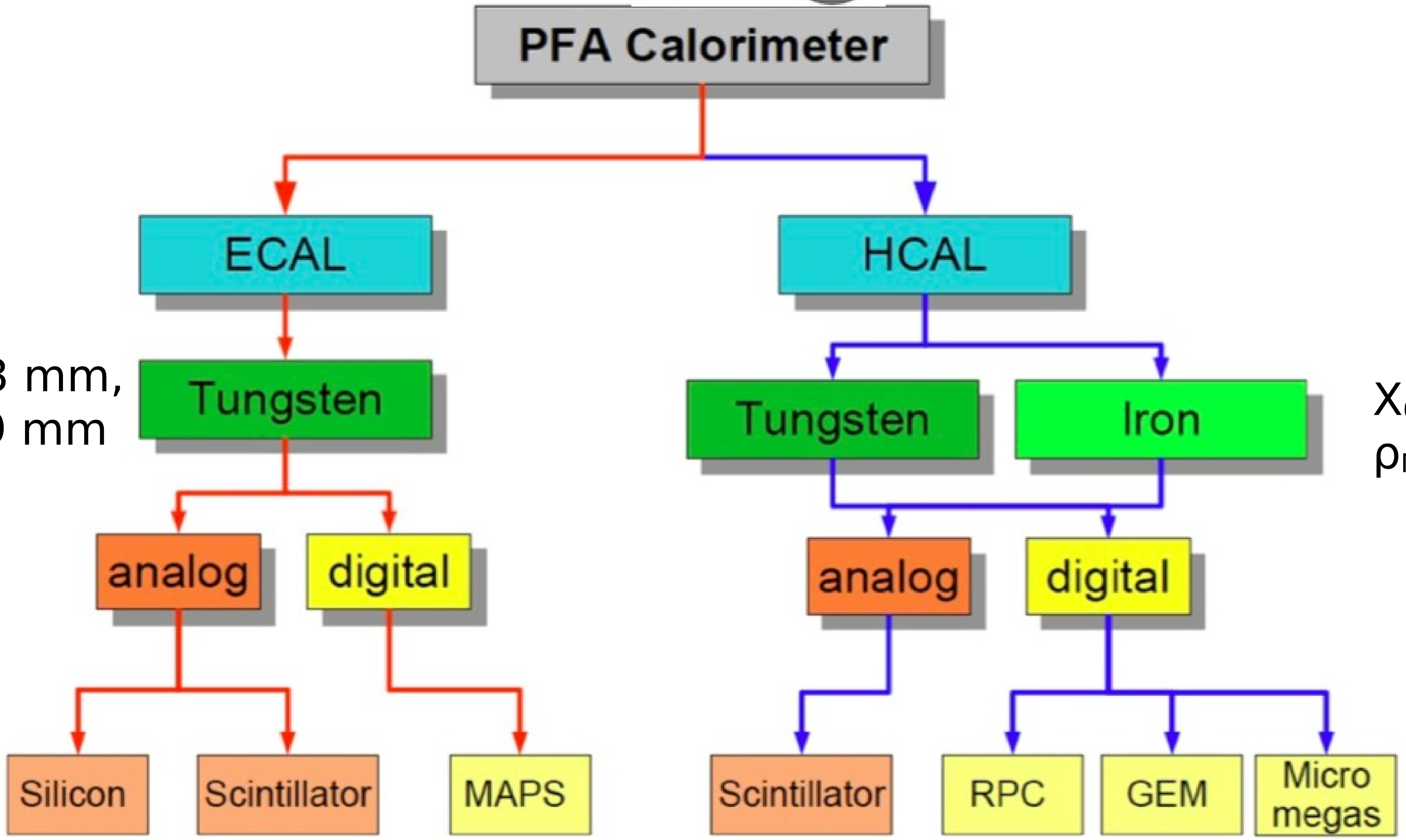
On behalf of the CALICE Collaboration

Instrumentation School – iThemba Labs
South-Africa August 2023

Supported by AIDA innova

Calorimeters for Particle Flow Algorithm

Mainly organised within the CALICE Collaboration



ECAL: $X_0 \sim 3$ mm, $\rho_M \sim 9$ mm

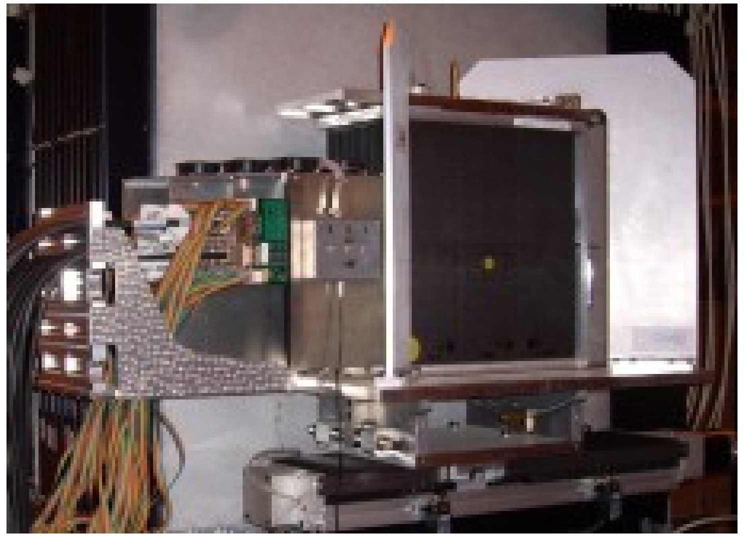
HCAL: $X_0 \sim 20$ mm, $\rho_M \sim 30$ mm

All projects of current future high energy colliders propose highly granular calorimeters

Steps of R&D

Physics Prototype

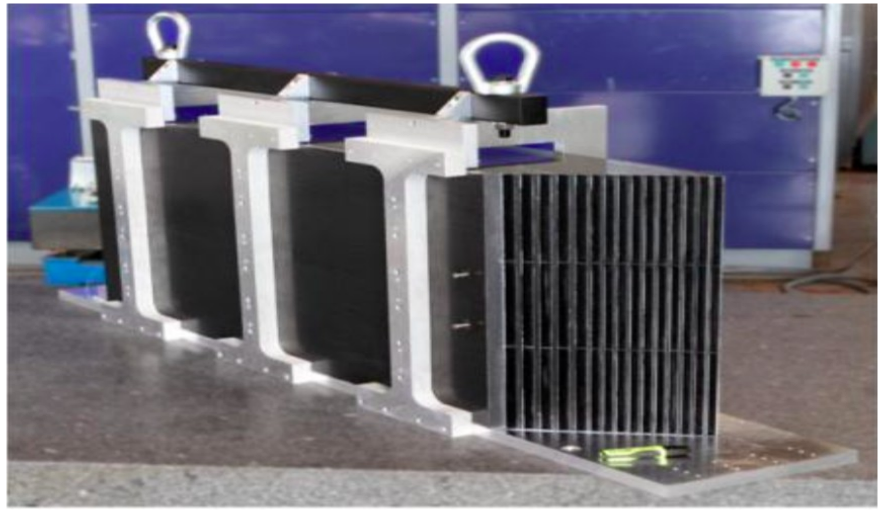
2005 - 2011



Proof of principle of granular calorimeters
Large scale combined beam tests

Technological Prototype

2010 - ...

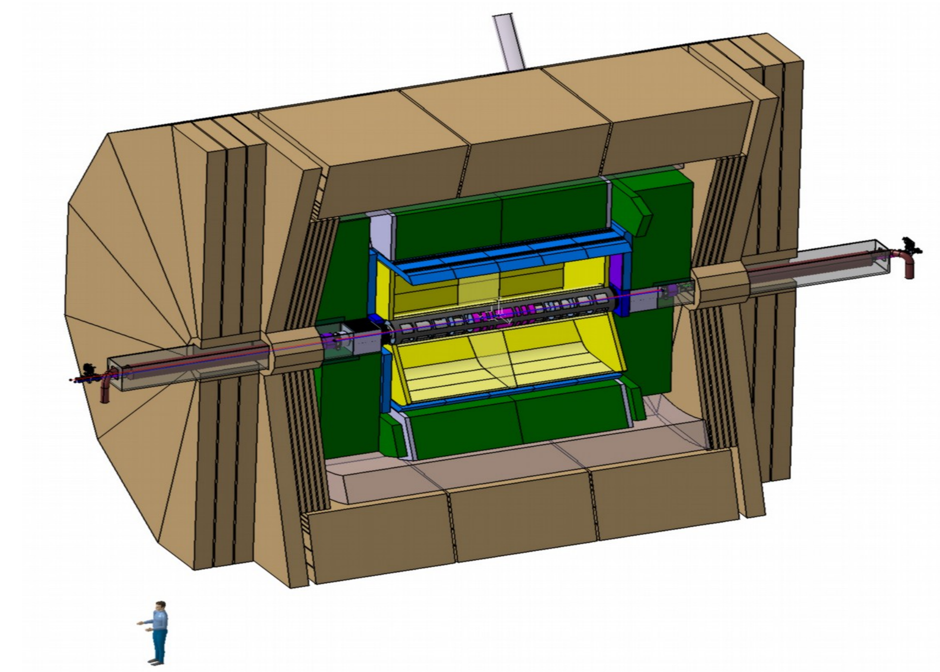


Engineering challenges

Higher granularity

Lower noise

LC detector

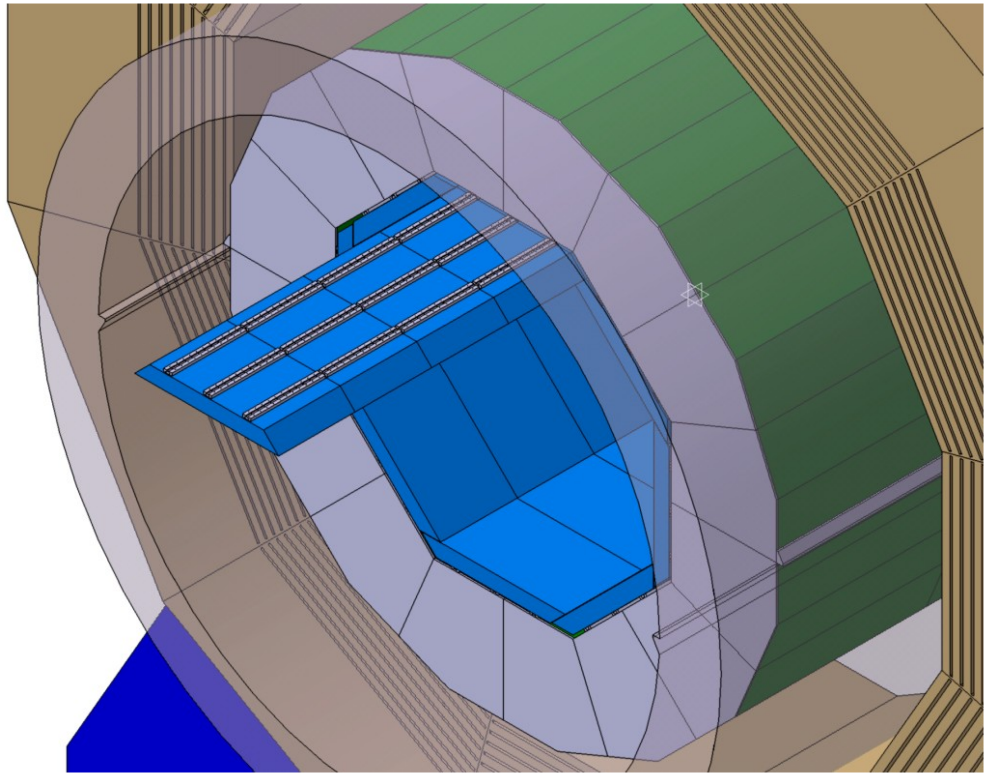


The goal
- Typically 10^8 calorimeter cells

Compare:
- ATLAS LAr ~10^5 cells
- CMS HGCAL ~10^7 cells

Silicon Tungsten electromagnetic calorimeter

Optimized for Particle Flow: Jet energy resolution 3-4%, Excellent photon-hadron separation



The SiW ECAL in the ILD Detector

- O(108) cells
- "No space"
=> Large integration effort

Basic Requirements:

- Extreme high granularity
- Compact and hermetic
- (inside magnetic coil)

Basic Choices:

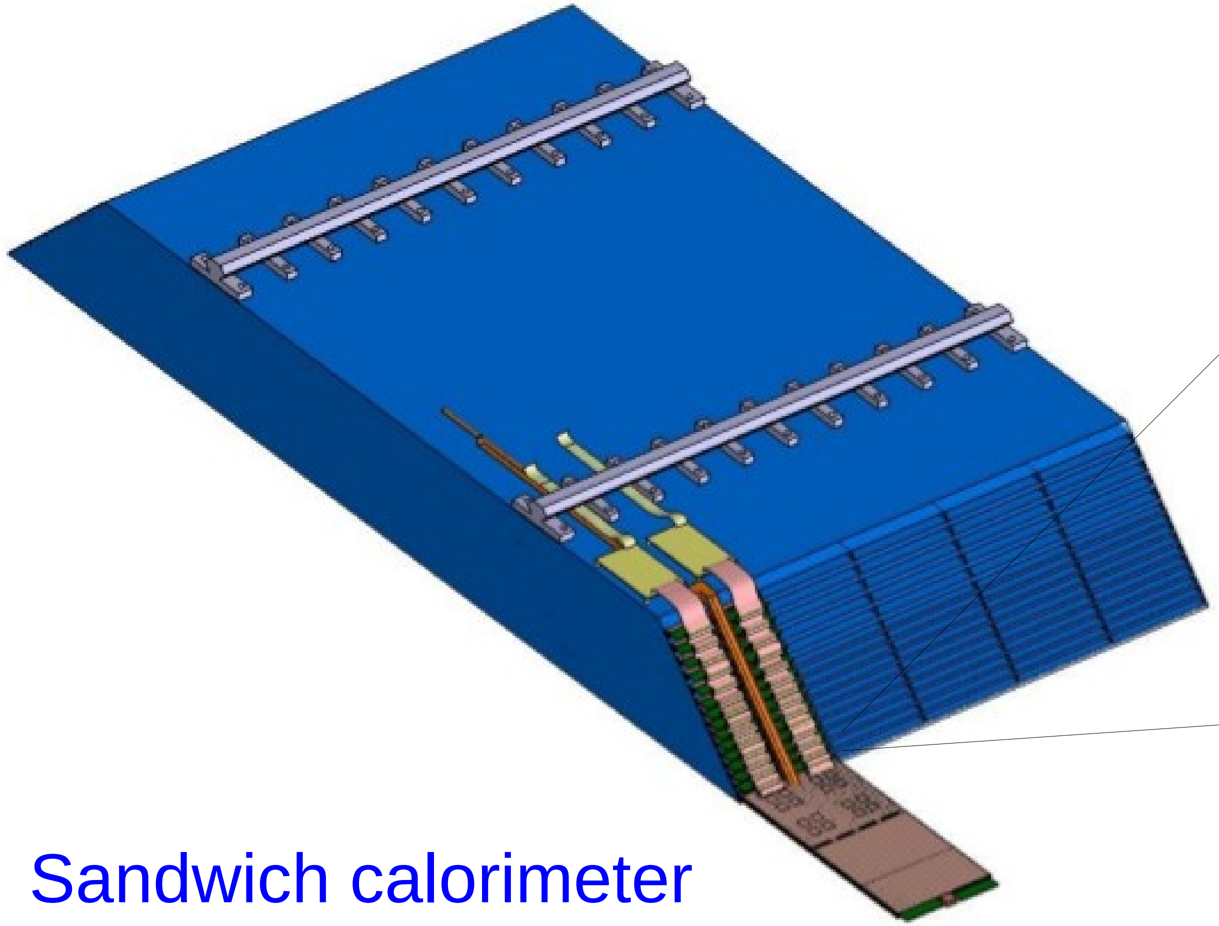
- Tungsten as absorber material
  - X_0=3.5mm, R_M=9mm, λ_I=96mm
  - Narrow showers
  - Assures compact design
- Silicon as active material
  - Support compact design
  - Allows for pixelisationRobust technology
  - Excellent signal/noise ratio: 10 as design value

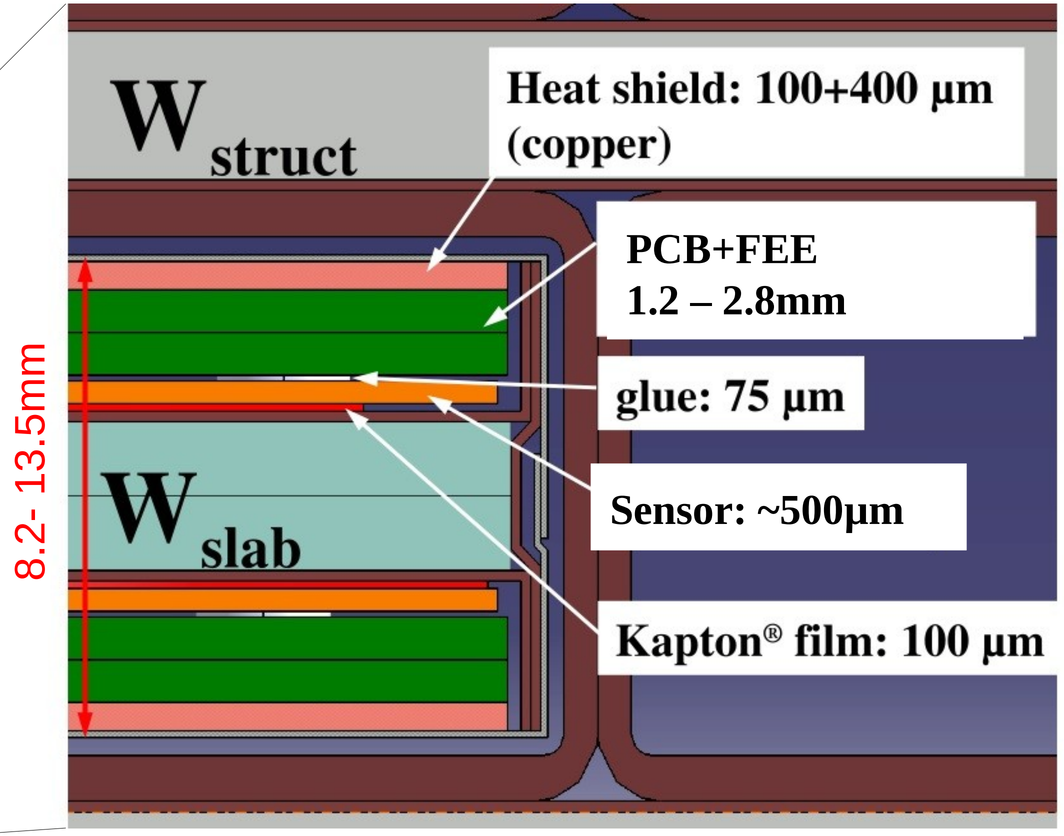
All future e+e- collider projects feature at least one detector concept with this technology

•Decision for CMS HGCAL based on CALICE/ILD prototypes

Silicon Tungsten electromagnetic calorimeter – Example ILD

Ecal alveolar structure



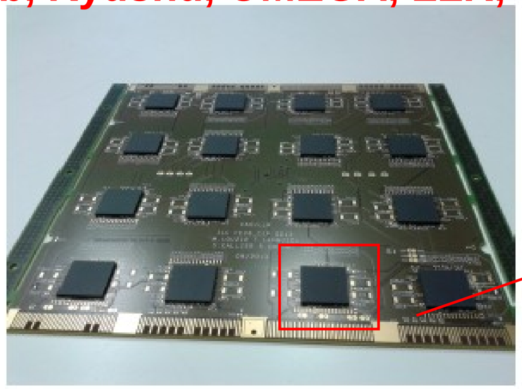


Sandwich calorimeter
26 layers (+/- 4)
Thickness: ~20cm, 24 $X_0/1\lambda_I$
Pixel size ~5x5 mm^2
Expected elm. energy resolution 15-20%/√E

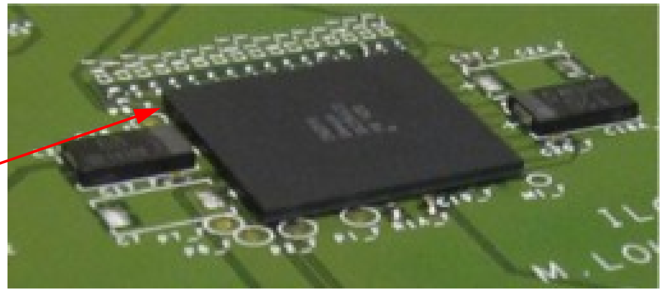
- Two layers within 13mm max.
- Key feature: Embedded electronics

SiW Ecal Technological prototype – Elements of (long) layer

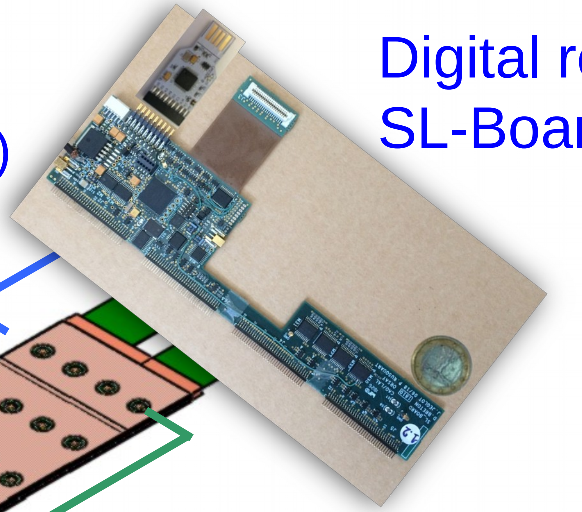
ASIC+PCB+SiWafer
=ASU
Size 18x18 cm^2
(IJCLab, Kyushu, OMEGA, LLR, SKKU)



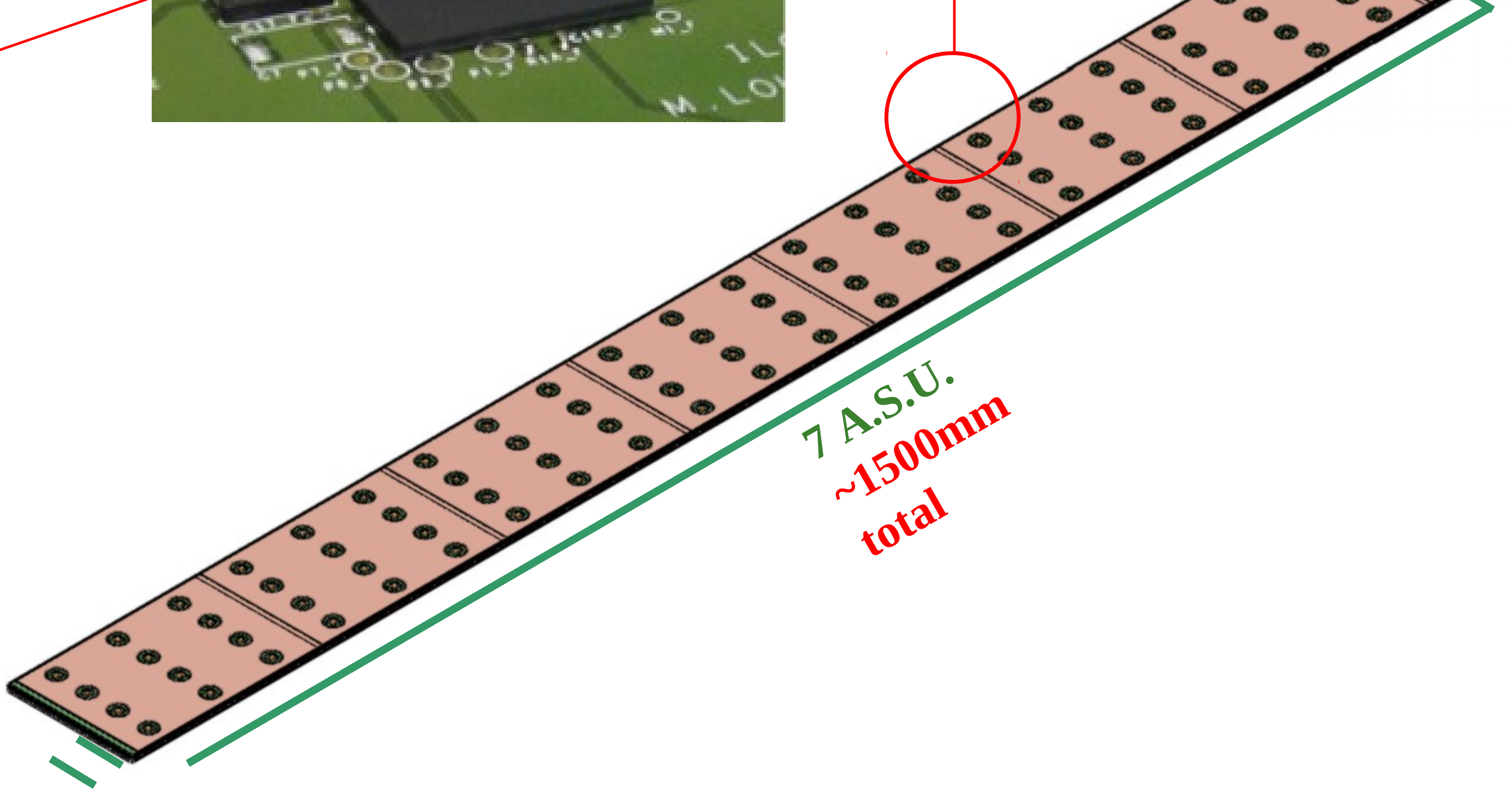
ASIC SKIROC2(a)
(OMEGA)
Wire Bonded or
In BGA package
(IJCLab, Kyushu, LLR)



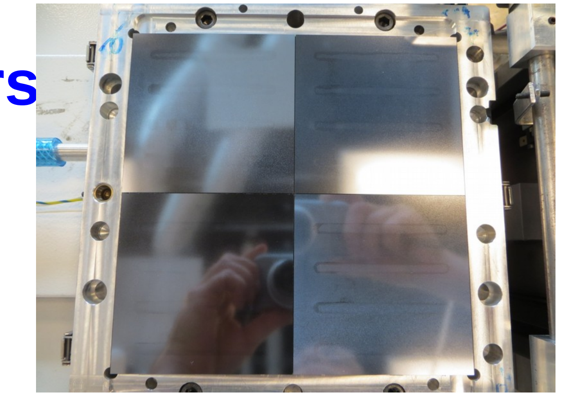
Interconnection
(IJCLab)
HV Supply
(IJCLab, LLR)



Digital readout
SL-Board (IJCLab)



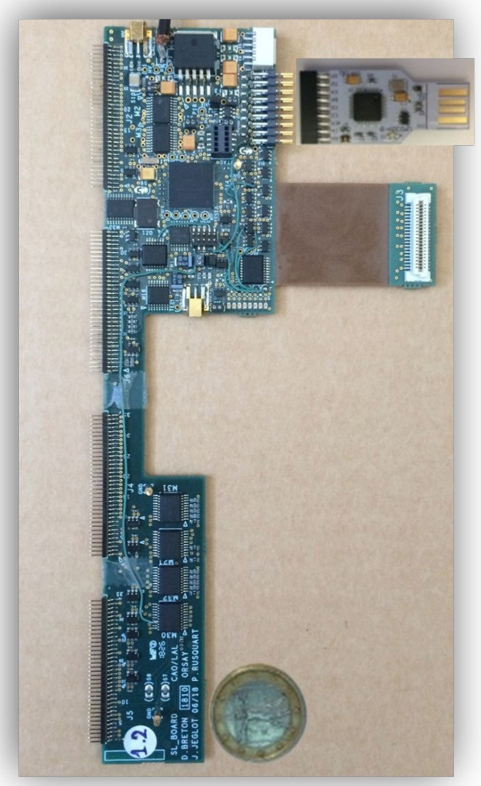
Si Sensors
glued
onto PCB
Pixel size
5.5x5.5 mm^2
(LPNHE, IFIC)



The beam test set ups comprised mainly **short layers** consisting of one ASU and a readout card each

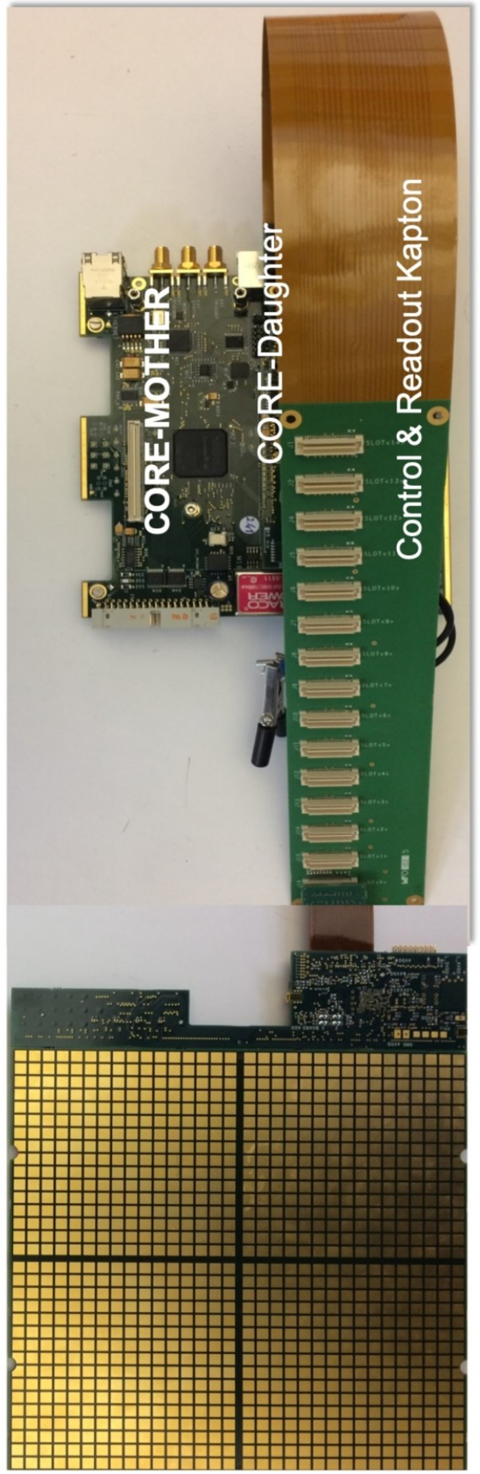
Compact readout

Current detector interface card (SL Board) and zoom into interface region



SL Board

Complete readout system



"Dead space free" granular calorimeters put tight demands on compactness

- Current developments in for SiW ECAL meet these requirements

System allows to read column of 15 layers <-> to be expected in ILD

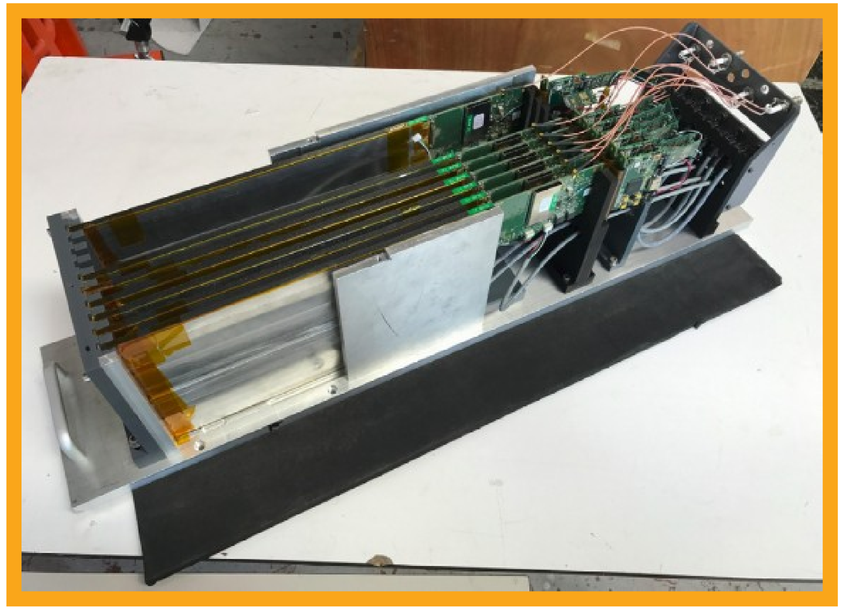
- Important that full readout system goes through scrutiny in beam tests

Readout piloted by performant firmware

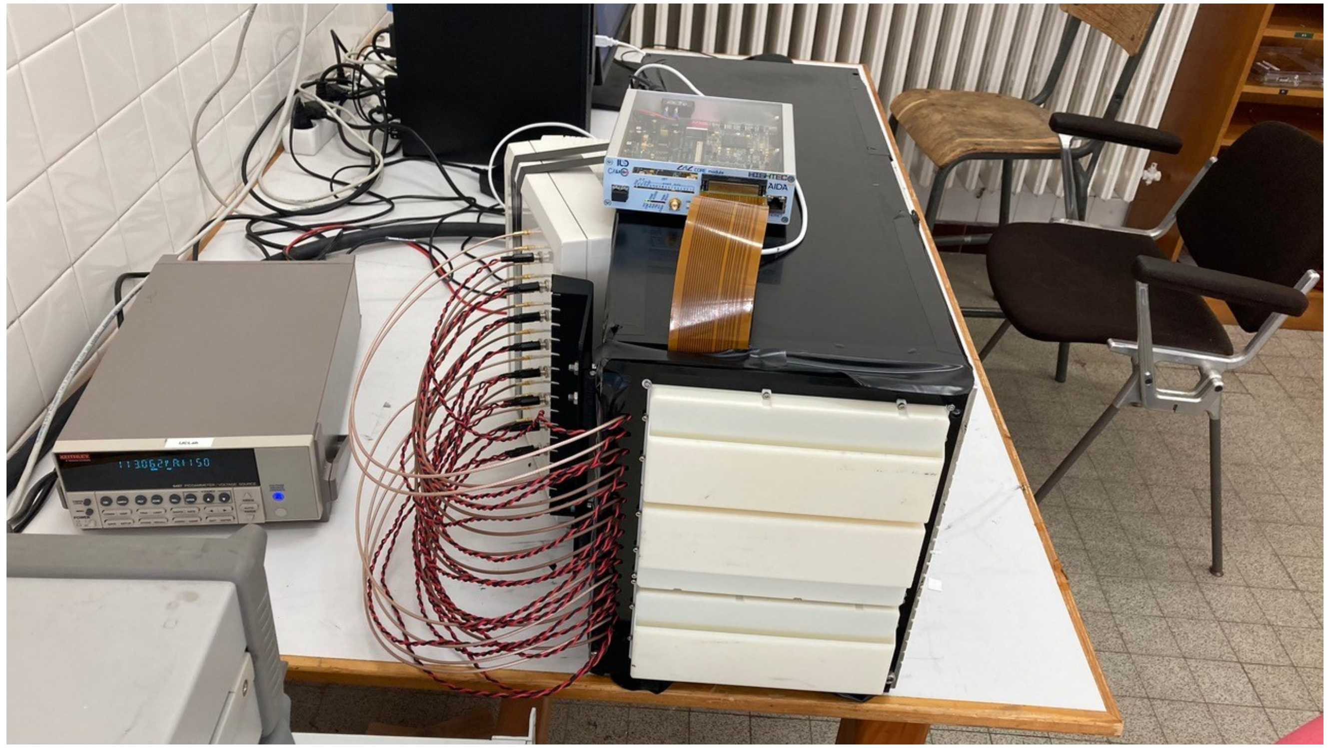
Deliverable of AIDA-2020 and HIGHTEC

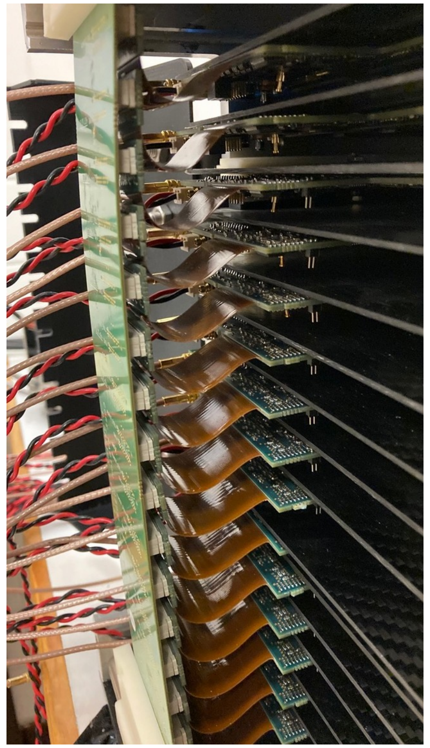
SiW ECAL Technological Prototype – Development phases

≤ 2018



> 2018





Up to 7 short layers ($18x18x0.5cm^3$)

- Up ~10 X_0

1024 channels per layer => 7186 cells

Technical tests at "MIP level"

First version of r/o system

15 short layers equivalent to 15360 readout cells

- Partially by ***recycling*** of ASUs from earliear stacks
- Up to 21 X_0

Overall size $640x304x246mm^3$

Flexible mechanical structure to adapt to beam conditions

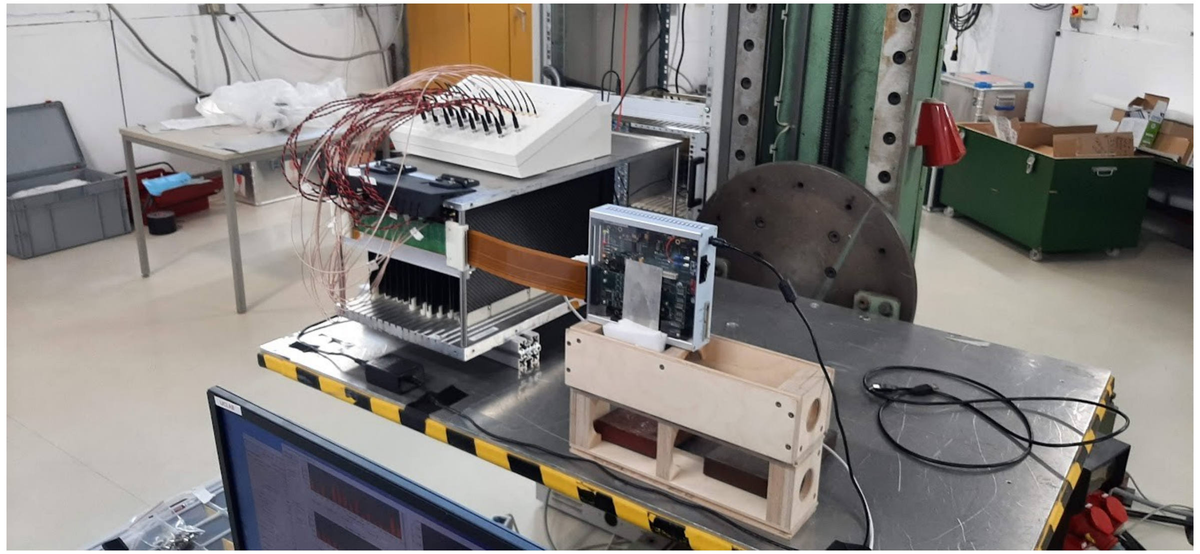
Commissioned 2020-2022

- ~450000 calibration constants for one ASIC feedback capa setting

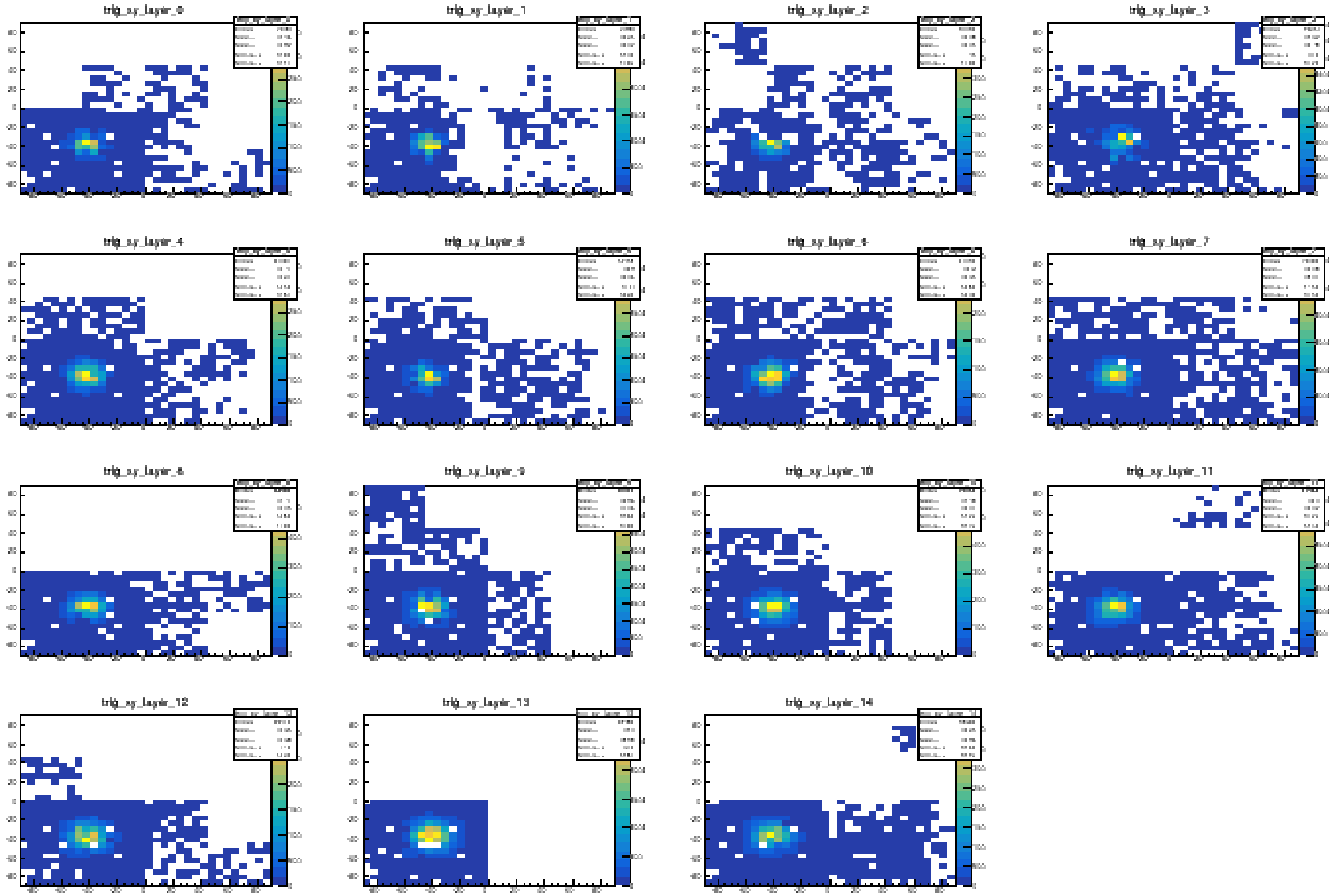
Testbeams (finally) in November 2021 and during 2022

SiW-ECAL in beam test @ DESY

Detector Setup



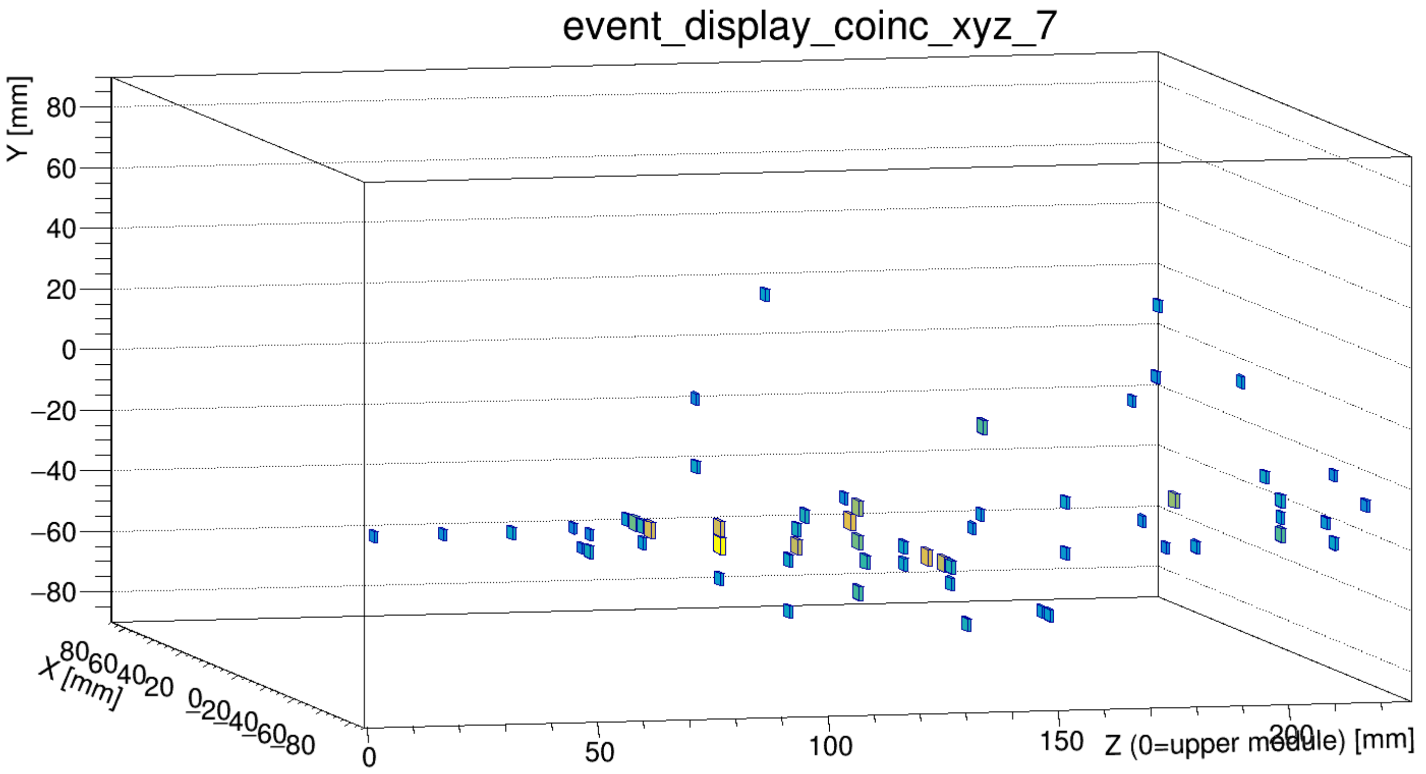
Detector in beam position

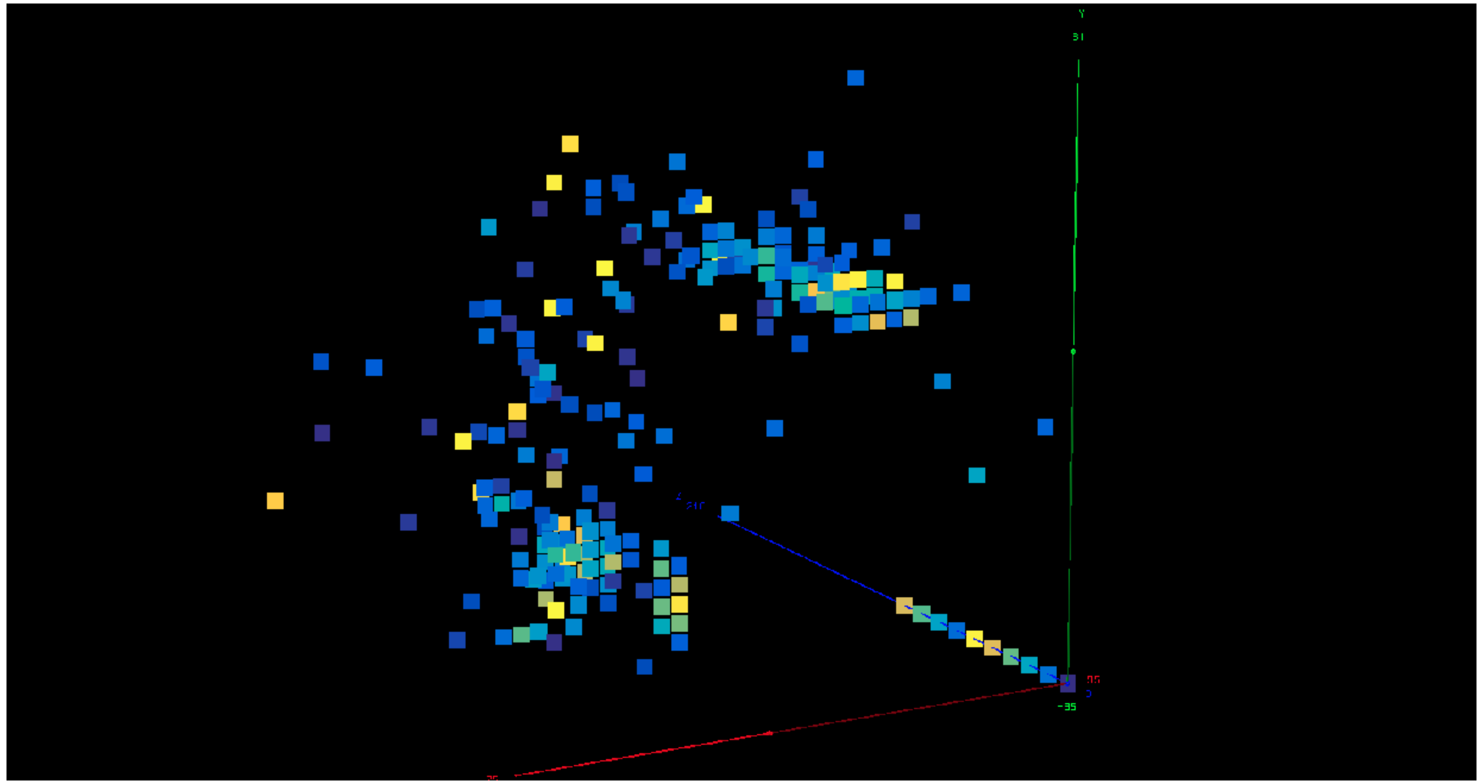


Beam spot in 15 layers

SiW-ECAL Beam tests 2022 – Onlline/Offline Event Displays

First contained electron showers since physics prototype (2011)





J. Kunath (LLR)

Y. Okugawa (IJCLab)

Clear showers measured during beam test campaigns

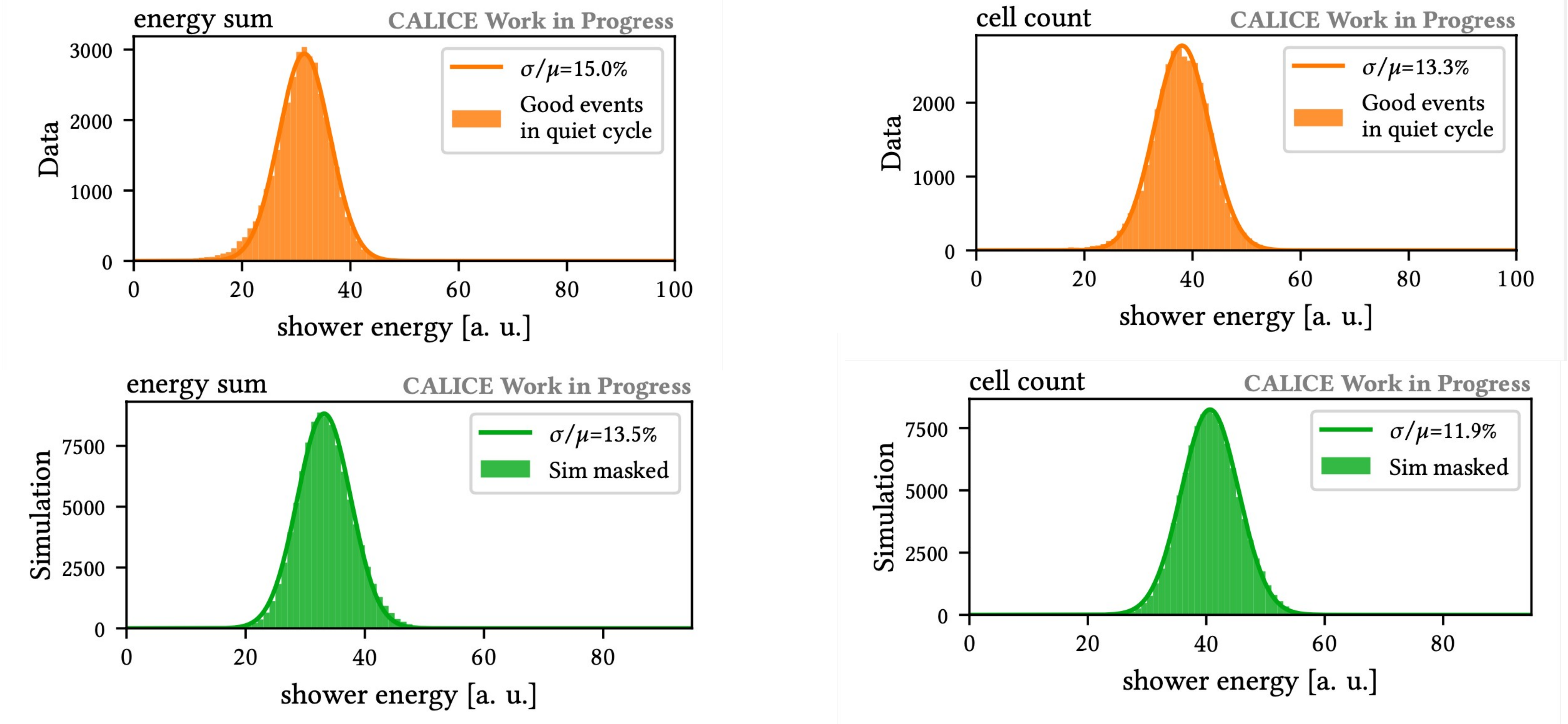
- Requires full event reconstruction
- These (and more) "high level" views are available already while a run is going on

"Particle separation continued"

- Two electrons "seen" in 20 GeV e- run at CERN

First results from DESY beam test 03/22

J. Kunath, F. Jimenez-Morales, SiW Ecal Analysis Meeting, 22/09/22



After proper filtering energy resolution in right ballpark for current prototype
Convergence in agreement data/MC

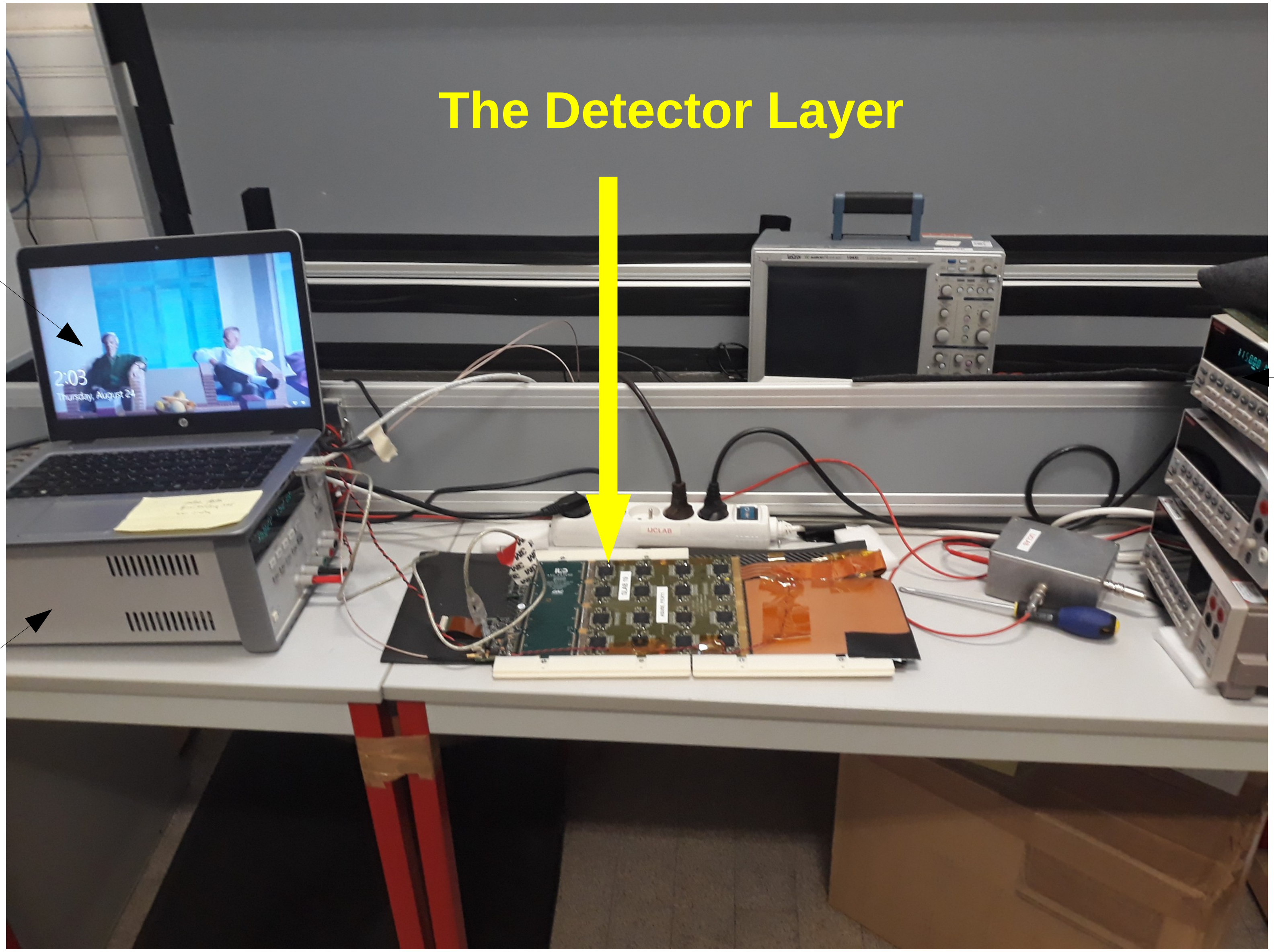
Your turn now – The goal

- You will work with one of the layers that we brought to beam test in 2022

- Your job will be to commission it to a point that it can measure signals from the source and in the best case cosmic rays
  - Signals from source need a “silent detector”
  - Cosmic ray signals need an “extremely silent detector”
  - => You will spend most of your time with disabling noisy cells and judging whether or not the detector is now “silent enough”
  - The tools that our DAQ system provides will assist you with this task
  - ... and apologises that I didn't bring the best of our layers but a layer that will be discarded in the future

The setup

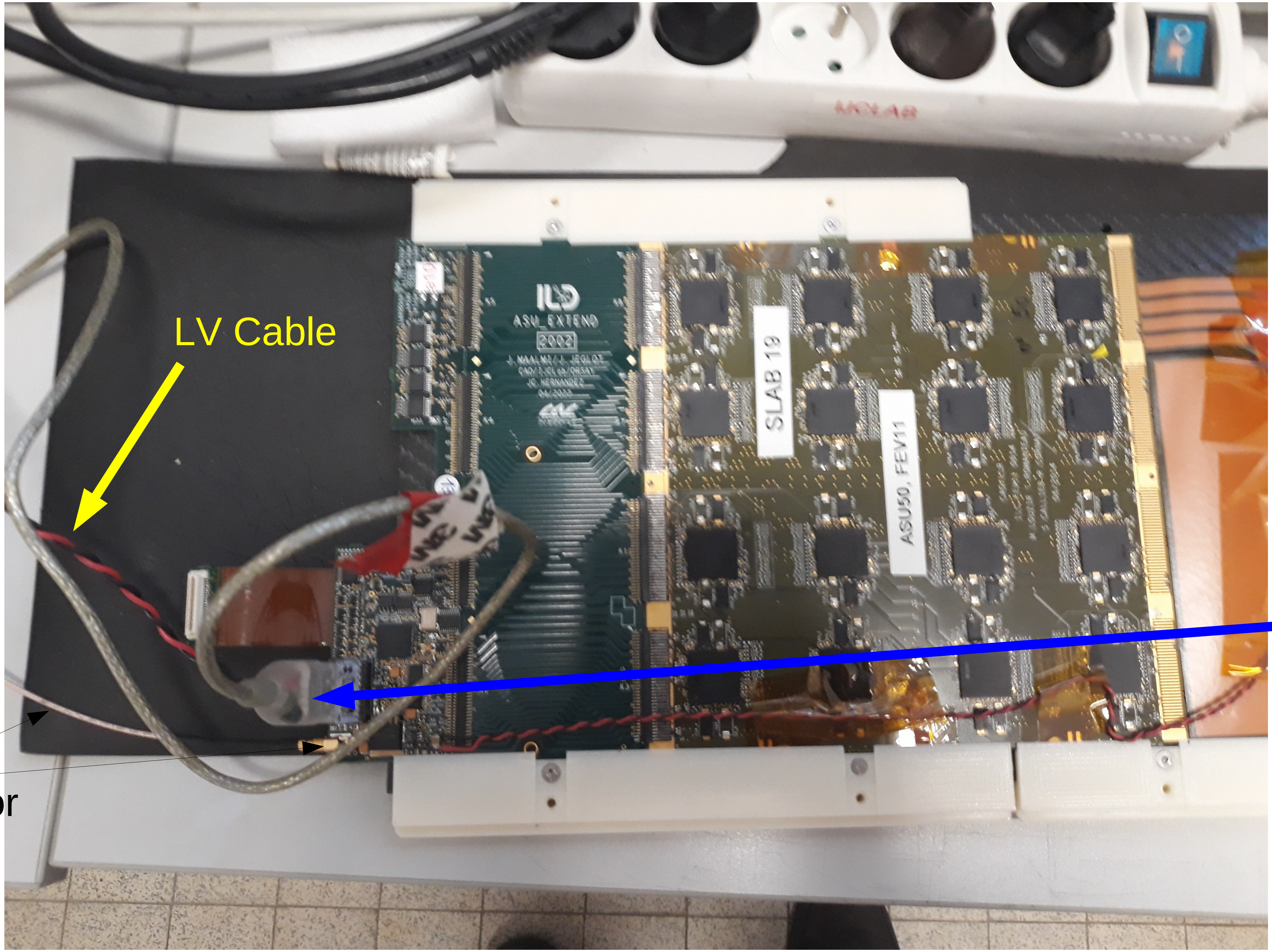
DAQ-PC



HV Power Supply (~150 V to bias Si sensors)

LV Power Supply (~ 3.6 V for front end electronics)

The first steps – Cabling up

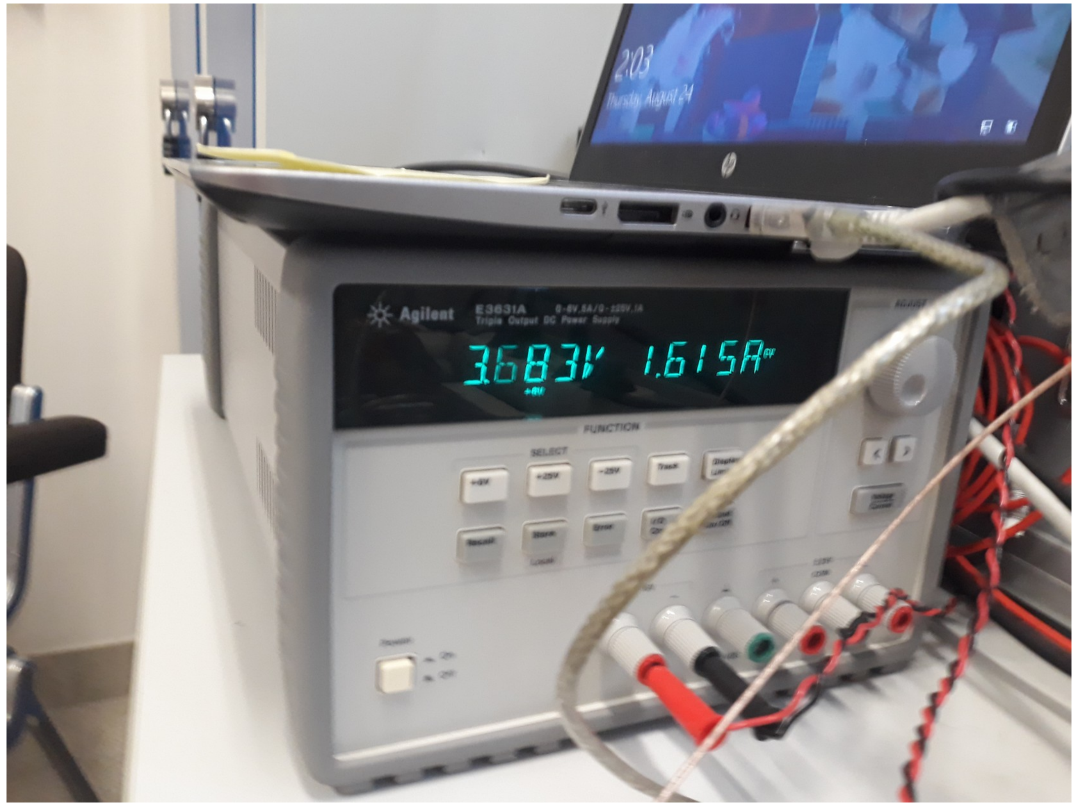


USB-Connection
To DAQ-Computer

HV Cable
And connector

The first steps – Switching On

1) Turn on LV



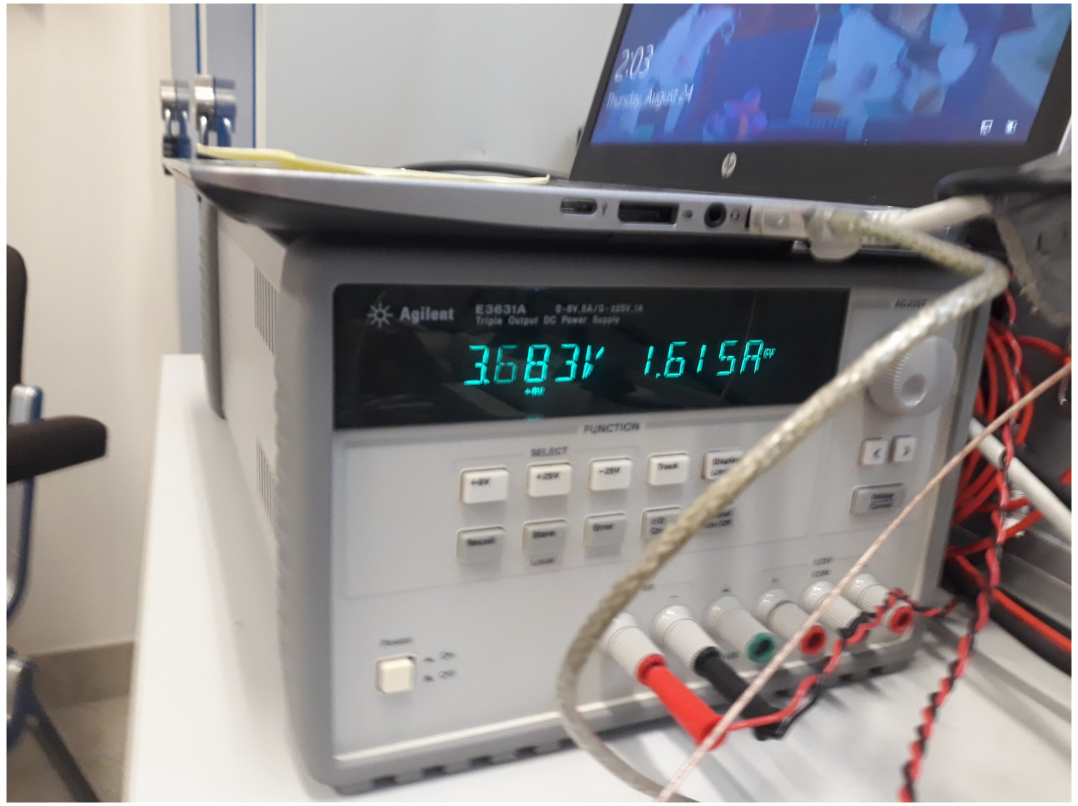
2) Turn on HV

Tune to 3.6-3.7 V
- ~0.5A after start-up
- ~1.5-2A during runnign

Tune **slowly** to 150 V
- Watch leakage currents
- Order 5-10 muA@150 V
- If much more detector is damaged!

The first steps – Switching On

1) Turn on LV



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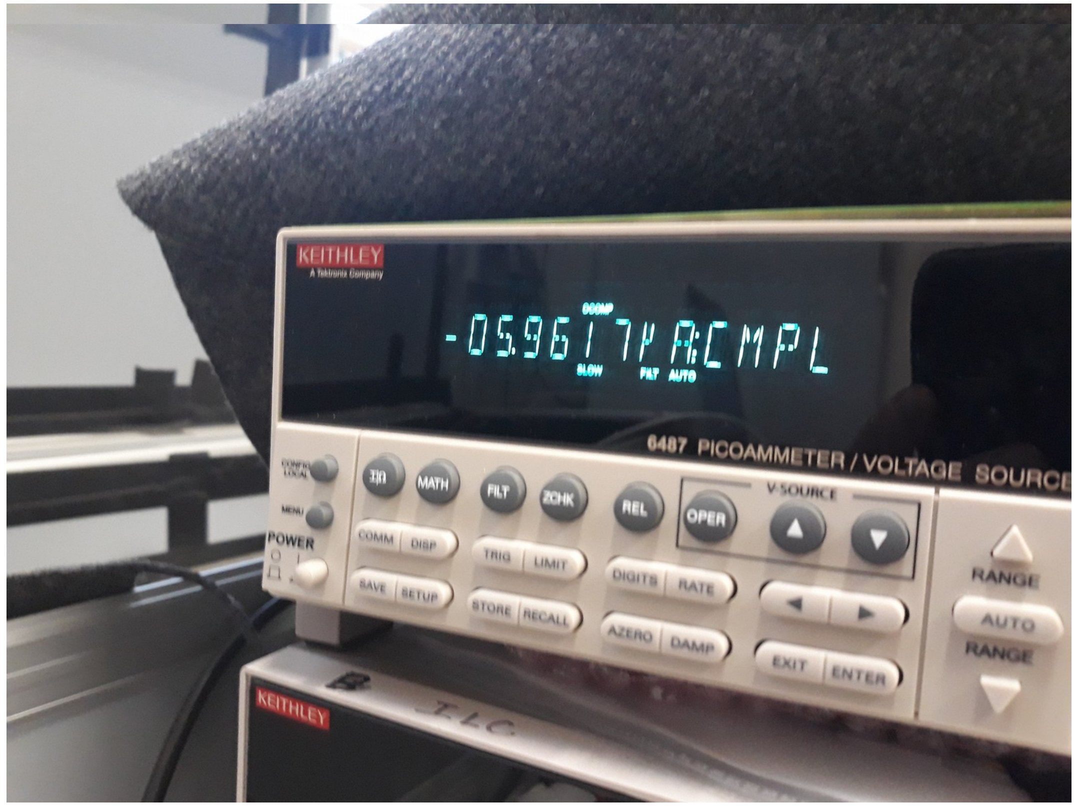
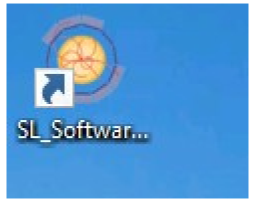
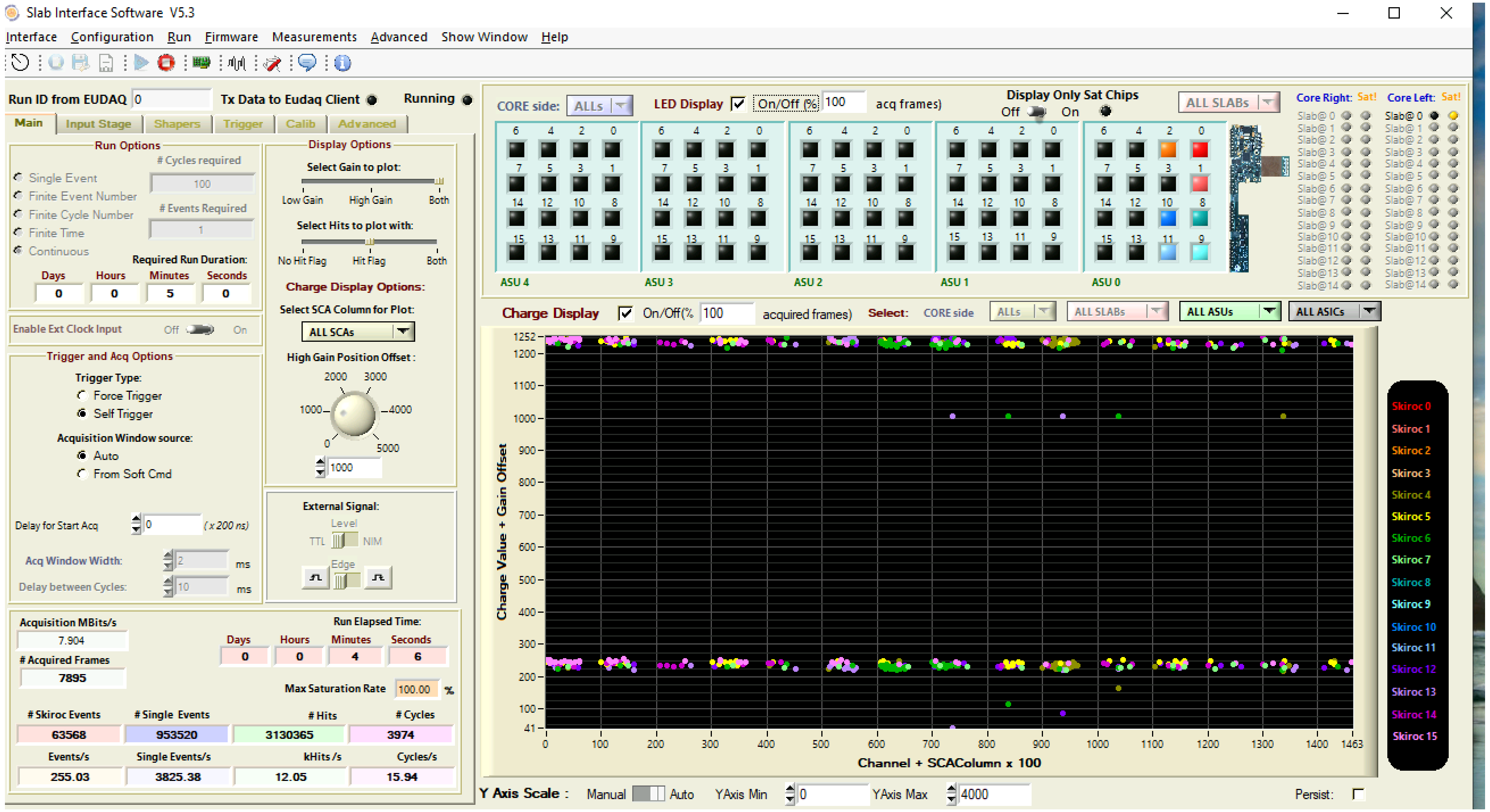


Tune **slowly** to 150 V
- Watch leakage currents
- Order 5-10 muA@150 V
- If much more, detector is damaged!

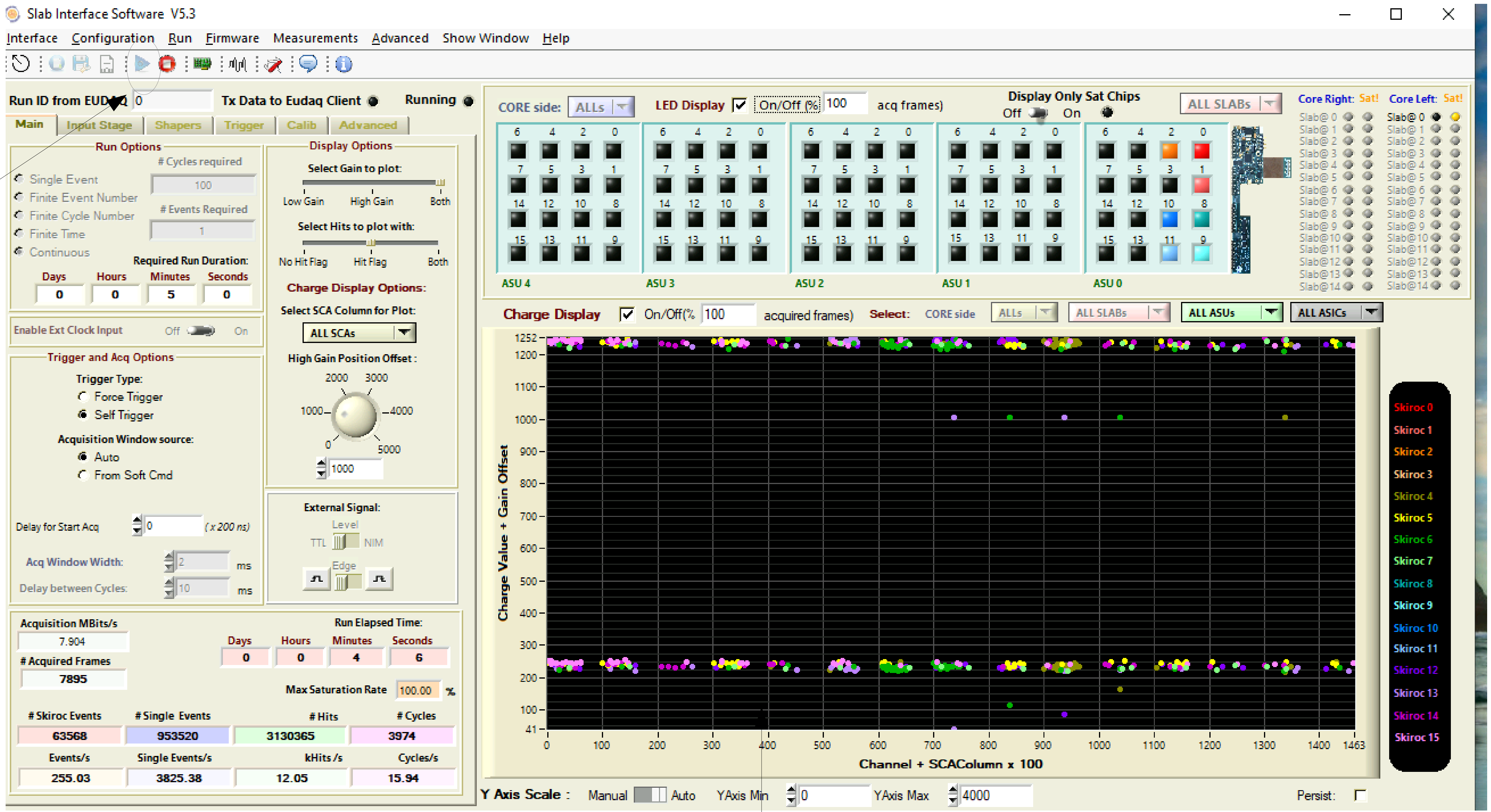
The first steps – Launching the DAQ

Click on  symbol on DAQ PC

This window will appear



The first steps – Your first run

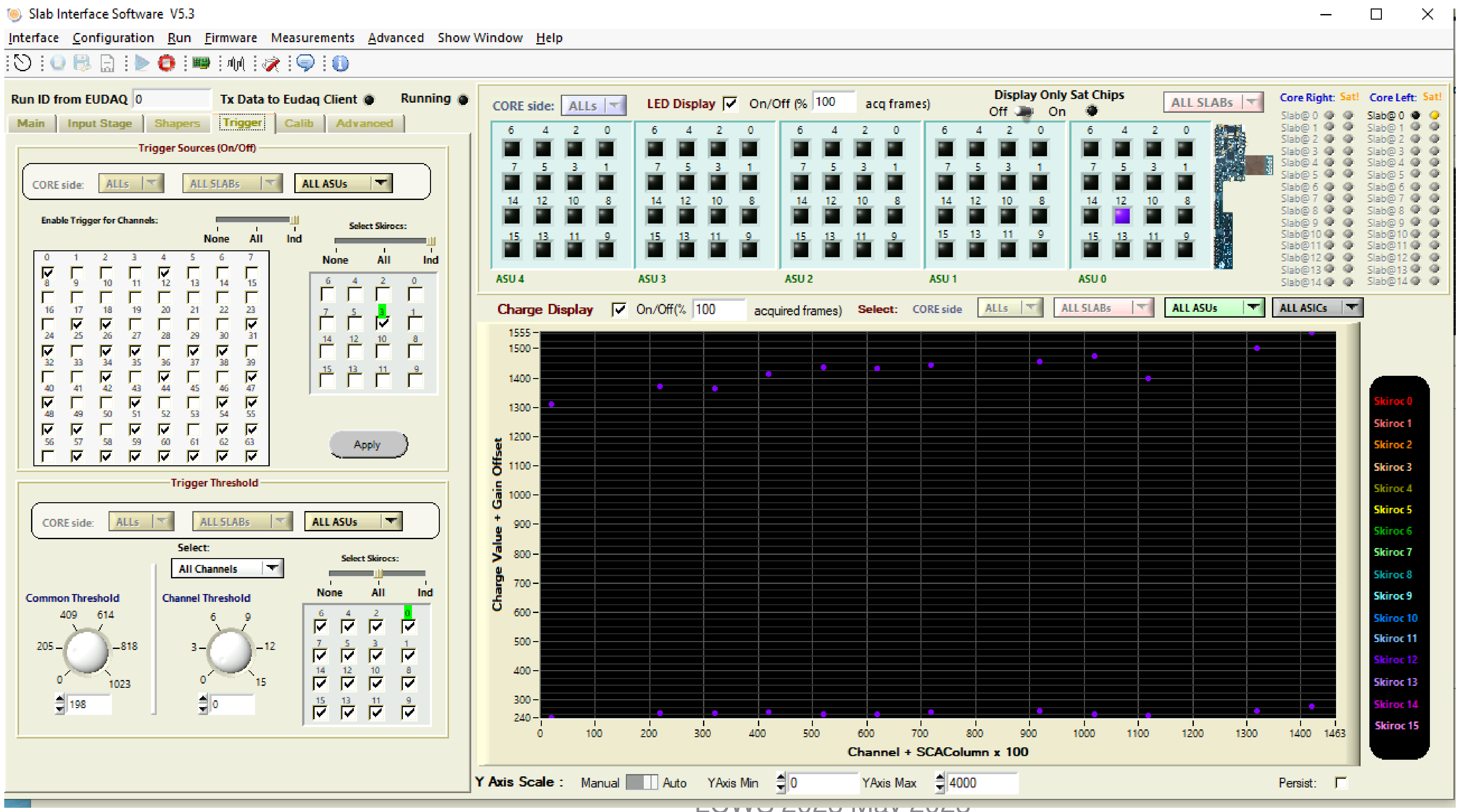


Click on run

You should see the noise signals of the 1024 Cells => You're up and running!!!!

Getting familiar with the Setup

- Switch to “Trigger” Panel
  - Here you can enable or disable the triggers of the individual cells and/or set trigger thresholds
  - You can watch your effects by looking at online displays available under “Measurements”



- I recommend that you just play around for a while with the panel

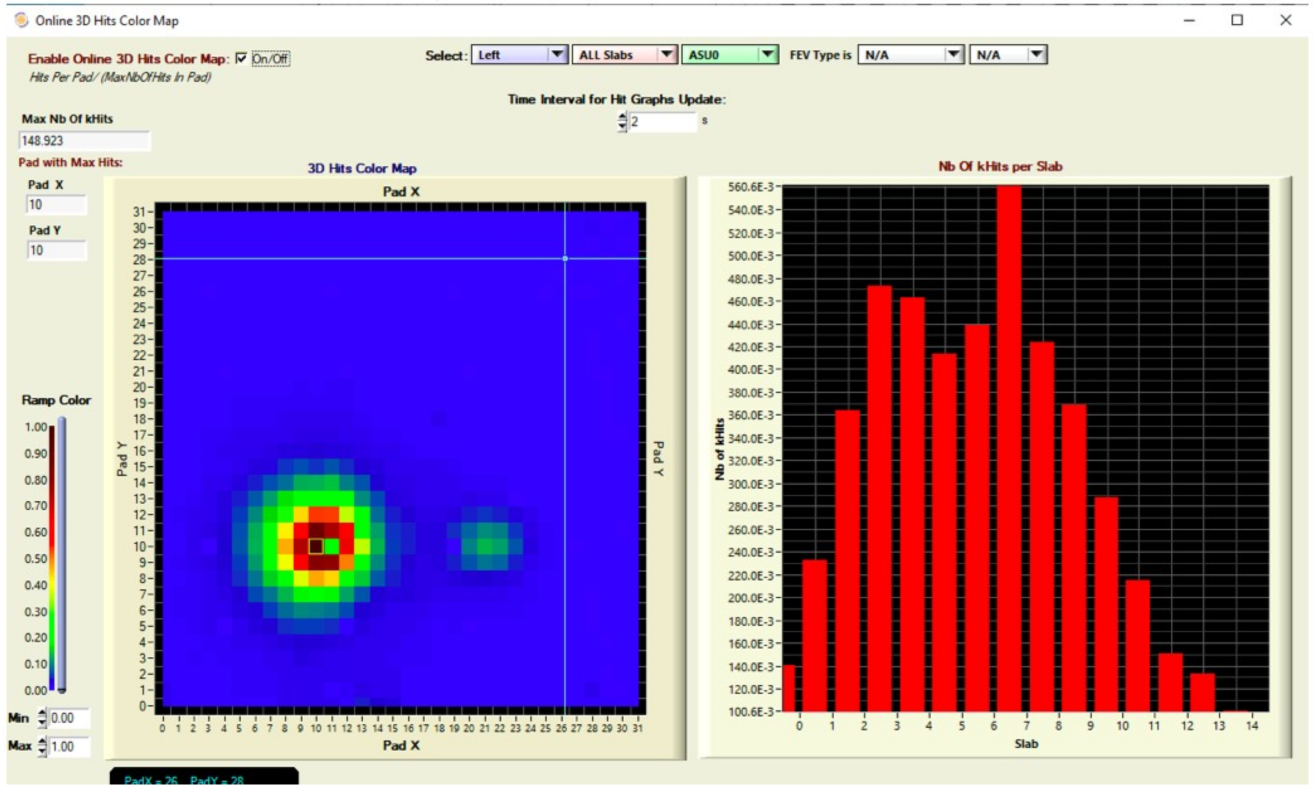
- While playing I will explain and you will discover the different functionalities

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Online Monitoring

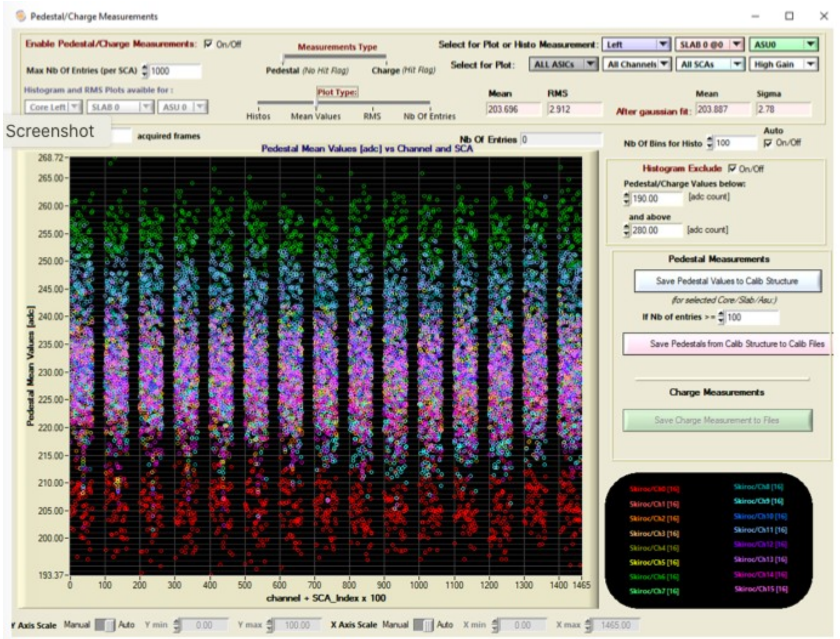
CNRS IN2P3 Les deux infinis

Jihane Maalmi, CALICE Meeting Valencia



Online Hit Maps and shower profiles

Allow for real time beam and detector tuning
e.g. Adaptation of beam rates or thresholds



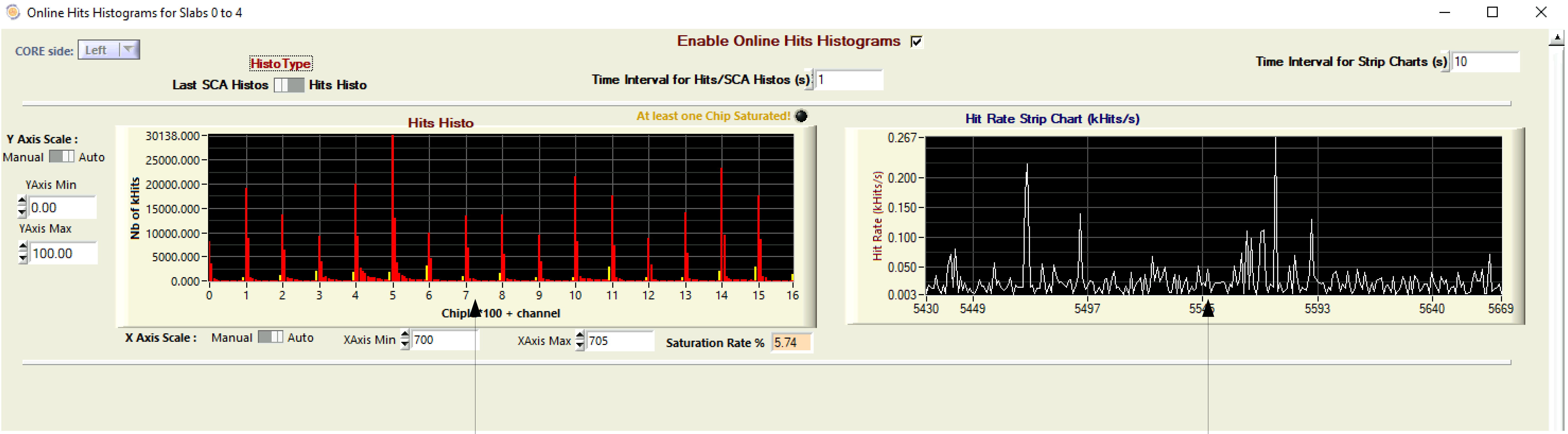
Further online tools

Pedestal measurement and subtraction
Charge measurement and histogramming
MIP gain correction

These are just a few examples from the powerful online suite

Online Monitoring – A real time example

Rate Monitoring of the layer you will work with – Plot made this morning



Most of the time only first buffers in ASICs are filled, few yellow bars => This is good

Not too bad rate ~10 Hz (for 1024 cells)

Commissioning the Detector

1) If the network connection to the ubuntu-machine works

Run a number of scripts to mask very noisy cells

```
root@pc-calice2: /home/calice/labcomm/TB2022-06/SiWECAL-TB-analysis/SLBcommissioning/masking
File  Edit  View  Search  Terminal  Help
root@pc-calice2:/home/calice/labcomm/TB2022-06/SiWECAL-TB-analysis/SLBcommissioning/masking# source commissioning_mask.sh 21082023 masking 0
```

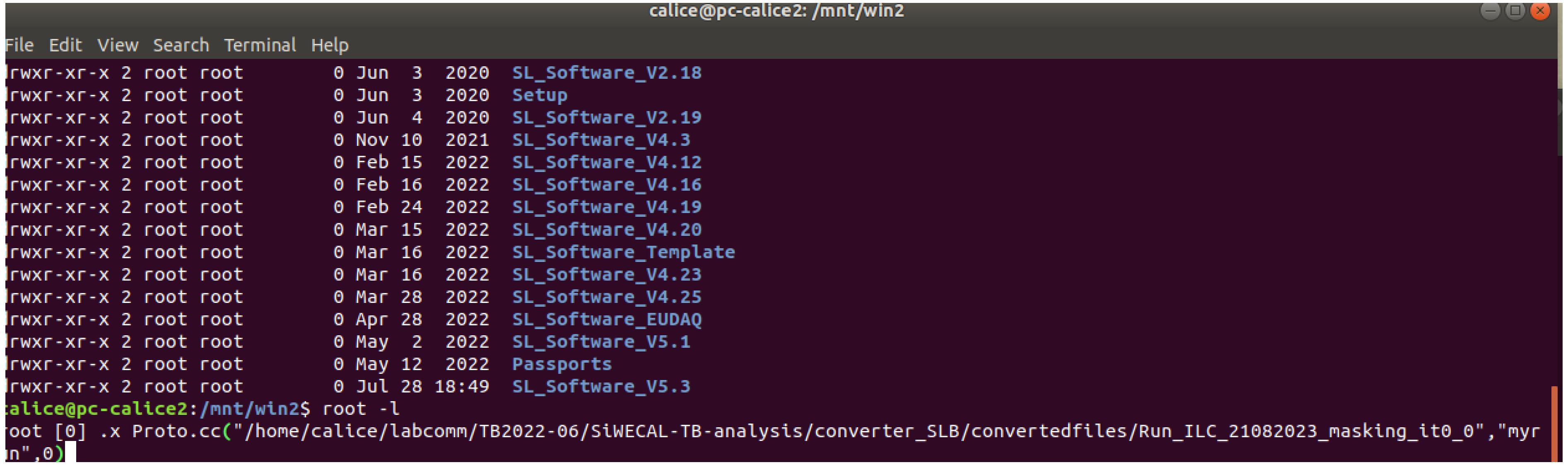
Watch the results with a number of small root scripts, e.g.

```
calice@pc-calice2: /mnt/win2
File  Edit  View  Search  Terminal  Help
drwxr-xr-x 2 root root        0 Jun  3  2020  SL_Software_V2.18
drwxr-xr-x 2 root root        0 Jun  3  2020  Setup
drwxr-xr-x 2 root root        0 Jun  4  2020  SL_Software_V2.19
drwxr-xr-x 2 root root        0 Nov 10  2021  SL_Software_V4.3
drwxr-xr-x 2 root root        0 Feb 15  2022  SL_Software_V4.12
drwxr-xr-x 2 root root        0 Feb 16  2022  SL_Software_V4.16
drwxr-xr-x 2 root root        0 Feb 24  2022  SL_Software_V4.19
drwxr-xr-x 2 root root        0 Mar 15  2022  SL_Software_V4.20
drwxr-xr-x 2 root root        0 Mar 16  2022  SL_Software_Template
drwxr-xr-x 2 root root        0 Mar 16  2022  SL_Software_V4.23
drwxr-xr-x 2 root root        0 Mar 28  2022  SL_Software_V4.25
drwxr-xr-x 2 root root        0 Apr 28  2022  SL_Software_EUDAQ
drwxr-xr-x 2 root root        0 May  2  2022  SL_Software_V5.1
drwxr-xr-x 2 root root        0 May 12  2022  Passports
drwxr-xr-x 2 root root        0 Jul 28 18:49  SL_Software_V5.3
calice@pc-calice2:/mnt/win2$ root -l
root [0] .x test_read_masked_channels.C("/mnt/win2/SL_Software_V5.3/Run_Data/Run_ILC_23082023_masking_it1_0/Run_Settings")
```

Commissioning the Detector

1) If the connection to the ubuntu-machine works cont'd

... or



- Instructions how to connect the ubuntu-machine to the daq-laptop will be distributed in a separate file

Commissioning the Detector

2) If the connection to ubuntu-machine does not work

... we start out from a file used for the 2022 running for this layer that I have pre-installed

We may switch anyway to this file at one point since it gives an easier start for source and cosmic running

... but try first your own commissioning if the connection to the ubuntu-machine works.

Seeing signals

1) Put the source onto the detector and observe whether you can see signals from the source
- Remember that it takes about 3.6 eV to create a e/hole pair in Si

2) Once signals from the source can be spotted one should switch to cosmic rays
- It might be that quite a number of cells more will have to be disabled than for source running
- Remember that one expects roughly 1 cosmic muon/cm2/s at Sea level

3) Try to record data from these runs and analyse them (using the scripts mentioned on previous slides)
- If the network connection to the ubuntu-machine doesn't work we'll “transfer” the data with USB Sticks and run the scripts

Backup

The CALICE Collaboration

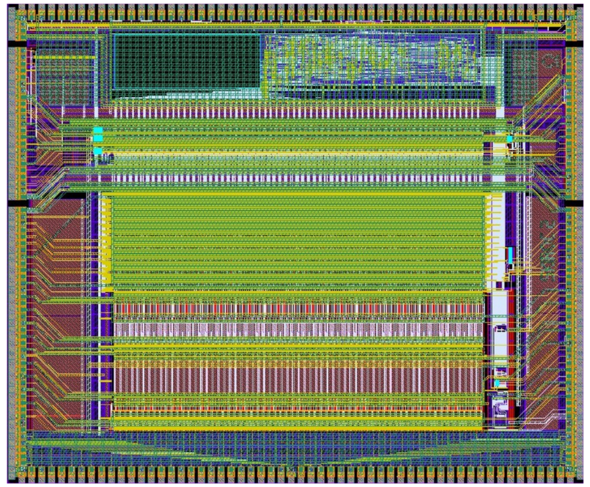
Calorimeter R&D for large imaging calorimeters

~270 physicists/engineers from 62 institutes and 18 countries from 4 continents

- Integrated R&D effort
- Acceleration of detector development due to *coordinated* approach
- MOU 2005
  - IN2P3 among founding members, first Spokesperson Jean-Claude Brient

ASICs – The "ROC Family"

SKIROC
(for SiW Ecal)



SiGe 0.35µm AMS,

Size 7.5 mm x 8.7 mm, 64 channels

High integration level

(variable gain charge amp,

12-bit Wilkinson ADC, digital logic)

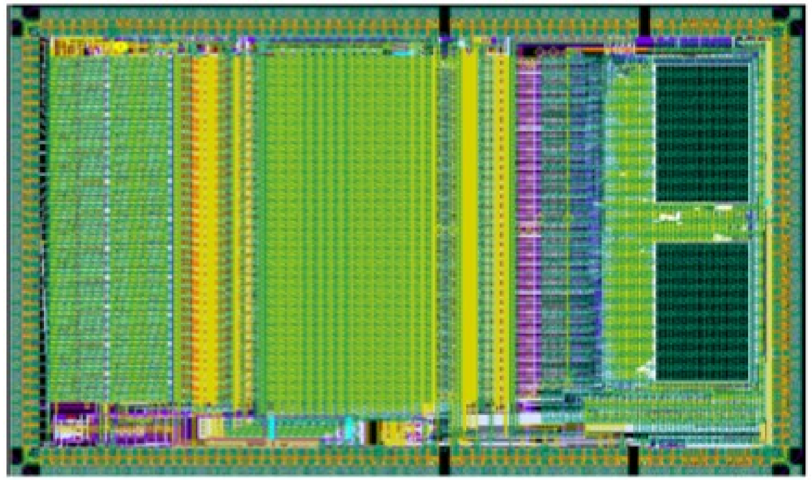
Large dynamic range (~2500 MIPS)

low noise (~1/10 of a MIP, 400 fC)

Auto-trigger at ½ MIP

Low Power: (25µW/ch) power pulsing

SPIROC
For optical readout, Tiles + SiPM



Variant of SKIROC

36 channels, 15 bit readout

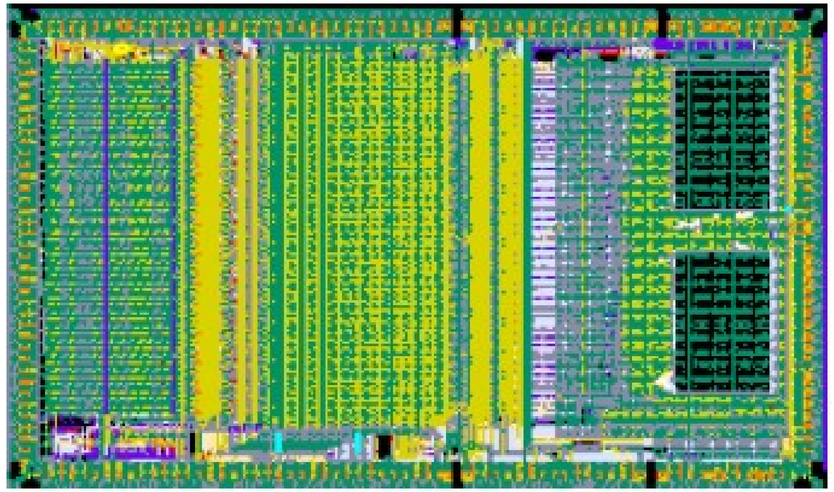
Auto-trigger down to ½ p.e,

80 fC for $G=1x10^6$

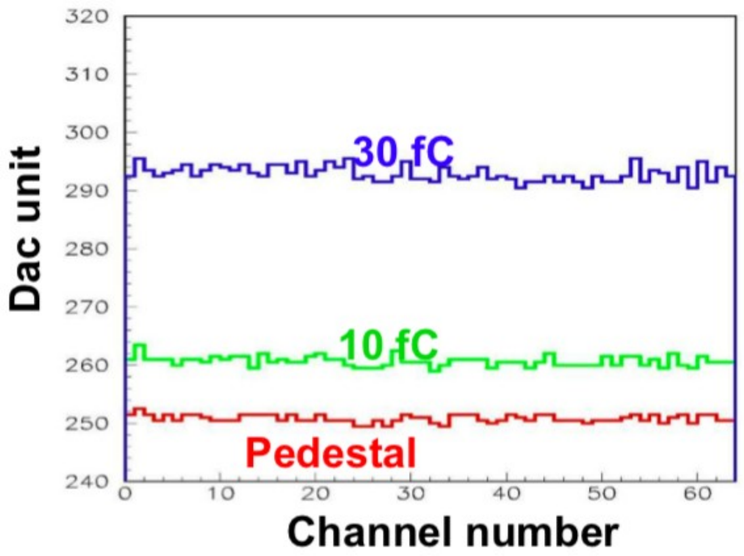
Timing to ~ 1ns

Low Power: (25µW/ch) power pulsing

HARDROC
For gaseous r/o - GRPC



64 Channels with three thresholds

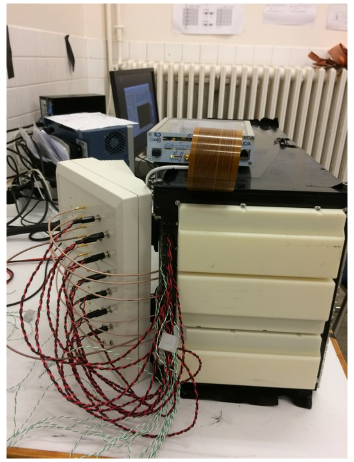


Power pulsing

Variant for Micromegas: MICROROC

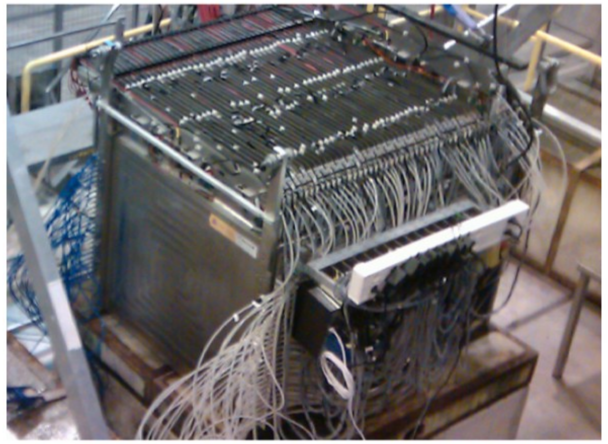
CALICE (Technological) Prototypes

ScECAL



SiECAL

AHCAL



SDHCAL

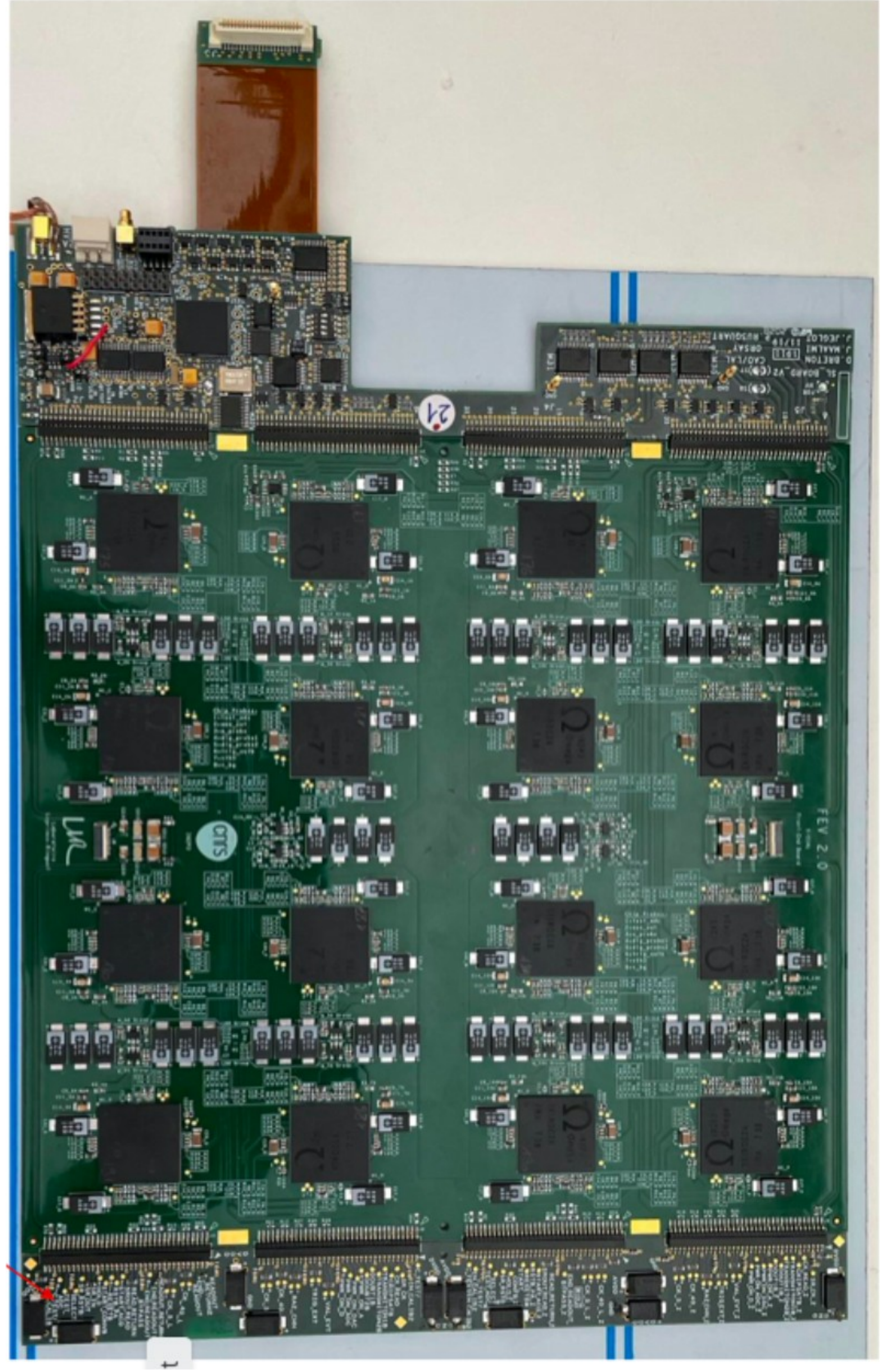
Name	Sensitive Material	Absorber Material	Resolution	Pixel size/ mm^3	~Layer size**/cm^3	~Layer depth/X_0	~Layer depth/λ_I	# of Pixels/ layer	# of layers	Comment
ScECAL	Scintillator	W-Cu Alloy	Analogue, 12bit	5x45x2	23x22x0.5	0.73	0.03	210	32	2x16 x and y strips
SiECAL	Si	W	Analogue, 12bit	5.5x5.5x 0.3 (0.5, 0.65)	18x18x 0.24 (- 0.63)	0.6-1.6	0.02-0.06	1024	≥22	Can be run in different configs.
AHCAL	Scintillator	Fe*/W	Analogue, 12bit	30x30x3	72x72x2/ 1.4	1/2.9	0.11	576	38	Running with Fe and W
SDHCAL	Gas	Fe*	Semi-digital 2bit	10x10x6	100x100x2 .6	1.1	0.12	9216	48	

*Stainless Steel

**Only absorber + sensitive material for z direction, air gaps, electronics discarded here (would add 5-10%)

SiW ECAL PCB - New FEV 2.1

LLR, IJCLab, LPNHE, OMEGA



Improved Layout

- Better shielding of AVDD and AVDD PA plans and minimisation of cross-talk between inputs and digital signals.

Power Pulsing Mode: new philosophy

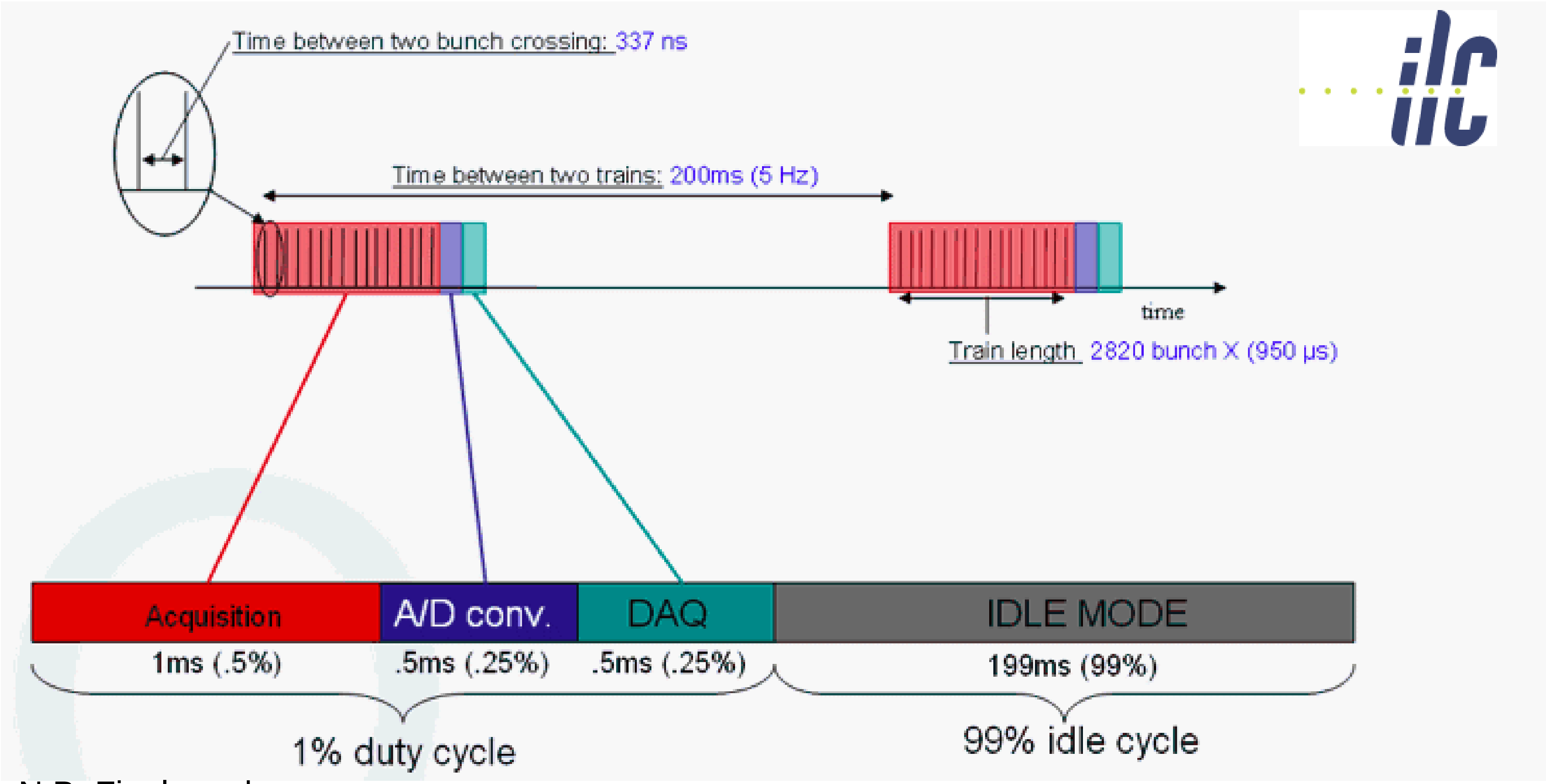
- limiting the current through a layber (current limiter present on the SL Board) to:
  - avoid driving high currents through the connectors and makes the current peaks **local** around the SKIROCs chips
  - avoid voltage drop along the slab
  - ensure temperature uniformity
- Large capacitors with low ESR for **local** energy storage (around each SKIROC chip)
- Generate **local** power supply with LDO (Low Drop Out) to avoid voltage variations

- 25 PCBs delivered beginning of March 2023

This board will enable us to finish the ongoing R&D,
join the LUXE Experiment (see later) and be ready in case of ...

Beam Structure and Detector Operation

- Linear collider beams come in bunch trains
  - CLIC: repetition frequency 50 Hz, ILC: repetition frequency 5 Hz (minimum)



N.B. Final numbers may vary

- Power pulsing of electronics:

- Electronics switched on during > ~1ms of bunch train and data acquisition
- Bias currents shut down between bunch trains

Exploiting beam structure can/will lead to power economic operation of linear collider detectors

Detector requirements

Track momentum: $\sigma_{1/p}$ $< 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[GeV]\sin^{3/2}\theta)]$ μm (1/3 x SLD)

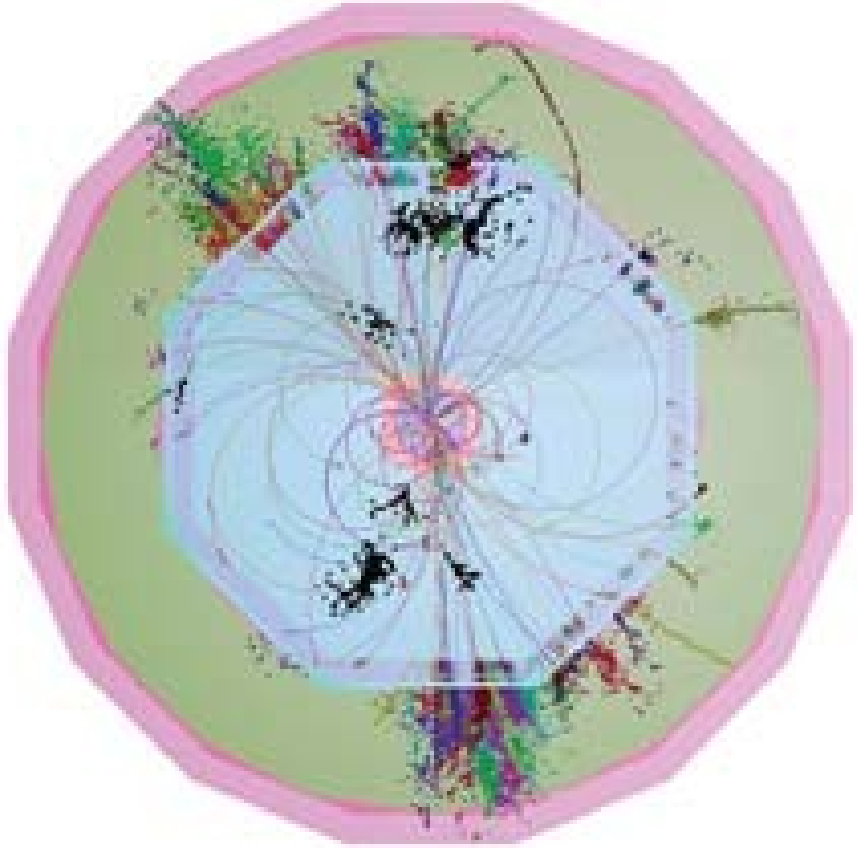
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(GeV))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : θ_{min} = 5 mrad

(for events with missing energy e.g. SUSY)



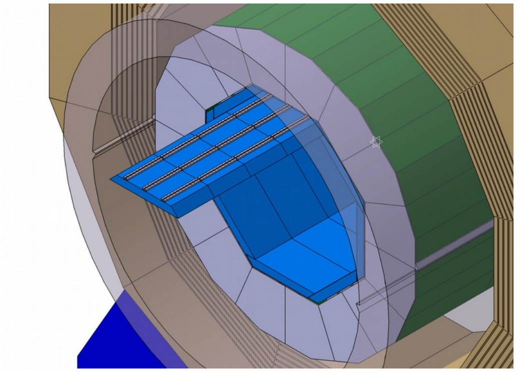
Final state will comprise events with a large number of charged tracks and jets(6+)

- High granularity
- Excellent momentum measurement
- High separation power for particles

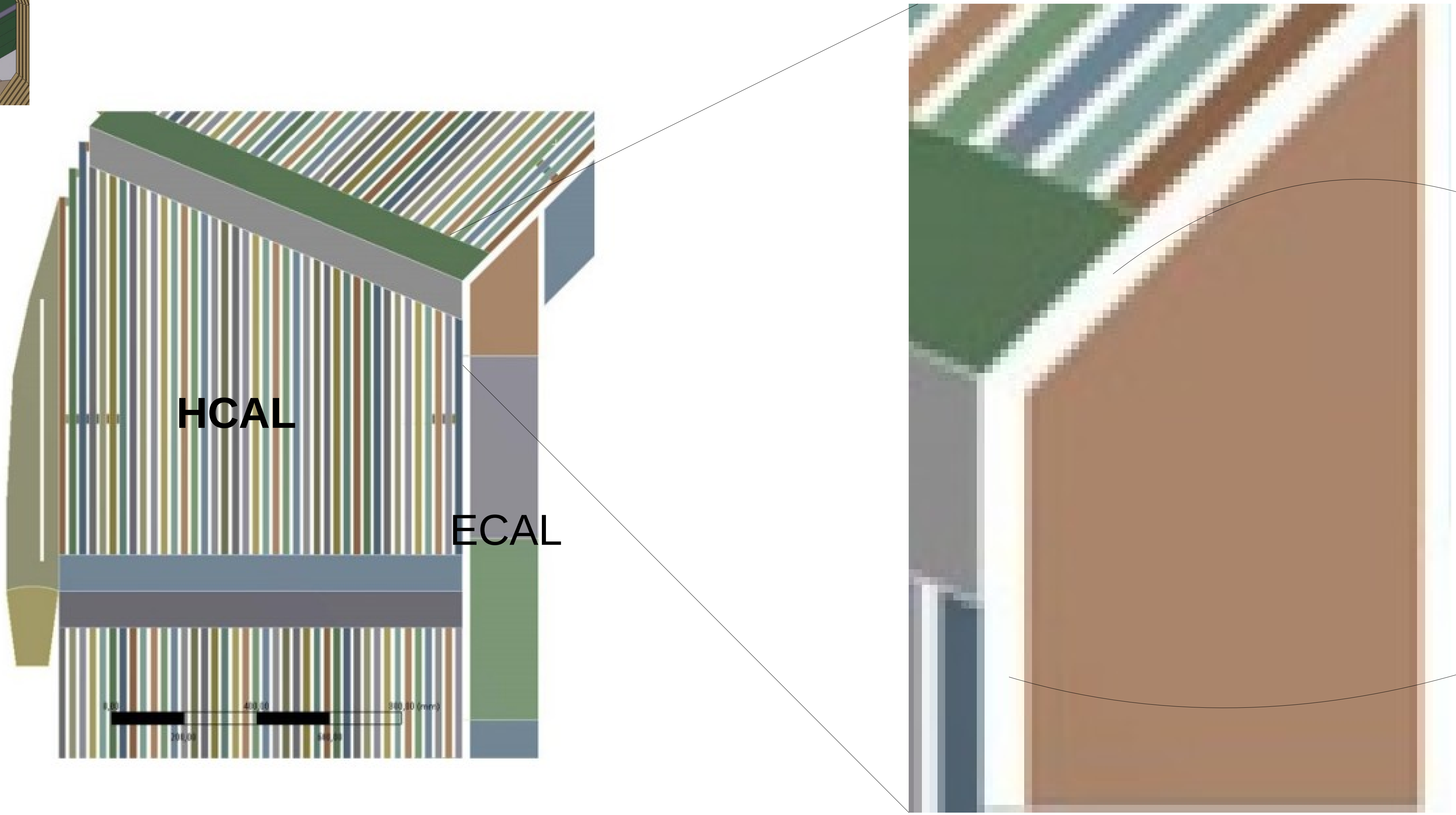
Particle Flow Detectors

Detector Concepts: ILD, SiD and CLICdp

Requirements on compactness



- Successful application of PFA requires calorimeters to be inside the magnetic coil
  => Tight lateral and longitudinal space constraints



40-70mm for services as readout, cooling and power

~200mm for up to 30 layers with 10-20 kcells each

Calorimeter has to be conceived as one device with electromagnetic and hadronic sections

Detector requirements