EP-R&D Silicon Working Group 1.1

Hybrid Detectors

Small pitch 3D Timing (& planar ☺)

Evangelos –Leonidas Gkougkousis

CERN EP-R&D

CERN – June 23nd, 2022

•Introduction, EP-R&D W.P. 1.1 – Hybrid Sensors

Planar Sensors (J. Haimberger, V. Gkougkousis)

- ✓ Radiation damage and trapping model validation though TCAD
- ✓ Timing and efficiency at < 1e17 n_{eq}/cm^2 using fast neutrons and ps protons (thicknesses 50, 100, 200, 300 μm)

LGADs (V. Gkougkousis)

- ✓ Radiation damage mechanisms and modeling on different dopant types (TIPP2021, ArXiV Preprint, PicoSecond Workshop 2021)
- ✓ Indium-Lithium gain layer radiation hardness investigations (Trento2021)
- ✓ Process simulations and SiMS – Carbon/Boron (LINK)

Silicon Electron Multiplier (M. Halvorsen, LINK, ArXiV Preprint, IEEE)

- ✓ Structure optimization and electrostatic simulations
- ✓ Timing and transient Simulations
- ✓ Process iterations (Metal Assisted Etching)

Talks @ Trento 2022

Small Pitch 3Ds for tacking and timing (V. Gkougkousis, LINK)

- ✓ β particles timing studies on irradiated and unirradiated devices
- ✓ Test beam with SPS pions (Tracking + Timing)
- ✓ Proton and neutron irradiations > 1e17 n_{eq}/cm^2
- ✓ New small pitch production optimized for gain at electrode region

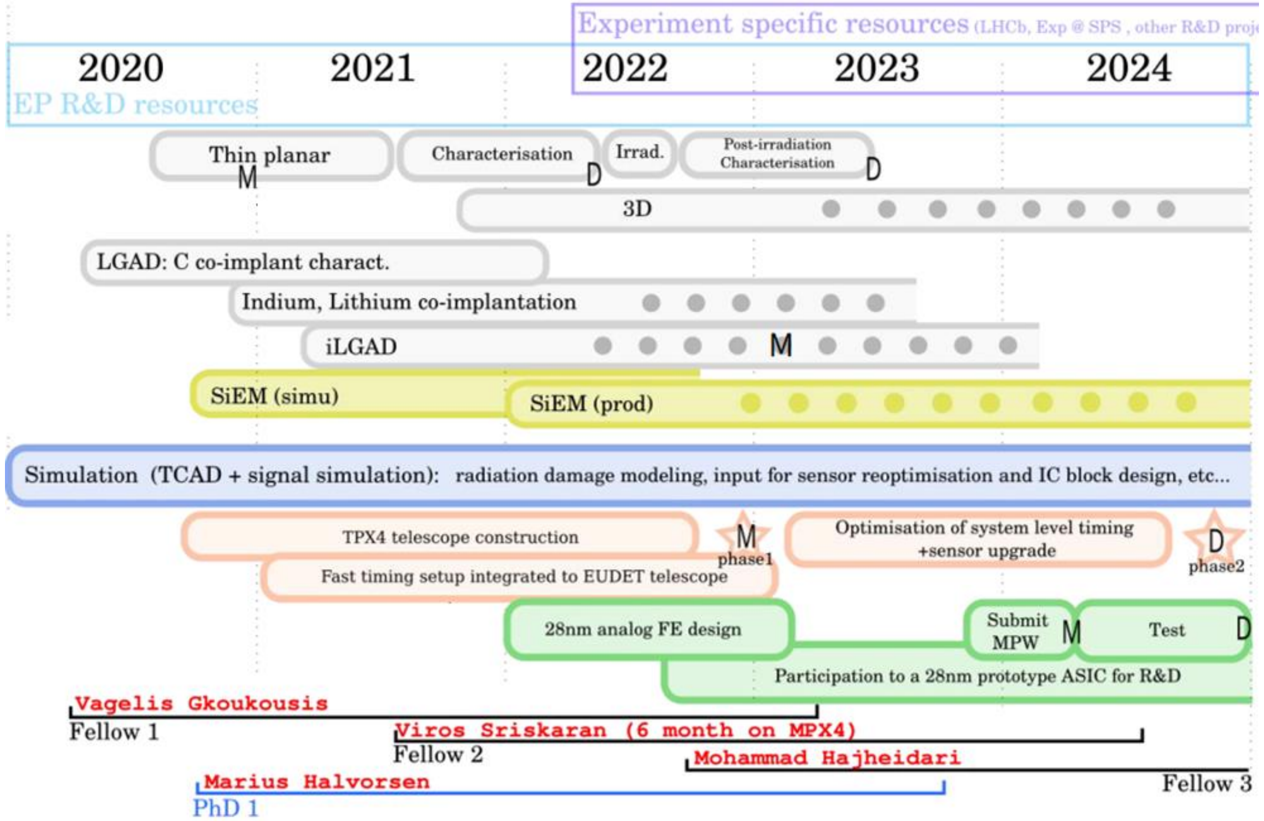

Vagelis Gkougkousis


Jakob Haimberger


Marius Halvorsen


Victor Coco


Paula Cliins



•3D Sensors

Timing at Extreme Fluences

3D Sensors: Decoupling of charge generation and drift volume
(*Standard columns, TimeSpot, Hex geometries* ect.)

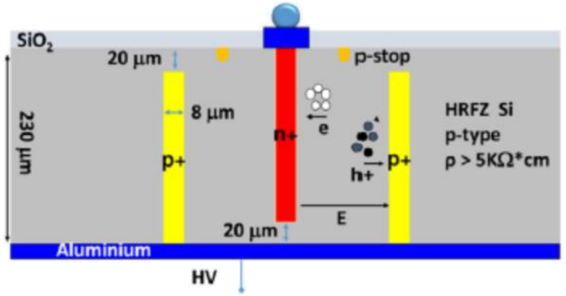
Pros

- High radiation tolerance up to several times 10^{16} n_{eq}/cm^2
- Short drift distances with fast rise times
- Reduced Landau fluctuation, practically non-existent for perpendicular tracks

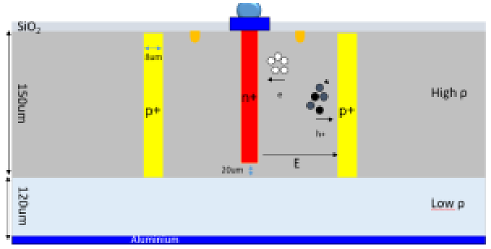
Cons

- Non-uniform field geometry
- High cost
- Increased cell capacitance

Double Sided
(thicker, more expensive)

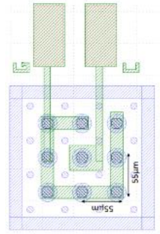


Single Sided
(thinner, simpler process)



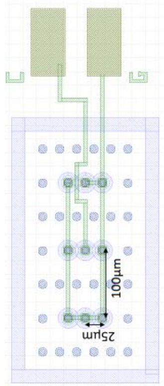
Pixel Size vs Field Uniformity

ATLAS IBL Type

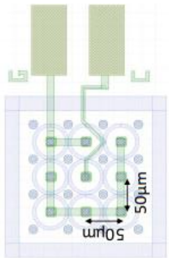


- ✓ Double sided n-on-p process
- ✓ Pixel Size 55 × 55 μm²
- ✓ Active thickness 230 μm
- ✓ High Resistivity (> 2 kΩm × cm) Fz silicon

ATLeS Pre-Production type



- ✓ Single sided n-on-p process
- ✓ Pixel Size 25 × 100 μm²
- ✓ Active thickness 150 μm
- ✓ High Resistivity (> 2 kΩm × cm) Fz silicon

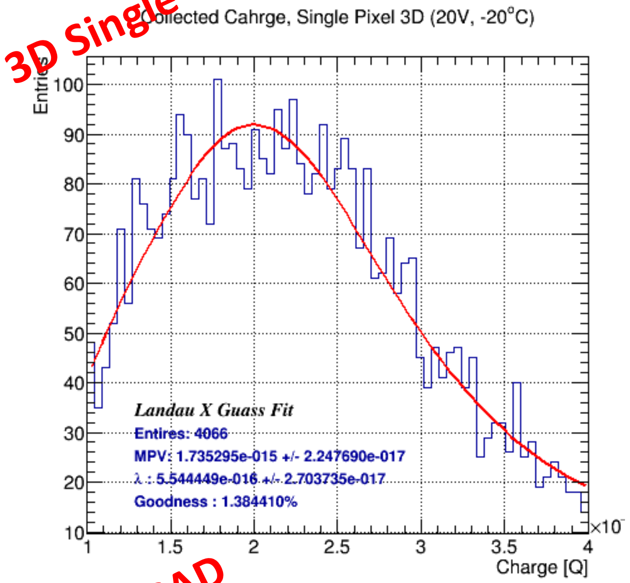


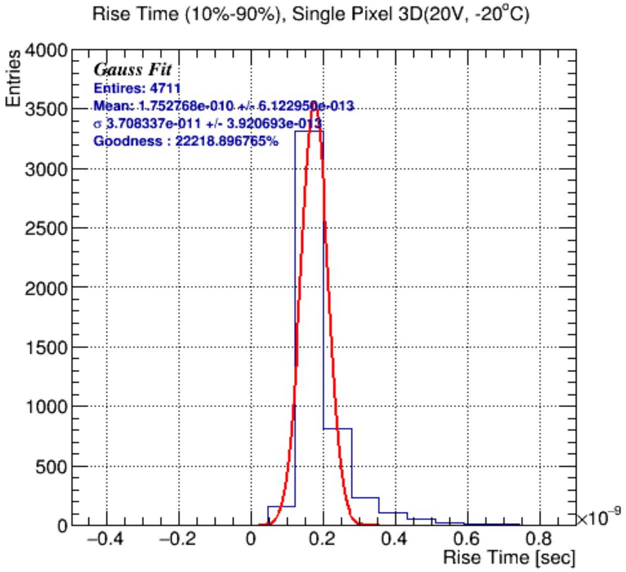
- ✓ Single sided n-on-p process
- ✓ Pixel Size 50 × 50 μm²
- ✓ Active thickness 150 μm
- ✓ High Resistivity (> 2 kΩm × cm) Fz silicon

•3D Sensors - Timing

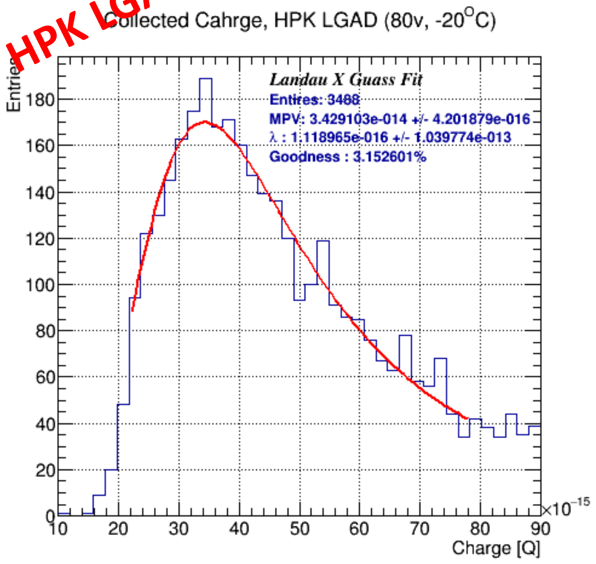
Presentation: V. Gkougkousis, "Single cell 3D timing: Time resolution assessment and Landau contribution evaluation via test-beam and laboratory measurements", 17th Trento workshop on advanced radiation silicon detectors (link)

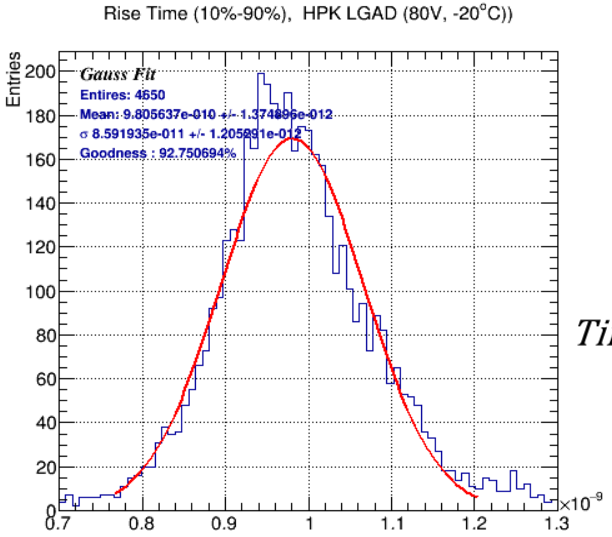
3D Single Cell





HPK LGAD

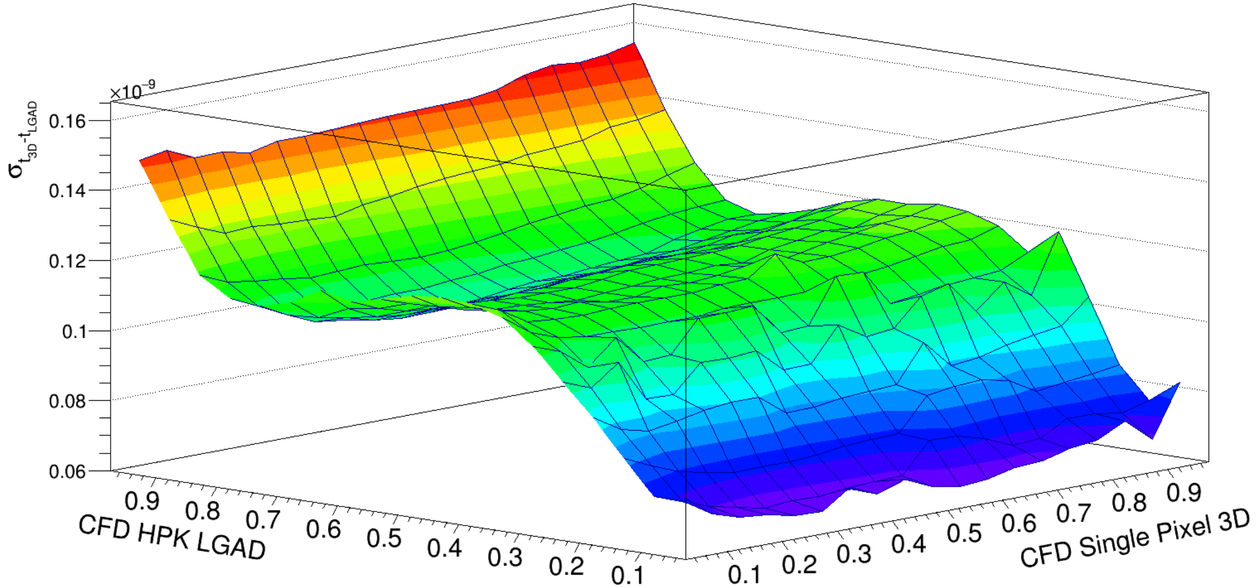




- **Extremely fast rising edge (< 180 psec)**
- **Linear stable behavior with CFD, good SNR control**

$$(\sigma_{\text{Dut}})_{CFD_{ij}} = \sqrt{(\sigma^2_{\text{Tot}})_{CFD_{ij}} - (\sigma^2_{\text{Ref}})_{CFD_i}}$$

CFD Map, LGAD - Single Pixel 3D (-20°C, 20V)



2D optimization plot – 0.5% binning

$$\textit{Time Resolution:}\quad \sigma^2_{tot} = \underbrace{\sigma^2_{timewalk}}_{\sigma^2_{Dist.} + \sigma^2_{Landau}} + \underbrace{\sigma^2_{jitter}}_{\left(\frac{t_{rise}}{S/N}\right)^2} + \underbrace{\sigma^2_{conversion}}_{\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2} + \underbrace{\sigma^2_{Clock}}_{\text{Fixed Term} \sim 5\text{-}7\,psec}$$

•Planar Sensors

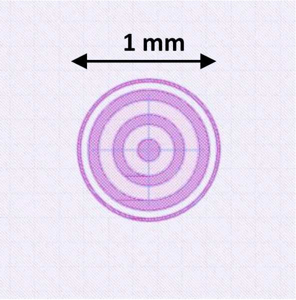
Sensors: CERN EP-R&D n-on-p planar sensor run with ADVACAM at 50, 100, 200 and 300 μm active thickness (TimePix4 bonded sensors also from this run, see Kazu's talk here)

Test Structures

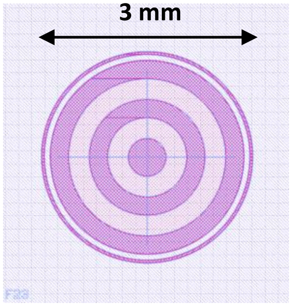
- Small diodes (3.14 mm2 active area) Circular diodes for timing studies due to lower capacitance
- Big diodes (28.27 mm2 active area) Circular diodes for radiation damage studies
- 5x5 Pixel matrix (0.003 mm2 active area) for charge sharing and interpixel efficiency – timing studies

Issues

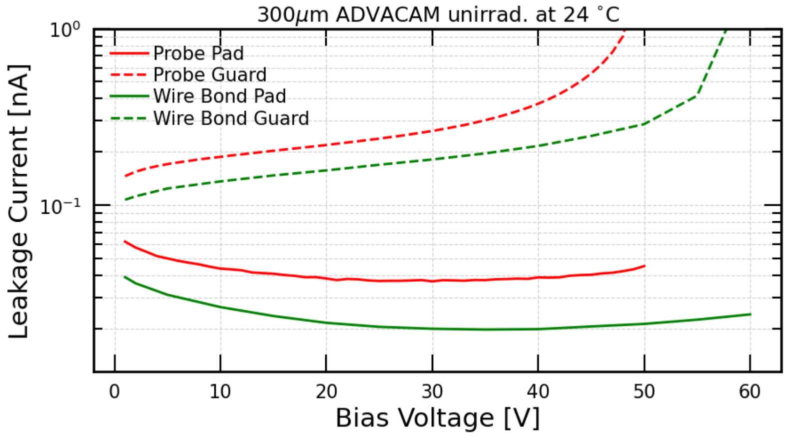
- Early breakdown due to high p-spray concentration leading to impact ionisation at the interface between p-spray and electrode implant
- Breakdown first visible in guard ring due to bigger interface region compared to pad

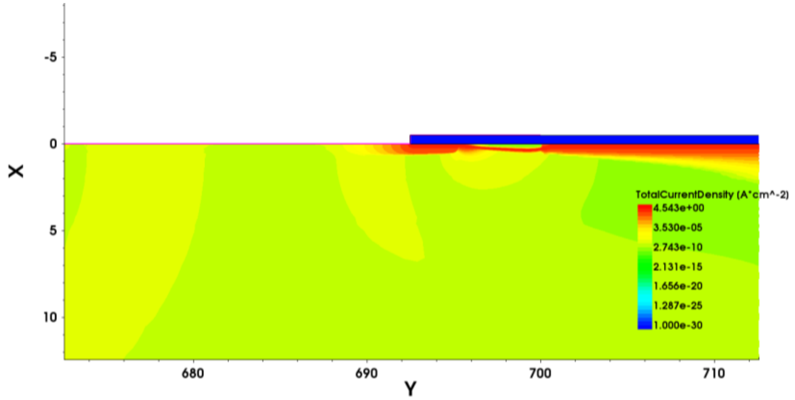


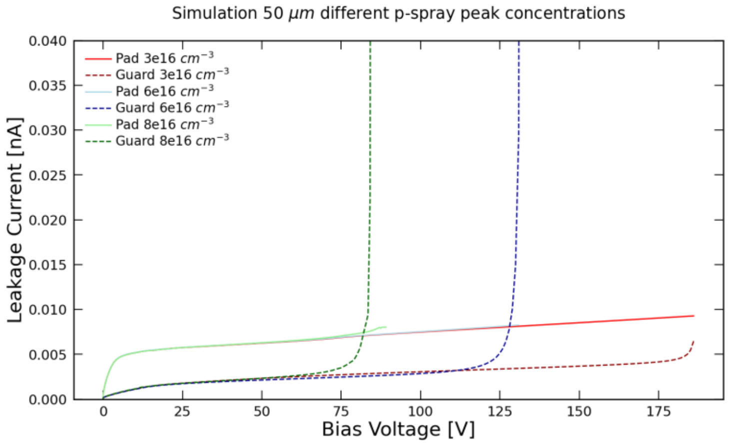
Small Diode



Big Diode







Irradiations

(both 3D and planar)

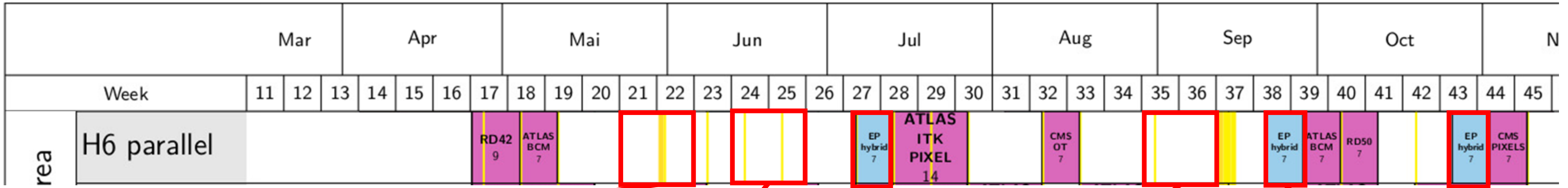
Neutron @ JSI (Ljubljana)

- ✓ $1 \times 10^{15}\ n_{eq}/cm^2$
- ✓ $8 \times 10^{15}\ n_{eq}/cm^2$
- ✓ $6 \times 10^{16}\ n_{eq}/cm^2$
- ✓ $1 \times 10^{17}\ n_{eq}/cm^2$

Proton @ PS

- ✓ $1 \times 10^{15}\ n_{eq}/cm^2$
- ✓ $8 \times 10^{15}\ n_{eq}/cm^2$
- ✓ $6 \times 10^{16}\ n_{eq}/cm^2$
- ✓ $1 \times 10^{17}\ n_{eq}/cm^2$

•Test Beam Planning



Primary user
Parallel user
Parasitic user

25 May – 8 June

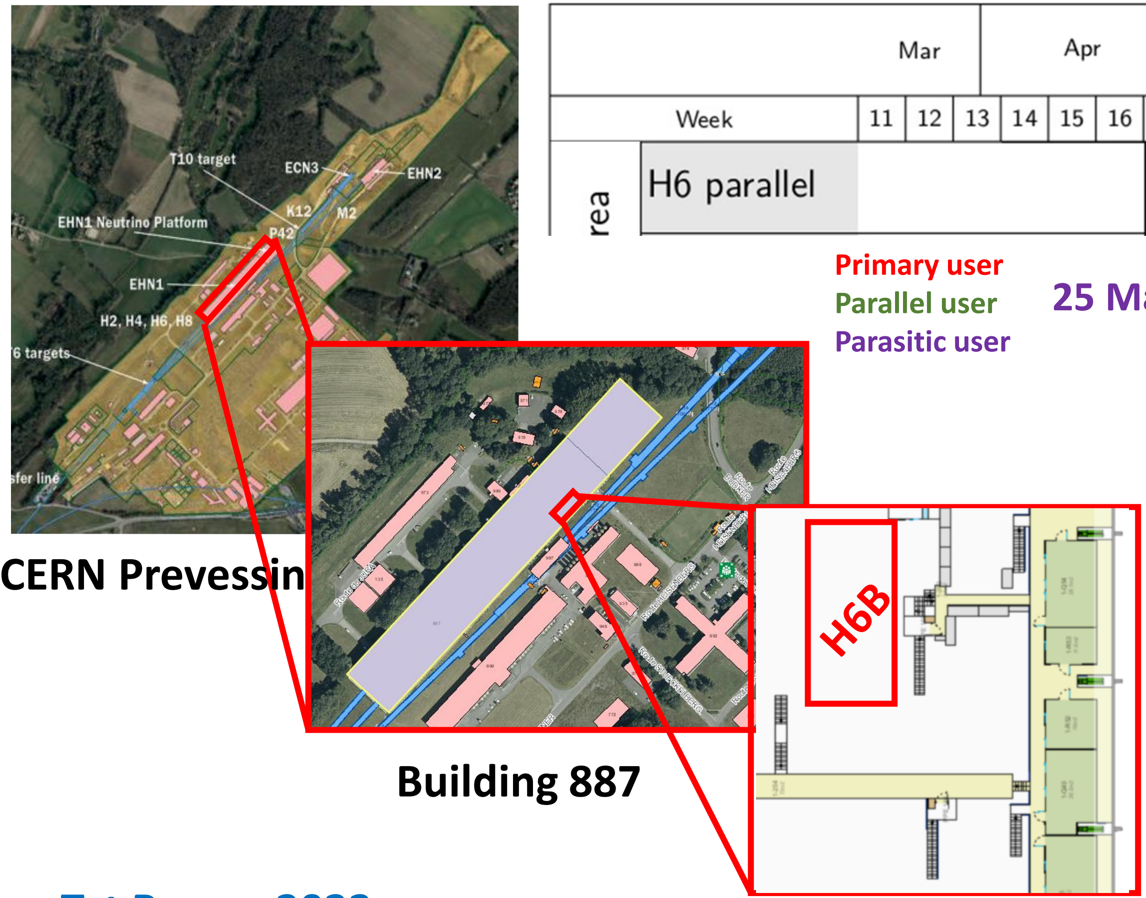
15 – 29 June

6 July – 13 July

31 August - 14 September

20 - 27 September

17 – 24 October

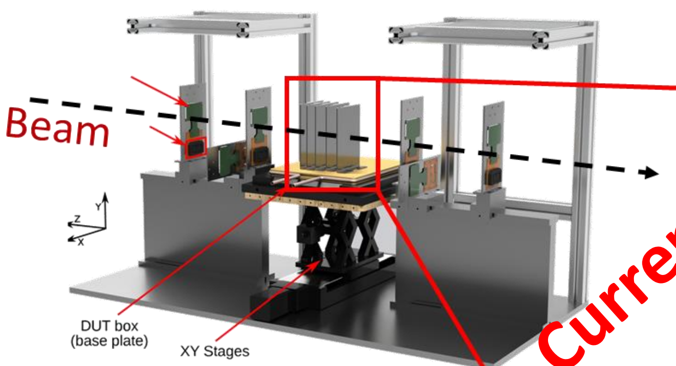


CERN Prevessin

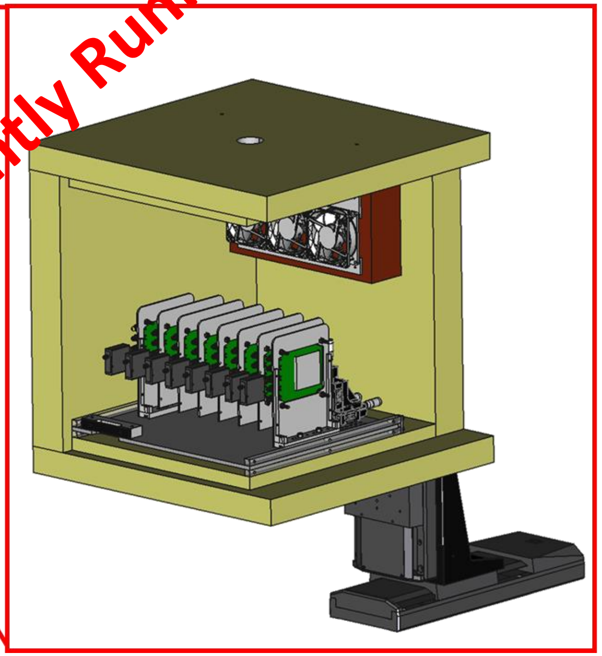
Building 887

Tet Beams 2022

- Several periods but only two as primary user
- Main target irradiated Planar / 3D sensors
- No / Limited possibility of extension
- Extensive infrastructure developments



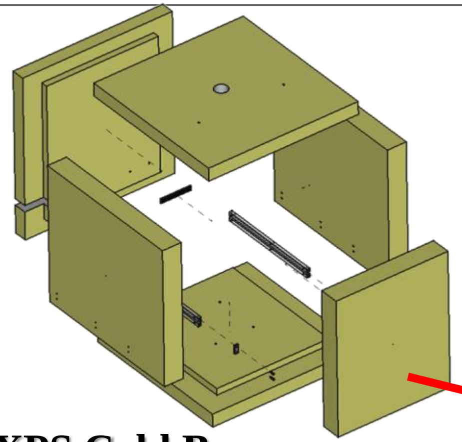
Currently Running!!



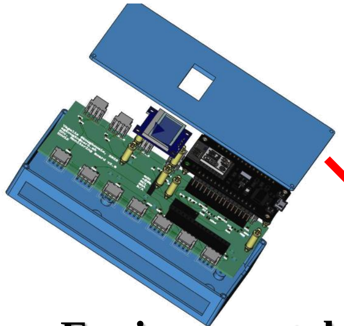
The Setup

- AIDA Telescope
- Custom Cold Box
- DUTs on individual stages
- Discrete electronics and Oscilloscope

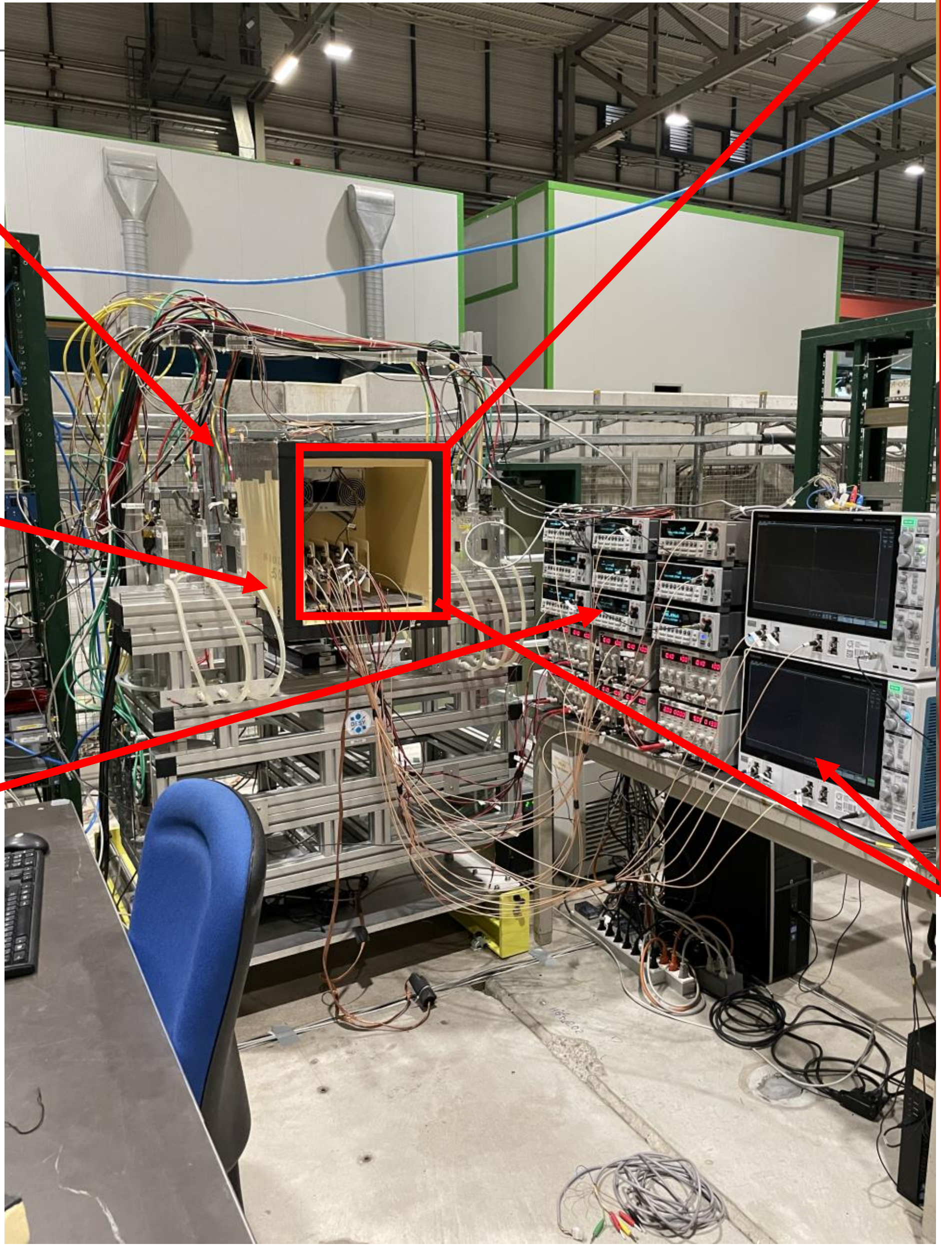
•Setup @ SPS

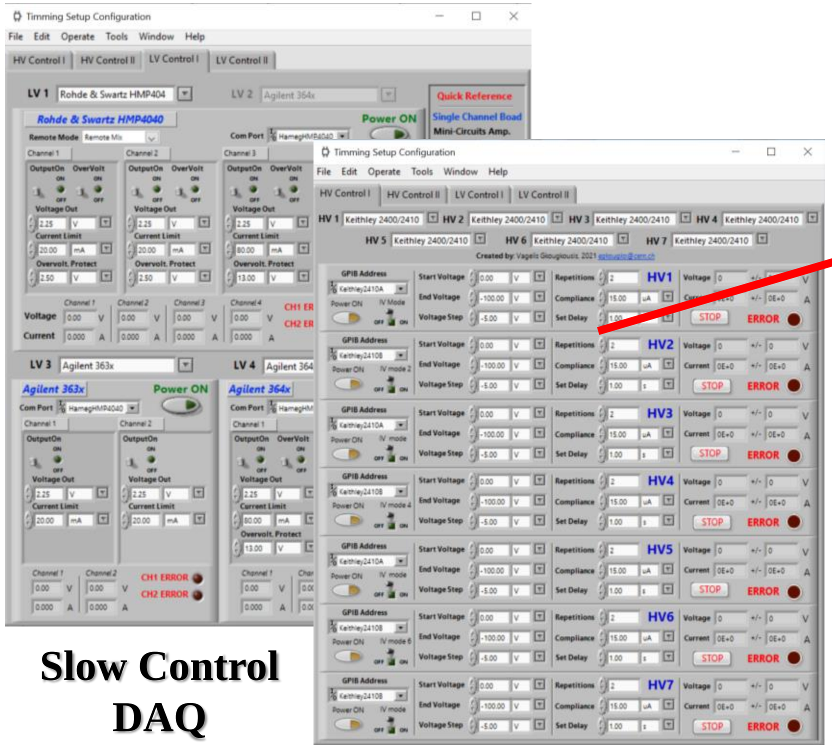


XPS Cold Box

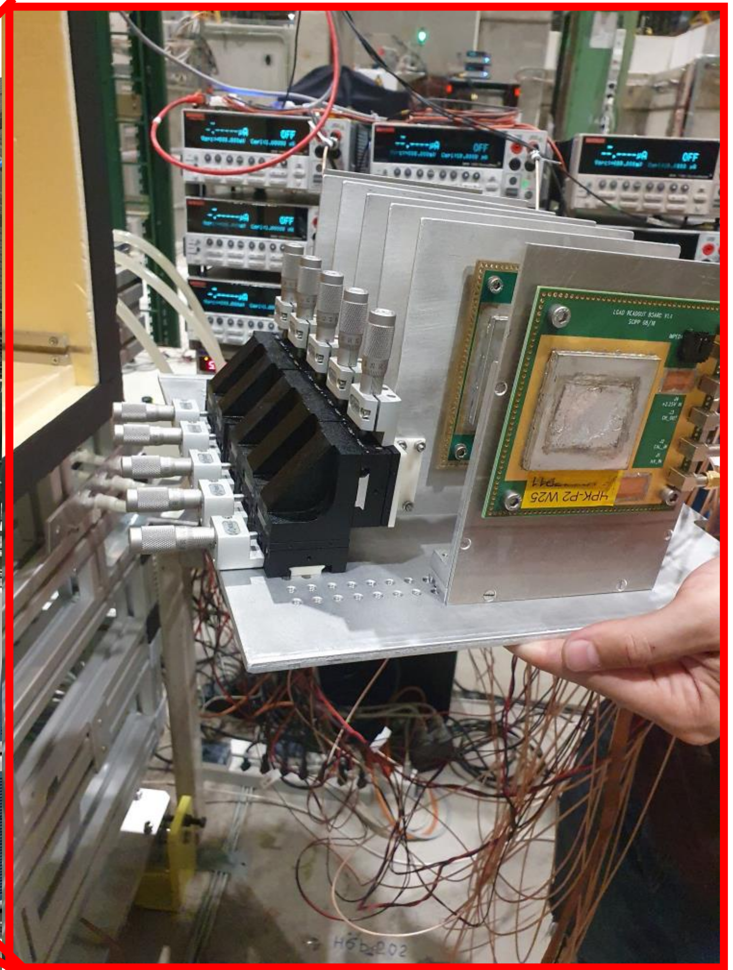


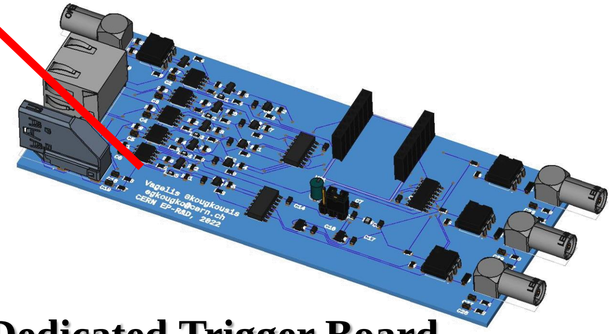
Environmental Control





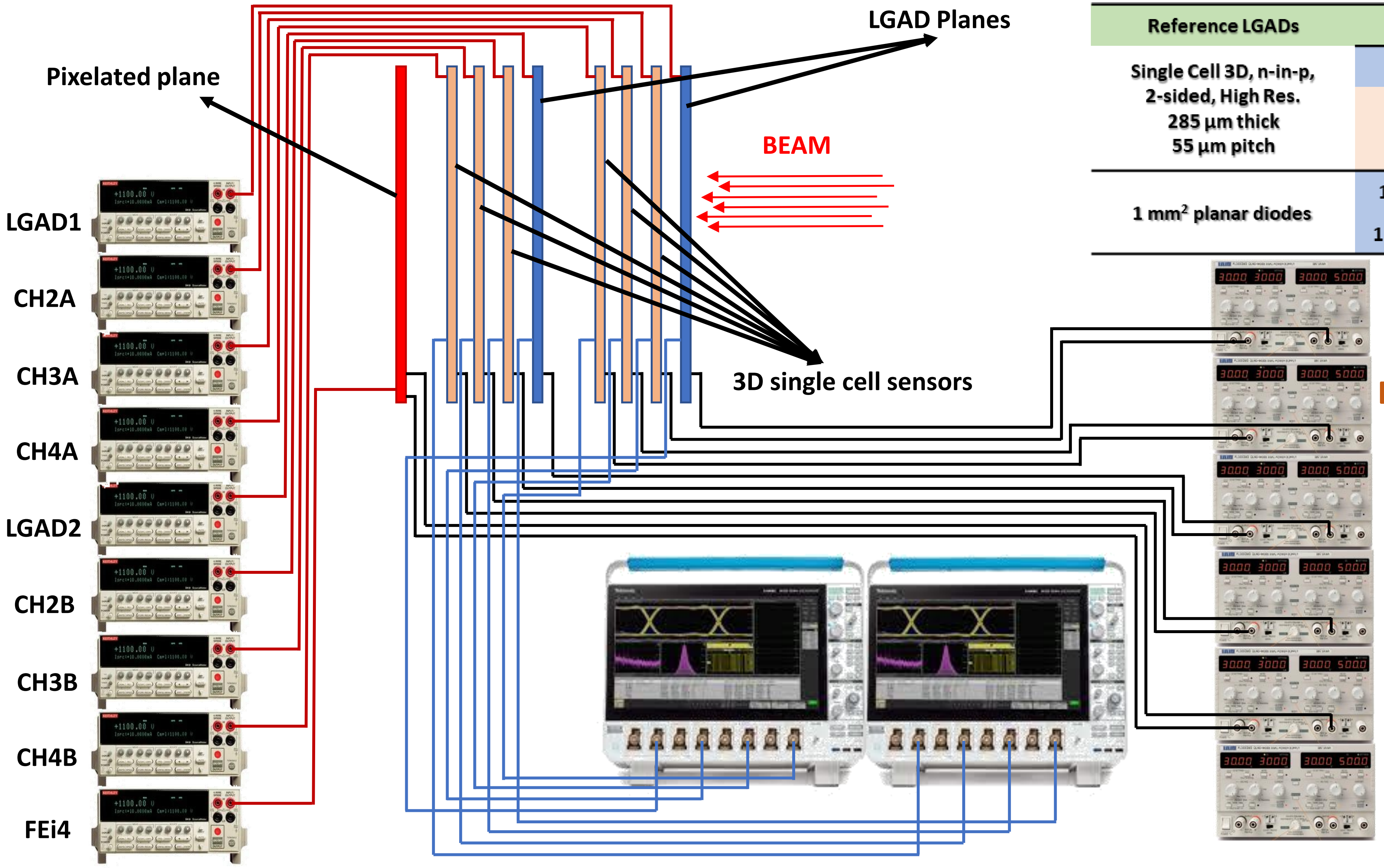
Slow Control DAQ





Dedicated Trigger Board

•Test Beam Configuration



June Test Beam Planning

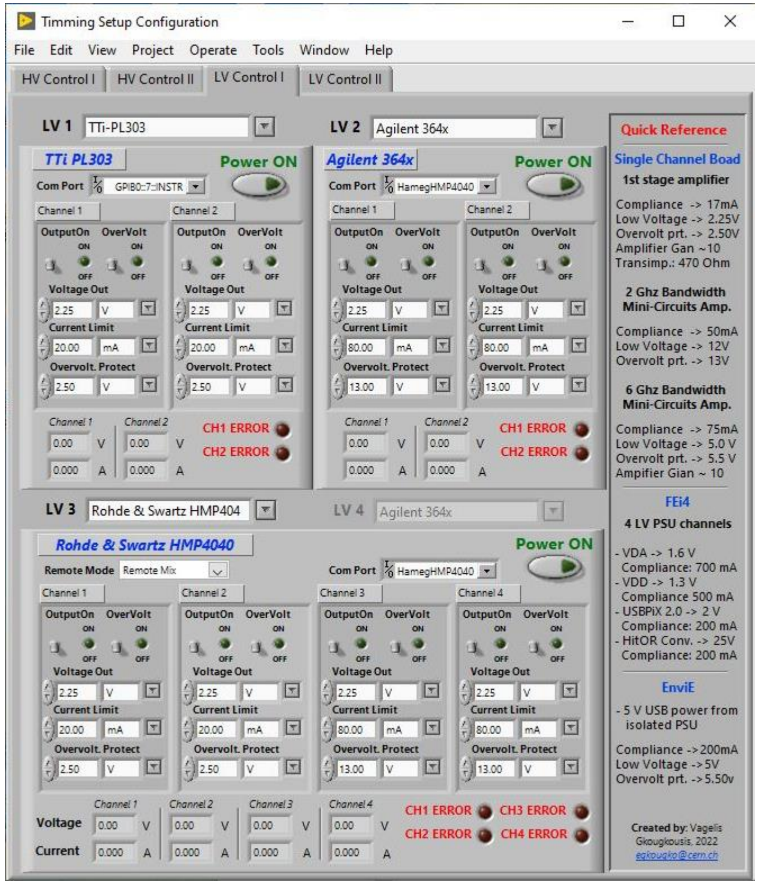
Sample type	Sample no.	Fluence (n_{eq}/cm^2)
Reference LGADs	2	Unirradiated
Single Cell 3D, n-in-p, 2-sided, High Res. 285 μm thick 55 μm pitch	1	Unirradiated
	1	1×10^{15}
	1	8×10^{15}
1 mm² planar diodes	1 x 50 μm thick	Unirradiated
	1 x 100 μm thick	Unirradiated

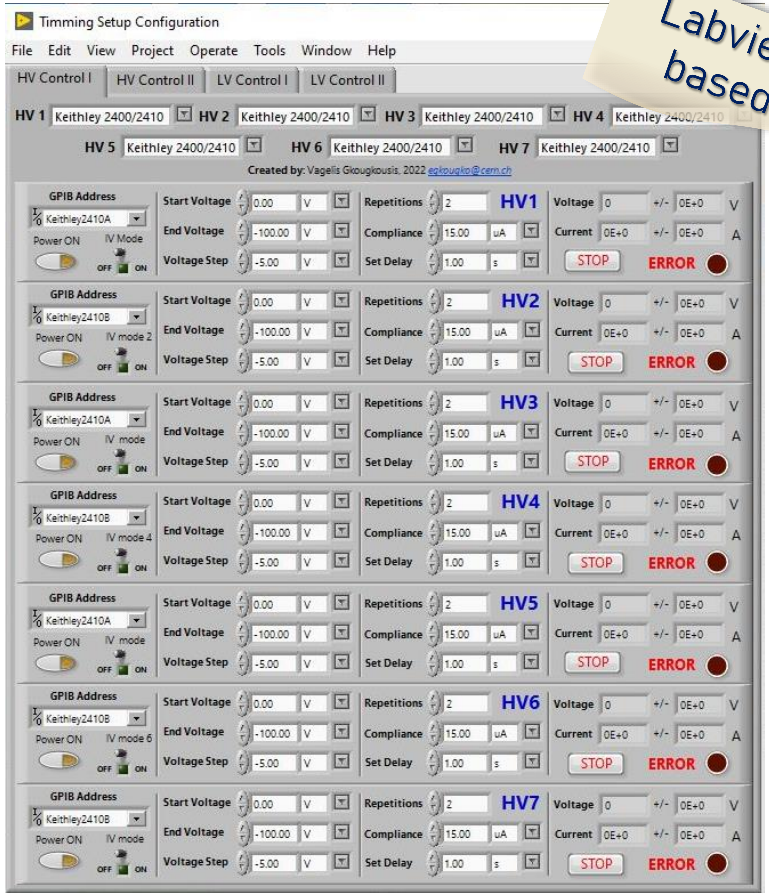
Equipment List

- 2 x Oscilloscopes
- 9 x Keithley 2410
- 6 x TTi PL303
- 8 Second stage amplifiers
- 6 micro-positioning stages
- Humidity – Temperature monitoring system (EnViE)
- Cold Box for -20°C operation
- Trigger Interface Board V2.0
- SMA Cables

•HV & LV Control/monitoring

➢ Precompiled executable available on GitLab: here



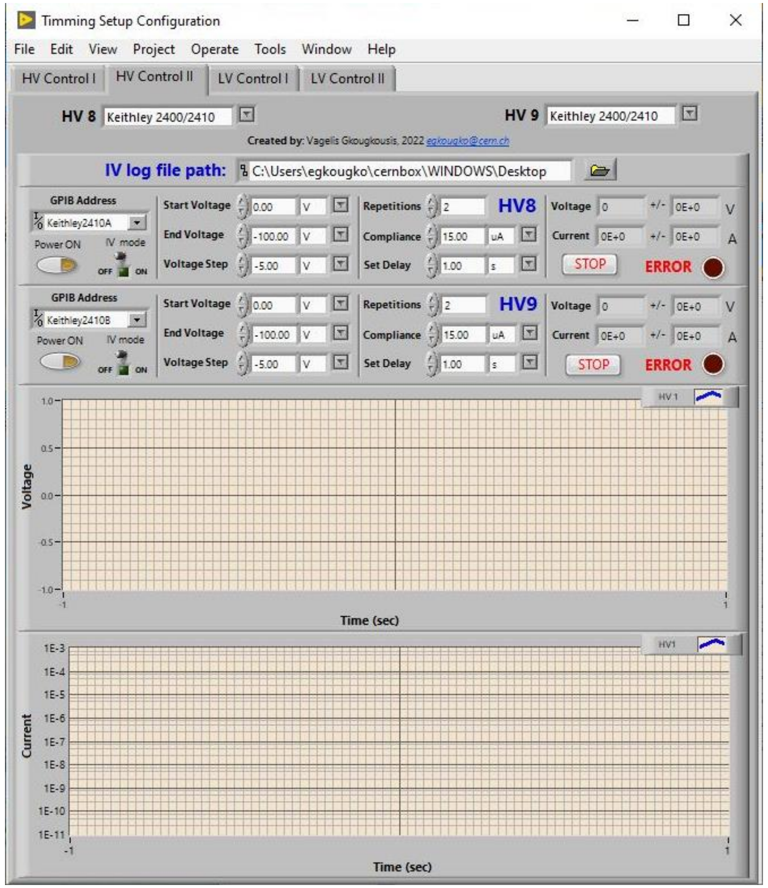


Labview based

High voltage

KEITHLEY

2400/2410 series



Multi-model Support with Polymorphic UI

Agilent Technologies

363X series

KEYSIGHT TECHNOLOGIES

364X series

ROHDE&SCHWARZ

HMP4040

Aim TTi

PL330DP

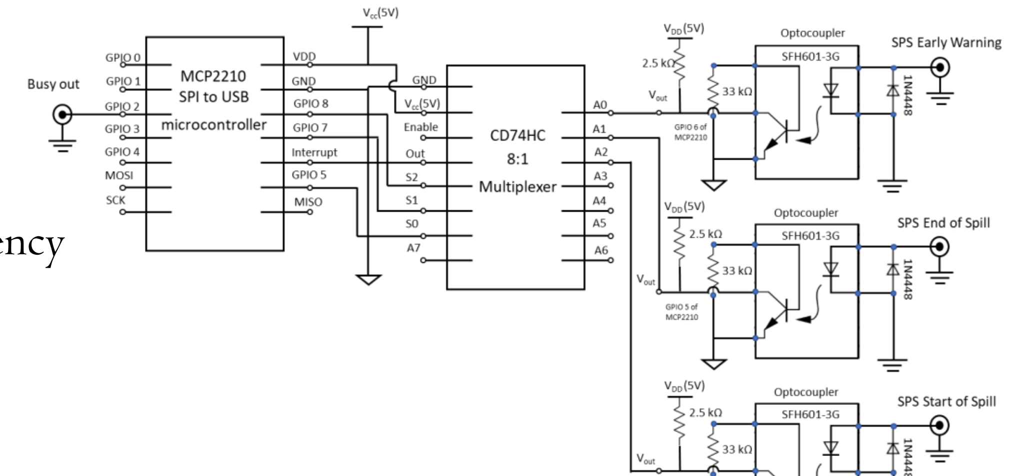
Aim TTi

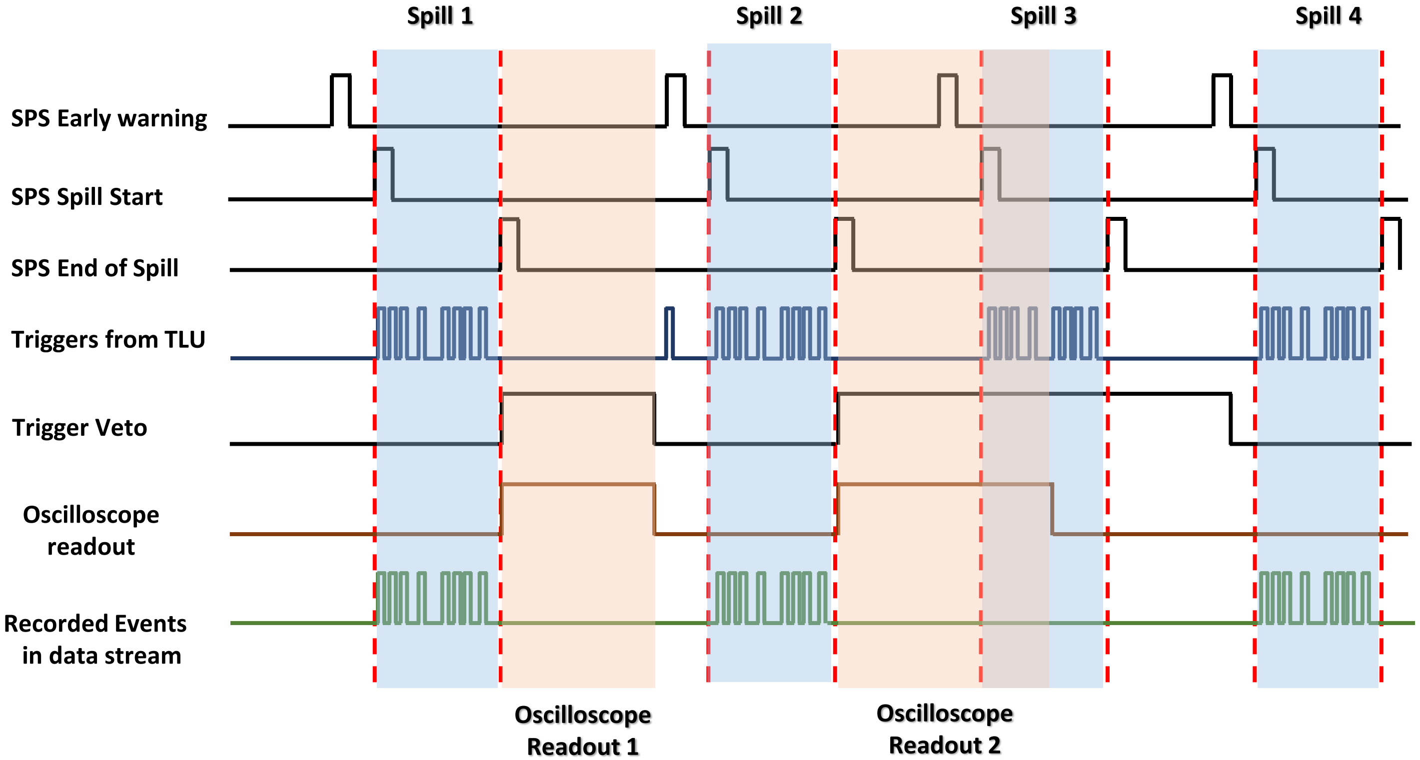
PL303QMD

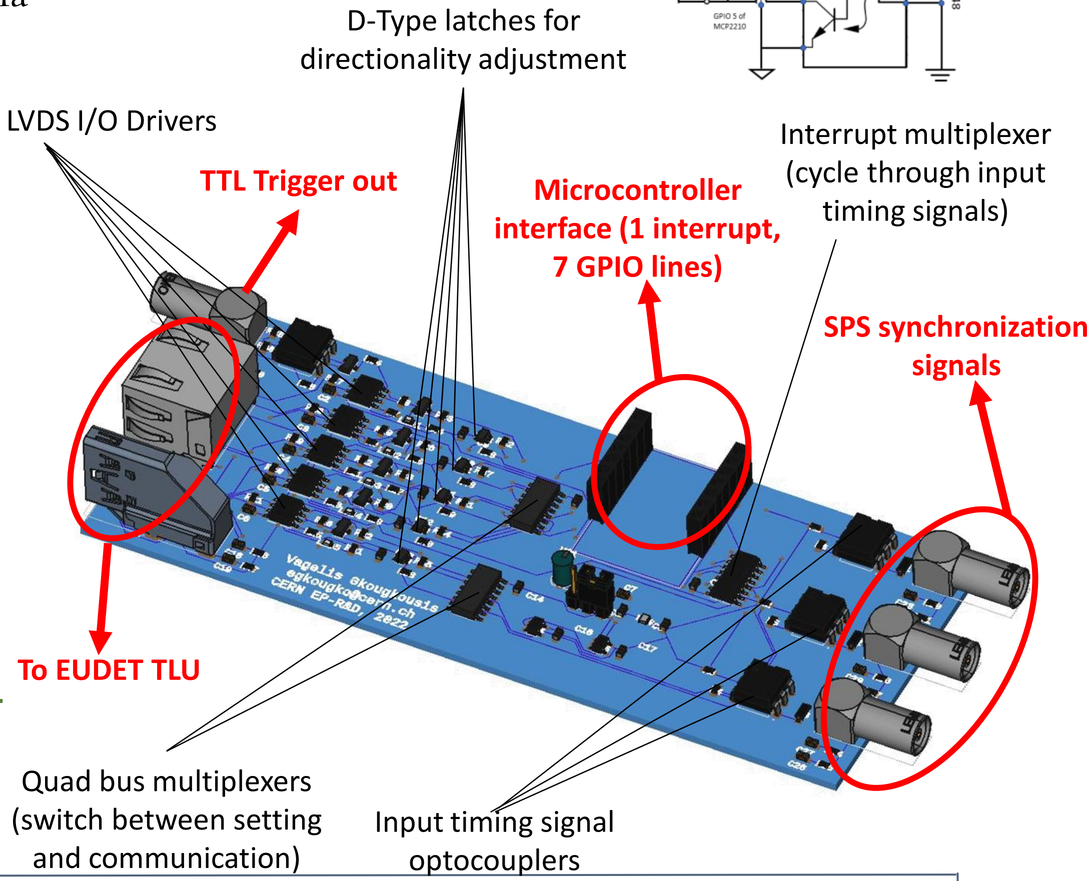
- 9x HV channels
- 16x LV channels
- Constant monitoring & logging
- Live protection

•Trigger Interface Board (TiB)

- Oscilloscope in fast readout mode with binary format
- Event readout only between SPS-spills or when event buffer full ti increase efficiency
- TLU Synchronization by vetoing data taking during read-out
- RJ-45 or HDMI for EUDET TLU communication (EUDET 2 compatible)
- **Versatile design**, I/Os **Reconfigurable** and microcontroller **Reprogrammable** via USB





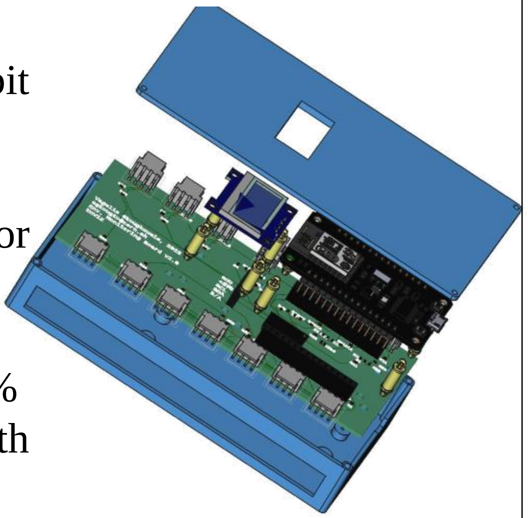


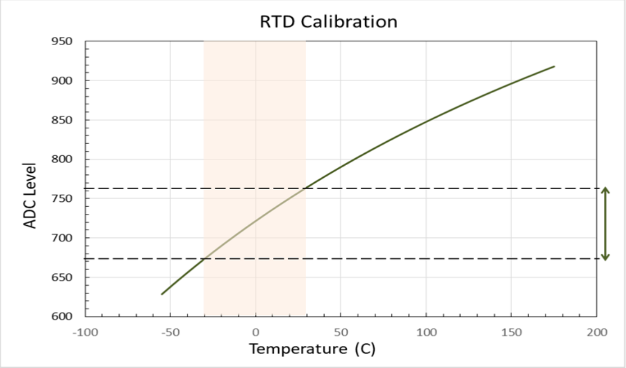
•Temperature Regulation

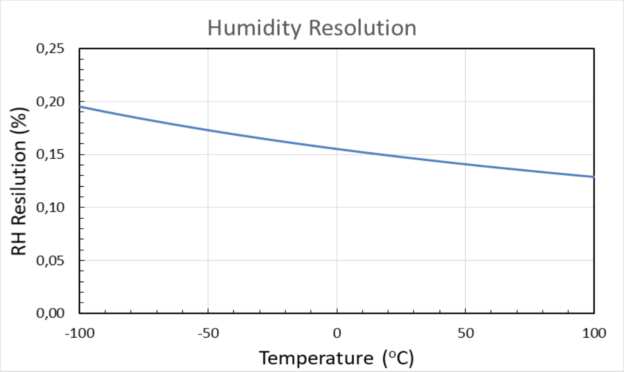
- ➢ Running at a crisp **-18 °C**
- ➢ **EnviE GitLab with schematics: here**
- ➢ Glycol cooling with temperature feedback - Labview control
- ➢ Humidity regulation though N_2 feeds

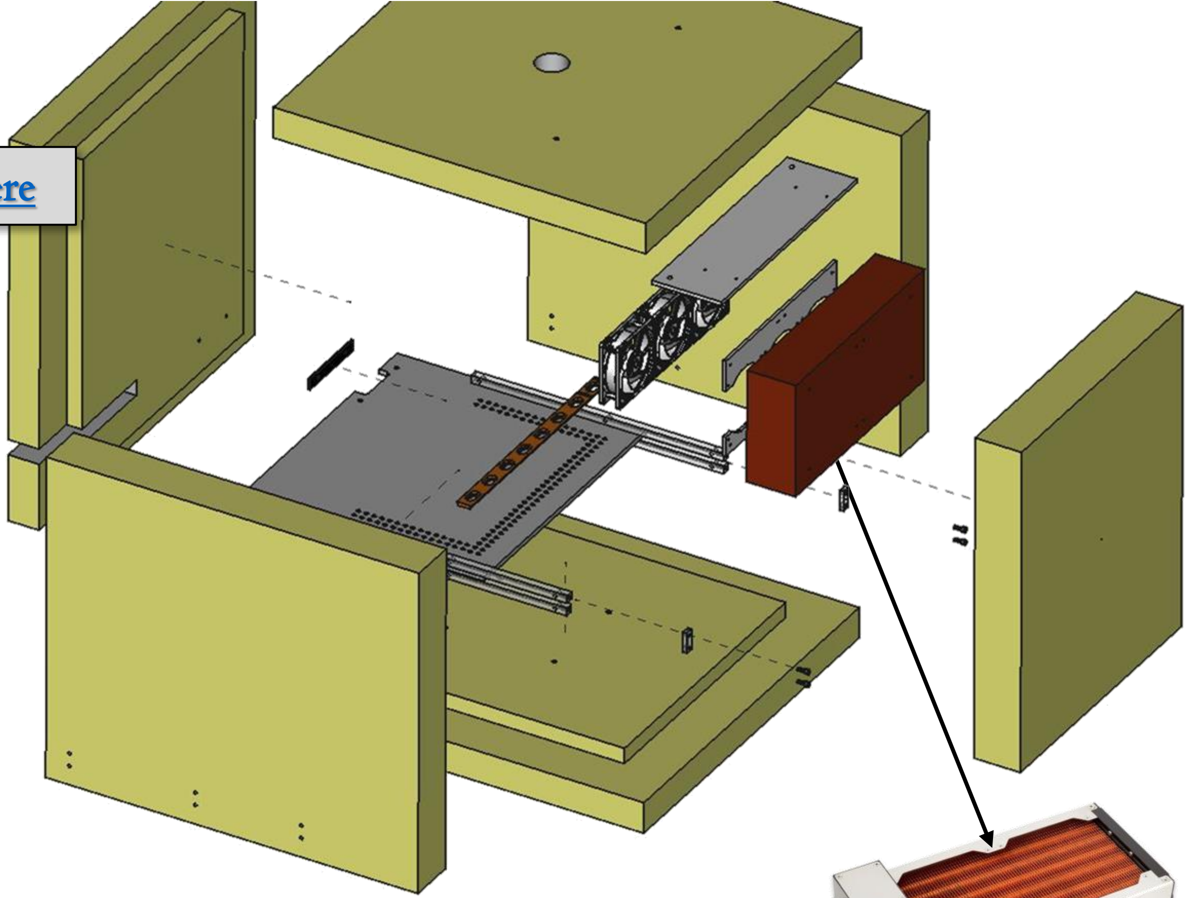
Environmental Expander V2.0 (EnviE)

- ESP8266 based with integrated 10-bit ADC, I2C and WiFi 802.11b
- Integrated OLED 128X64 pixel screen
- High precision voltage dividers and sensor decoupling
- ARDUINO / LoUA core web interface
- Temperature resolution of 0.8 °C ± 0.06 %
- Humidity resolution 0.1 % with temperature compensation









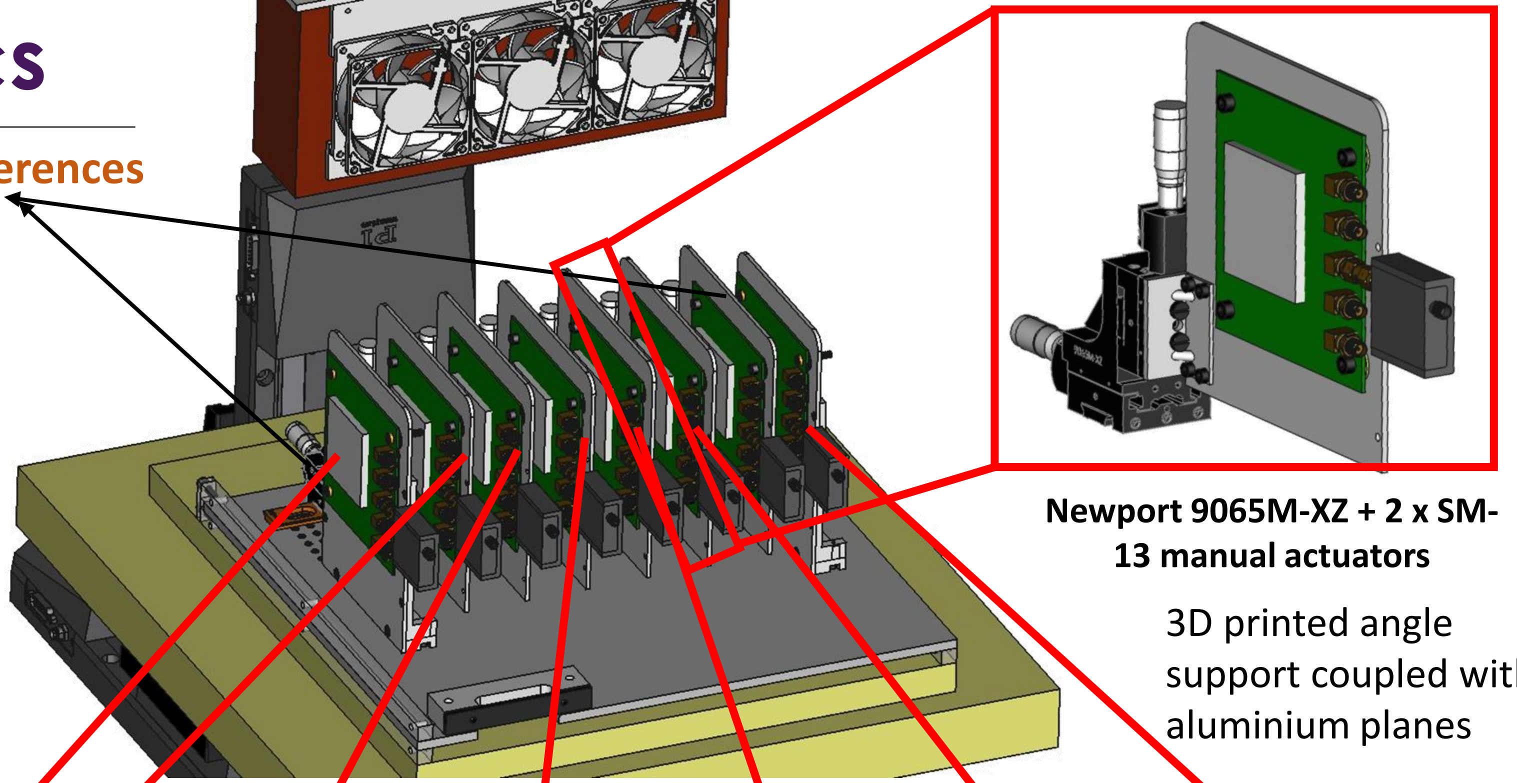
Water cooling block

- ➢ 6 c.m. thick XPS foam insulation
- ➢ Outer dimensions of 50 x 48 x 48 cm^3
- ➢ Use of commercial water-cooling block (link)
- ➢ 3 x Axial Fan DC 80x80x25mm 24V 111.6m^3/h – low remperature tested to -20°C (link)
- ➢ Total cost ~ 400 CHF

•Alignment & Mechanics

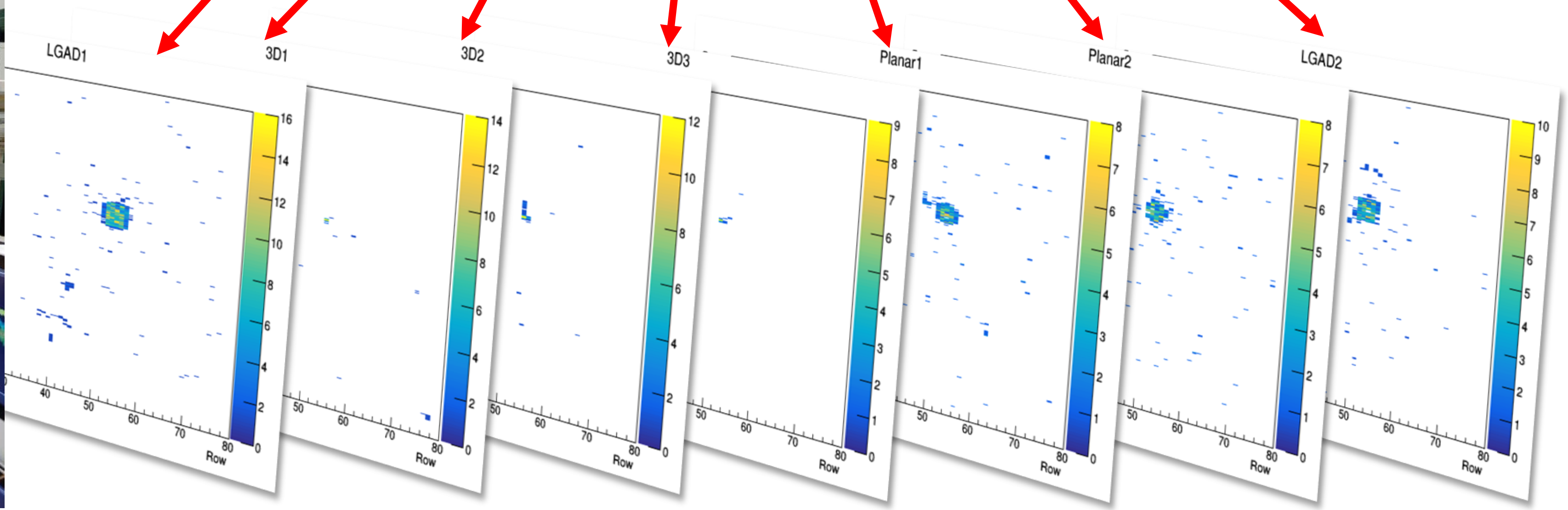
HPK LGAD Timing references

- Coincidences between DUTs and LGADs required for timing
- Alignment crucial to increase data efficiency
- Efficiency defined by largest overlapping region
- Micrometric on-line alignment using projections on FEi4 matrix
- ROI defined in addition to other trigger conditions

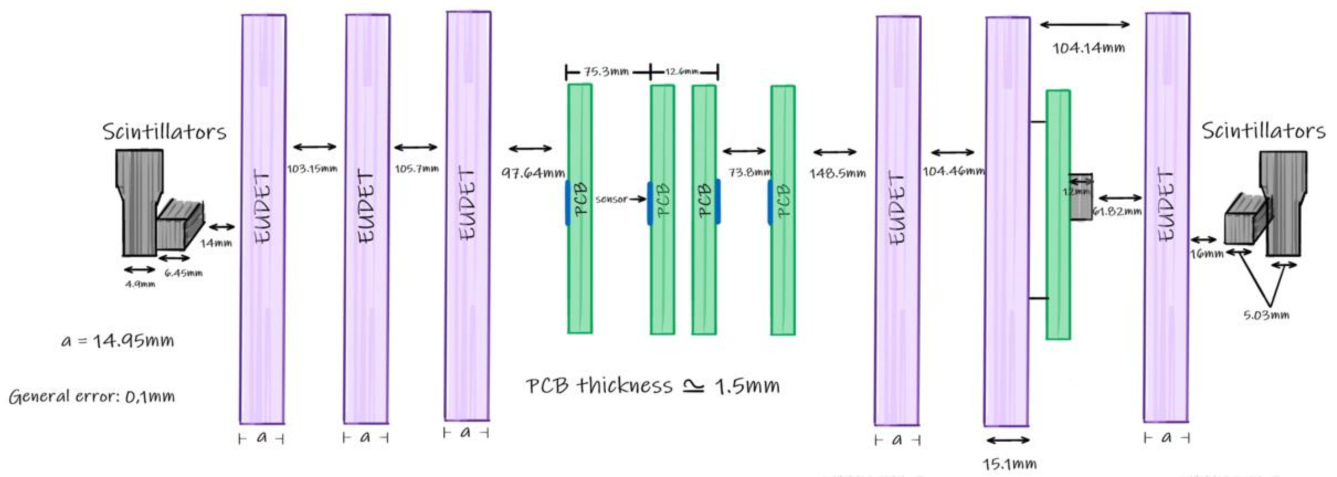


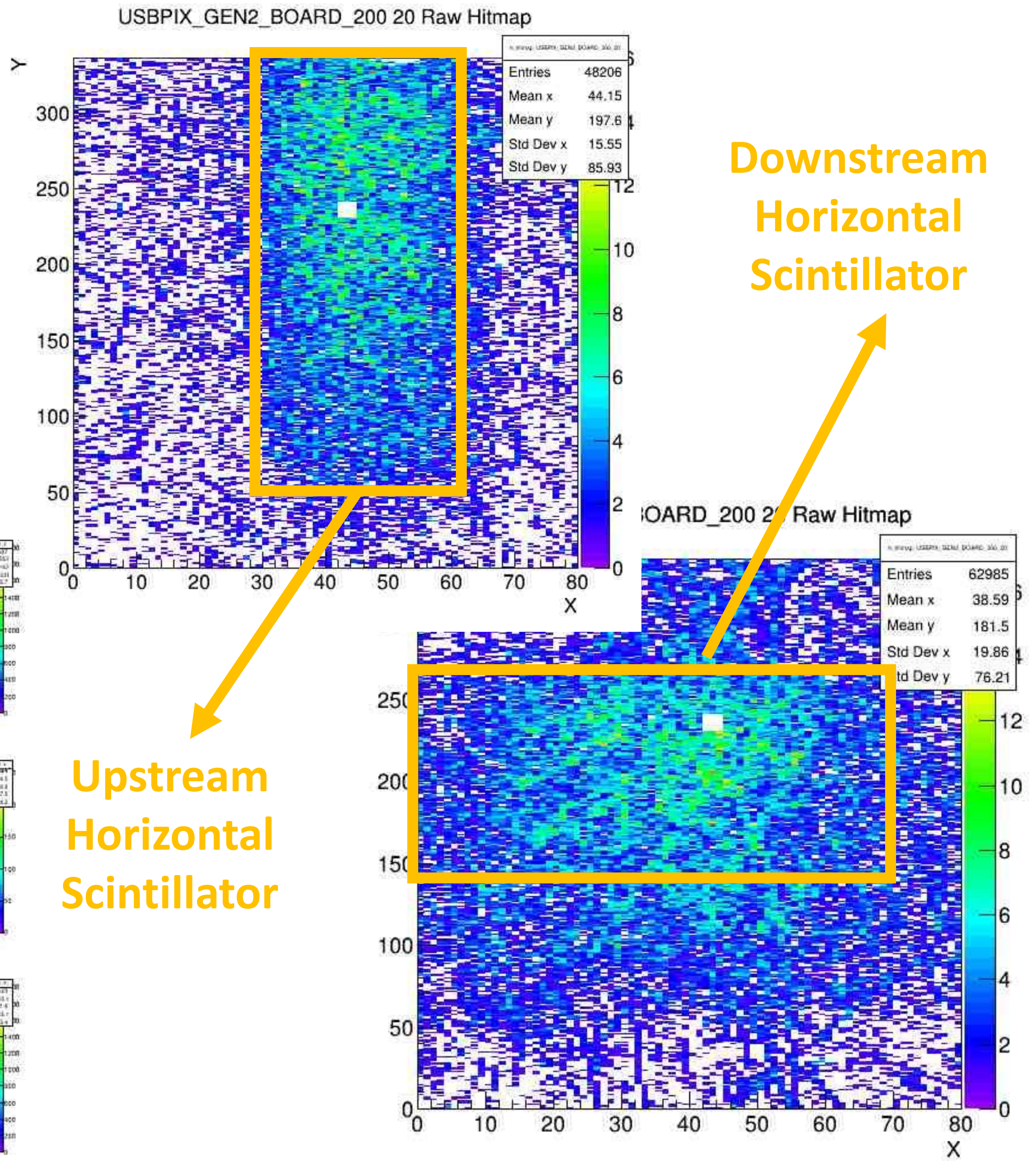
Newport 9065M-XZ + 2 x SM-13 manual actuators

3D printed angle support coupled with aluminium planes



•Tracking and ROI

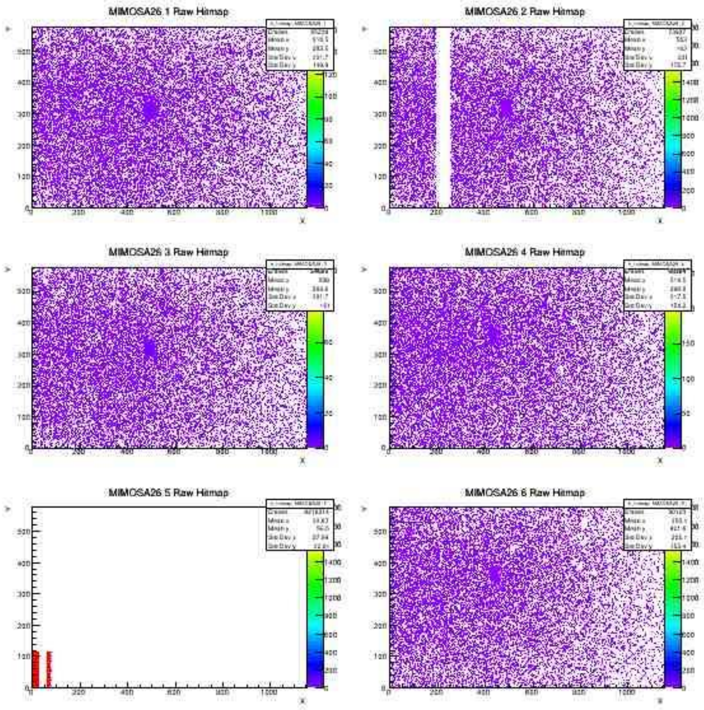




Telescope Planes

- **6 MIMOSA planes for tracking**
- **Plane no. 5 known to be bad**
- **Expected 5μm tracking resolution**
- **Estimated acquired number of events ~1M**

- Limited beam control as parasitic user
- Suffer from low intensity and low data rates of EUDAQ



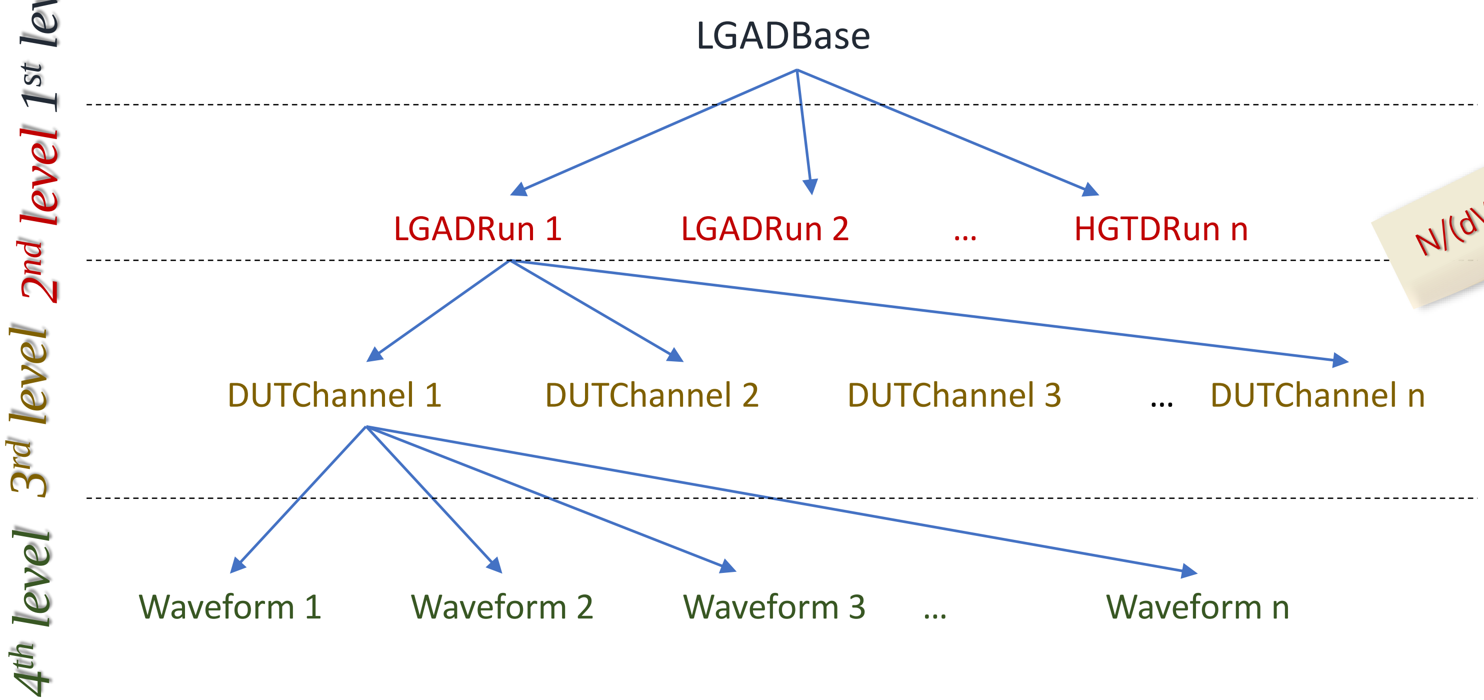
•Analysis Framework

➢ Code available on git: https://gitlab.cern.ch/egkougko/lgadutils

➢ Four main classes with dedicated header and implementation files, one wrapper class handling user interaction

C++ 11

- LGADUtils → Wrapper to handle user I/O and pass arguments
- ➢ LGADBase → Basic framework function and infastructure
- ➢ LGADRun → Timing resolution, CFD maps, multi DUT operations
- ➢ LGADChannel → Mean pulse shape, mean pulse properties form entire run
- ➢ WaveForm → Single Waveform properties and time walk corrections
- ➢ Bonus: LGADSel → **Selector Class with auto-set 64 channel support**



- Iterative re-fitting and re-binning algorithm
- Fitting of discrete and variable binning quantities
- Bayesian uncertainties at efficiency level
- Event by event FFT transimpedance correction

N/(dV/dt) , T_{Rise}/SNR

Quantity	***Applied Fit type***
Min, Max voltage :	Gauss, Gauss x Landau fit
Start, stop, min, max indices :	Gauss, Gaussian fit
Noise / pedestal :	Gaussian fit
Min, Max, Rise, Trigger time :	Gaussian fit
Charge, dV/dT, Jitter, ToT:	Gauss x Landau fit
FFT:	Variable bin Gaussian

•Iterative Re-fitter & signal templates

File: LGADFits.cxx

- Centralized fitter engine for all fits
- Fully automated, including limits, method and Minuit minimization
- 36 Iterations per fit with limits and bin size variation to determine best combination
- Over-binning protection, automatic variable discreetness test
- Variable binning for FFT, frequency histograms
- Supported ROOFit, Standalone Minuit, Integral optimization or Shape

Dataset Type	Statistic Categorization	Bin Selection Criteria		
		Lower 3 bin number variations	Optimum Bin number	Higher 3 bin number variations
Discrete Datasets	$\frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma} < \sqrt{N_{elements}} < N_{bins\_max}$	$\left[\lfloor\sqrt{N_{elements}}\rceil - n \times \left\lfloor\frac{\sqrt{N_{elements}} - \frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma}}{3}\right\rceil\right]$ with 1 < n < 3	$\lfloor\sqrt{N_{elements}}\rceil$	$\left[\lfloor\sqrt{N_{elements}}\rceil + n \times \frac{N_{bins\_max} - \sqrt{N_{elements}}}{3}\right]$ with 1 < n < 3 **
		Lowest bin number	Rest of the bin number array	
	$\sqrt{N_{elements}} \leq \frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma} < N_{bins\_max}$	$\lfloor\sqrt{N_{elements}}\rceil$	$\lfloor\sqrt{N_{elements}}\rceil + n \times \left\lfloor\left\|N_{bins\_max} - \sqrt{N_{elements}}\right\| / 6\right\rceil$ with 1 < n < 6 **	
	$\sqrt{N_{elements}} \leq N_{bins\_max} < \frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma}$			
	$N_{bins\_max} \leq \sqrt{N_{elements}}$	$n \times \lfloor N_{bins\_max}/7\rceil$ with 1 < n < 7		
		Lower 3 bin number variations	Optimum Bin number	Higher 3 bin number variations
Continuous Datasets	$\frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma} < \sqrt{N_{elements}}$	$\left[\lfloor\sqrt{N_{elements}}\rceil - n \times \left\lfloor\frac{\sqrt{N_{elements}} - \frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma}}{3}\right\rceil\right]$ with 1 < n < 3	$\lfloor\sqrt{N_{elements}}\rceil$	$\left[\lfloor\sqrt{N_{elements}}\rceil + n \times \left\lfloor\frac{\frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma}}{3}\right\rceil\right]$ with 1 < n < 3
	$\sqrt{N_{elements}} \leq \frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma}$	$\left[\left\lfloor\frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma}\right\rceil - n \times \left\lfloor\frac{\frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma} - \sqrt{N_{elements}}}{3}\right\rceil\right]$ with 1 < n < 3	$\left\lfloor\frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma}\right\rceil$	$\left[\left\lfloor\frac{\left\|\lim_{fit} High - \lim_{fit} Low\right\|}{\sigma}\right\rceil + n \times \left\lfloor\frac{\sqrt{N_{elements}}}{3}\right\rceil\right]$ with 1 < n < 3

Template Method

- Point by Point projection of all time-walk corrected (though CFD) signal pulses
- Landau X Gauss fit on projected point by point distribution
- Extraction of a "characteristic" signal composed of the MPVs of the Point by point projection fits
- RooKeyPdf for analytical description of signal
- Re-iteration on all events and fit of each waveform with the extrapolated analytical signal description
- Re-caclculate all quantities

•16 Channel Board

IGFAE Instituto Galego de Física de Altas Enerxías

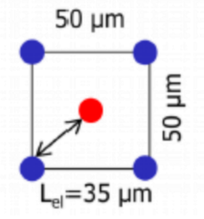
CERN

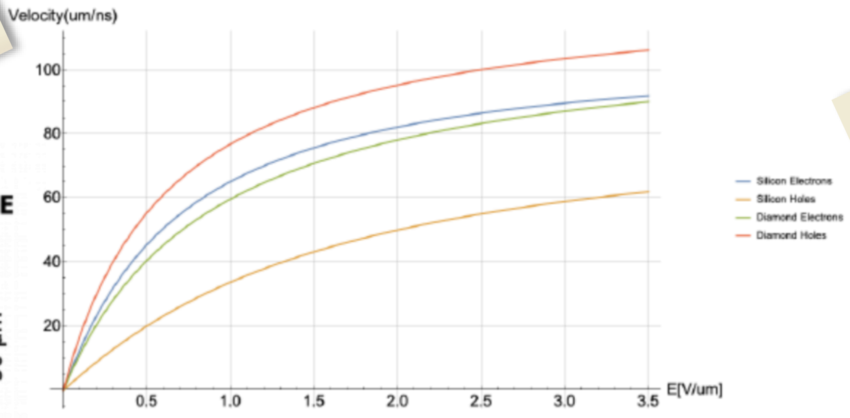
Timeline

- July 2021 — Design submission
- October 2021 — Initial tests
- March 2022 — 2nd Mezzanine iteration
- August 2022 — Test beam measurement with planar matrix

The issue….

50x50 µm², 1E





- Assuming a linear filed dependence and a -15 V operation point at 35 µm column distance:

$$|E| \cong 0.43\ V/\mu m$$

- Estimating drift velocity for electrons:

$$v^e_{drift} = \frac{\mu_{0,e} \times E}{\left[1 + \left(\frac{\mu_{0,e} \times E}{v^e_{sat.}}\right)^{\beta_e}\right]^{1/\beta_e}}$$

with $v^e_{sat.} = 107\ \mu m/ns,\ \mu_{0,e} = 1417 \frac{cm^2}{Vs},\ \beta_e = 1.109$

$$\boldsymbol{v^e_{drift} \approx 41.4\ \mu m/ns}$$

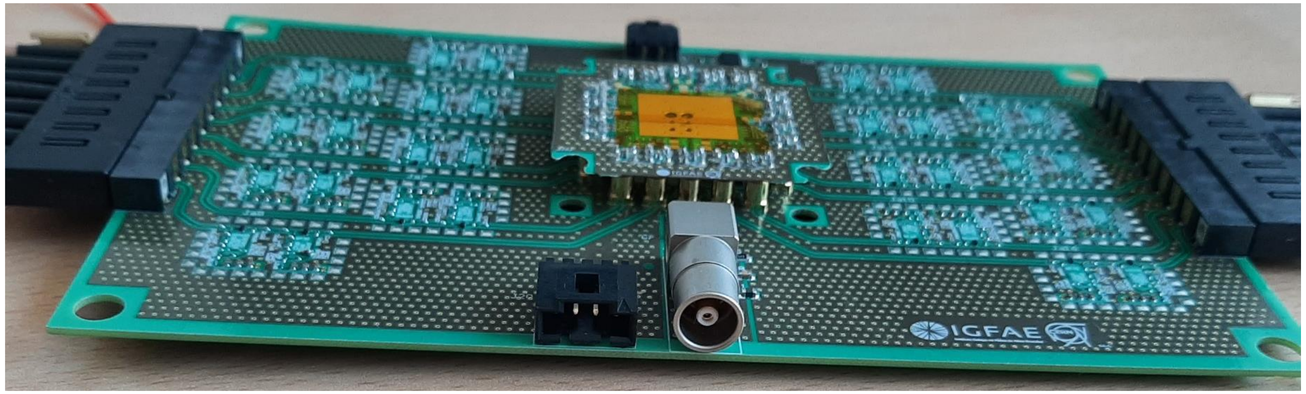
- Extrapolated Rise time and Frequency:

$$t_{Rise} \approx \frac{1}{3} \times t_s = \frac{1}{3} \times \frac{d/2}{v^e_{drift}} \approx 140\ psec \Rightarrow \mathbf{2.3\ GHz}$$

The solution

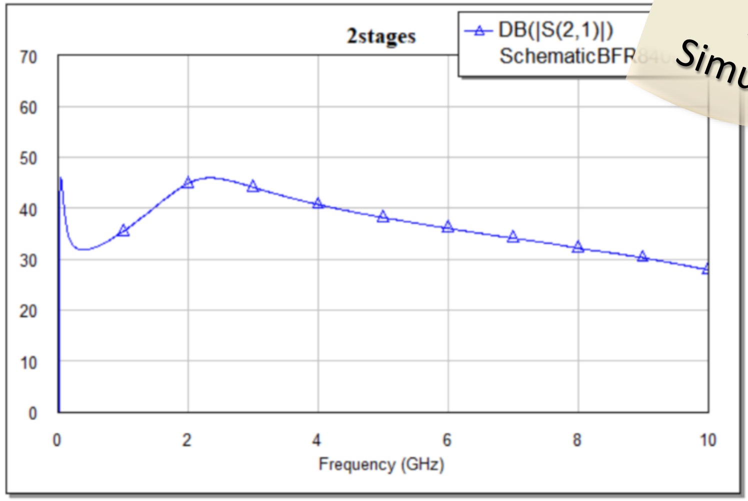
- ❖ High frequency multichannel versatile board
- ❖ Mezzanine design for fast sensor interchangeability
- ❖ Suitable for matrices (AC-LGAD applications) but also for single pad devices

- ➢ High Frequency SiGe discreate electronics @ 12 GHz bandwidth
- ➢ 2 Stage configuration with a transimpedance followed by a voltage stage
- ➢ Low max current (~10mA) with well behaved gain linearity vs V_{DD}
- ➢ Ruggers 3000 High Frequency substrate
- ➢ Pre-assembled miniaturized coaxial edge connectors with panel-mounted SMA plugs (1m cable length)
- ➢ 140 x140 mm outer dimensions



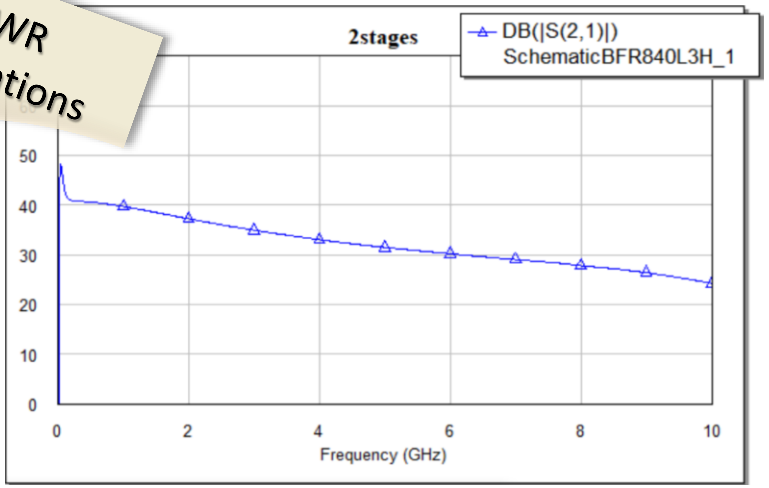
•Simulations and performance

Initial design



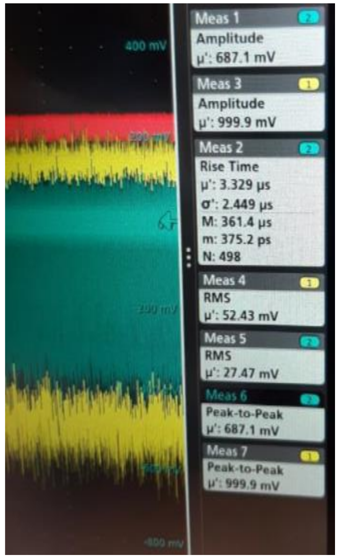
AWR Simulations

Modified –Uniform design

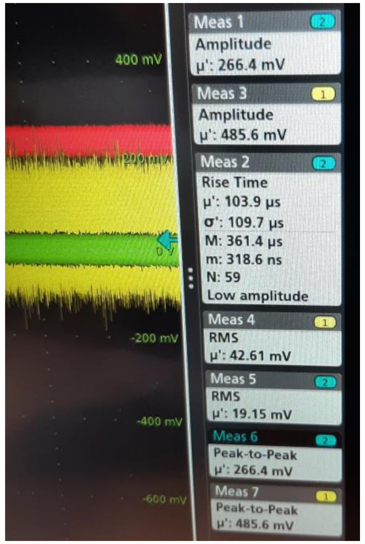


- ➢ Optimized design for uniform response with frequency
- ➢ No sharp gain change discontinuities
- ➢ No undershoot/overshoot observed
- ➢ Gain moderated to ~70 for a two-stage configuration
- ➢ 20% Higher SNR than UCSC board (with both stages)
- ➢ 2 x SNR with respect to UCSC board + niniCircuits second stage amplifier
- ➢ On going energy and transimpedance simulation

With signal injection

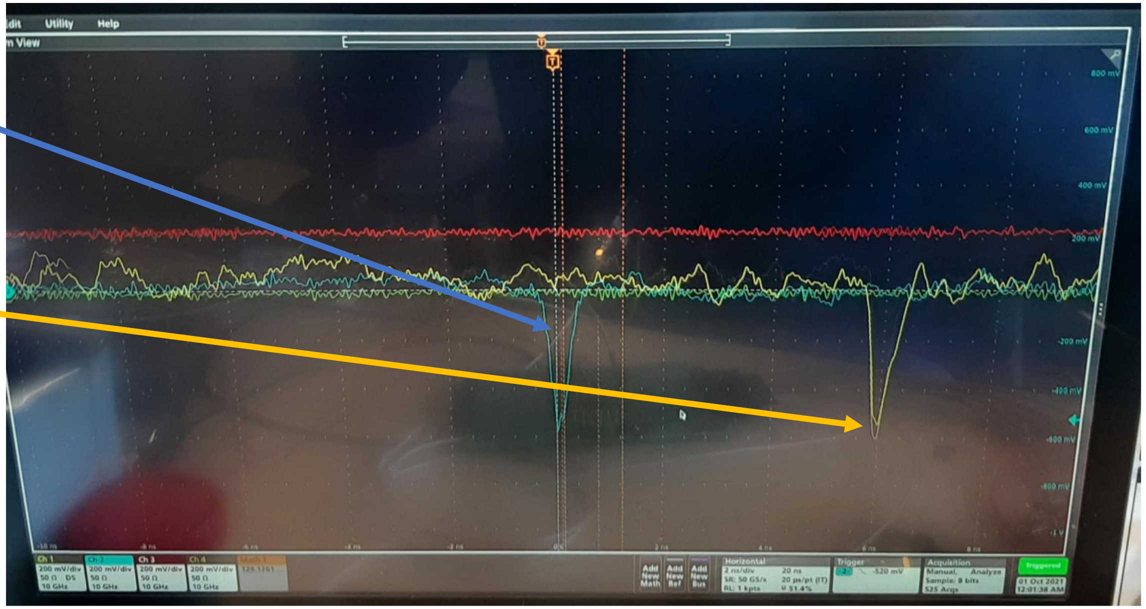


Without signal injection



Blue: 16 channel board

Yellow: UCSC board (only one stage)



•Towards the Future: Sampic

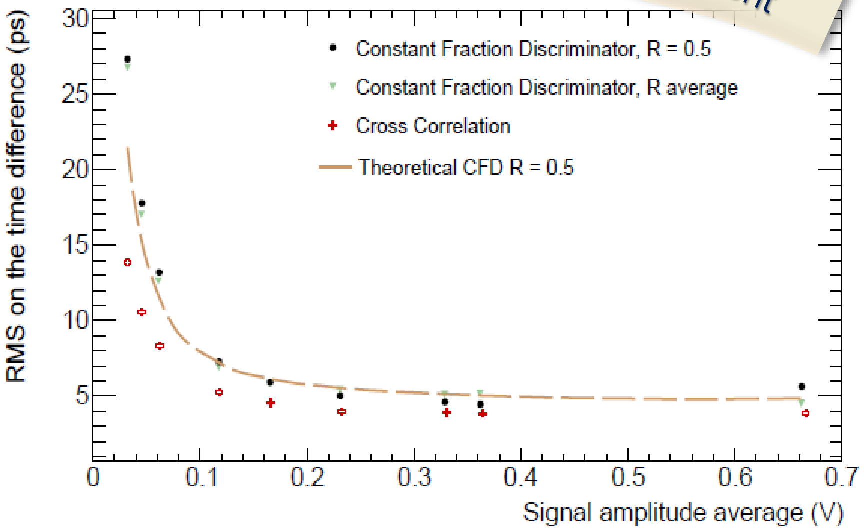
The ASIC (SAMPIC)

- Technology: AMS 0.18µm
- Sampling: between 3 and 8.4 GS/sec on 16 channels (depends on DAC setting)
- 16 channels per chip
- Signal Bandwidth of 1.6GHz
- Discrimination noise 2 mV, chip noise < 1.3 mV RMS
- Max input Signal: 1V unipolar (0.1V to 1.1V)

No minimum ToT Requirement

ADC

- 8 to 11 bit Wilkinson ADC at 1.3GHz
- Upon triggering 64 samples digitalized in parallel per channel
- Resolution adjustment possible to improve timing by reducing bit count
- Time resolution between 5 ps (calibrated) and 15ps (uncalibrated)



Calibration

- Calibration files provided for all operational points of the ADC
- Channel by channel calibration to be performed by user
- 64 channels x 4 operation points = 256 calibration runs

Connectivity

- USB2.0 + LabWindows based software (provided)
- UDP Based Ethernet, direct PC connection – no router support

•Conclusions

3D Pixels - Planar measurement campaign

- Several productions under investigation of different pixel size and thickness
- ***Estimate filed non-uniformity impact on time resolution vs pixel size***
- ***Determine minimal acceptable thickness for time resolution applications (SNR)***
- ***Investigate effects after irradiation up to 1e17 n_{eq}/cm^2 in protons and neutrons***

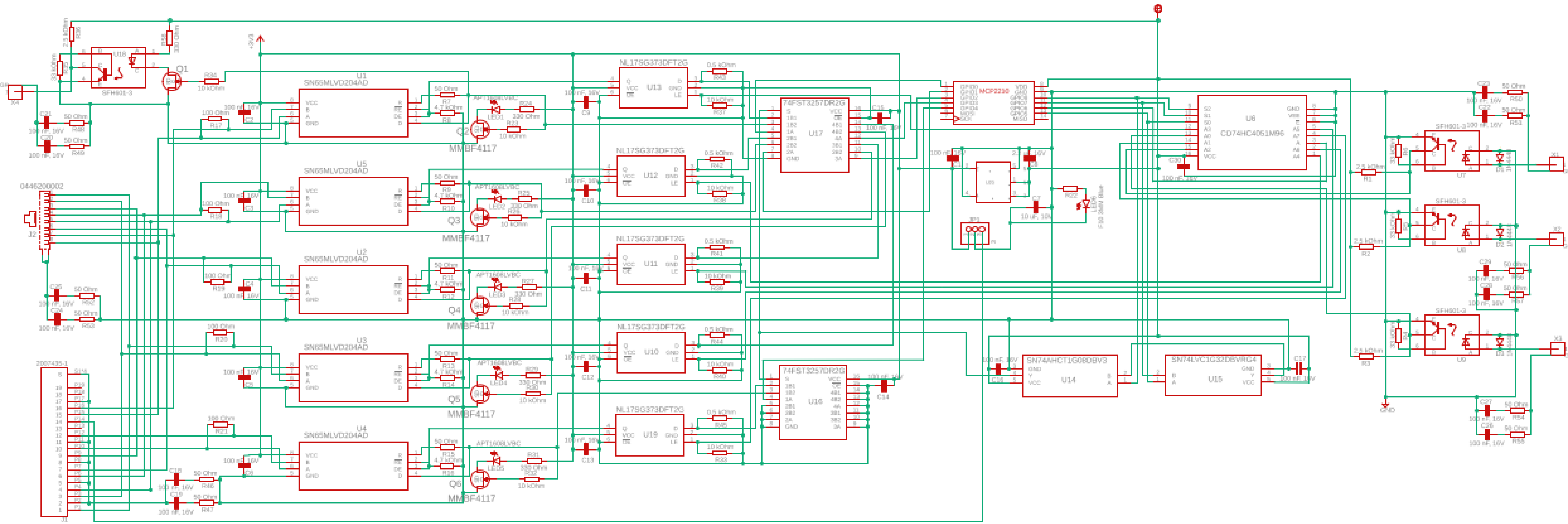
} **Primary Goals**

Test-Beam Setup

- ***Trigger Interface board:*** Versatile, allows interfacing any acquisition instrument with EUDET
- ***Control Software:*** Polymorphic UI with seemingless multi-instrument support
- ***Cooling:*** XPS cold box with web interface temperature controllable system @ -18^{o}C
- ***Mechanics:*** Micrometric alignment with individual DUT stages
- ***Analysis Framework:*** Advanced framework with signal shapes, iterative re-fitting and shape-based noise rejection

•Backup

•TIB Schematics



•Event by Event Strategy

File: WaveForm.cxx

- A four sequential step analysis approach
- Analysis escalates in a pyramid structure

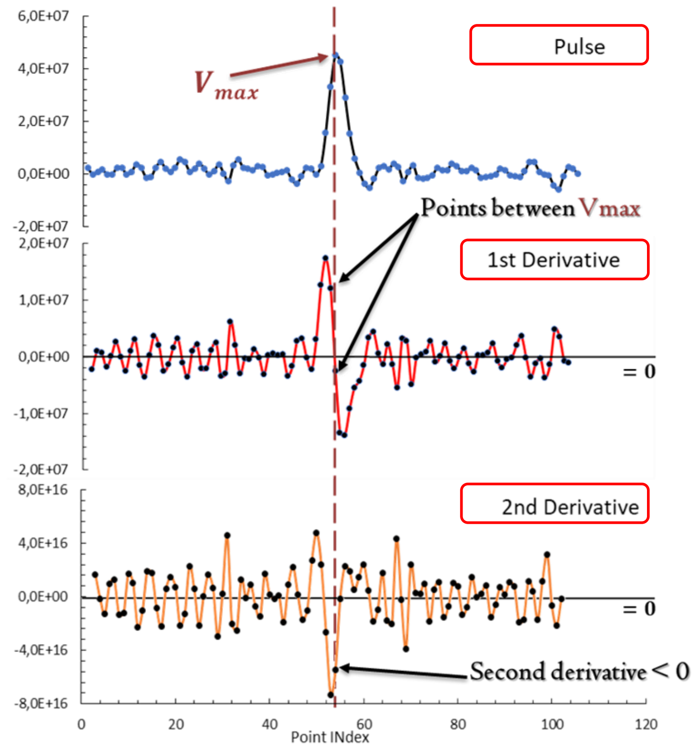
Five preliminary sequential steps before we even start looking at the waveform

Step 1: Set Waveform values → Determine polarity → Find max, min point → Find start, stop point → Determine if noise → Determine if pulse within window

Step 2: Define noise points → Use Gaussian fit for noise/Pedestal → Pedestal subtraction/ inversion → Recalculate start, stop points, min, max

Step 3: Compute charge → Determine rise time → Determine CFD Time → Compute dV/dT → Determine Trigger Time → Estimate Trigger & CFD ToT

Step 4: Perform CFD time to voltage Correction (Time Walk) → Signal FFT → Noise FFT



IsNoise Algorithm

- If $SD_{maxima} > SD_{minima}$
  $D_m(max) > D_m(min)$
  or $SD_{maxima} < 1.05 * SD_{minima}$
  $D_m(max) > D_m(min)$

Positive polarity

Number of points with $0.8 \cdot V_{max}$

- If $N_{points} > 2$ test 0.7 , 0.6 & $0.5 \cdot V_{max}$ to account for wavy waveforms
- If $N_{points} > 2$ then require $dN_{points} < 8/12/16/20$

•Fits infrastructure

Available fitting options

File:
LGADFits.cxx

➢ Root multi-iterative automatic fitting for:

I. Gauss **II. Gauss X Landau**

```
int IterativeFit (std::vector<double> *w, std::pair<double, double> &gmean, std::pair<double, double> &gsigma,
                  TH1D* &FitHist, double &minchi2, std::string methode = "Gauss", std::pair<int, int> points =
                  std::make_pair(-1, -1))
```

➢ Unpinned 2-dimentional Linear fitting through RooFit and Minuit:

```
int LinearFit (std::vector<double>* vec, std::pair<double, double> &slope, std::pair<double, double> &intersept,
               std::vector<double>* vecErr = NULL);
```

➢ Roofit Convolution fitting (no iterative readjustment) for:

I. Gauss X Landau **II. Gauss X Linear**

```
int RooConvFit (std::vector<double>* vec, std::pair<double, double> &magMPV, std::pair<double, double>
               &magSigma, std::string conv);
```

➢ Tow point linear interpolation:

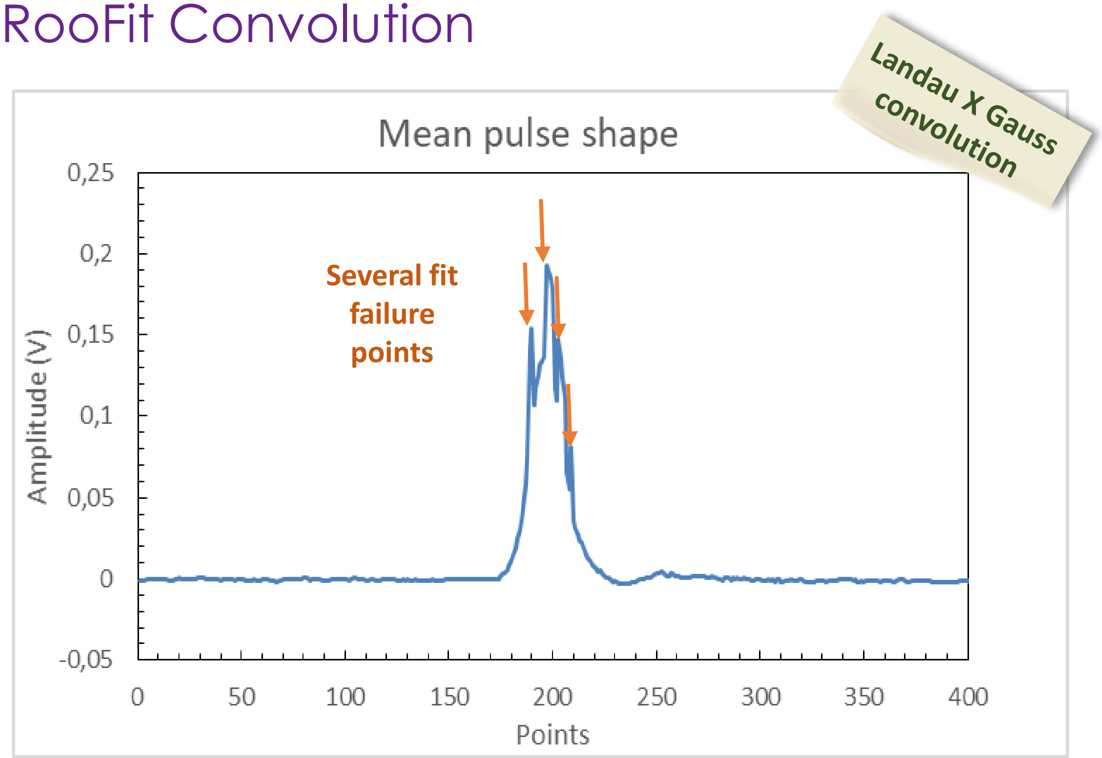
```
double LinearInter(double x1, double y1, double x2, double y2, double y3);
```

➢ Fast Furrier transform algorithm: `double FFT(std::vector<double> *w, Long64_t snrate, int start, int stop);`

•Average pulse shape (RooFit)

Starting point, Non-optimized RooFit Convolution

I. Average calculated from 100 events
II. Each waveform is time aligned at 20% CFD
III. For all events, the same point of each waveform projected in TH1F
   - ✓ as many THIF as points in waveform
   - ✓ each with as many entries as events (100 here)
IV. Each TH1F fitted with a Landau X Gauss distribution
V. MPV, sigma and uncertainty extracted
VI. Fitting performed in RooFit using RooFit Convolution and Minuit
VII. No starting parameters or optimization
VIII. Plot the MPVs of each point in a single waveform



•Average pulse shape (RooFit)

Initial RooFit Optimization

I. Fit Binning:
   - ✓ Symmetric fit limits: $x_{av.} \pm (5 \times \sigma)$
   - ✓ Bin width defined as: $\sigma / 3$
   - ✓ High statistics re-optimization, increase no. of bins if: $N_{points} > 1.5 \times N_{bins}$

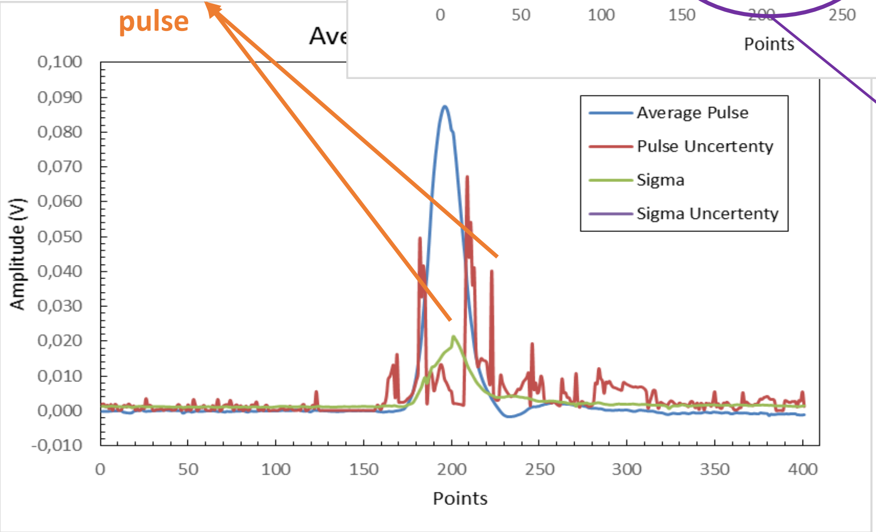
II. Parameter constraints:
   - ✓ Asymmetric limits for Landau MVP: $-4 \times |x_{RMS}| < x_{fit} < 2 \times |x_{RMS}|$
   - ✓ Asymmetric limits for Landau sigma: $-0.001 \times \sigma < \sigma_{fit} < 2 \times \sigma$
   - ✓ Symmetric limits for Gauss mean: $-2 \times \sigma < \sigma_{fit} < 2 \times \sigma$

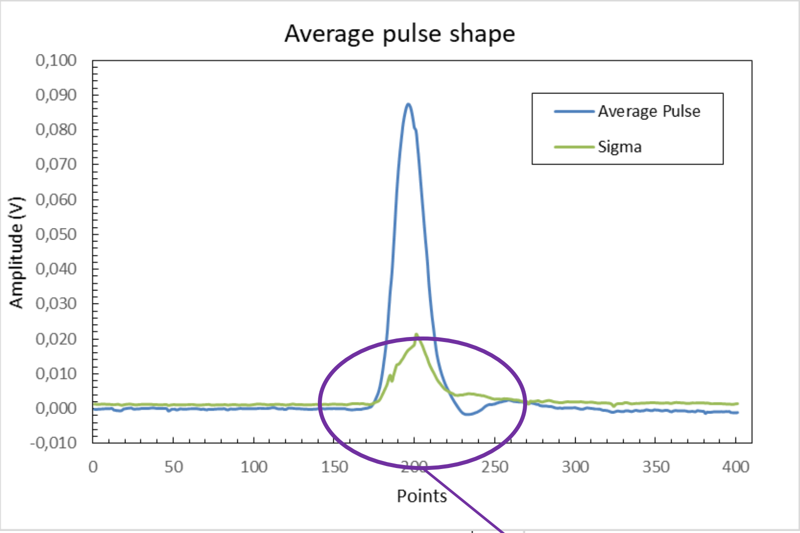
III. Parameter Initial values:
   - ✓ Landau **MPV** = x_{RMS}
   - ✓ Gauss **sigma = 0**

IV. No re-iteration implementation

Smooth pulse shape

High uncertainties at the beginning and end of pulse



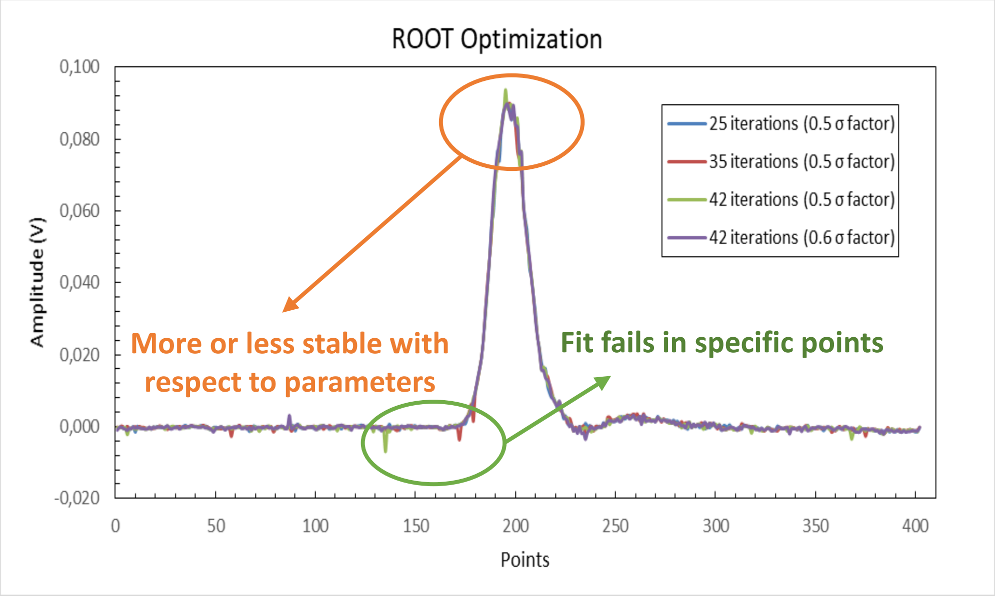


Reasonable sigma with respect to MPV, no outliers

•Average pulse shape (Root)

Root Optimization (no RooFit)

- Constraint parameter values but not fixed
- Manually defined convolution function
- 1000 convolution steps
- Select the fit with the best agreement (minimization of **$|1-x^2/NDF|$**)



I. Iterative approach

II. Fit Binning:

✓ Asymmetric fit limits:

lower: $\mathbf{x_{min} - ((n\text{-}5)/10) \times \sigma}$

upper: $\mathbf{x_{max} - ((n\text{-}5)/2) \times \sigma}$

where $7 < n < 2$ → **6 cases**

✓ Bin number defined at least as:

$\mathbf{N_{bins} = \sqrt{N_{events}}}$

augmented by:

$\mathbf{(x_{max} - x_{min})/(0.5 \times \sigma \times \alpha/4)}$

where $14 < \alpha < 7$ → **7 cases**

X

42 total iterations

III. Parameter constraints:

✓ Asymmetric limits for Landau MVP:

$\mathbf{x_{RMS} - 3\times\sigma < x_{RMS} < x_{RMS} + 3\times\sigma}$

✓ Function integral limits set to:

$\mathbf{0.1\times Int. < X < 10\times Int.}$

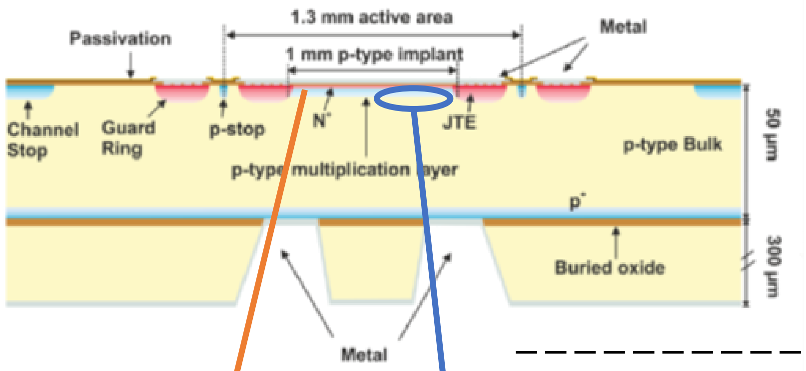
IV. Initial values:

✓ Landau **MPV** = $\mathbf{x_{RMS}}$

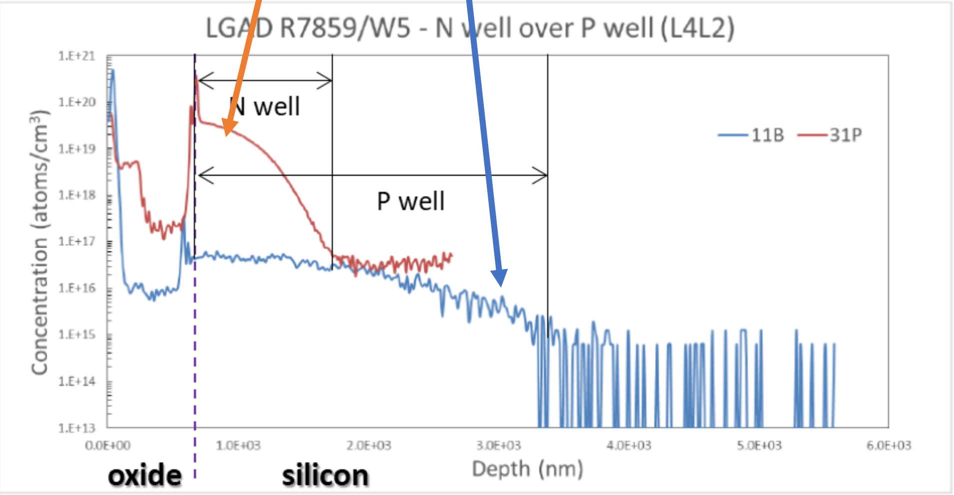
✓ Convolution **Integral = distribution integral**

✓ Convoluted sigma set to : **σ / 4**

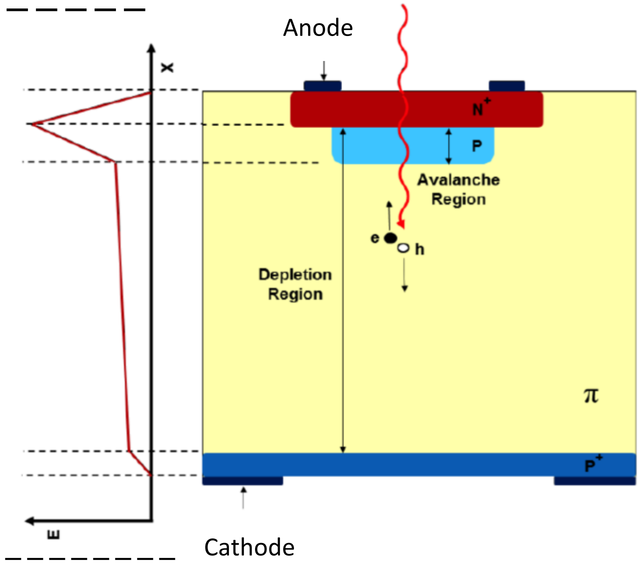
•LGAD Time Reference

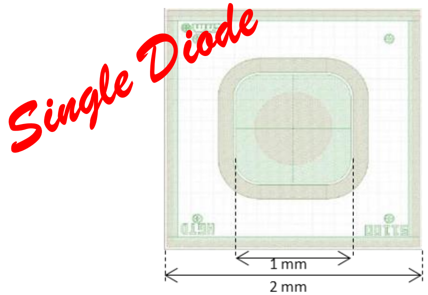


- ✓ Invented at CNM, initially considered for tracking by IFAE, proposed for timing by UCSC
- ✓ Secondary p implant under collection electrode introducing moderate gain (10 -50)
- ✓ Up to 35 µm thickness on SoI or wafer to wafer bonding (typically 50 µm)
- ✓ HPK, CNM, FBK, MiCRON, BNL (USA), NDL (China)



- ✓ Requires precise diffusion control for layer thickness:
  - ✓ Thin highly doped n-well layer (~ 1 – 1.5 µm)
  - ✓ Gain layer ~ 2 µm
  - ✓ p-stop ~3 -3.5 µm
- ✓ Different gain layer species possible:
  - ✓ Boron (standard)
  - ✓ Gallium
  - ✓ Boron +Carbon





- ➢ 4” Si-on-Si wafers (High Resistivity ~2 kΩ•cm)
- ➢ 50 µm thickness on 250 µm support wafer
- ➢ Different implantation species
- ➢ Single diodes of active area 0.7 x 0.7 mm

Standard Boron
Boron + Carbon Spray (not confined)
Gallium