EP-R&D Silicon Working Group 1.1

Hybrid Detectors

Sensor Characterization: from process to timing

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CERN EP-R&D

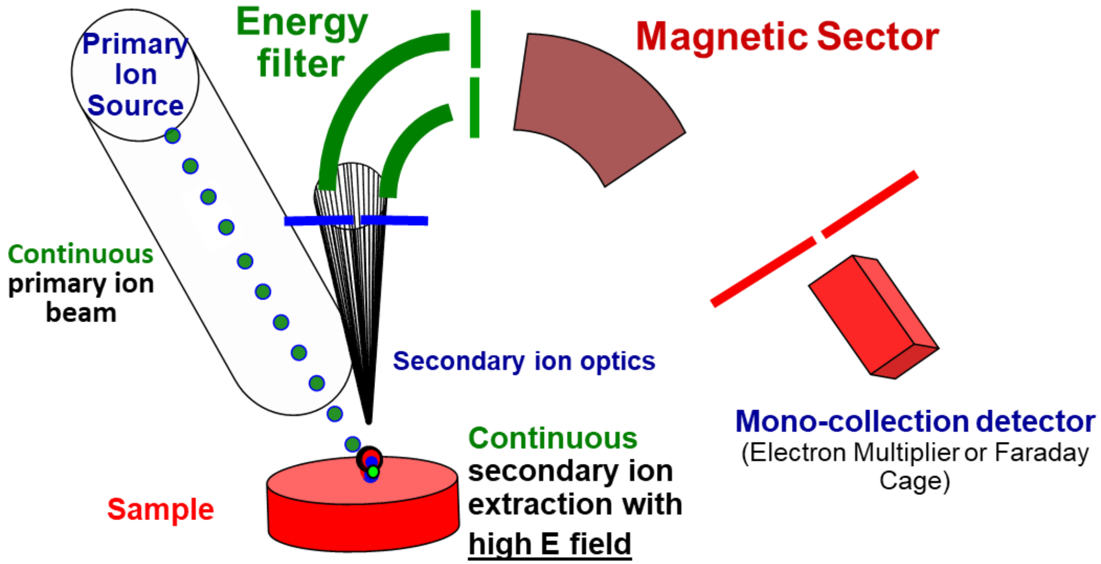
Geneve – June 20th, 2022

•Process Characterization

Secondary Ion Mass Spectroscopy

Why ?

- Accurately study gain layer to correctly reproduce impact ionization in TCAD simulations
- Understand radiation damage and acceptor removal vs gain layer geometry
- Test Carbon concentration and its relation to radiation damage improvement
- Evaluate process flow in case of issues and establish failure point (see Jakob's presentation about ADVACM planar)



Primary Ion Source

Energy filter

Magnetic Sector

Continuous primary ion beam

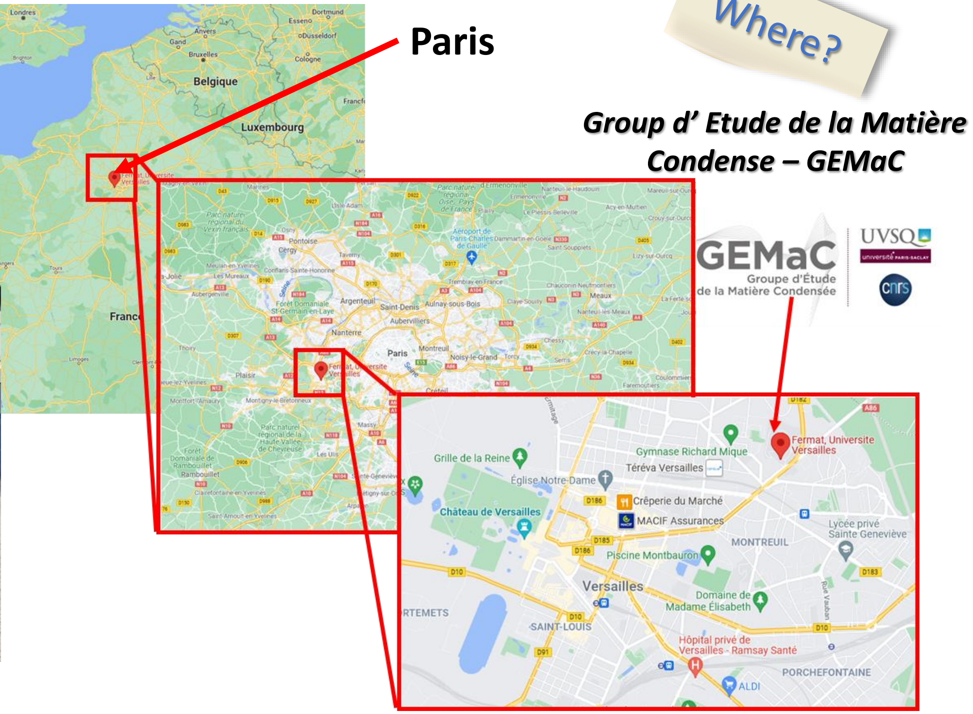
Secondary ion optics

Mono-collection detector
(Electron Multiplier or Faraday Cage)

Continuous secondary ion extraction with <u>high E field</u>

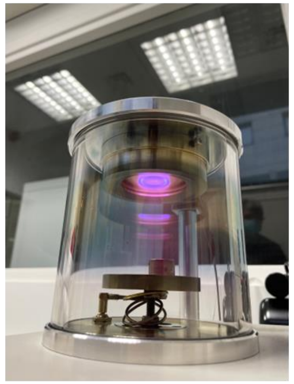
Sample

Where?



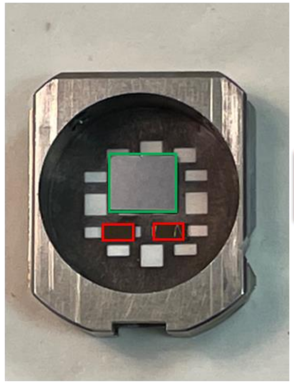
Group d' Etude de la Matière Condense – GEMaC

Step 1: Metallization



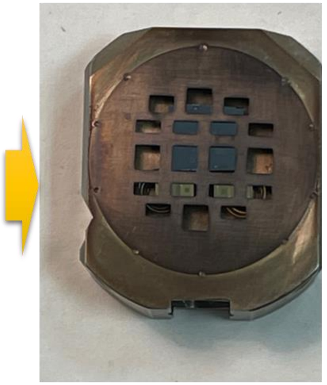
PECVD deposition of 50nm Au on sample surface using Ar plasma

Step 2: Mounting



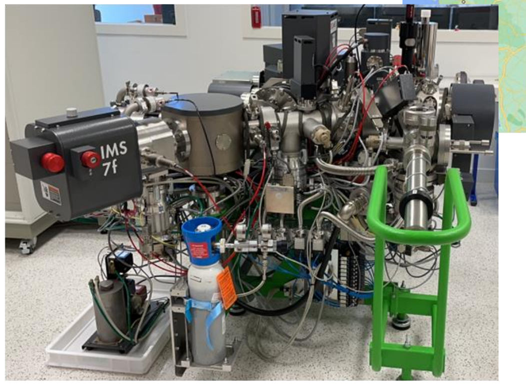
Placement in holder with appropriate calibration sample

Step 3: Fixing-Tensioning



Vertical mounting via spring loaded pressure plate and inspection of planarity

Step 4: Measurements



Introduction to machine secondary vacuum 4.7×10^{-8} mbar introduction vacuum, 6.3×10^{-10} mbar primary vacuum, O_2 or **Cs** ions

•Process Characterization

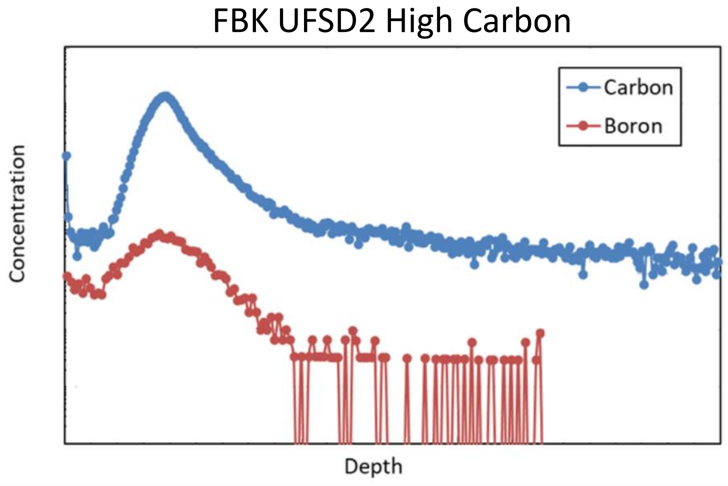
Carbonated LGAD Profiles

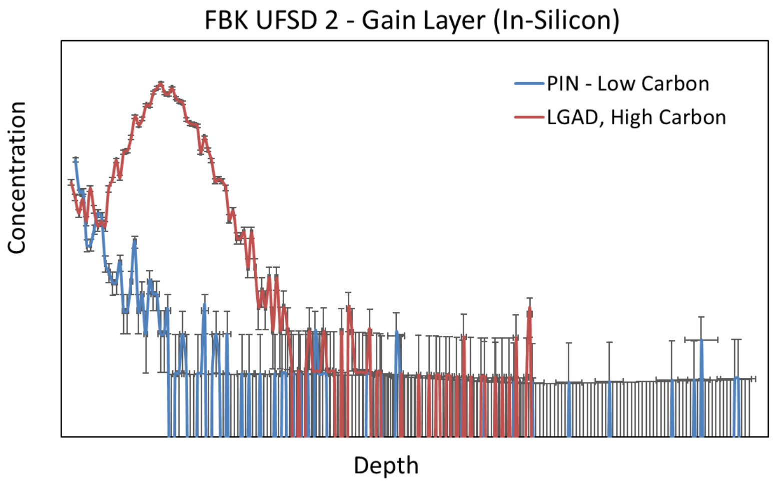
Presentation: V. Gkougkousis, “Detailed process characterization of carbonated LGADs through Secondary Ion Mass Spectroscopy”, 17th Trento workshop on advanced silicon radiation detectors (link)

Carbon Content

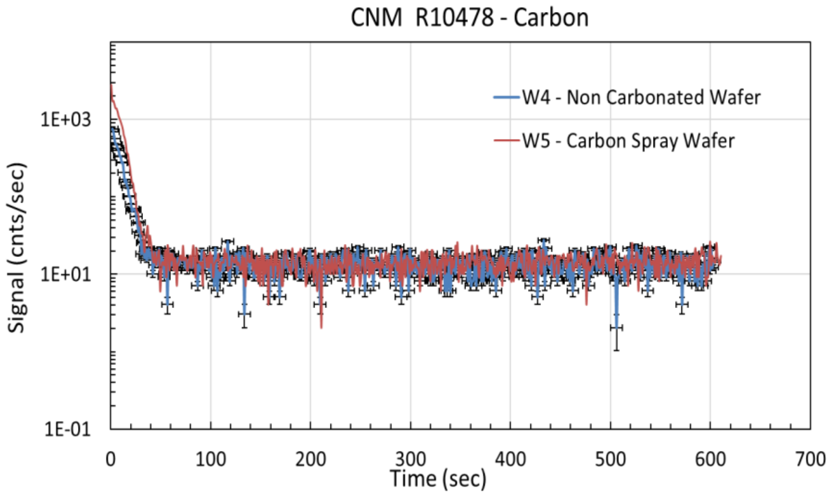
Gain Layer

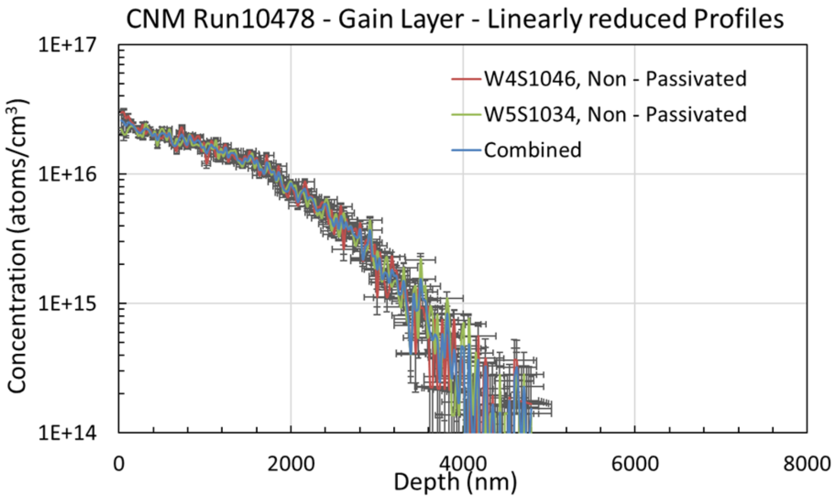
FBK


FBK UFSD2 High Carbon


FBK UFSD 2 - Gain Layer (In-Silicon)

CNM


CNM R10478 - Carbon

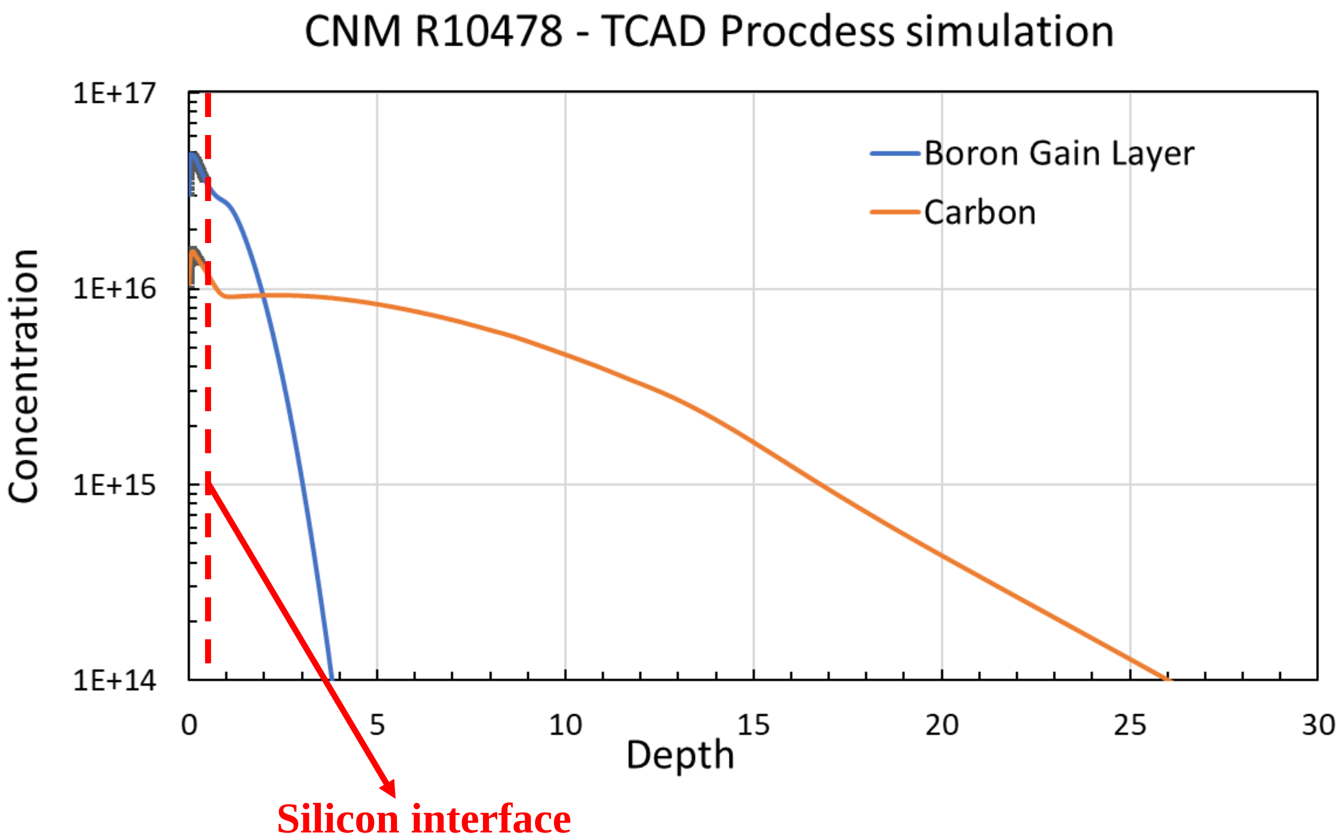

CNM Run10478 - Gain Layer - Linearly reduced Profiles

- ✓ No Carbon detected to the level of > 4×10^{16} atoms/cm^3 for the CNM samples
- ✓ CNM Carbonated vs. Non-carbonated samples at the same background level concerning carbon signals
- ✓ FBK Carbon peak in agreement with gain layer peak as expected though their process
- ✓ Carbon tails at higher end due to measurements and crater edge effects
- ✓ Highly accurate detection limits of 4×10^{16} atoms/cm^3 for carbon and 1.3×10^{14} atoms/cm^3 for Boron with 5 nm layer precision

•Process Characterization

Carbon Simulation – Boron Deactivation

- ✓ Complete TCAD Simulation of the total thermal budget and implantation step for boron and Carbon
- ✓ Results for Boron in agreement with SiMS measurements in both depth and dose
- ✓ Carbon Profile deep diffused with average concentrations at the limit of detection

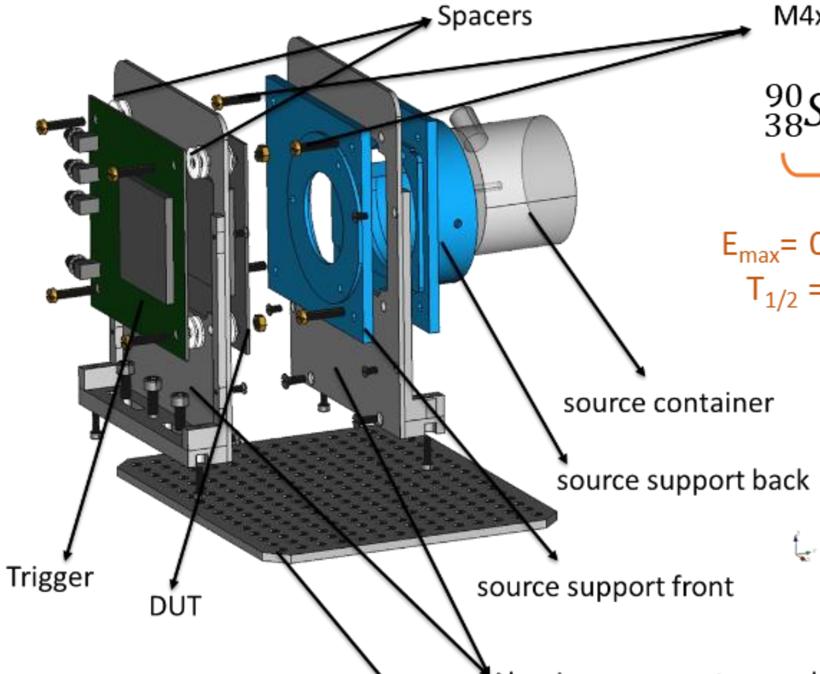


Simulation Parameters

- **Cz High Resistivity Si substrate**
  - <100> orientation (dicing, radiation hardness)
  - Resistivity >4 kΩhm*cm
  - P concentration of 10^{12} atoms/cm^3
  - Active thickness 50 μm
- **Native oxide: 1.9 nm**
- **Screen Oxide: 50 nm (deposited)**
- **MC implantation:**
  - ✓ 3000 tracks
  - ✓ Max track splits 6, splints per element 3
  - ✓ CristalTRIM algorithm
  - ✓ Clock seed randomization
  - ✓ Optimization error: ± 10^{14} atoms/cm^3
  - ✓ Full cascade BCA damage (binary collision approx.,)
- **Diffusion (Transport) Mode: Dopant dependent**
  - Boron → Charged Pair
  - Phosphorus → Charged Pair
  - Carbon → Neutral React
- **Activation Models (See next slide)**
- **Synopsys info**
  - ✓ Version 2019.12 with Advanced Calibration
  - ✓ MGOALS meshing algorithm

•Laboratory Measurements

β Source Characterization



$$\underbrace{{}^{90}_{38}Sr \rightarrow e^-}\; \underbrace{{}^{90}_{39}Y \rightarrow e^-}\; {}^{90}_{40}Zr$$

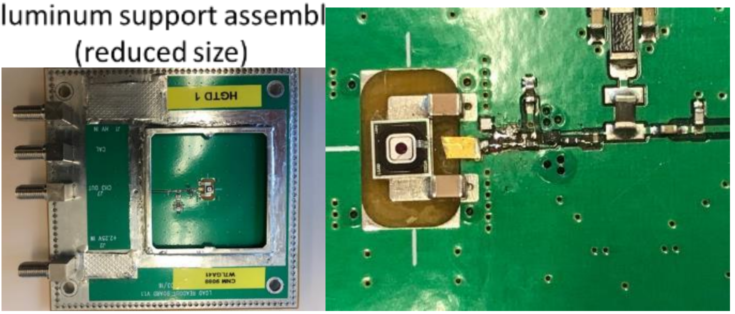
E_{max}= 0.46 MeV
$T_{1/2}$ = 28,8 y

E_{max}= 2.28 MeV
$T_{1/2}$ = 64 h

90 µm Al absorber
+ 500 µm Si

Minimum charge for good timing

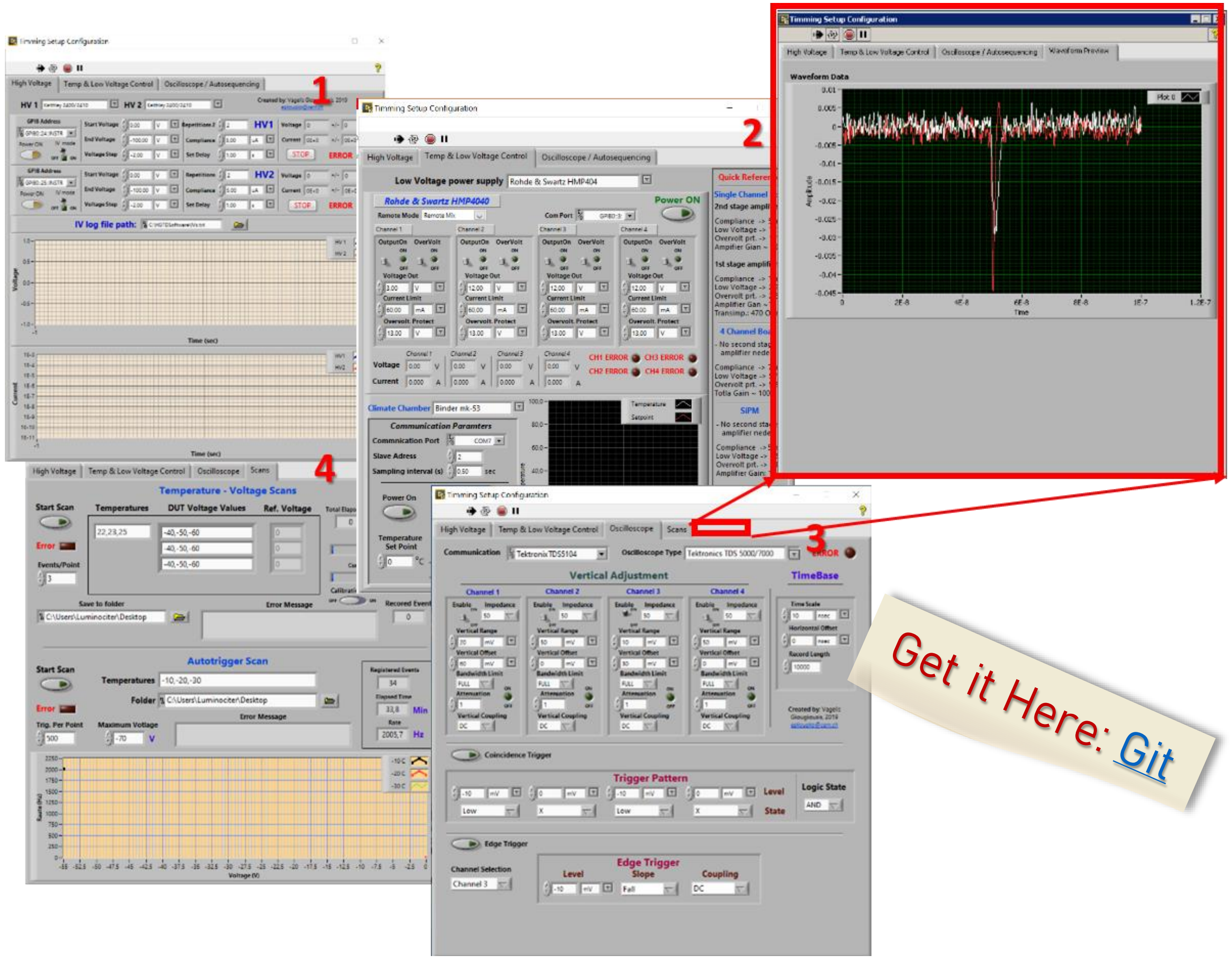
5 σ from noise



- High frequency SiGe (~2GHz) amplifier
- Mean sensor + amplifier noise < 1.5 mV
- 5000 recorded events per point

Timing Configuration & Automation Software (TiCAS)

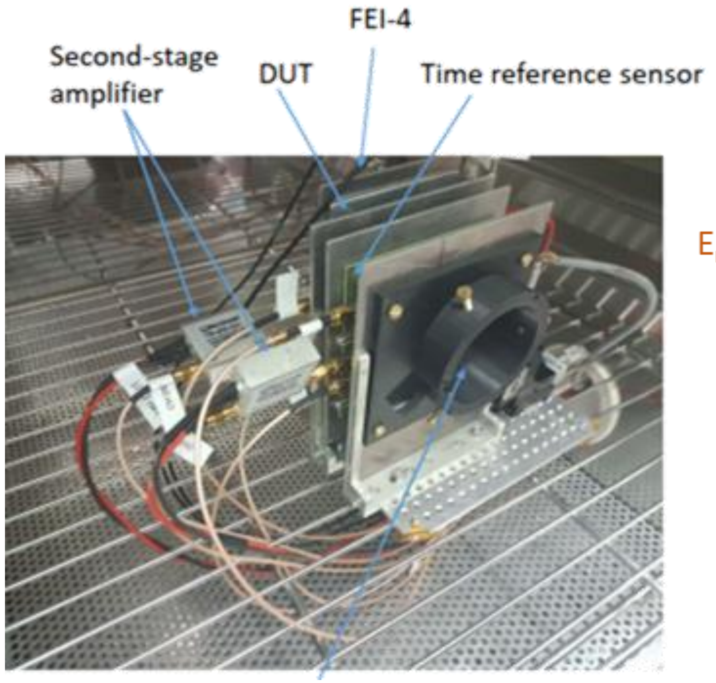
- ➢ Real-time Waveform Visualization
- ➢ Dynamic adaptable UI with universal instrument support
- ➢ Support for all LeCroy, Tektronix and Agilent oscilloscopes



Get it Here: Git

•Laboratory Measurements

β Source Characterization



$$\underbrace{^{90}_{38}Sr \rightarrow e^-}_{E_{max}=0.46\text{ MeV},\; T_{1/2}=28{,}8\text{ y}} \; \underbrace{^{90}_{39}Y \rightarrow e^-}_{E_{max}=2.28\text{ MeV},\; T_{1/2}=64\text{ h}} \; ^{90}_{40}Zr$$

90 μm Al absorber
+ 500 μm Si

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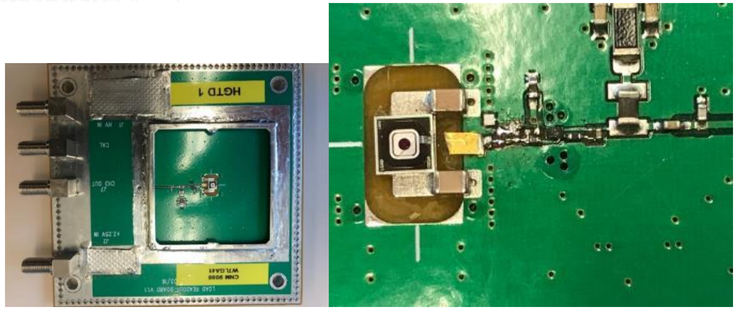

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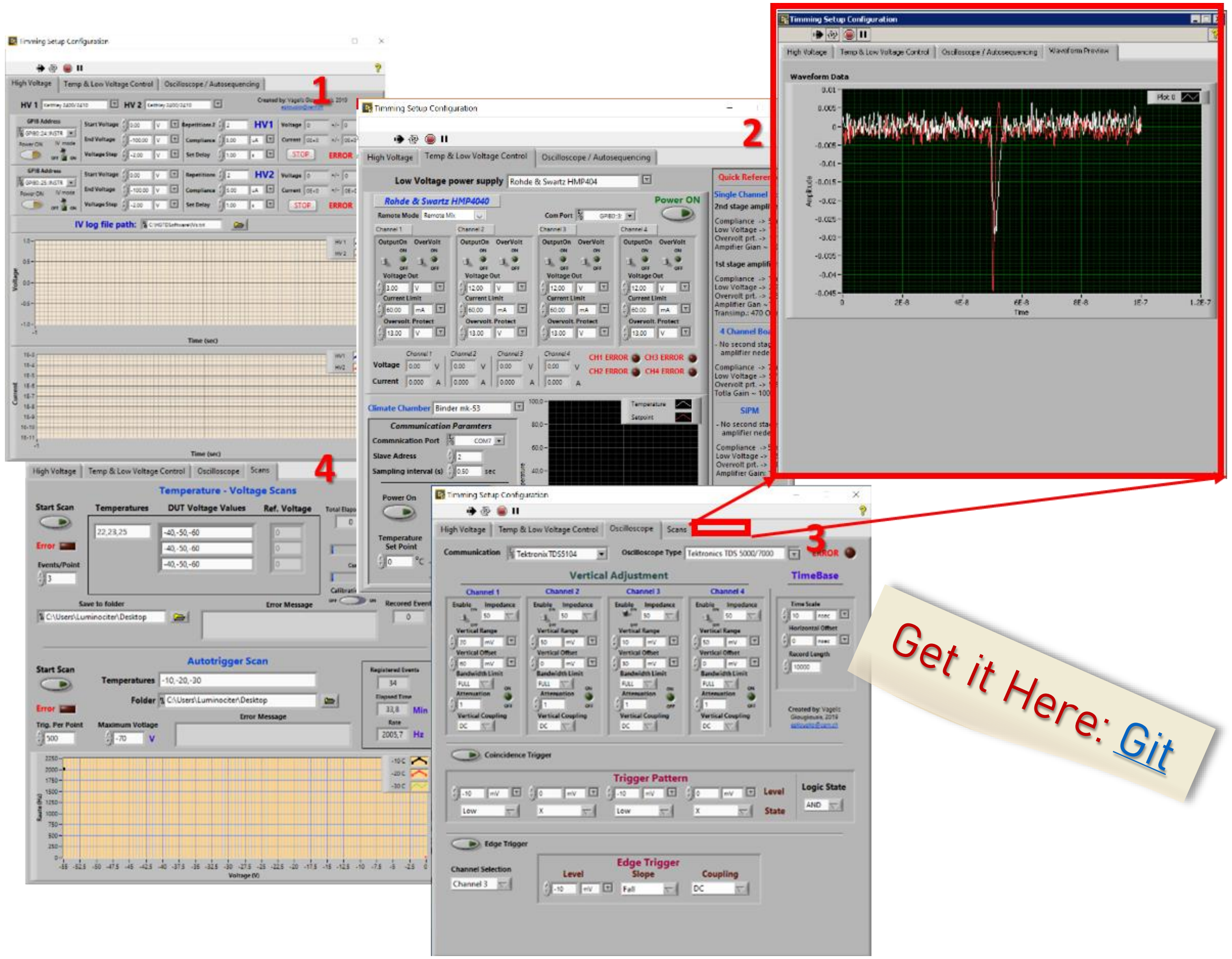


Get it Here: Git

•3D Sensors

Timing at Extreme Fluences

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

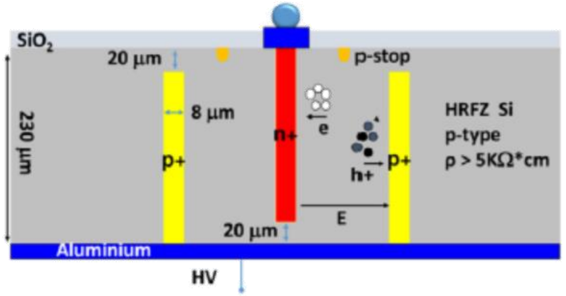
Pros

- 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

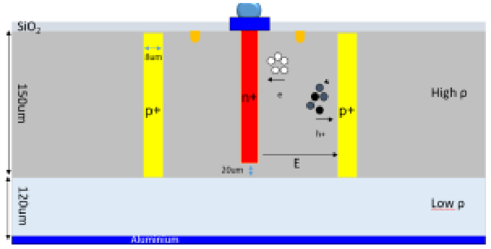
Cons

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

Double Sided
(thicker, more expensive)

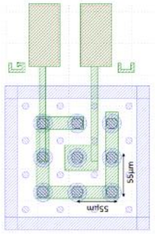


Single Sided
(thinner, simpler process)



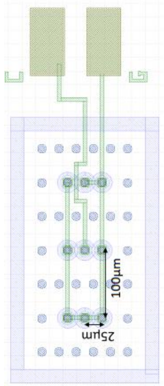
Pixel Size vs Field Uniformity

ATLAS IBL Type

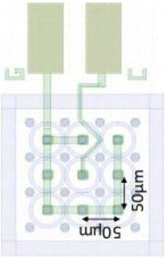


- ✓ Double sided n-on-p process
- ✓ Pixel Size 55 × 55 µm^2
- ✓ Active thickness 230 µm
- ✓ High Resistivity (> 2 kΩm × cm) Fz silicon

ATLeS Pre-Production type



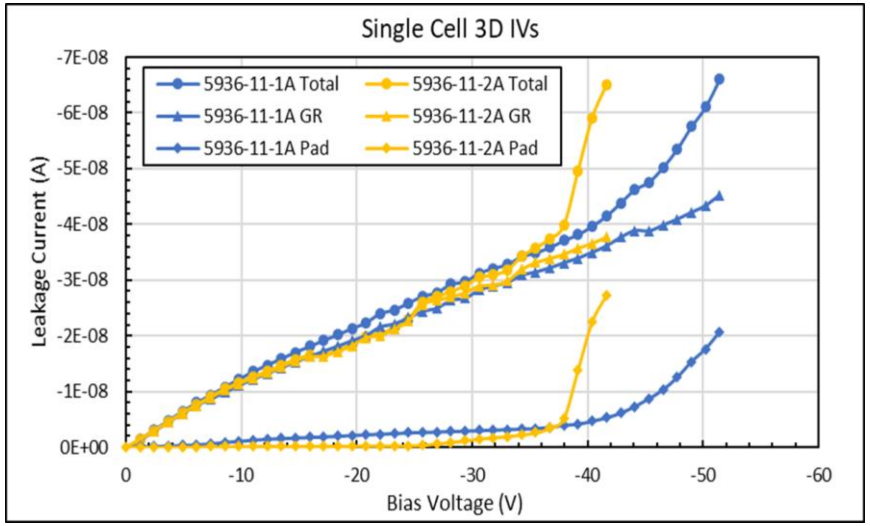
- ✓ Single sided n-on-p process
- ✓ Pixel Size 25 × 100 µm^2
- ✓ Active thickness 150 µm
- ✓ High Resistivity (> 2 kΩm × cm) Fz silicon



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

•Laboratory Characterization

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)



- ➢ Initial results demonstrate a 40 psec time resolution
- ➢ Uniform response across all thresholds

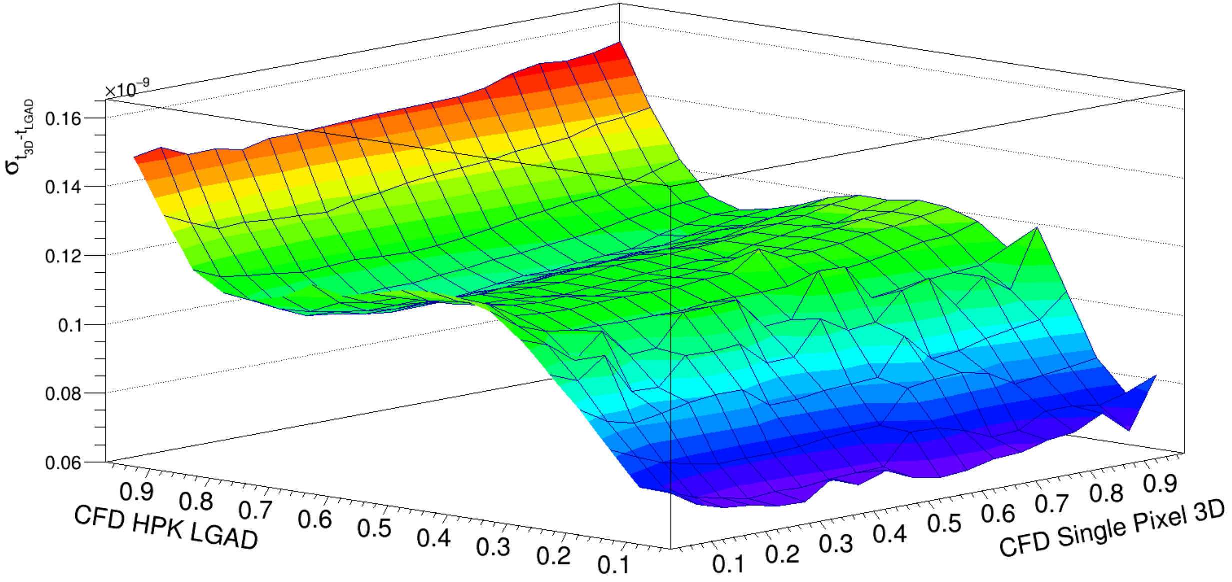
Irradiations

Neutron @ JSI (Ljubljana)
- ✓ 1×10^{15} n_{eq}/cm^2
- ✓ 8×10^{15} n_{eq}/cm^2
- ✓ 6×10^{16} n_{eq}/cm^2
- ✓ 1×10^{17} n_{eq}/cm^2

Proton @ PS
- ✓ 1×10^{15} n_{eq}/cm^2
- ✓ 8×10^{15} n_{eq}/cm^2
- ✓ 6×10^{16} n_{eq}/cm^2
- ✓ 1×10^{17} n_{eq}/cm^2

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

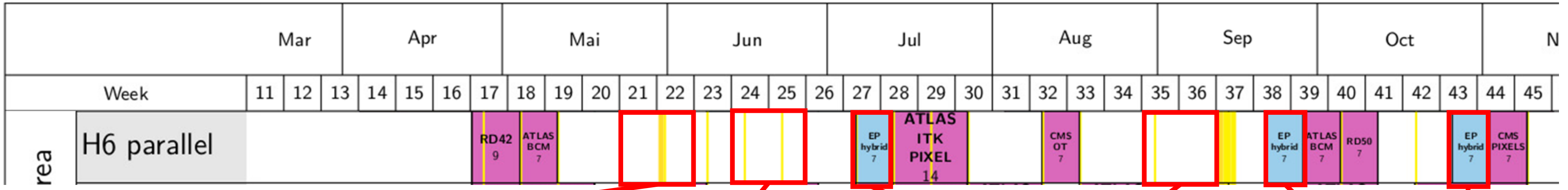
CFD Map, LGAD - Single Pixel 3D (-20°C, 20V)



2D optimization plot – 0.5% binning

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

•Test Beam



Primary user
Parallel user
Parasitic user

25 May – 8 June

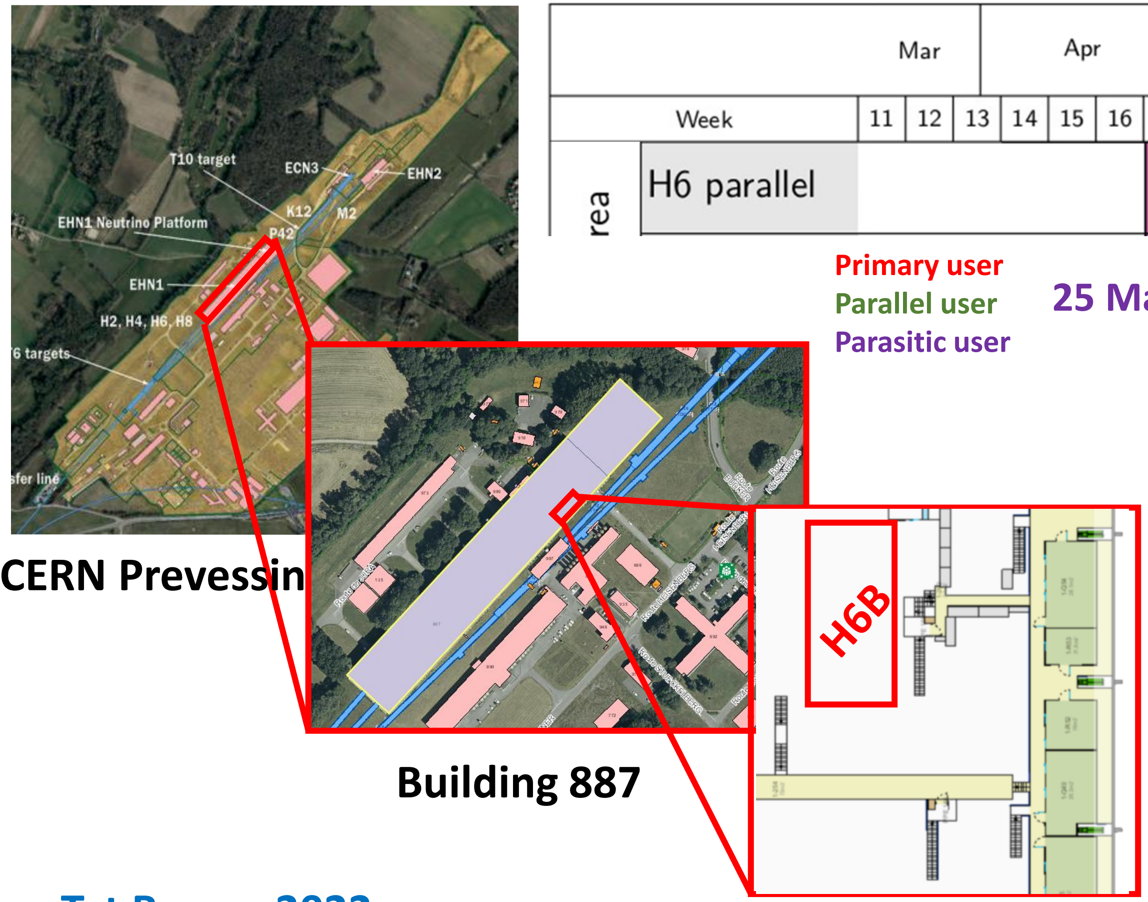
15 – 29 June

6 July – 13 July

31 August - 14 September

20 - 27 September

17 – 24 October

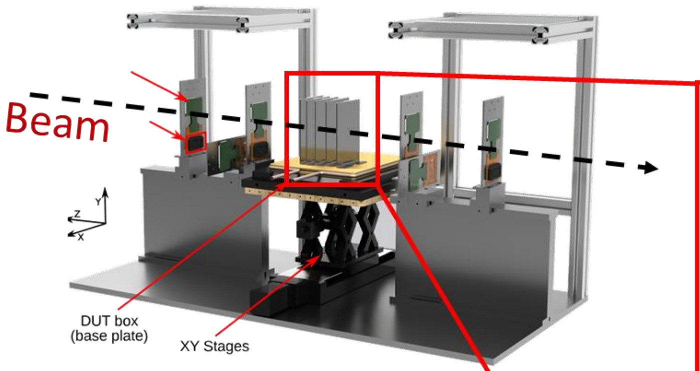


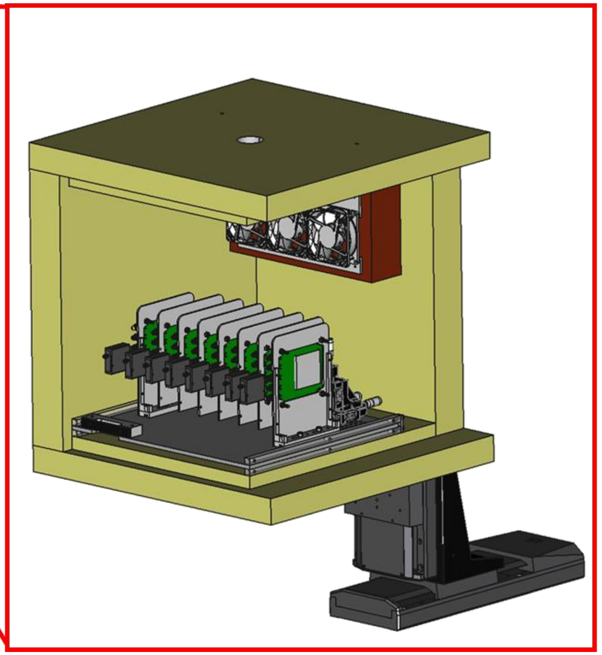
CERN Prevessin

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

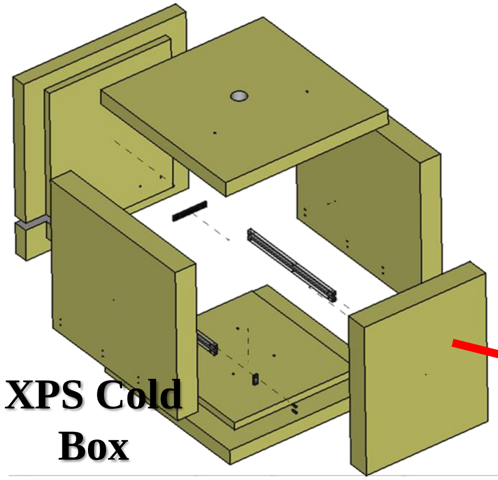




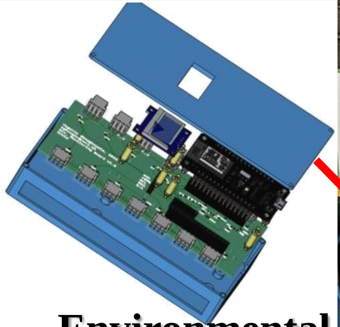
The Setup

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

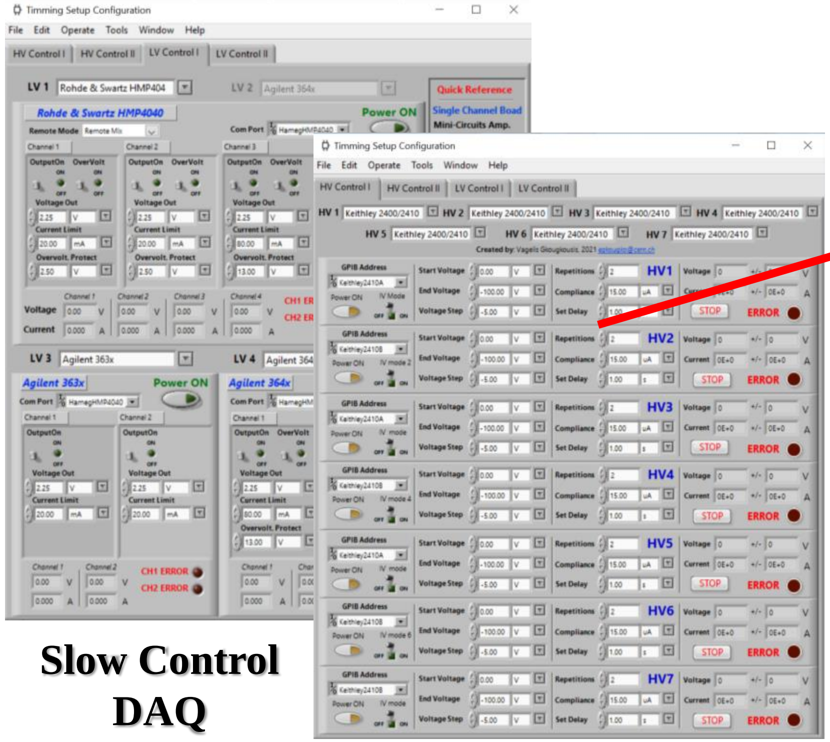
•Test Beam



XPS Cold Box



Environmental Control



LV 1 Rohde & Swartz HMP404 — LV 2 Agilent 364x

Rohde & Swartz HMP4040 — Remote Mode: Remote Mix — Com Port: HamegHMP4040

Channel 1: Voltage Out 2.25 V; Current Limit 20.00 mA; Overvolt. Protect 2.50 V

Channel 2: Voltage Out 2.25 V; Current Limit 20.00 mA; Overvolt. Protect 2.50 V

Channel 3: Voltage Out 2.25 V; Current Limit 80.00 mA; Overvolt. Protect 13.00 V

Voltage: Channel 1 0.00 V, Channel 2 0.00 V, Channel 3 0.00 V, Channel 4 0.00 V

Current: Channel 1 0.000 A, Channel 2 0.000 A, Channel 3 0.000 A, Channel 4 0.000 A

LV 3 Agilent 363x — LV 4 Agilent 364x

Agilent 363x — Com Port: HamegHMP4040

Channel 1: Voltage Out 2.25 V; Current Limit 20.00 mA

Channel 2: Voltage Out 2.25 V; Current Limit 20.00 mA

Agilent 364x — Com Port: HamegHMP4040

Channel 1: Voltage Out 2.25 V; Current Limit 80.00 mA; Overvolt. Protect 13.00 V

HV 1 Keithley 2400/2410 — HV 2 Keithley 2400/2410 — HV 3 Keithley 2400/2410 — HV 4 Keithley 2400/2410

HV 5 Keithley 2400/2410 — HV 6 Keithley 2400/2410 — HV 7 Keithley 2400/2410

Created by: Vagelis Gkougkousis, 2021 egkougko@cern.ch

HV1: GPIB Address Keithley2410A; IV Mode; Start Voltage 0.00 V; End Voltage -100.00 V; Voltage Step -5.00 V; Repetitions 2; Compliance 15.00 uA; Set Delay 1.00 s; Voltage 0 +/- 0 V; Current 0E+0 +/- 0E+0 A

HV2: GPIB Address Keithley2410B; IV mode 2; Start Voltage 0.00 V; End Voltage -100.00 V; Voltage Step -5.00 V; Repetitions 2; Compliance 15.00 uA; Set Delay 1.00 s; Voltage 0 +/- 0 V; Current 0E+0 +/- 0E+0 A

HV3: GPIB Address Keithley2410A; IV mode; Start Voltage 0.00 V; End Voltage -100.00 V; Voltage Step -5.00 V; Repetitions 2; Compliance 15.00 uA; Set Delay 1.00 s; Voltage 0 +/- 0 V; Current 0E+0 +/- 0E+0 A

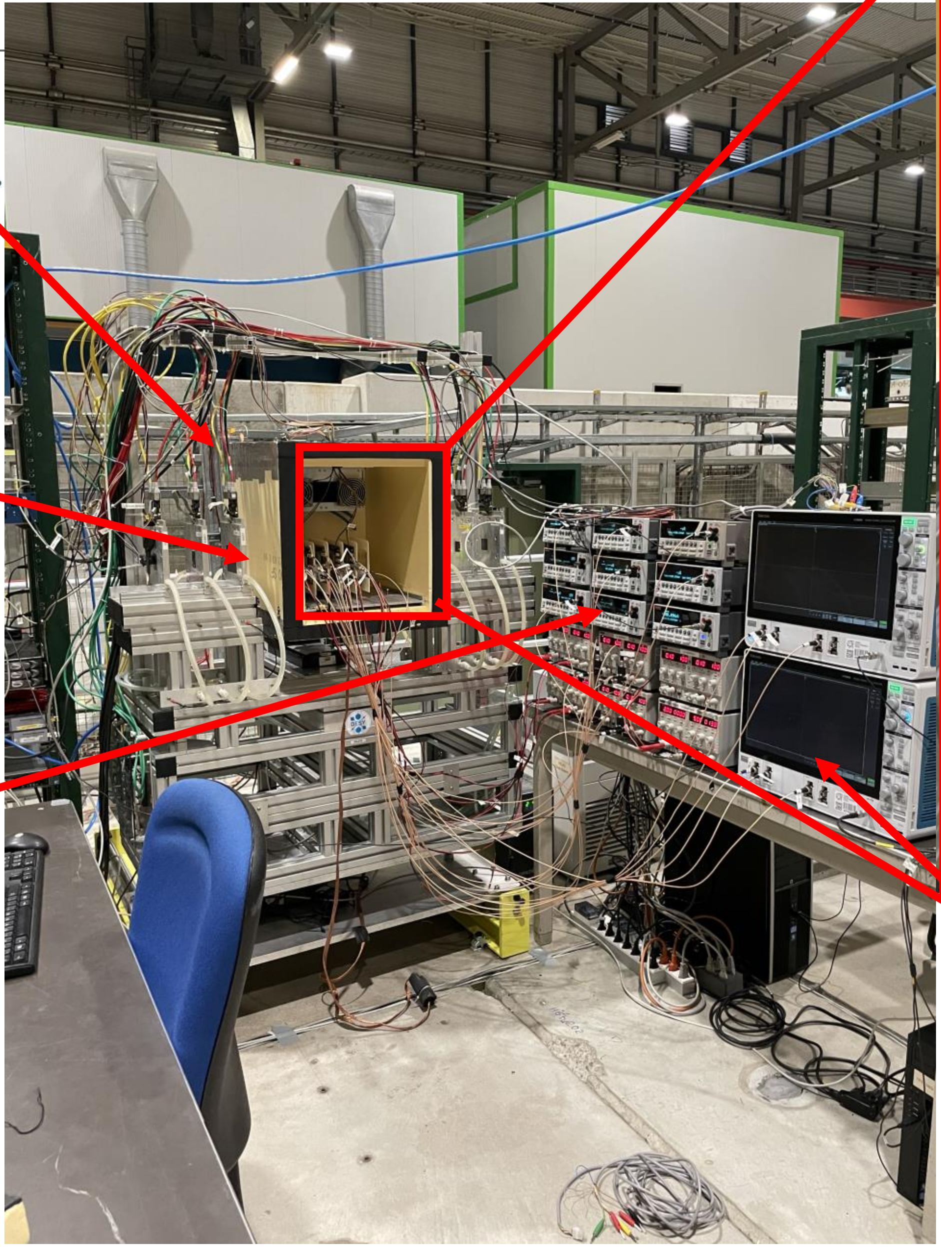
HV4: GPIB Address Keithley2410B; IV mode 4; Start Voltage 0.00 V; End Voltage -100.00 V; Voltage Step -5.00 V; Repetitions 2; Compliance 15.00 uA; Set Delay 1.00 s; Voltage 0 +/- 0 V; Current 0E+0 +/- 0E+0 A

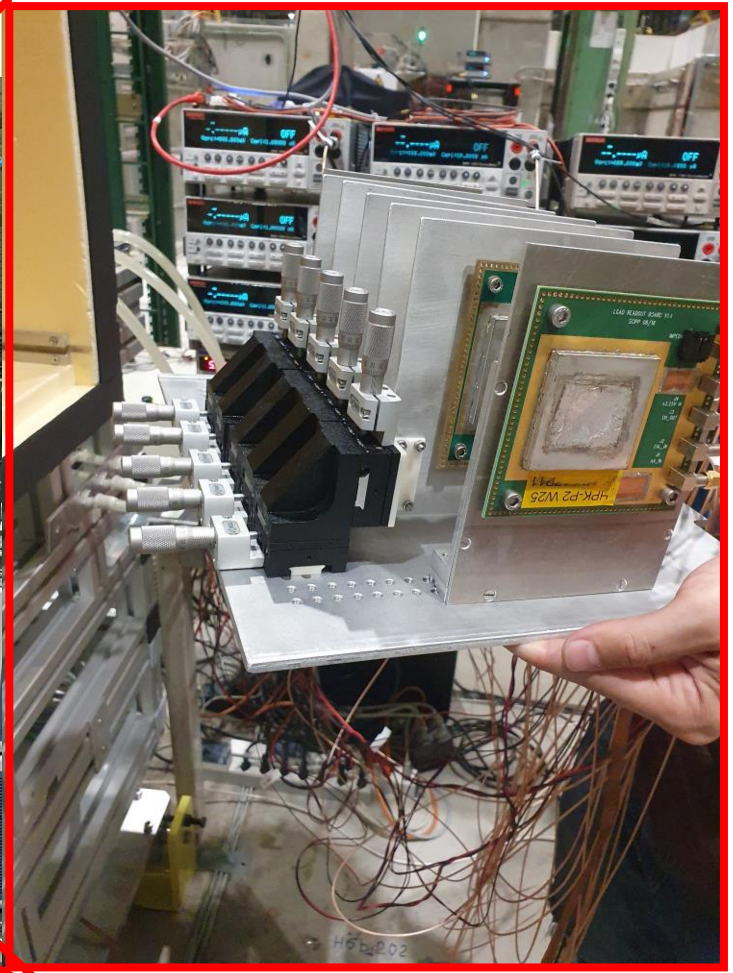
HV5: GPIB Address Keithley2410A; IV mode; Start Voltage 0.00 V; End Voltage -100.00 V; Voltage Step -5.00 V; Repetitions 2; Compliance 15.00 uA; Set Delay 1.00 s; Voltage 0 +/- 0 V; Current 0E+0 +/- 0E+0 A

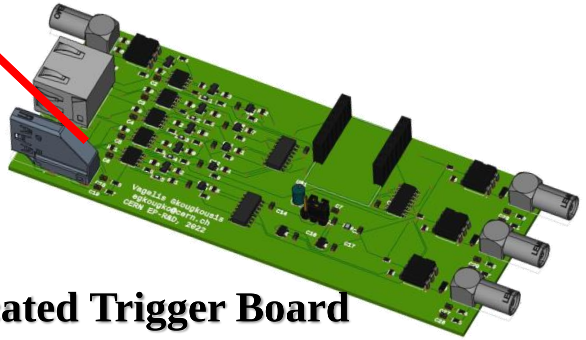
HV6: GPIB Address Keithley2410B; IV mode 6; Start Voltage 0.00 V; End Voltage -100.00 V; Voltage Step -5.00 V; Repetitions 2; Compliance 15.00 uA; Set Delay 1.00 s; Voltage 0 +/- 0 V; Current 0E+0 +/- 0E+0 A

HV7: GPIB Address Keithley2410B; IV mode; Start Voltage 0.00 V; End Voltage -100.00 V; Voltage Step -5.00 V; Repetitions 2; Compliance 15.00 uA; Set Delay 1.00 s; Voltage 0 +/- 0 V; Current 0E+0 +/- 0E+0 A

Slow Control DAQ





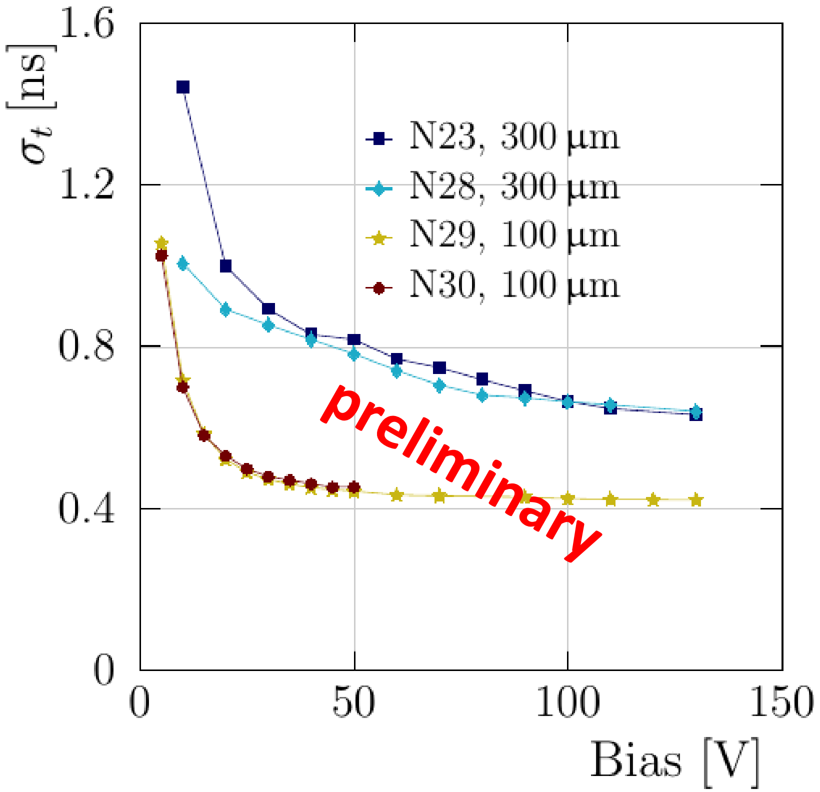


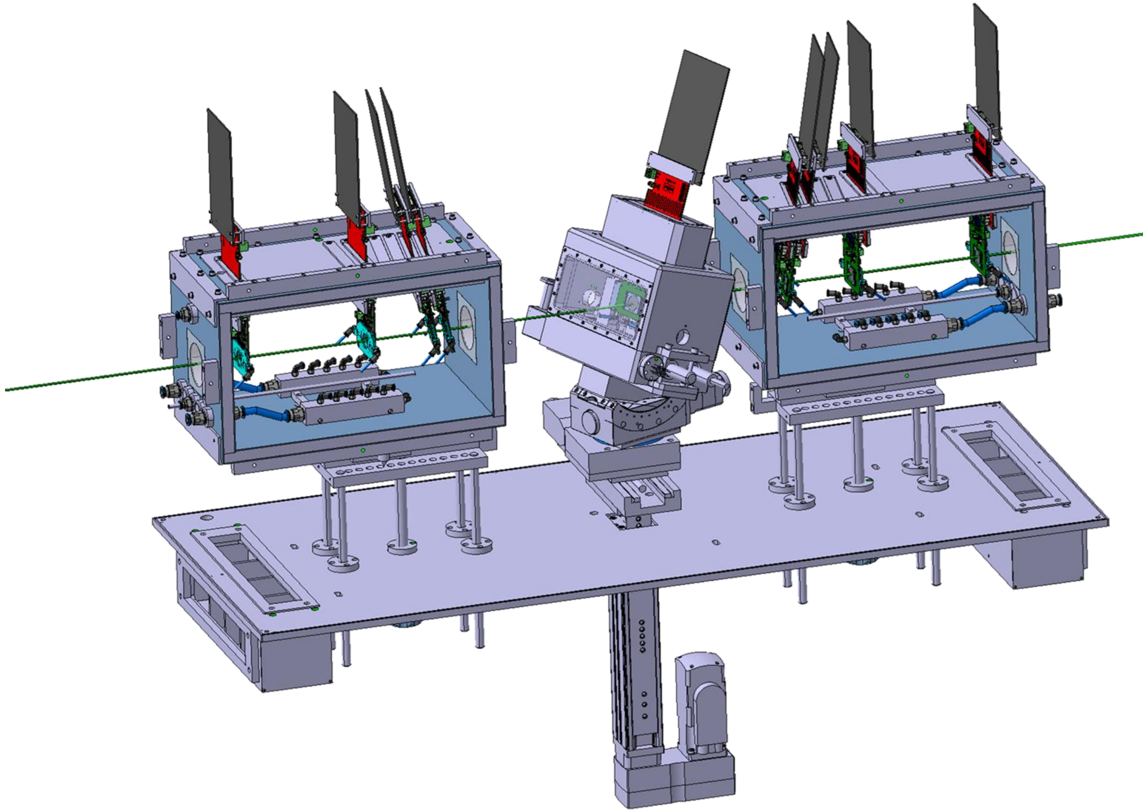
Dedicated Trigger Board

•TimePix 4 Telescope

- Only one arm with 3 Planes in 2021
- Already preliminary results available
- Result with time walk and per pixel corrections (~ 600 psec improvement)

- Plan for 2022 for 6 planes
- 2nd week of July next beam time slot
- Expecting DUT operation at the end of the year

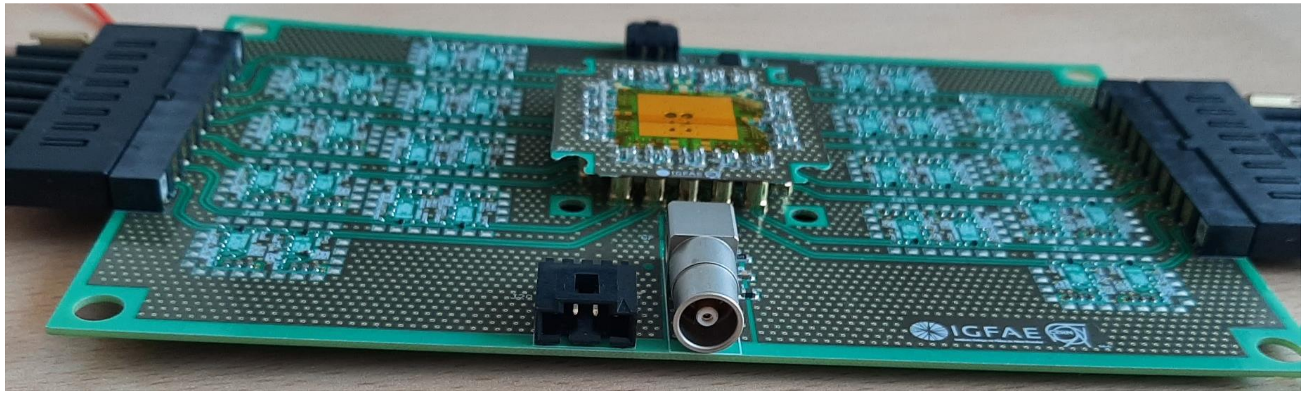




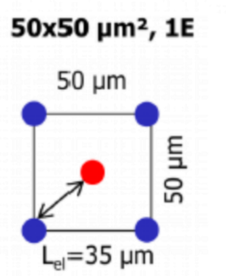
•16 Channel Board

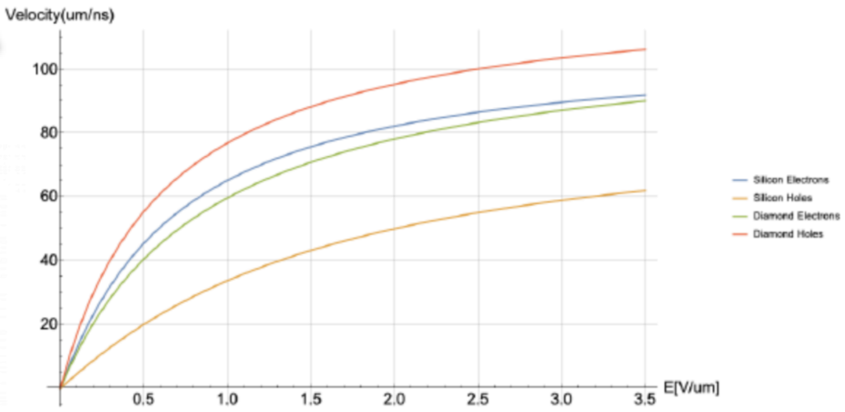
The solution

- ➢ High Frequency SiGe technology discreate electronics with 12 GHz bandwidth
- ➢ 2 Stage configuration with a transimpedance followed by a voltage amplifier
- ➢ Low max current (~10mA) with well behaved gain linearity vs V_{DD}
- ➢ Independent Shielding per channel
- ➢ Ruggers 3000 High Frequency substrate
- ➢ Sensor Daughter board for versatile operation
- ➢ Pre-assembled miniaturized coaxial edge connectors with panel-mounted SMA plugs (1m cable length)
- ➢ 140 mm x 140 mm outer dimensions



The issue....





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

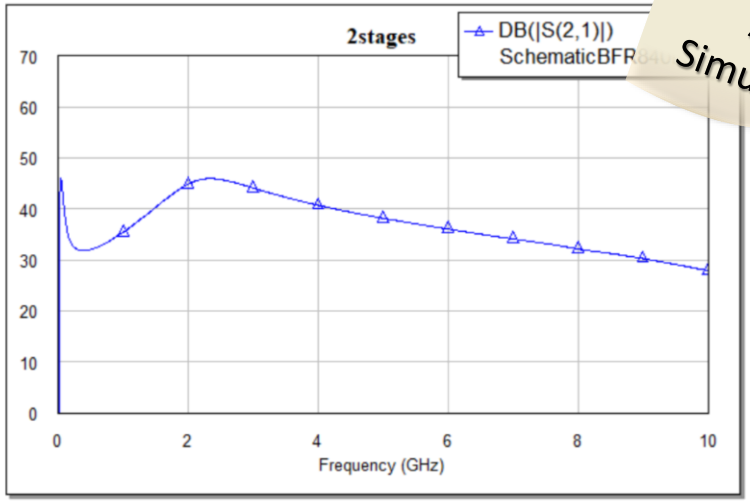
$$\boldsymbol{v^{e}_{drift} \approx 41.4\ \mu m/ns}$$

- Extrapolated Rise time and Frequency:

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

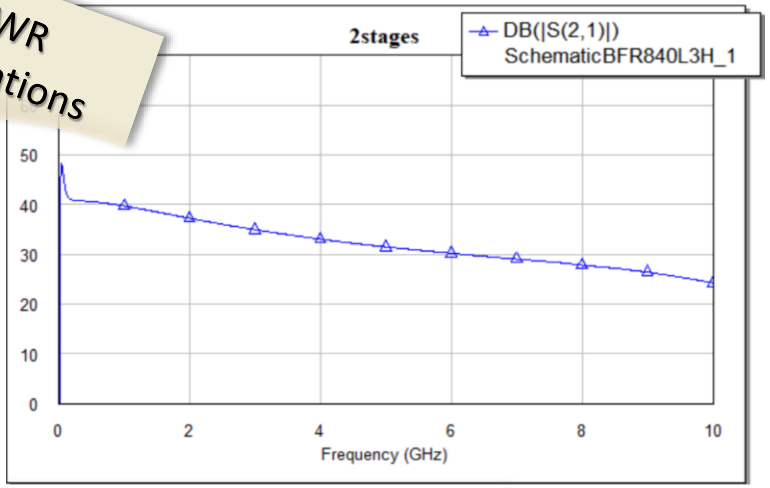
•16 Channel Board

Initial design



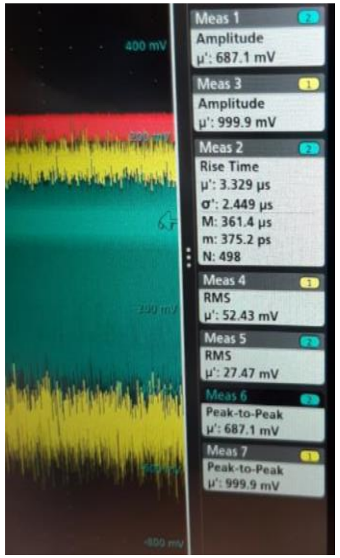
AWR Simulations

Modified –Uniform design



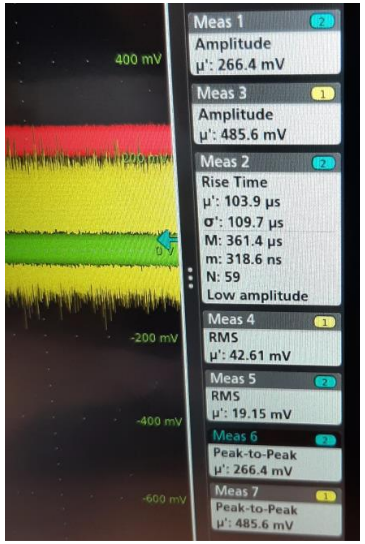
- Optimized design for uniform response with frequency
- No sharp gain change discontinuities
- No undershoot/overshoot observed
- Gain moderated to ~70 for a two-stage configuration
- 20% Higher SNR than UCSC board (with both stages)
- 2 x SNR with respect to UCSC board + niniCircuits second stage amplifier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

With signal injection



Meas 1
Amplitude
μ': 687.1 mV
Meas 3
Amplitude
μ': 999.9 mV
Meas 2
Rise Time
μ': 3.329 μs
σ': 2.449 μs
M: 361.4 μs
m: 375.2 ps
N: 498
Meas 4
RMS
μ': 52.43 mV
Meas 5
RMS
μ': 27.47 mV
Meas 6
Peak-to-Peak
μ': 687.1 mV
Meas 7
Peak-to-Peak
μ': 999.9 mV

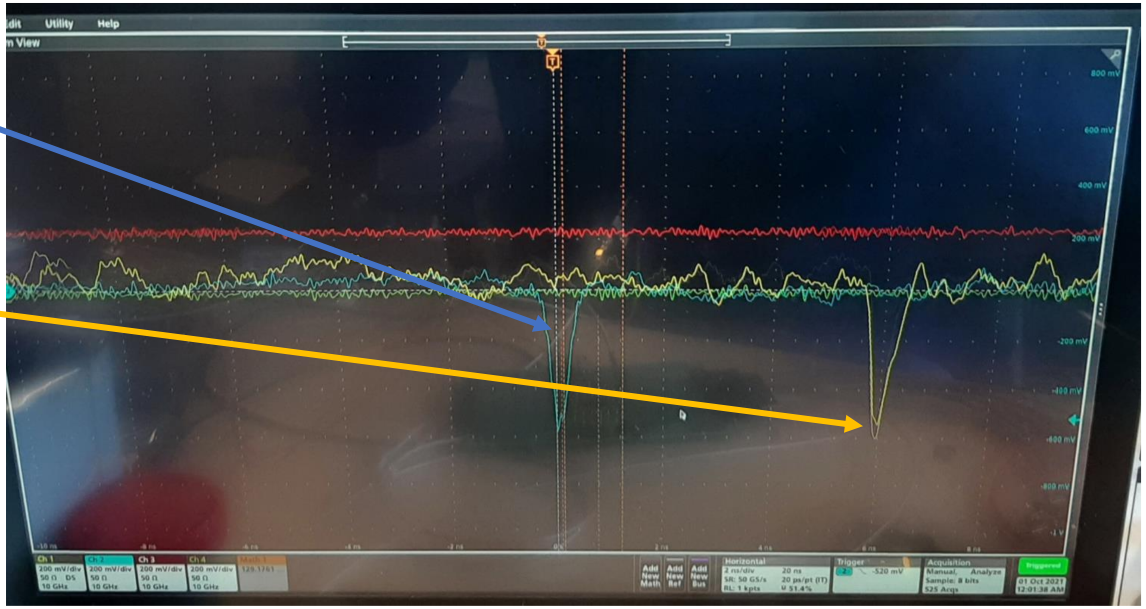
Without signal injection



Meas 1
Amplitude
μ': 266.4 mV
Meas 3
Amplitude
μ': 485.6 mV
Meas 2
Rise Time
μ': 103.9 μs
σ': 109.7 μs
M: 361.4 μs
m: 318.6 ns
N: 59
Low amplitude
Meas 4
RMS
μ': 42.61 mV
Meas 5
RMS
μ': 19.15 mV
Meas 6
Peak-to-Peak
μ': 266.4 mV
Meas 7
Peak-to-Peak
μ': 485.6 mV

Blue: 16 channel board

Yellow: UCSC board (only one stage)



•Conclusions

Characterization Systems

- ***Beta Source Setup:*** Three object system with a pixelated plane and alignment matrices for “true” efficiency measurements
- ***SiMS:*** Detailed Process Characterization and Simulation of delivered sensors
- ***Test beams:*** Unbiased Timing and detailed efficiency and timing (field maps)

3D Pixels

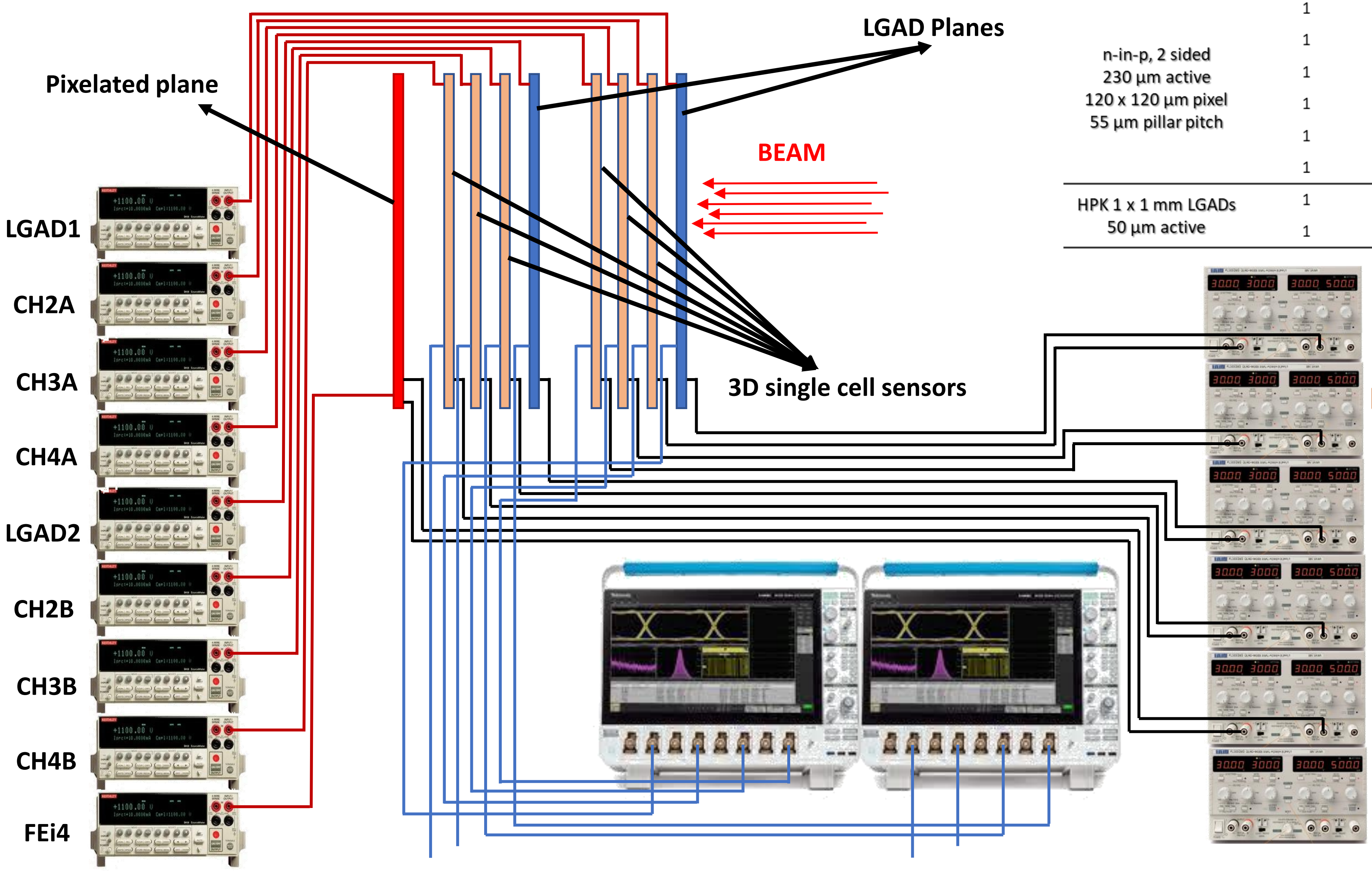
- ***3 different productions under investigation***
- ***Estimate filed non-uniformity impact on time resolution with respect tp pixel size***
- ***Determine minimal acceptable thickness for time resolution applications***
- ***Investigate effects after irradiation at 1e17 in protons and neitrons***

•Backup

•May Test-Beam Planning

DUT List

Type	Sample no.	Fluence (n_{eq}/cm^2)	Status	Actions
n-in-p, 2 sided 230 μm active 120 x 120 μm pixel 55 μm pillar pitch	1	1×10^{15} neutron	Wire bonding	Lab testing
	1	4×10^{15} neutron	@IFAE	Verification
	1	8×10^{15} neutron	Wire bonding	Lab testing
	1	6×10^{16} neutron		Lab testing
	1	1×10^{17} neutron		Lab testing
	1	Unirrad.		Ready
HPK 1 x 1 mm LGADs 50 μm active	1 1	Unirrad.	On Board Timing References	Ready



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