



WP1.1 Hybrid Silicon Detectors

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V. Gkougkousis [EP R&D Fellow], **J. Haimberger**, **M. Halvorsen** [EP R&D DOCT],
M. Moll, H. Schindler, , Viros Sriskaran [EP R&D FELLOW], ...

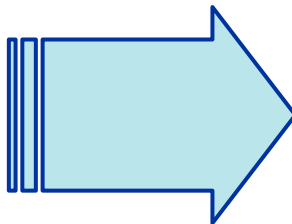
Motivations

MIP detection in next generation of collider experiments

from the CERN Strategic R&D Programme on Technologies for Future Experiments [CERN-OPEN-2018-006]

[fineprint in CERN-OPEN-2018-006]	HL-LHC	SPS	FCC-ee	FCC-hh
Fluence [$n_{\text{eq}}/\text{cm}^2/\text{y}$]	5×10^{16}	10^{17}	10^{10}	10^{17}
Max Hit rate [$\text{cm}^{-2} \text{s}^{-1}$]	2-4G	8G	20M	20G
Material budget per layer [X_0]	0.1-2%	2%	0.3%	1%
Pixel size [μm^2] inner trackers	50x50	50x50	25x25	25x25
Temporal hit resolution [ps] inner trackers	~50	~40	-	~10

- Timing resolution **10 to 50ps**
- Pixel pitches **25 to 50 μm**
- Fluences up to **$10^{17} n_{\text{eq}}/\text{cm}^2/\text{y}$**
- Max hit rate up to **$20\text{G}/\text{cm}^2/\text{s}$**



Challenges for sensor:

- with **internal gain** (rad. hardness? segmentation?)
- with **small drift path** (**3D**: fill factor? capacitance? **Planar**: total charge?)
- with **integrated FE** (**monolithic** see WP 1.2)

Challenges for front-end electronics:

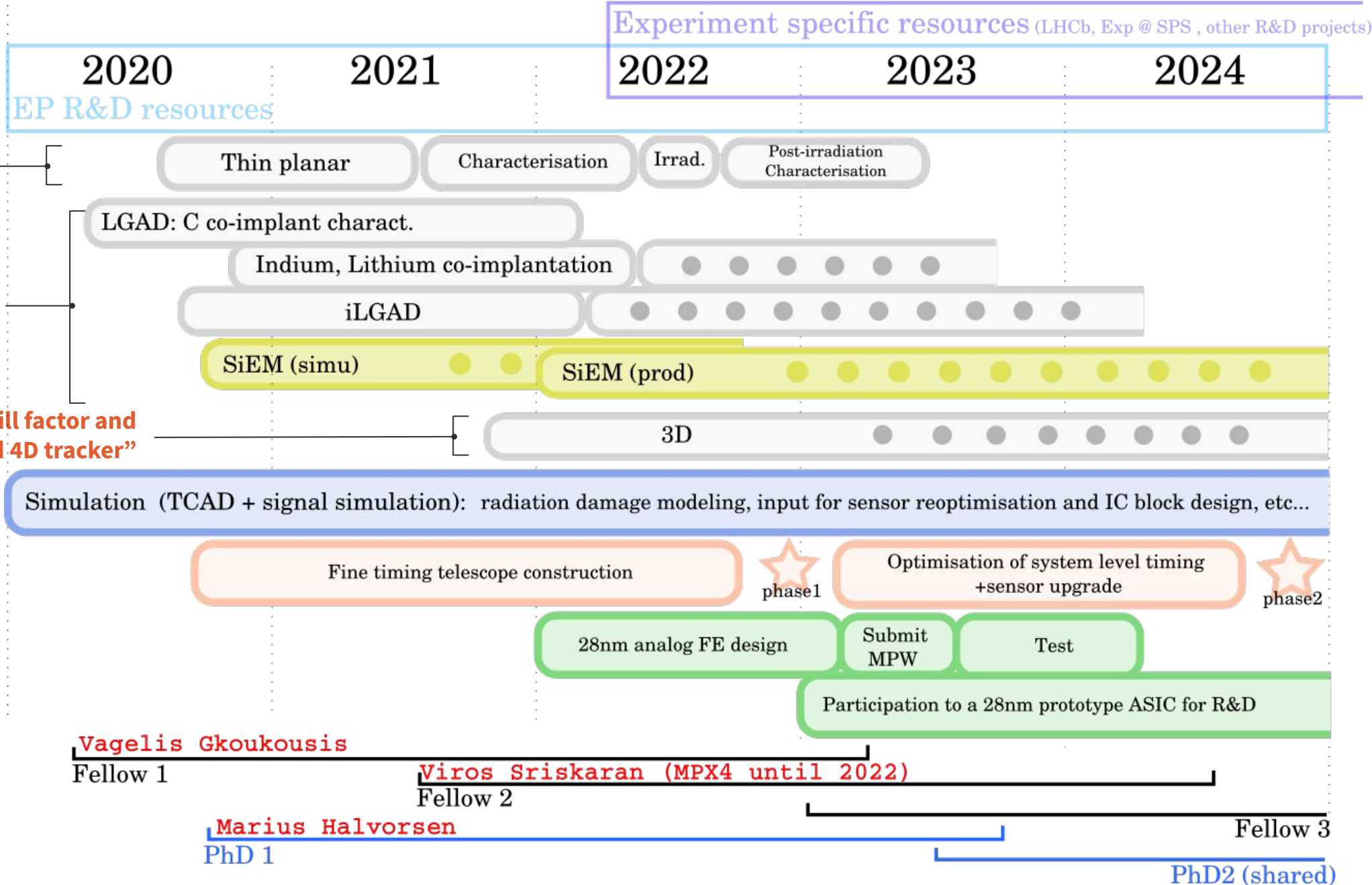
- For hybrid sensor Timepix4 sets limits of what can be achieved in 65nm
- need to go beyond \Rightarrow **28nm design**

Workplan

Planar: “the reference”

Sensor with internal gain:
“make them radiation hard
and small pitch”

3D technology: “improve fill factor and
characterise toward 4D tracker”



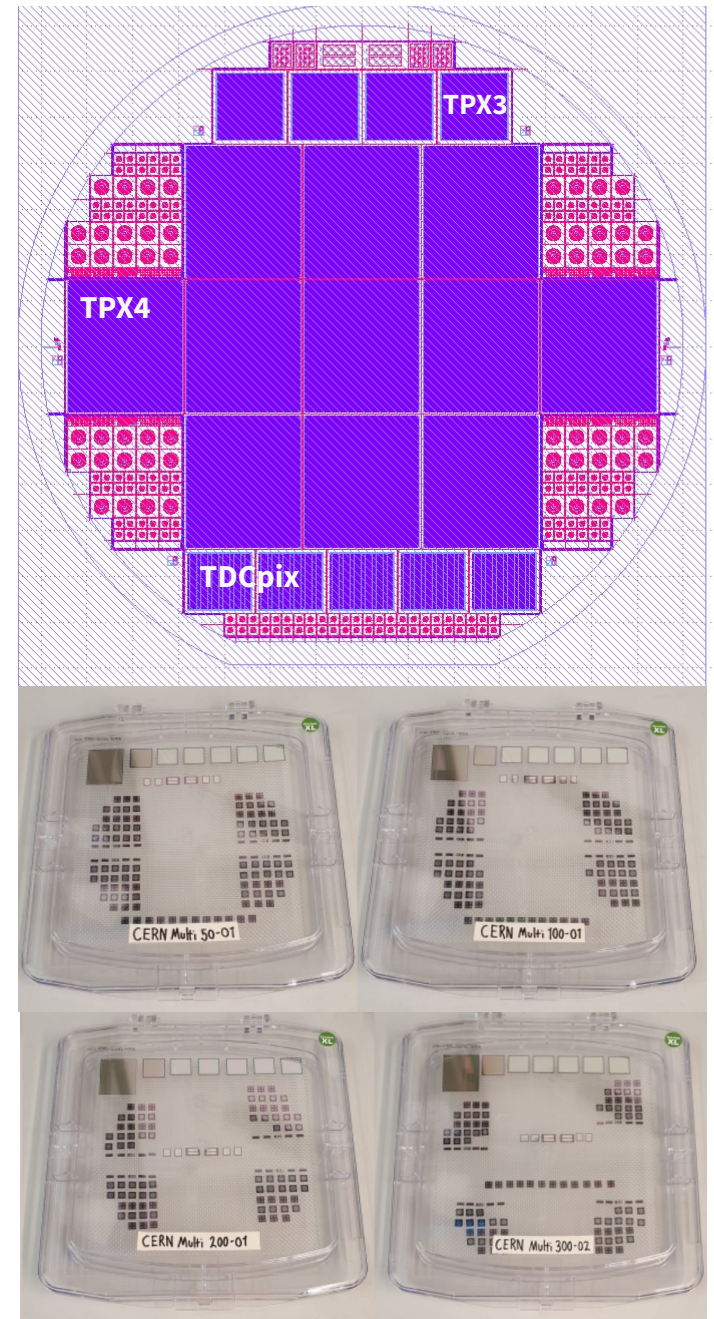
Sensors

Production and design

Planar Sensors production

contact persons: V. Coco, P. Collins

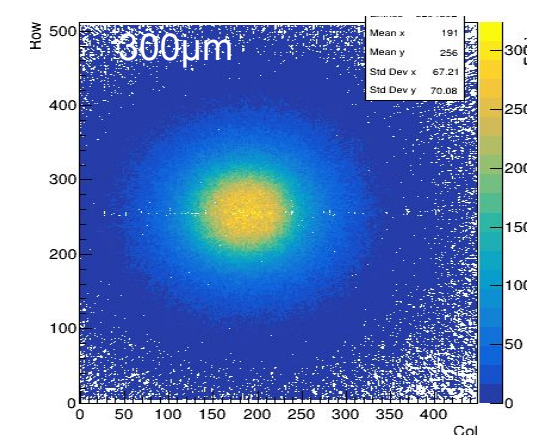
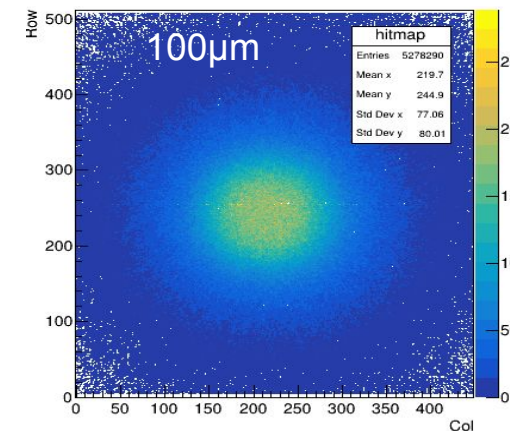
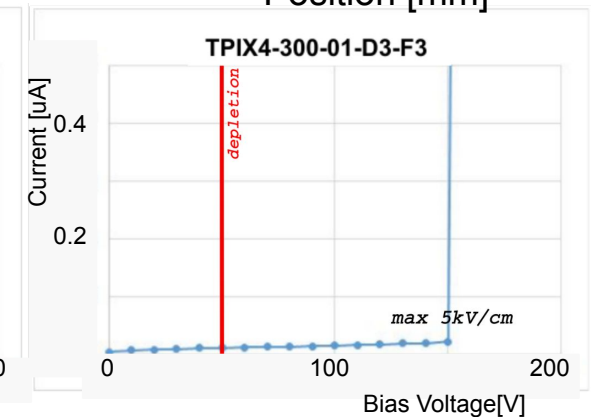
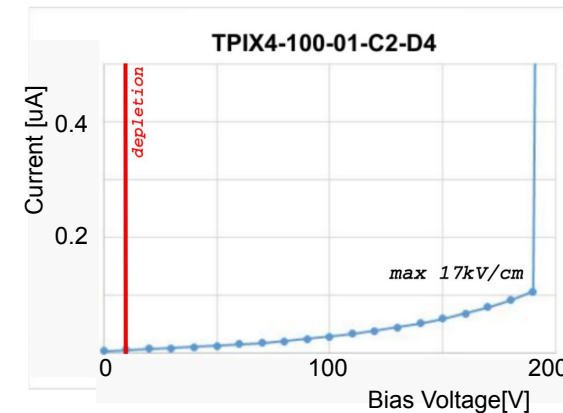
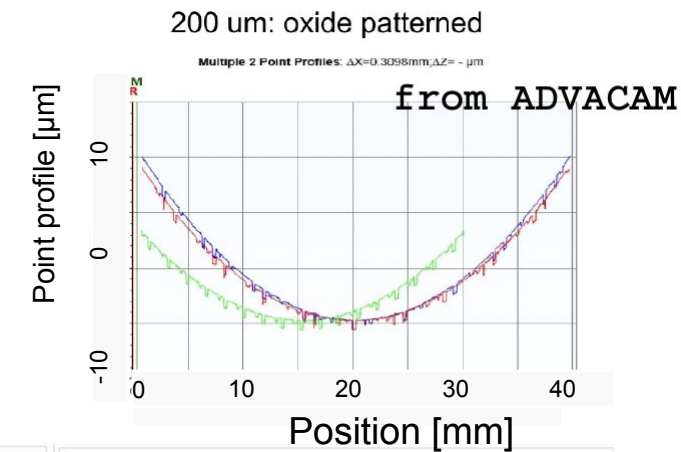
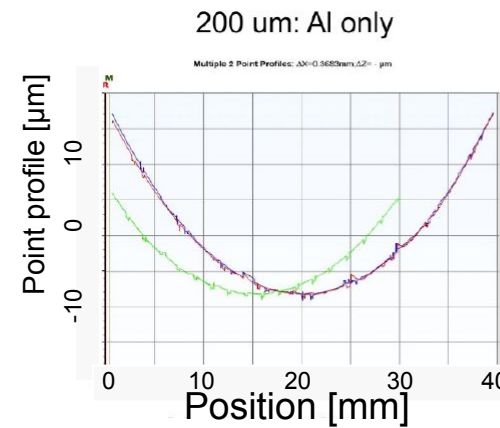
- Tender awarded to **ADVACAM** - January 2021
- **Production completed** - August 2021
- n-in-p, four thicknesses: 50,100,200 and 300 μ m
- **Sensors** for various users:
 - Timepix4 (Telescope, Sensor R&D, Medipix collaboration)
 - Timepix3 (Sensor R&D)
 - TDCpix (Sensor R&D, NA62 upgrade studies)
- Several **test structures** (PIN-diodes, small matrices, structure for resistivity and doping profile measurements)
 - important part of the R&D program
 - see slide 20



Planar Sensors production

contact persons: V. Coco, P. Collins

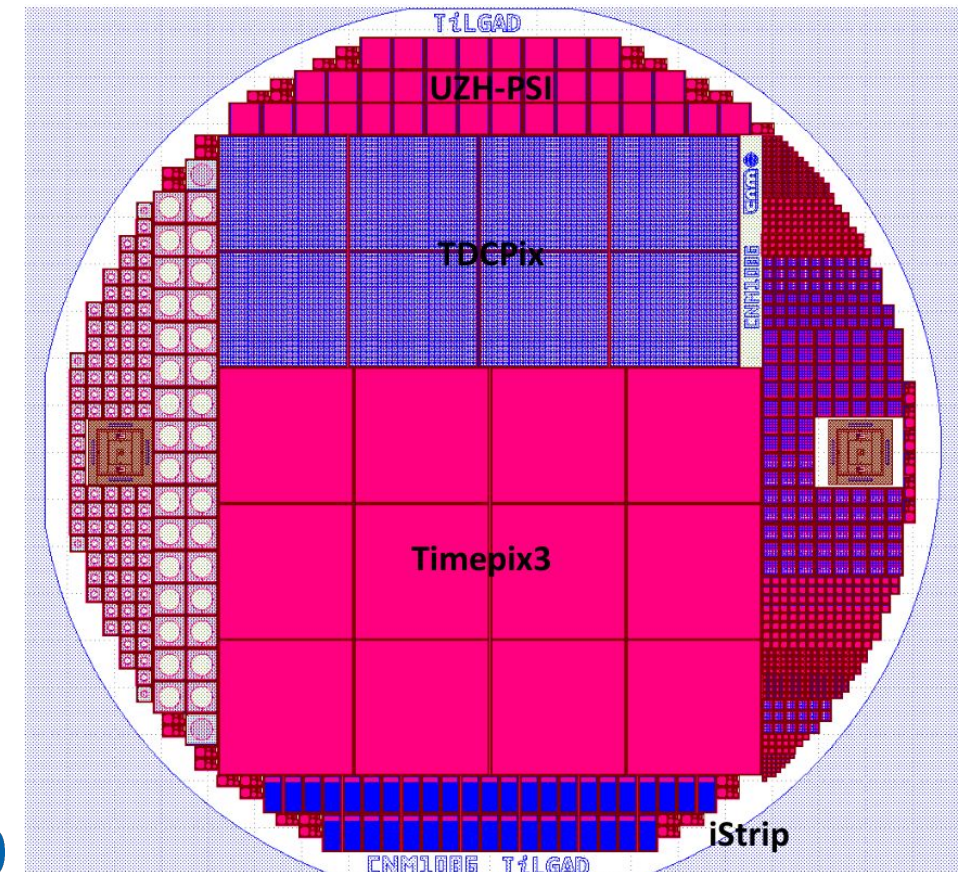
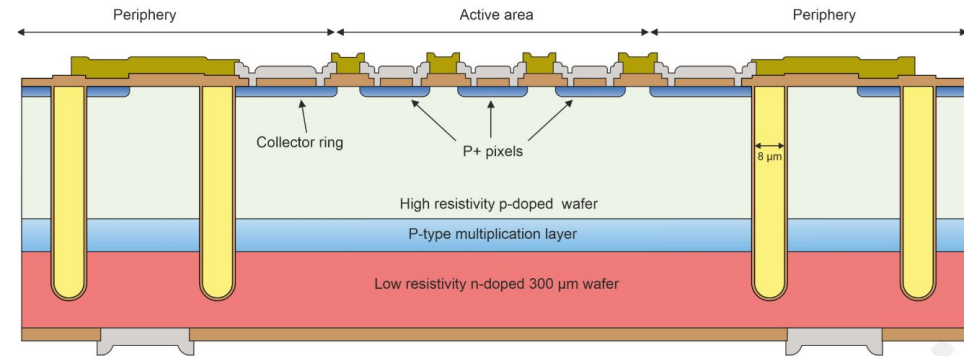
- **Large bow** observed on the thin sensors
 - 40% better with oxide pattern on the backside
 - **negligible after bonding** (5 μ m for the 100 μ m sensor)
- **Breakdown** well above depletion
 - earlier to than hoped for. To be investigated
 - will limit unirradiated measurements as function of electric field
- **4 sensors bonded to TPX4** asics
 - tested with Sr90 source at Nikhef
 - used in TPX4 telescope prototype
- All test-structure **delivered and** pre-irradiation **characterisation started**



iLGAD production with CNM

contact persons: M. Moll and E. Curras (SSD)

- LGAD technology provides **good time resolution**
 - internal gain improves signal to noise and reduces jitter
- **Segmentation is limited** in conventional LGADs.
 - n-implant (gain layer) side segmentation limited by edge effects
 - low fill factor expected for small pitch geometries
- **Backside (p-implant) readout allows for better segmentation** without affecting the gain layer
- Third generation of iLGAD in production at CNM
 - Mask design ready since April 2021
 - **Production to resume soon**

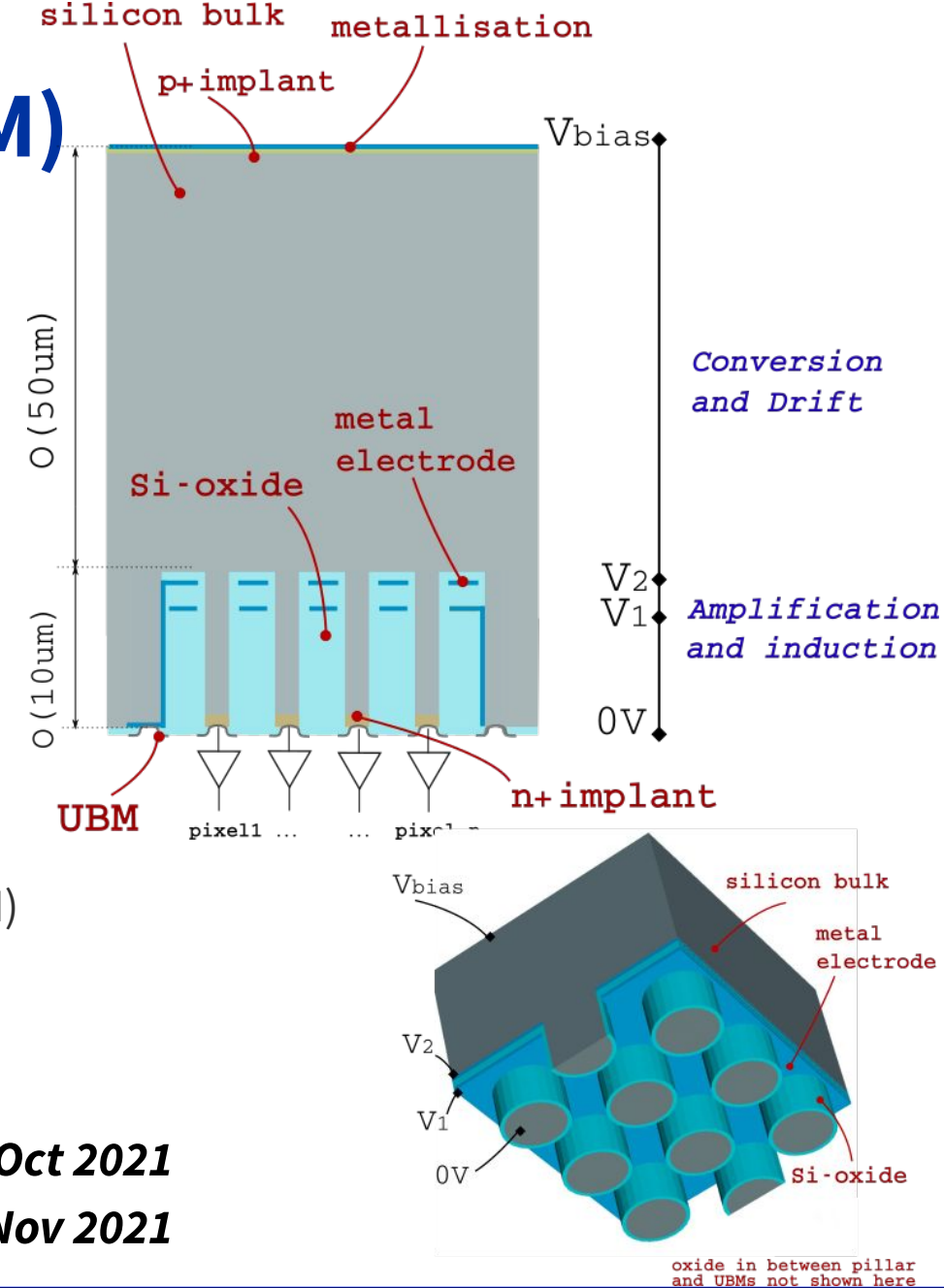


[S. Hidalgo Current Status of 3D and LGAD Production]

The Silicon Electron Multiplier (SIEM)

contact persons: M. Halvorsen, V. Coco

- Goal: make a **radiation hard sensor with internal gain**
- Generate **high electric field** regions by applying a potential difference to a set of electrodes.
 - inversely etched or grown pillars of Silicon (SiC, diamonds...)
 - single or multiple metallic electrode planes between pillars
 - localised high fields promote charge multiplication
- Production study will be started in 2022
 - DRIE based process (in discussion with CNM)
 - Metal assisted chemical etching process (in collaboration with PSI)
- Comprehensive simulation studies using Synopsys TCAD



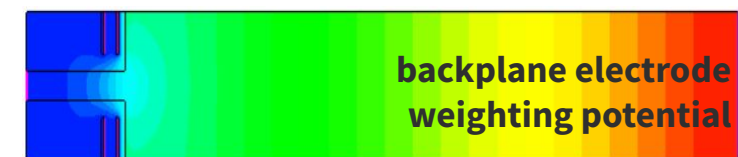
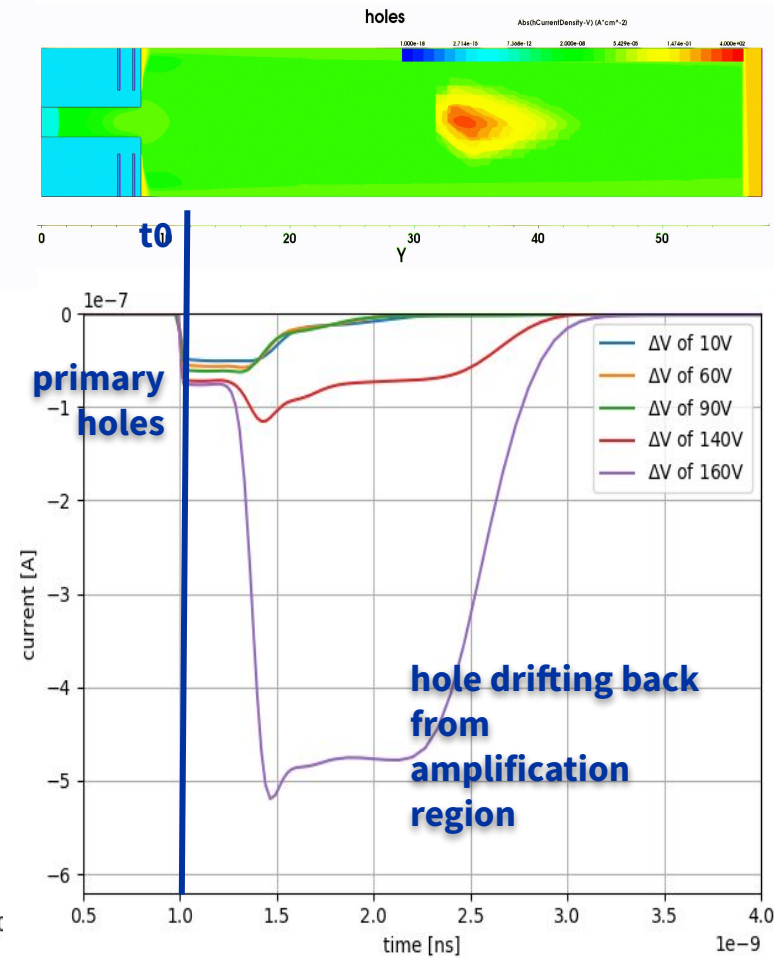
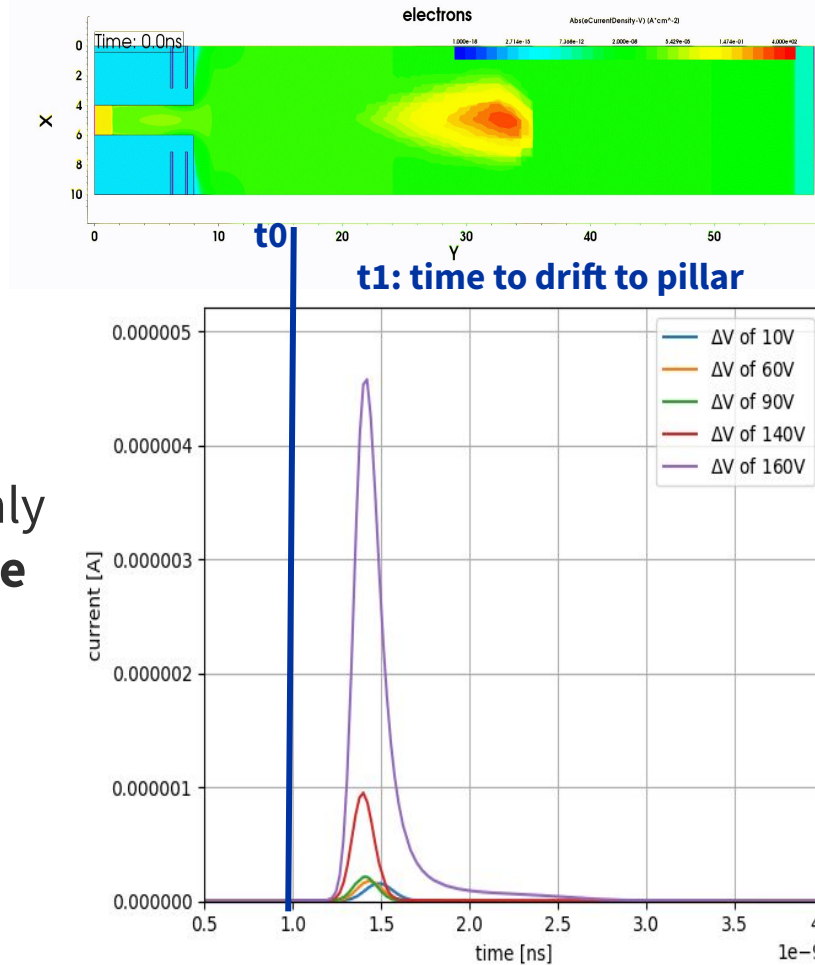
IEEE NSS MIC, Oct 2021

to be shown at 39th RD50 workshop, Nov 2021

SIEM - induced signal and amplification

contact persons: M. Halvorsen, V. Coco

- Field above 20V/ μm in the pillar
- Gain up to 20-30 simulated
 - $\text{Gain} = Q_{\text{readout}} / Q_{\text{injected}}$
- **Signal at readout electrode** is only induced by **charges moving in the pillar**
- Time resolution **expected to be similar to LGAD**
 - Full MIP simulations ongoing



Characterization

Setups and results

Source setup for sensor characterization

contact persons: V. Gkougkousis

- **^{90}Sr Charge measurements (vs V_{bias} & T):**

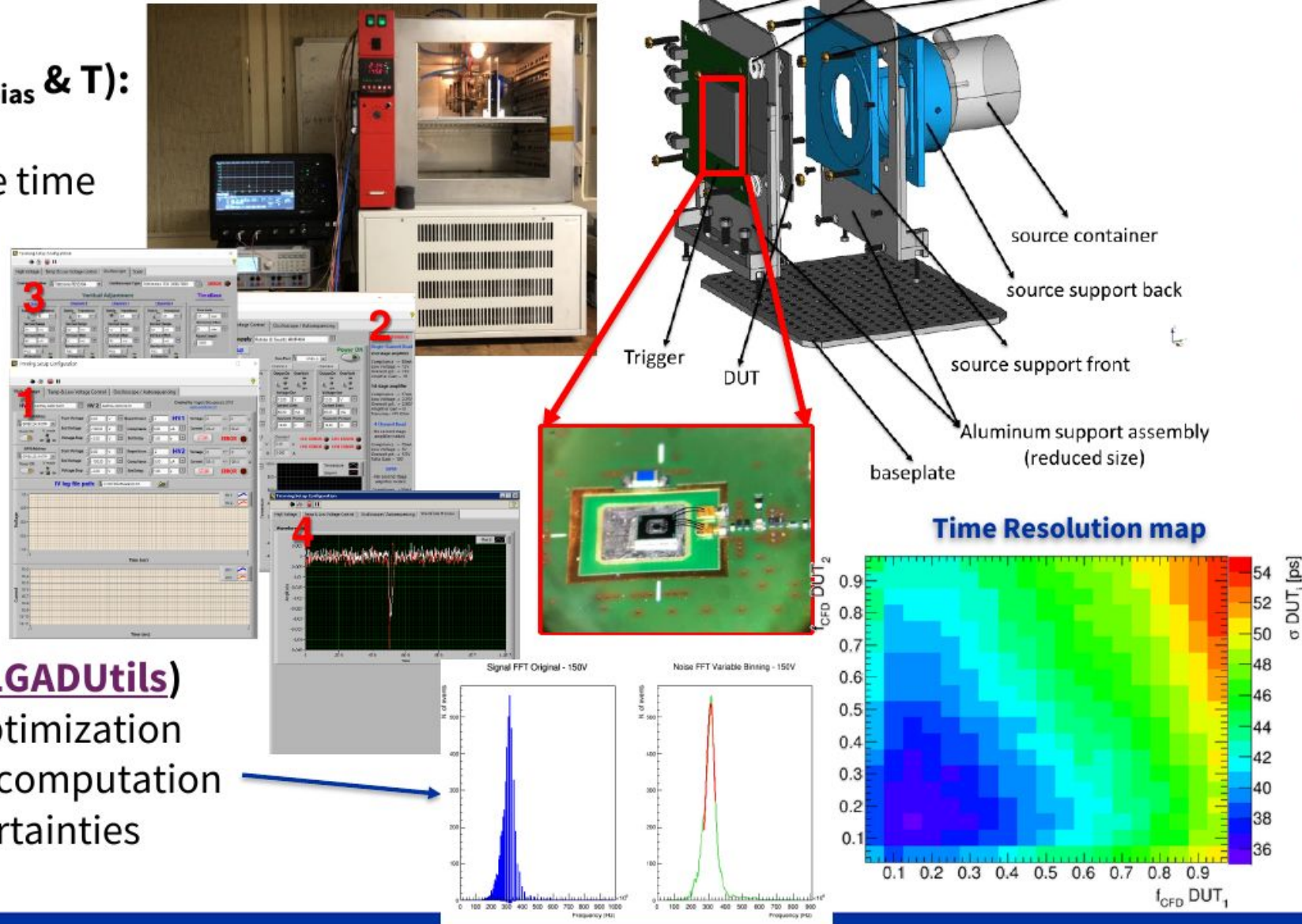
- ✓ Gain – Charge
- ✓ Time resolution, Jitter, Rise time
- ✓ Relative Efficiency
- ✓ Stability, Dark rate

- **Fully automated DAQ (TiCAS)**

- ✓ Graphical interphase
- ✓ Multi-instrument support
- ✓ Remote management
- ✓ Failsafe operation

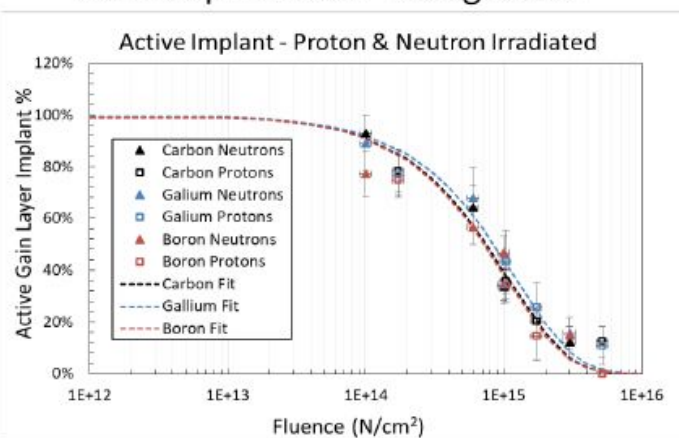
- **Waveform analysis framework (LGADUtils)**

- ✓ Iterative adaptive fitting optimization
- ✓ Waveform shapes and FFT computation
- ✓ Bayesian asymmetric uncertainties



LGAD characterization

contact persons: V. Gkougkousis



Acceptor level introduction rate

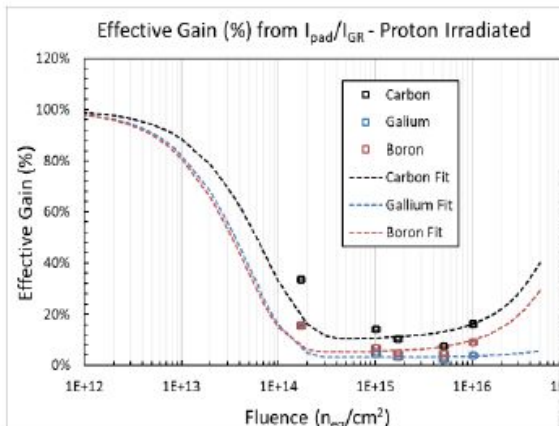
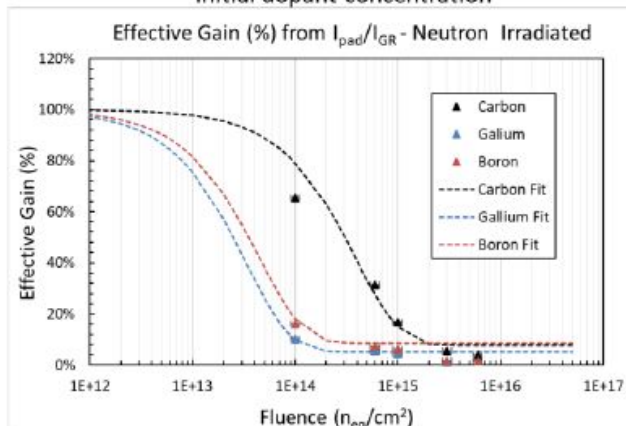
$$N_{eff}(\Phi) = N_{eff0} - N_c(1 - e^{-c\Phi}) + g_c\Phi$$

Effective dopant concentration

Removable dopant

Gain extraction constant

Initial dopant concentration



Active Gain Implant

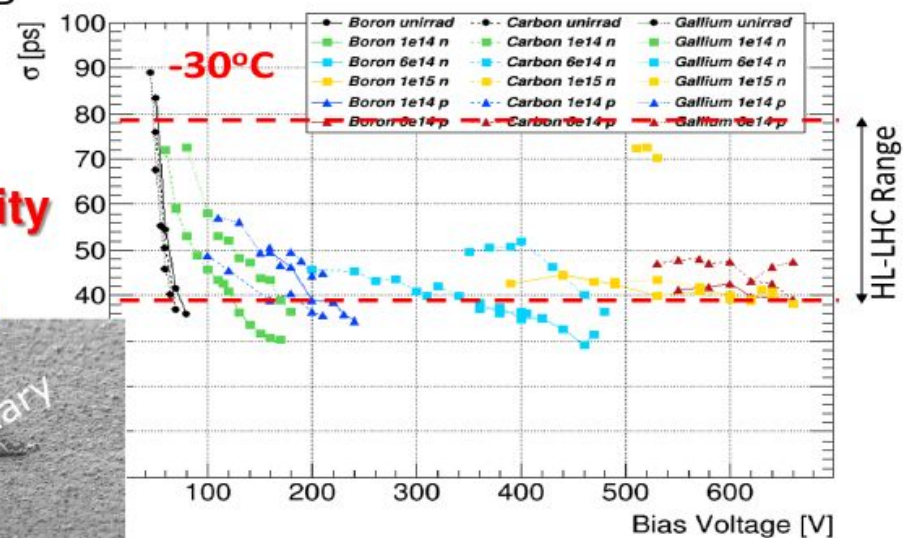
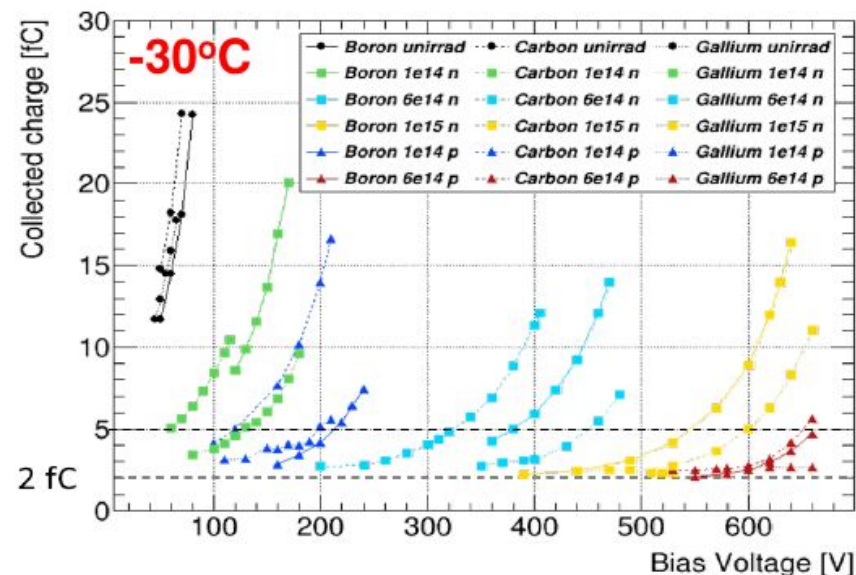
- ✓ Evaluated for B, B+C, G
- ✓ No implant effect observed

Effective Gain evaluation

- ✓ Similar behavior for G, B
- ✓ Up to 2-5 x better for B+C

MIPs Charge Collection

- ✓ 20% improvement of B+C vs B
- ✓ 20% degradation for G
- ✓ Similar time resolution



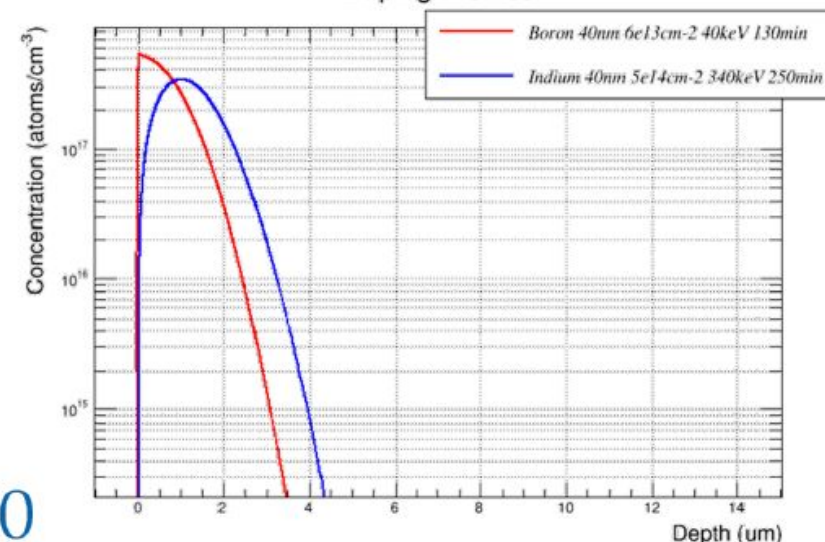
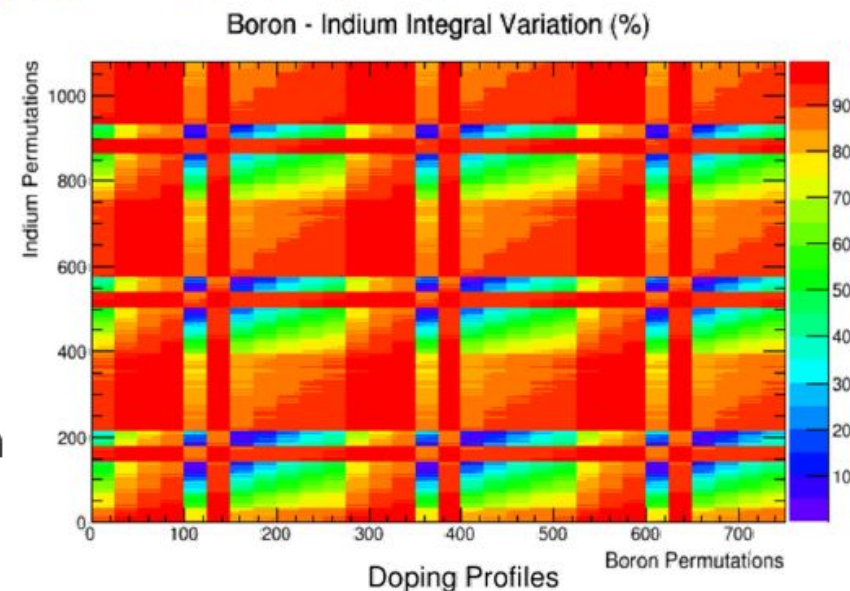
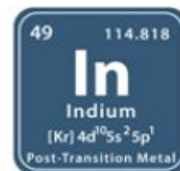
Mortality



LGADs with Indium and Lithium Implantations

contact persons: V. Gkougkousis

- **LGADs** susceptible to **radiation damage**
 - follow up on defect engineering studies (see slide 13)
- **Indium** implantation
 - Higher mass, less prone to lattice dislocations
- **Lithium** co-implant.
 - Boron with Lithium co-implantation demonstrates better neutron radiation hardness
 - Lithium's **light mass**, and increased **electronegativity** favor formation of Li_iO_i rather than B_iO_i
- **Implantation energy and doping profiles already optimized via TCAD simulations**
 - **Multiple wafer production variants** and **irradiation campaigns** are planned
- **Common RD50 founded project with CERN, CNM & JSI (RD50-2021-03)**



Test beam with 3D sensors

contact persons: V. Gkougkousis

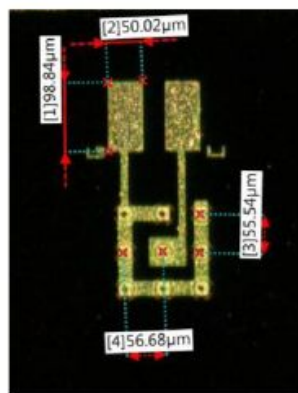
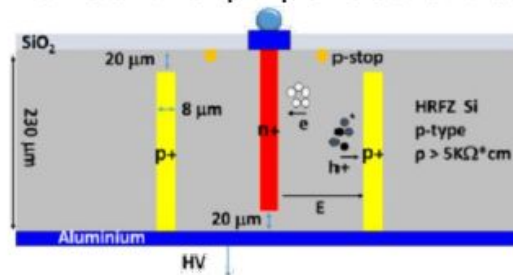
3D Sensors: Decoupling of charge generation and drift volume
(Standard columns, TimeSpot, Hex geometries ect.)

Pros

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

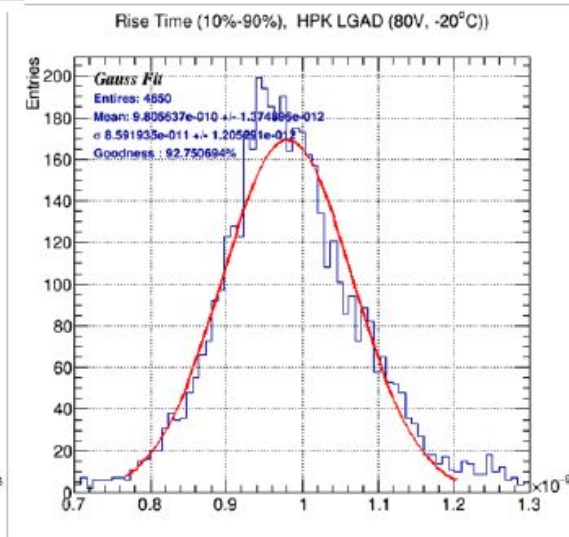
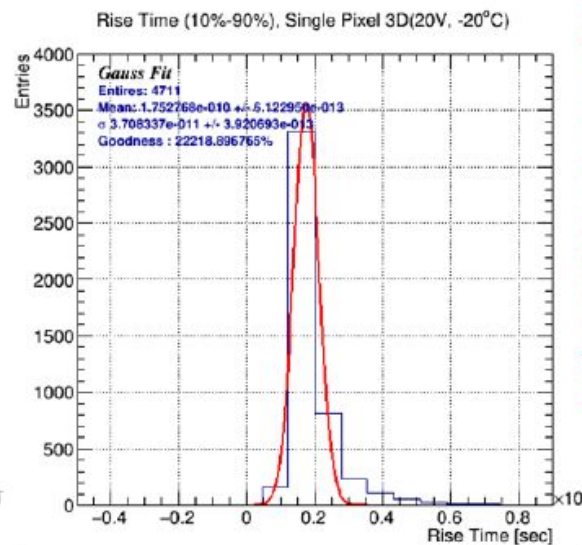
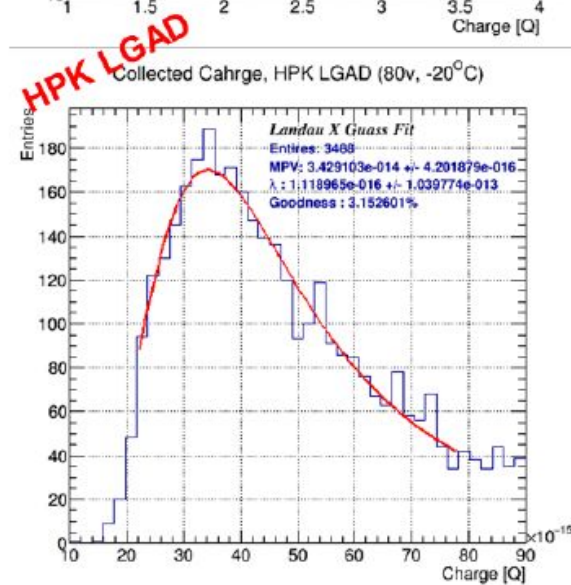
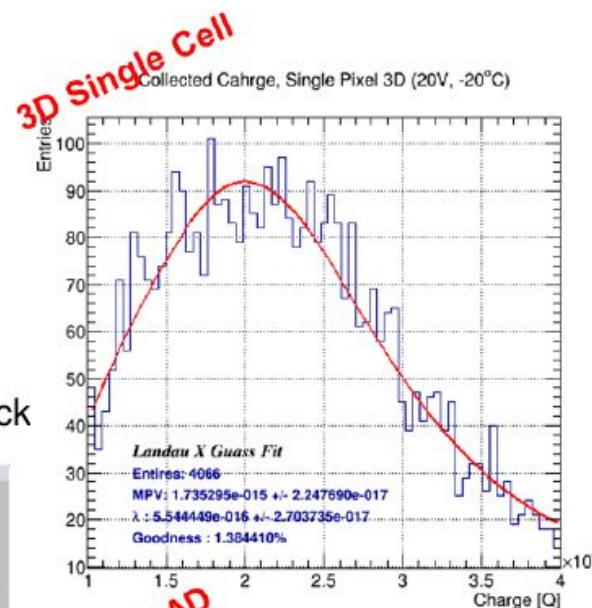
Cons

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



Tested Devices

- Process: 2-sided
- Substrate: high Z, p-type FZ Silicon, 4" wafers
- Thickness: $\sim 280 \mu\text{m}$
- Run: CNM 5936-11
- Pixel Geometry: $50 \times 50 \mu\text{m}$, 1^{E} , single cell
- Capacitance: $\sim 80 - 100 \text{ pF}$ per cell



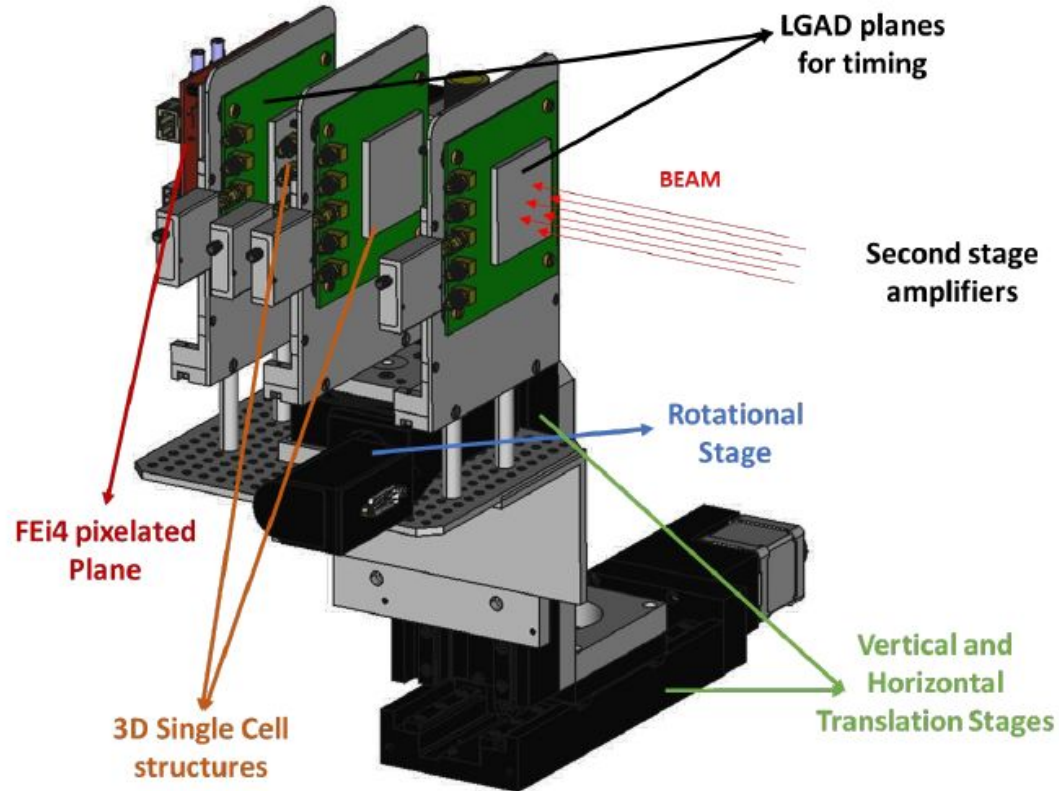
Test beam with 3D sensors

contact persons: V. Gkougkousis

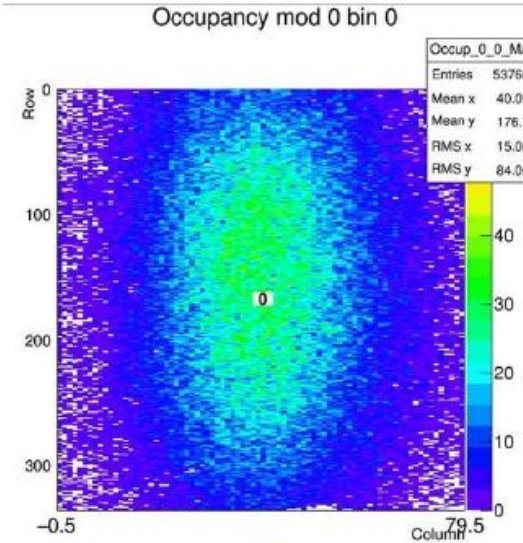
July - August
2021

1st 3D SPS test beam with timing

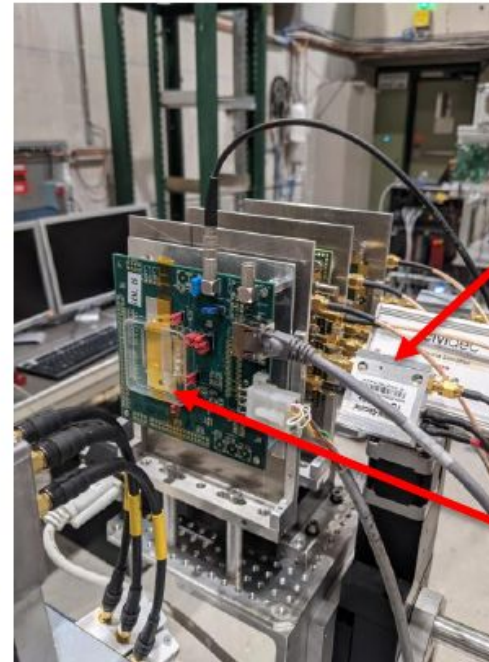
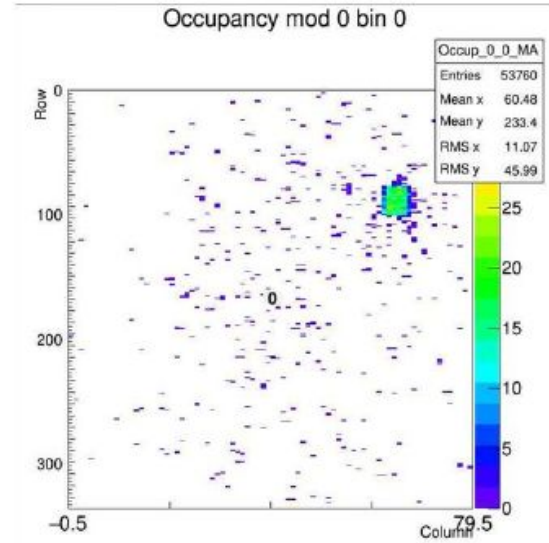
- Angular incidence scans on single pixel 3D sensors
- +/- 12° range at 1° steps
- Evaluation of the Landau contribution



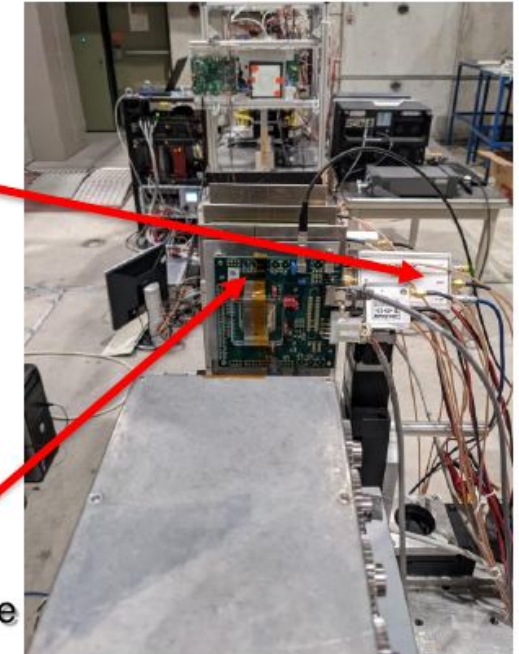
BeamSpot



LGAD 1



Second stage
amplifiers



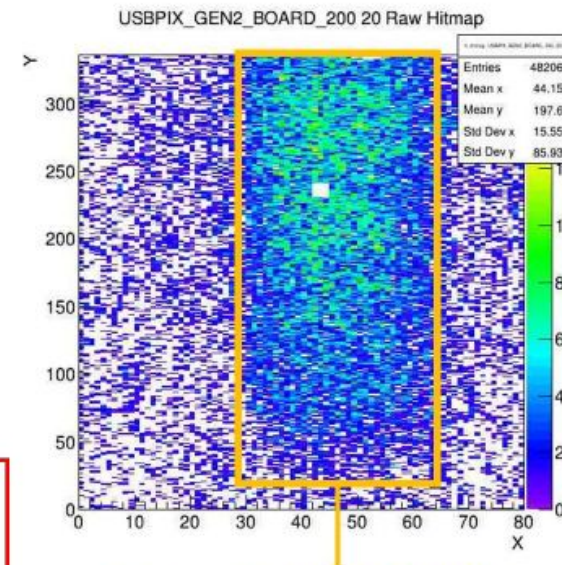
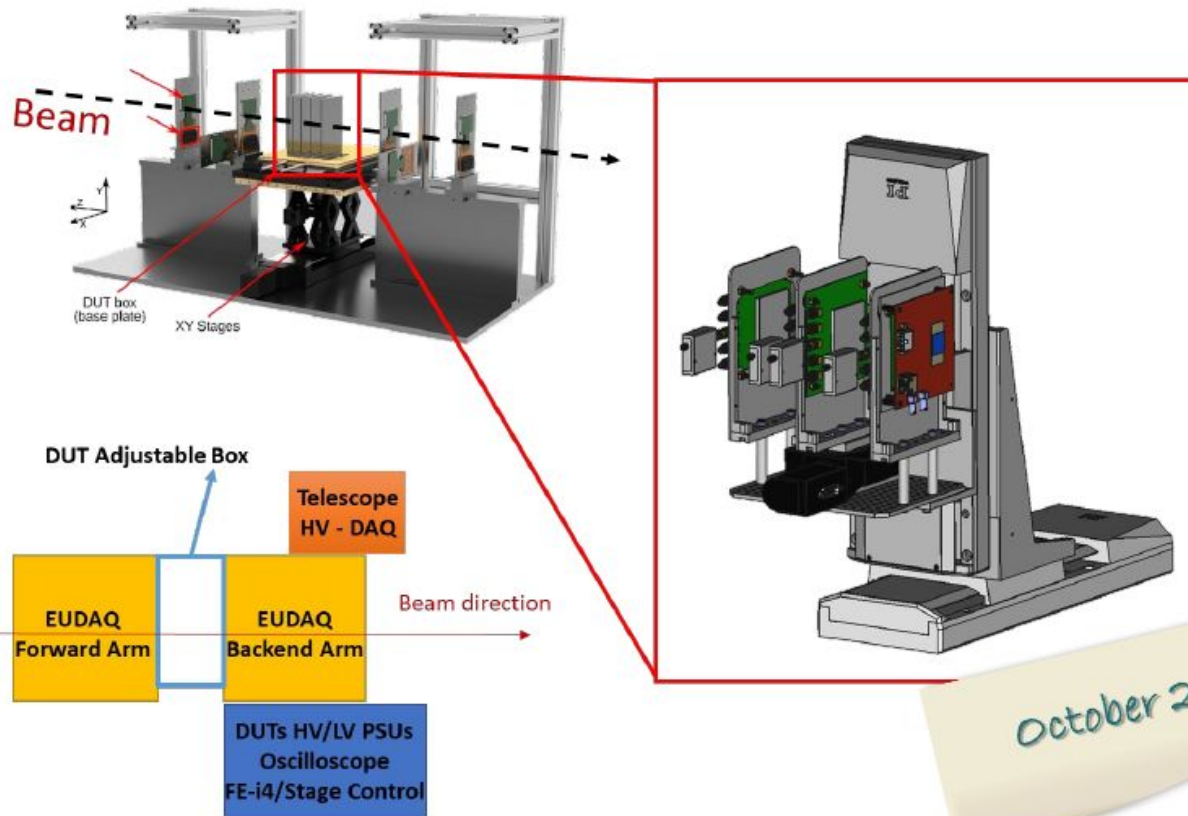
Pixelated plane

Test beam with 3D sensors

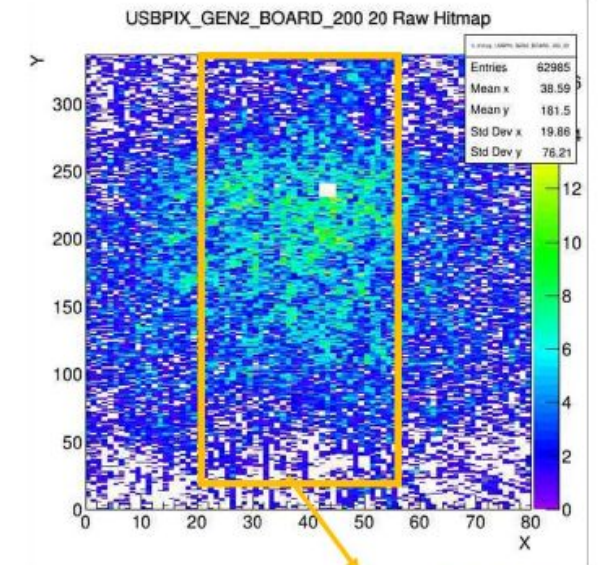
contact persons: V. Gkougkousis

2nd 3D SPS test beam with tracking and timing

- Tracking implemented through the AIDA telescope
- Detailed timing and field maps
- Non-irradiated sensors, vertical incidence angles



Upstream Horizontal Scintillator



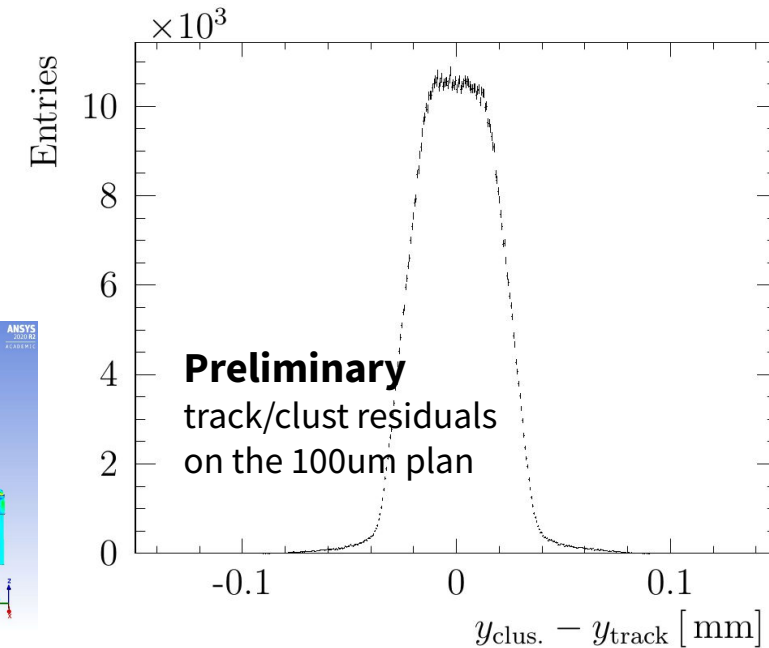
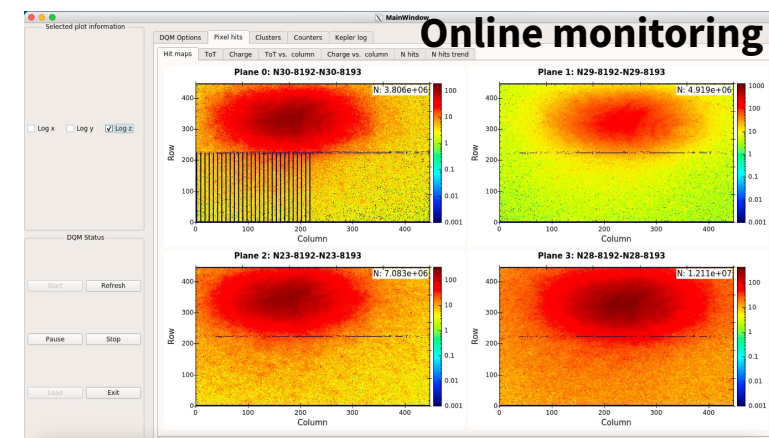
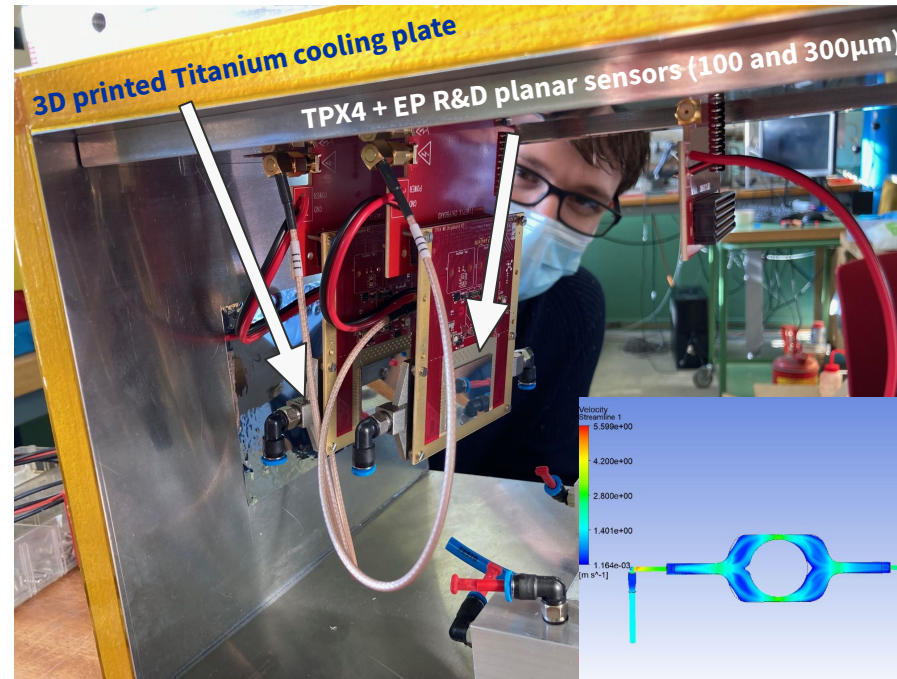
Downstream Horizontal Scintillator



TPX4-based 4D telescope

- Expect **30-40ps per track** in first phase (end 2022) and **25-30ps in second phase** (end 2024)
- **Pointing resolution @DUT** down to **2 μ m**
- **No rate limitation** (TPX4 up to 358MHz/cm², hit based)

Single arm prototype in beam two weeks ago!



- **CERN contrib:** mechanics, cooling and DUT box design [R. Dumps, M. Gose], slow control (motion and env. monitoring) [M. Halvorsen, W. Byczynski], hybrid sensors (from thin planar prod + TPX4) [V. Coco], LGAD based timing plane [V. Gkoukousis], reconstruction software [H. Schindler, T. Evans]
- **Collaboration** with Nikhef, Uni. of Santiago, Uni. of Oxford, Uni. of Dortmund, Uni of Manchester
- **AIDA-innova** WP.3 task 3.3 will derive from it (1 to 2 TPX4 planes for EUDET telescope)

Upgrade with the 16ch board

contact persons: V. Gkougkousis, E. Cid Lemos

16- Ch Base board

- 16-channel readout board with integrated 1st and 2nd stage amplifier
- SiGe Based with 12 GHz cut-off
- 10 mA per channel max current at < 1.3 mV noise
- 15 mm x 15 mm central opening with 140 mm x 140 mm outer dimensions
- Vertical miniaturized coaxial plug connectors for sensor board (16 channels + HV/RTD)

Total Gain:
70 - 38dB



10mV input → 687mV output

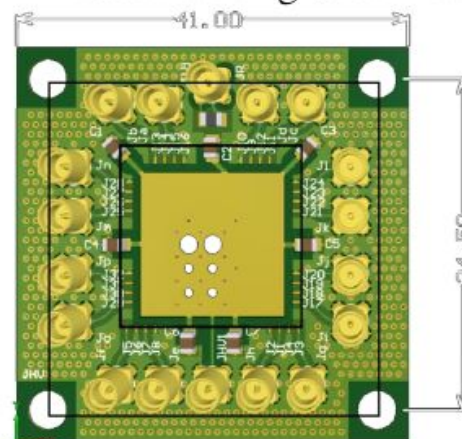
Estimated noise (high frequency domain): → 1 mv RMS

Multi-Channel Fast Readout - SAMPIC

- Technology: AMS 0.18 μ m
- Sampling: between 3 and 8.4 GS/sec on 16 channels
- 16 channels per chip
- Signal Bandwidth of 12 GHz
- Discrimination noise 2 mV, chip noise < 1.3 mV RMS
- Max input Signal: IV unipolar (0.IV to 1.IV)

Single sensor carrier board

- Quick sensor test turnaround
- Simplify probing, reduce damage
- Batch testing with better control



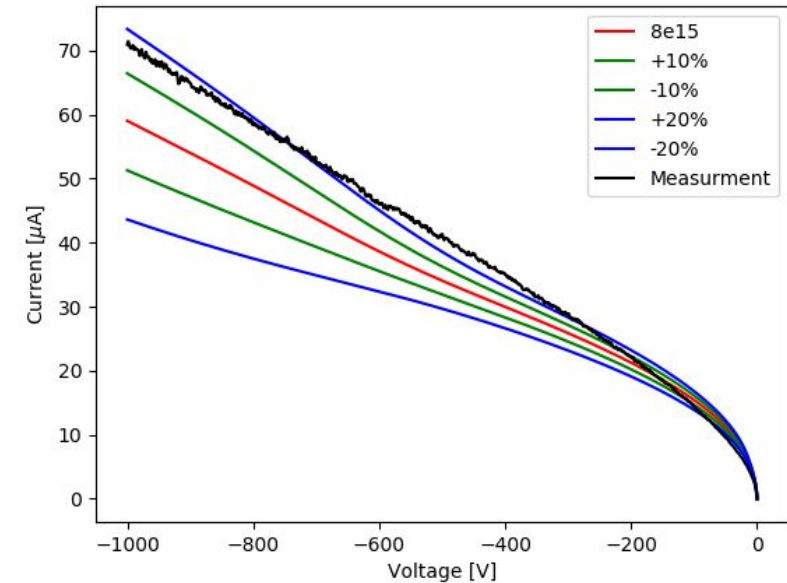
Simulation

Making sense of the measurement and helping design

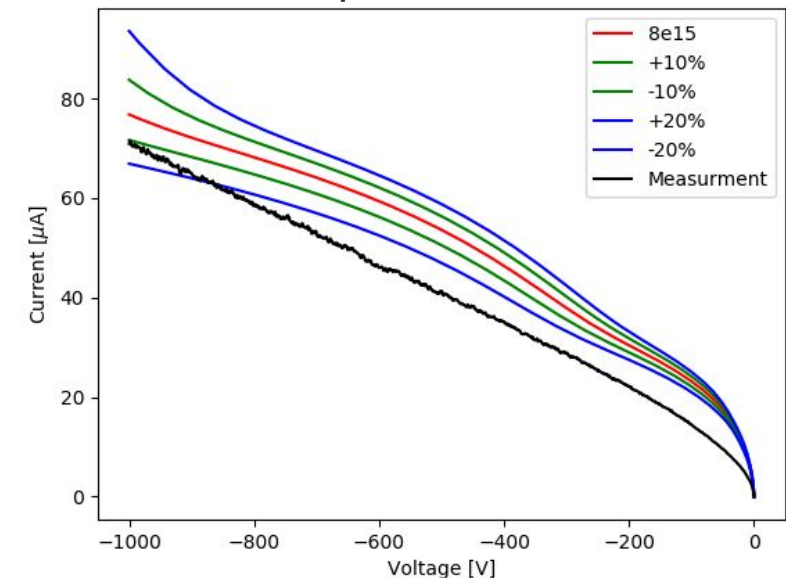
Motivation

- **MIP induced signal simulations is key component of sensor and IC design**
- Need two components:
 - device simulation (Synopsis TCAD): E field, current, rad. damage models etc...
 - MIP simulation (Garfield++)
- **Focus on time resolution estimation**
 - as function of fluence
 - for various geometries
- Uses the **test structures from planar sensor**
 - build some statistics
 - have a controlled design: NDA (ref. KC5204) signed to perform full process simulation, and **publish doping profile**
- Provide simulation inputs and measurement to the community

Penta Trap Simulation at 243K



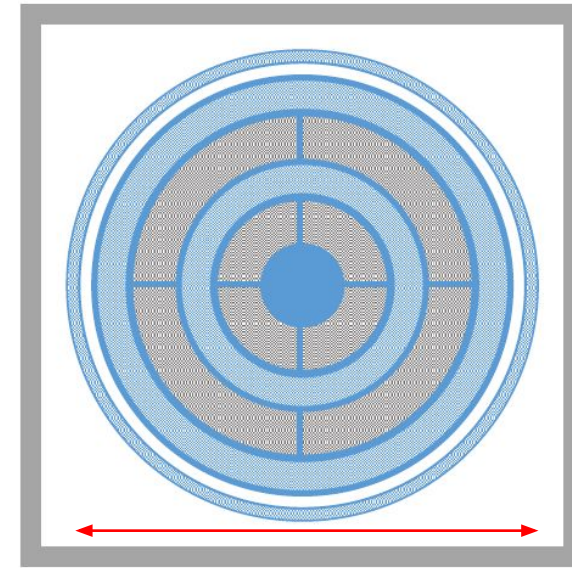
Tri Trap Simulation at 243K



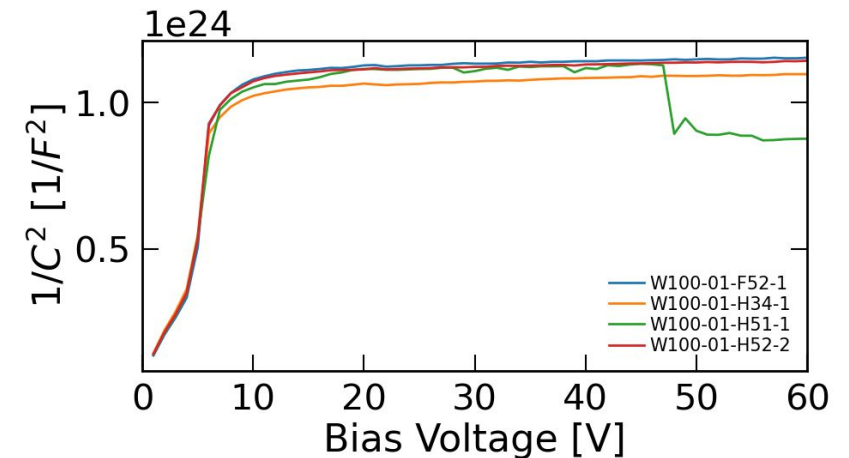
Measurement Campaign

contact persons: J. Haimberger

- **Diode test structures** for development of model
- 50, 100, 200, 300 μm thickness
 - impact of weighting field on timing
 - comparison with other types of detectors
- IV, CV and Charge collection measurements
 - Extract induced **signal shape**, **total charge** and **time resolution**
 - 60% of unirradiated IV/CV measured
- **Neutron** and **proton** irradiation for fluences from 10^{13} to $10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$
 - irradiation campaign to start begin of next year
- **4 Diodes** per point



1 mm diameter

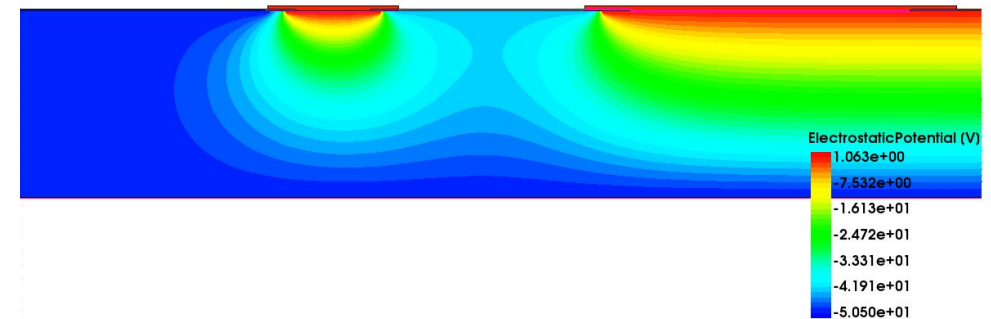
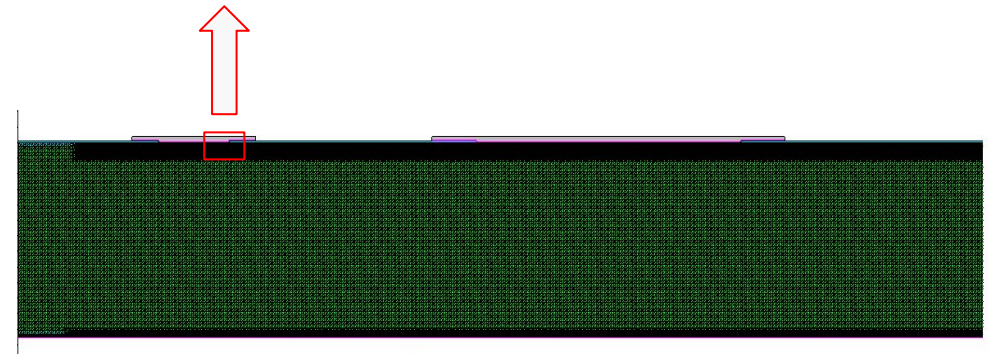
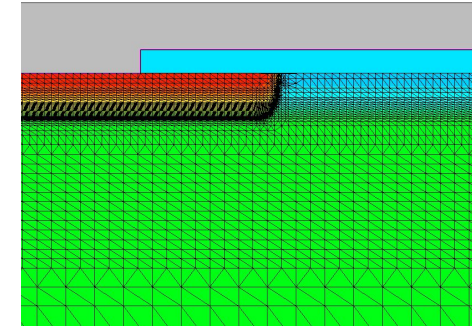


Device simulation

TCAD

contact persons: J. Haimberger

- Diode simulation
 - Large volume to simulate -> compromises have to be made
 - Currently **optimizing mesh size** for different thicknesses to reduce simulation time and still converge with the simulation
- Radiation damage
 - Modeled through **traps** which increase concentration with fluence
 - Exporting **trapping probability field** to Garfield++ by calculation it for each mesh point out of trap cross section and concentration



MIP induced signal simulation

Garfield++

contact persons: M. Halvorsen, H. Schindler

- Time resolution principles see “[W. Riegler et. al, Time resolution of silicon pixel sensors](#)”
- Time resolution from MIP with Garfield++ simulation:
 - Different thickness and sensor geometries
 - Different front-end electronics
 - See “[Time Resolution Study using Garfield++](#)”

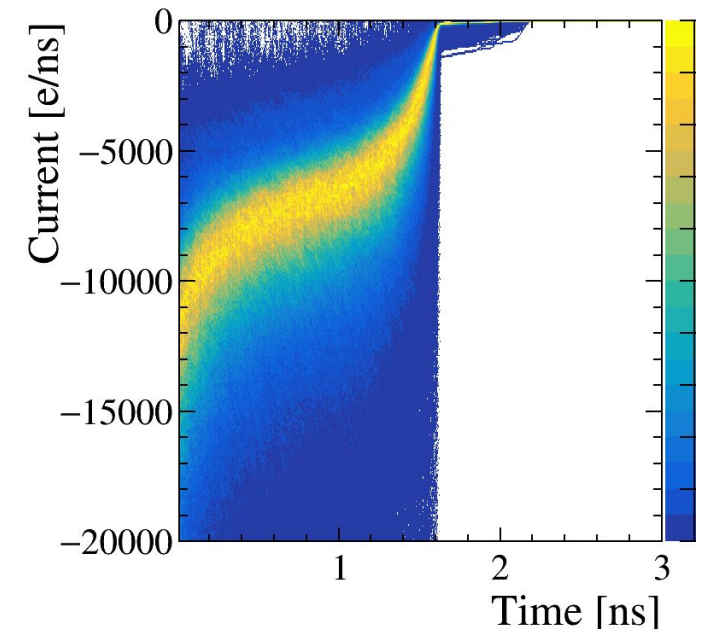
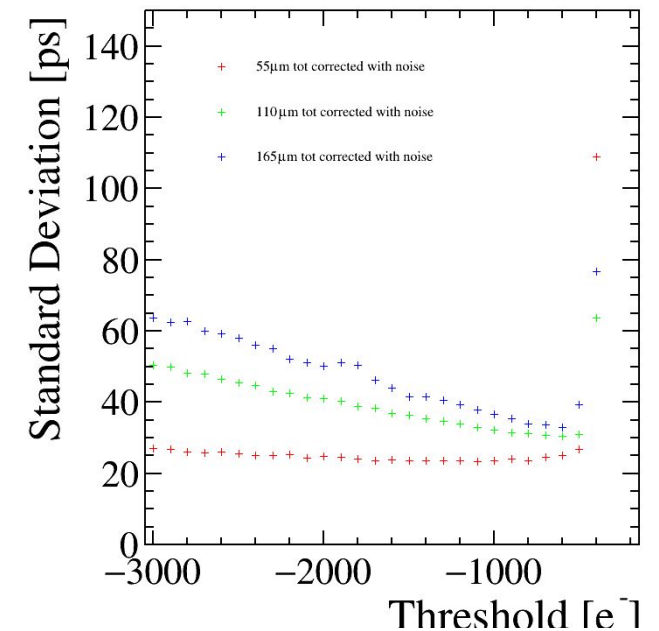
(Rita Silva, summer student)

- Under development:
 - Timing after irradiation (introduction of traps)

Input for IC design:

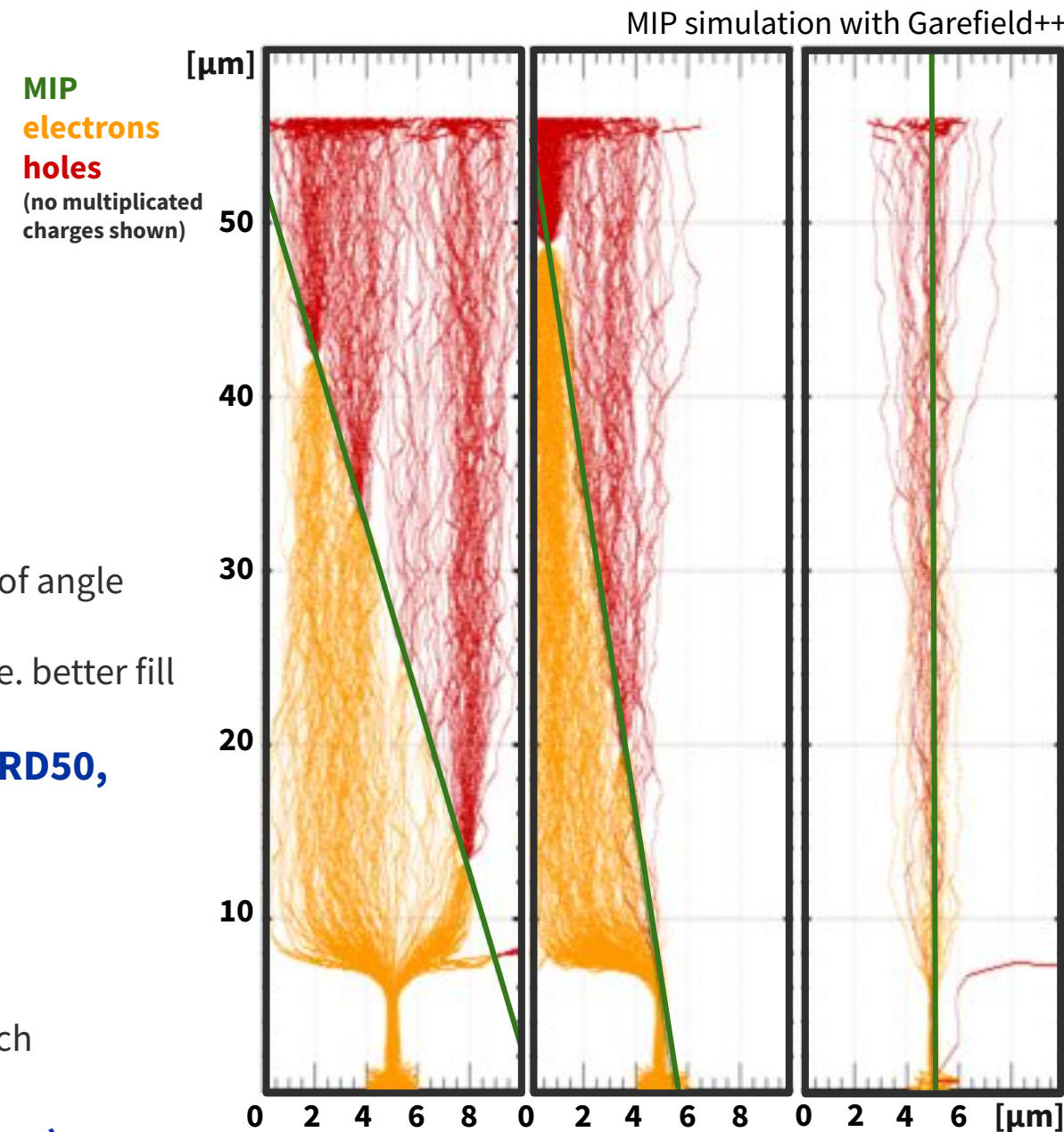
- capacitance and total charge for various sensors
- induced current time distribution

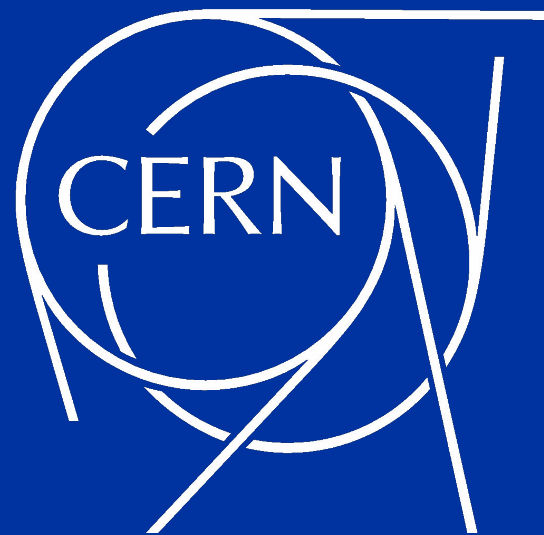
to be used by analog FE designer (R. Ballabriga Sune, V. Sriskaran)



Outlook

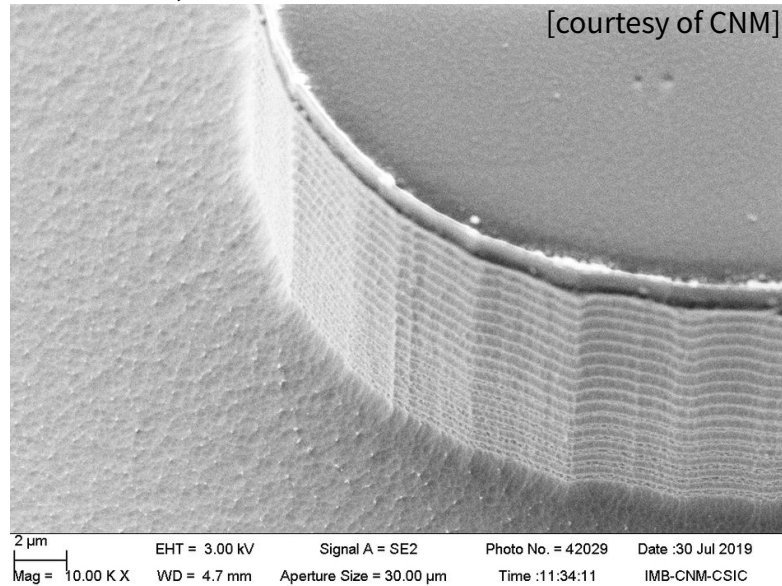
- **Planar sensor production completed**
 - Characterisation and simulation on-going
- **Several studies of sensor with internal gain**
 - Defect engineering for LGAD radiation hardness
 - iLGAD production to reach small segmentation
 - New approach to internal gain with SiEM investigated
- **3D technology investigation started**
 - Test beam campaign to measure time resolution as function of angle and intra-pixel position.
 - Next year focus on 3D production, towards smaller column (ie. better fill factor, smaller pitch)
 - **Will investigate synergies with other projects (RD50, AIDA-innova, Timespot,)**
- **Next year we start the IC side of the hybrid sensor**
 - 28nm Analog FE design targetting 30ps resolution and small power/footprint
 - Toward a small scale R&D ASIC for fast sensors with small pitch
 - **Will investigate synergies with other projects (AIDA-innova, EP-ESE, LHCb U2, NA62 upgrade,...)**





SiEM: Possible production process

contact persons: M. Halvorsen, V. Coco

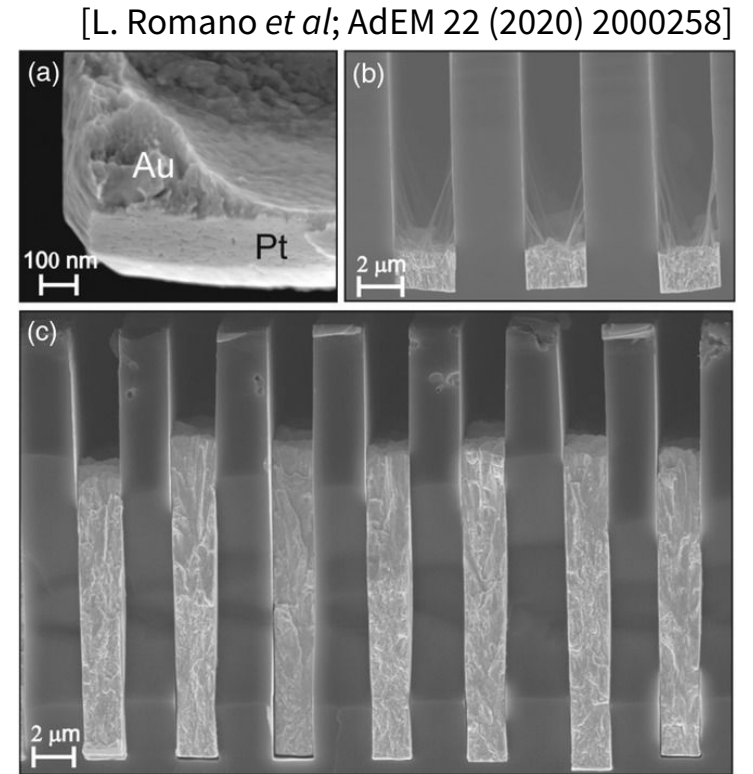


DRIE based

- what topology can really be achieved?
 - electrode/wall guard, thickness of oxide, corner shapes...
- electrical properties?
 - SiO_2/Si interface, scalloping, ...
- homogeneity of the production?
- performances

Production study to start in 2022

[submitted proposal to AIDA-innova blue-sky R&D, may need to find extra partners / funding otherwise]



Metal assisted etching

- less “production ready”
- more appropriate for single electrode structure
- no more constraints on the guard
- could be simpler

To be investigated further

[preparing collaboration agreement with PSI]

LGADs with Indium and Lithium Implantations

contact persons: V. Gkougkousis

Gkougkousis V. , 16th Trento Workshop (2021): [link](#)

- **LGADs** susceptible to **radiation damage**
 - follow up on B, B+C and B+Ga studies (see slide xxx)
- **Indium** implantation
 - Higher mass, less prone to lattice dislocations
- **Lithium** co-implant.
 - Boron with Lithium co-implantation demonstrates better neutron radiation hardness
 - Lithium's **light mass**, and increased **electronegativity** favour formation of Li_iO_i rather than B_iO_i
- **Implantation energy and doping profiles already optimized via TCAD simulations**
 - **Multiple wafer production variants** and **irradiation** campaigns are planned
- **Common RD50 founded project with CERN, CNM & JSI**
(RD50-2021-03)

