Advancement and Innovation for Detectors at Accelerators

Report from WP13 Prospective and Technology-driven Detector R&D

AIDAinnova Annual Meeting, Catania, March 20, 2024

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J. Stefan Institute and University of Ljubljana

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Projects

- Thin Silicon Sensors for Extreme Fluences

Make Si sensors radiation tolerant by using a thin bulk, internal amplification and using a gain implant that would withstand a factor of 50 higher fluences than what is presently available.

- The Silicon Electron Multiplier, a new approach to charge multiplication in solid state detectors

Make Si sensors radiation tolerant by a novel biasing method – electrodes embedded in silicon.

- Development of fine-sampling calorimeters with nanocomposite scintillating materials

Develop a new generation of fine-sampling calorimeters that use innovative scintillating materials based on perovskite nanocrystals dispersed in a plastic matrix to form fast (~100ps) and radiation resistant (~1 MGy) scintillators.

- Wireless Data Transfer for High-Energy Physics Applications

Develop mm-wave-based wireless communication as an alternative to optical and wired links in a HEP-like environment to reduce the material and optimize the read-out.

Project: eXFlu-innova

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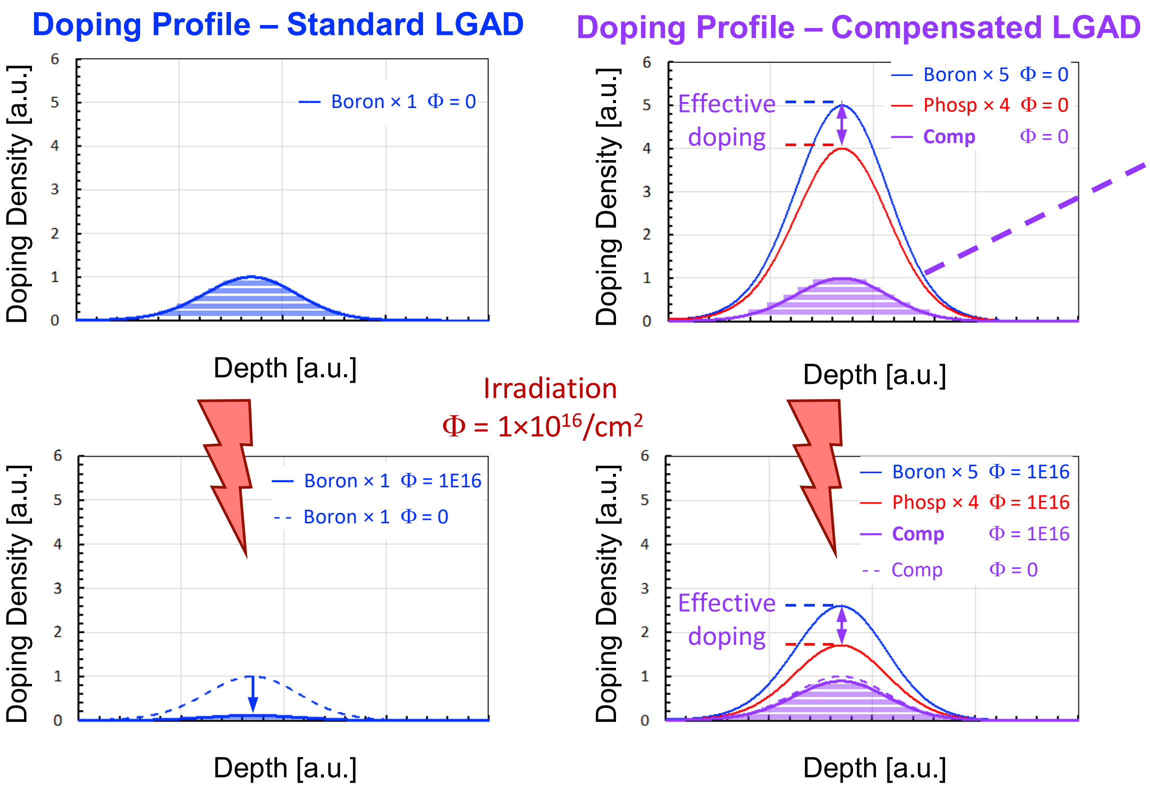
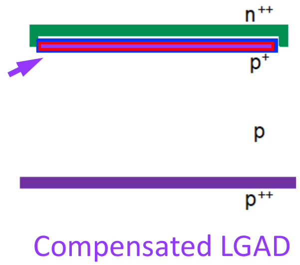
The principle: compensation with two dopants





Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density

Many unknowns:

- donor removal coefficient, from $n^+(\Phi) = n^+(0)\cdot e^{-c_D\Phi}$
- interplay between donor and acceptor removal (c_D vs c_A)
- effects of substrate impurities on the removal coefficients

Compensated Gain Layer Design – Split Table

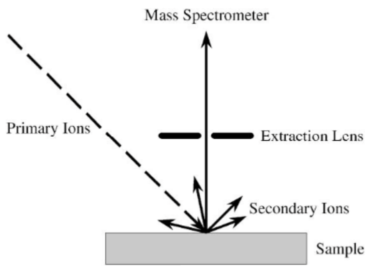
3 different combinations of $p^+ - n^+$ doping: 2 – 1, 3 – 2, 5 – 4

Active thickness 30 μm

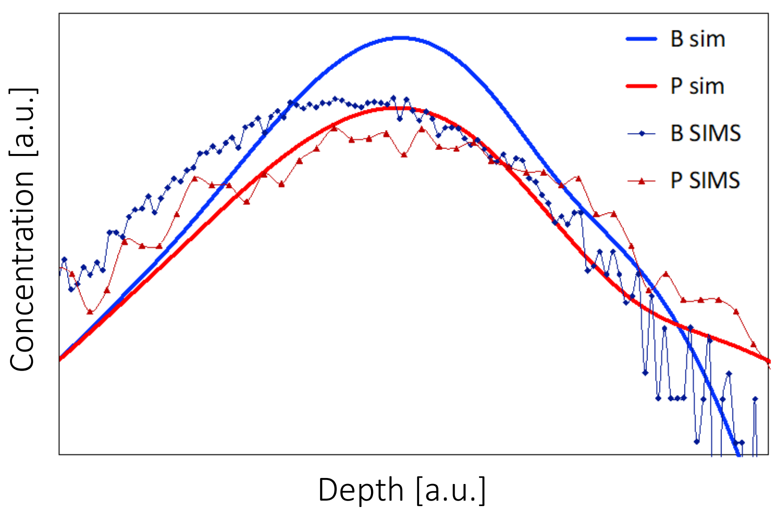
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

[a < b < c]

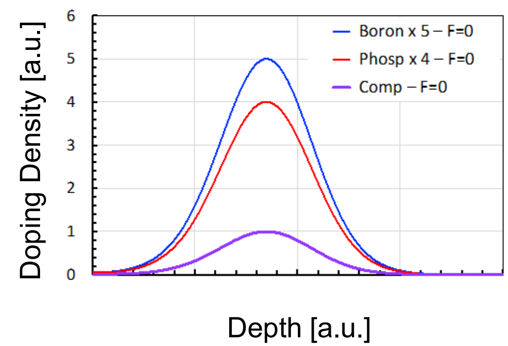
Checking the doped sample: Secondary Ion Mass Spectroscopy vs. planned profile



Compensated LGAD – W15 5-4
SIMS vs Process Simulation



Doping Profile – Compensated LGAD

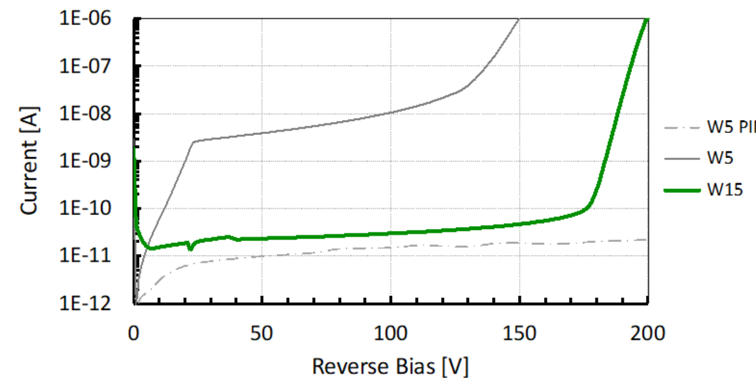


Planned: Boron:Phosp 5:4

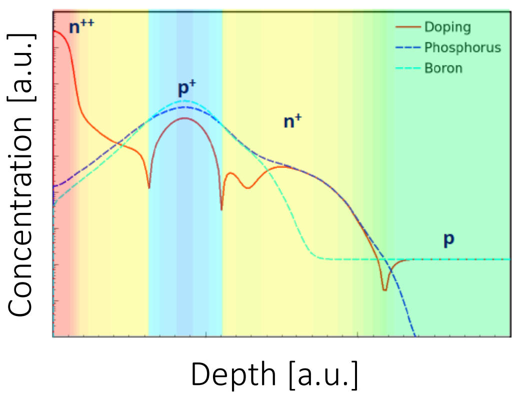
- Boron peak is shallower than phosphorus (profiles are not aligned)
- Boron peak is lower than predicted from simulation

SIMS Profile & I-V – 5–4

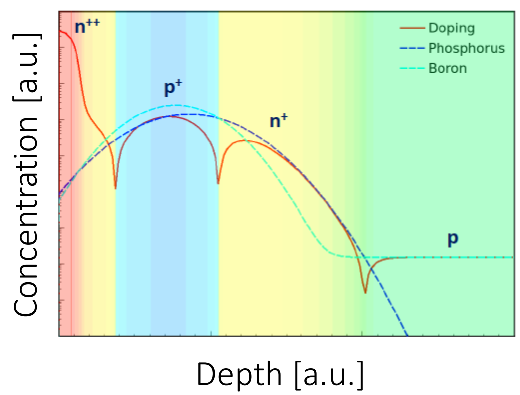
EXFLU1 – Compensated LGAD 5–4 – I-V



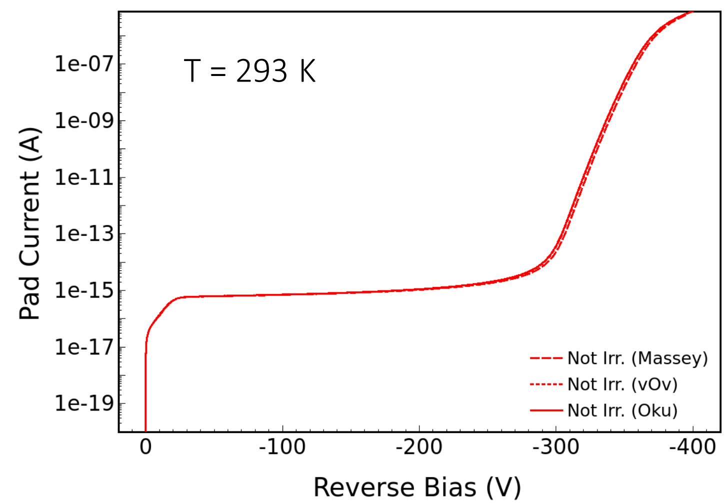
Doping Profiles
from Process Simulation



Doping Profiles
from SIMS



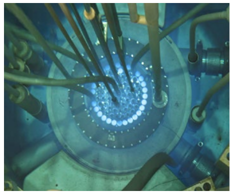
Simulated I-V from SIMS Profiles



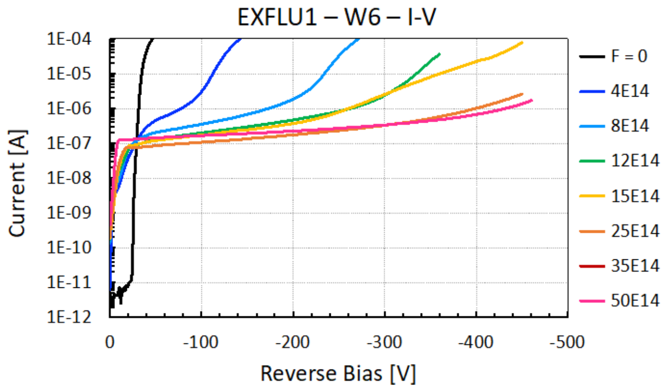
→ The simulated I-V reproduces the trend of the measured I-V from W15

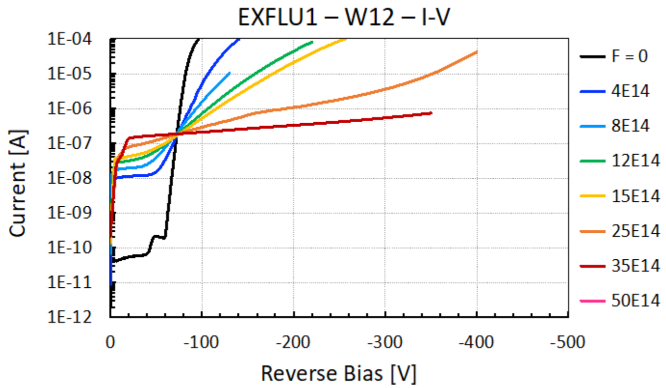
I-V from Compensated LGAD – Irradiated

Irradiated from 1E14 to 5E15 n_{eq}/cm^2



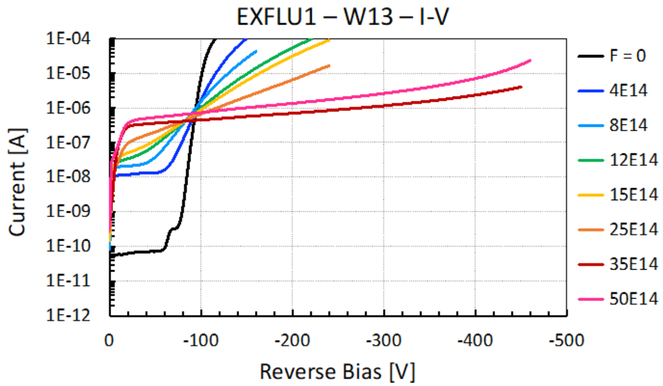
W6
2 – 1

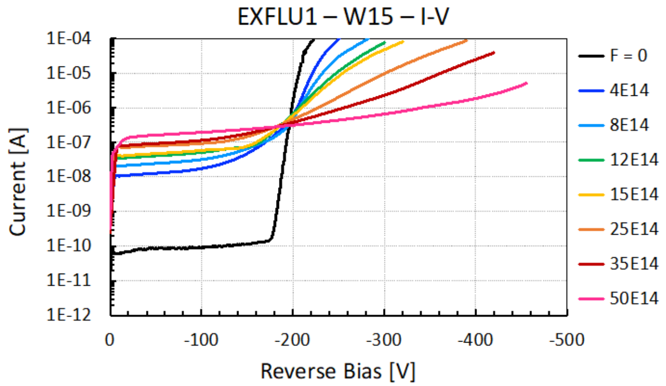




W12
3 – 2

W13
3 – 2 + C





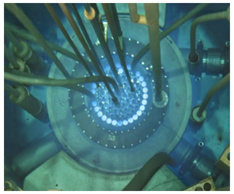
W15
5 – 4

$[\Phi] = n_{eq}/cm^2$

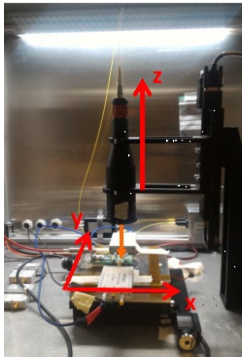
$T_{F=0} = + 20^oC$

$T_{IRR} = - 20^oC$

IR Laser Stimulus on Compensated LGAD

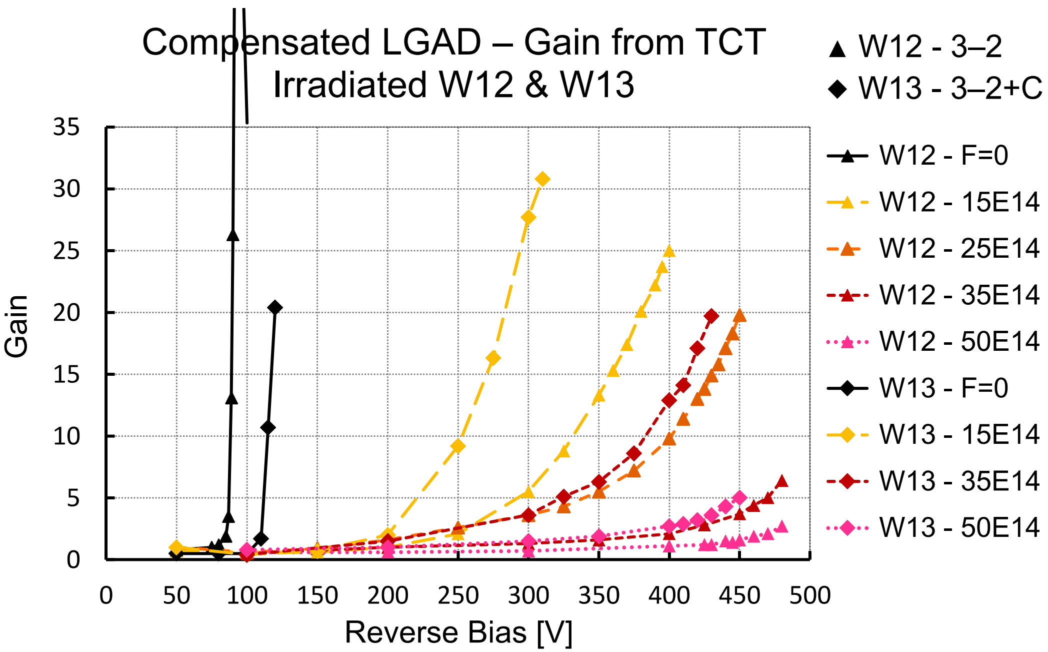


TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Laser intensity ~ 4 MIPs
T = -20^{o}C



Laser stimulus on a LGAD-PiN structures before and after irradiation

$$\text{Gain} = \frac{Q_{LGAD}}{< Q_{PiN}^{\text{No Gain}} >}$$



→ Good gain behaviour of the compensated LGAD sensors after irradiation

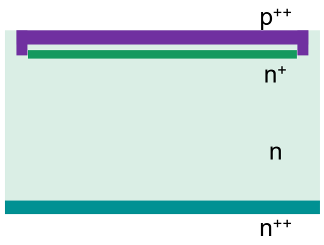
→ Even in compensated LGADs, **the usage of carbon mitigates the acceptor removal**

p-in-n LGAD to determine the donor-removal coeff.

A production batch is needed to study the donor removal coefficient, $\mathbf{c_D}$

Donor removal has been studied for doping densities of 10^{12} – 10^{14} atoms/cm^3

We need to study donor removal in the range of 10^{16} – 10^{18} atoms/cm^3



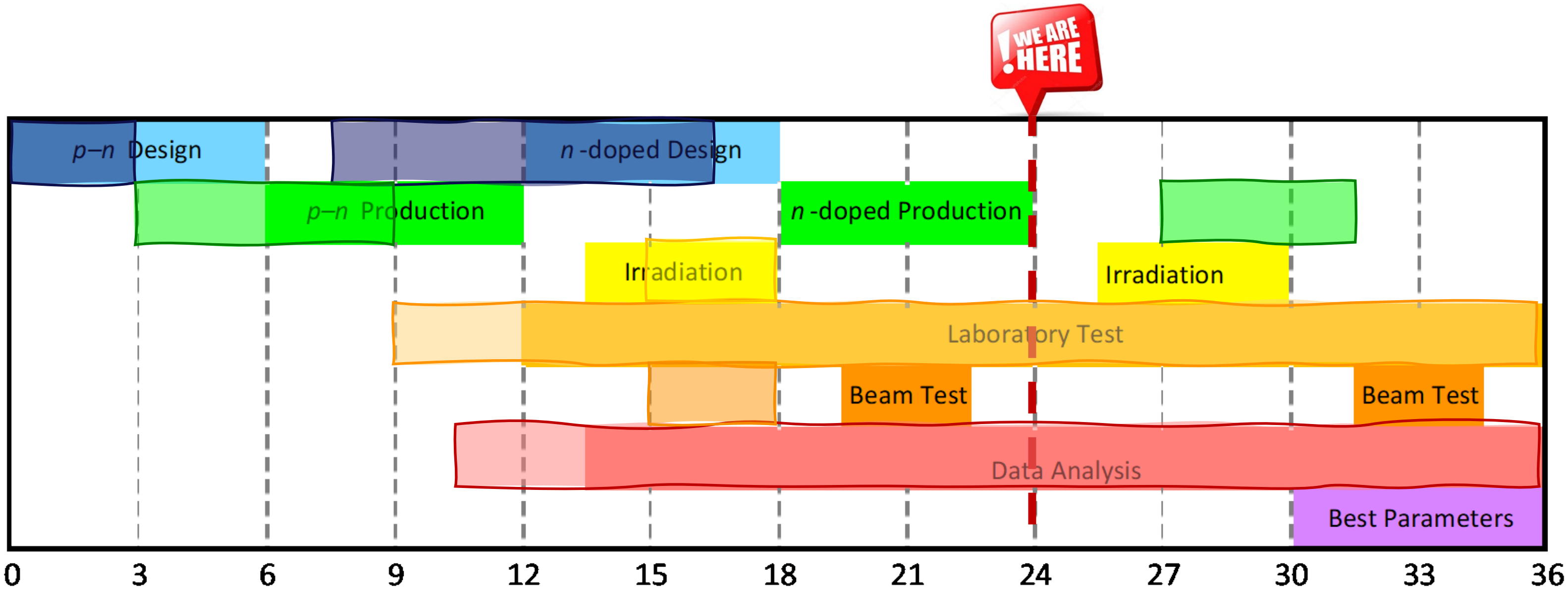
p-in-n LGAD

→ **The main goal of the p-in-n LGAD production is to study the c_D evolution and its interplay with Oxygen co-implantation**

NB: Oxygen has for donor removal a very similar effect of as carbon for the acceptor removal.

First and second p-in-n LGAD (NLGAD) batches produced by CNM

Project Flow



Deliverables:

1. **simulation and design** of the *p–n* compensated gain implant (M6) – DONE
2. **production** of *p–n* compensated sensors (M12) – DONE and *n*-doped sensors (M24) – WORK IN PROGRESS
3. **identifications of the best parameters** to manufacture compensated LGADs (M36) – pending

Colour code: fully coloured – planned, translucent – actual.

Summary on the eXFlu-innova

The eXFlu-innova activities are ongoing

- ▻ The p^+–n^+ design has been completed – Deliverable 1
- ▻ The p^+–n^+ production batch has been completed – Part of Deliverable 2
- ▻ The characterisation and testing on the p^+–n^+ sensors is almost complete
- ▻ The p-in-n LGAD batch is about to start

→ **Some delay in the eXFlu-innova activities**

An ERC Consolidator Grant awarded to further develop compensated LGAD sensors

Doping Compensation in Thin Silicon Sensors:
the pathway to Extreme Radiation Environments
CompleX

Project: SiEM

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Develop a new generation of fine-sampling calorimeters that use innovative scintillating materials based on perovskite nanocrystals dispersed in a plastic matrix to form fast (~100ps) and radiation resistant (~1 MGy) scintillators.

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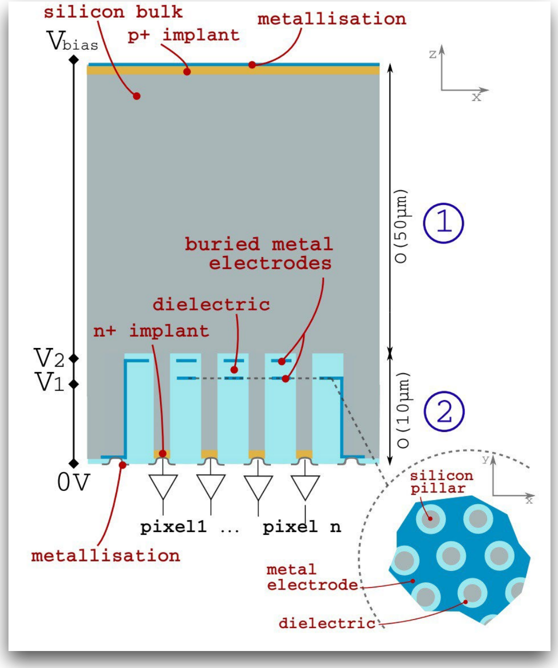
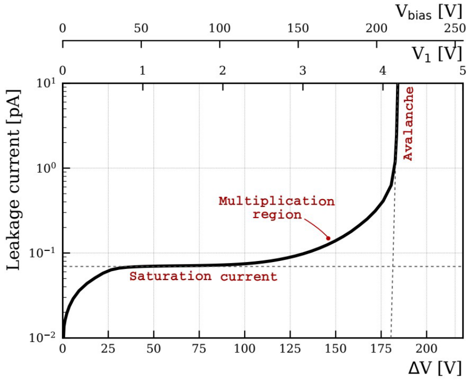
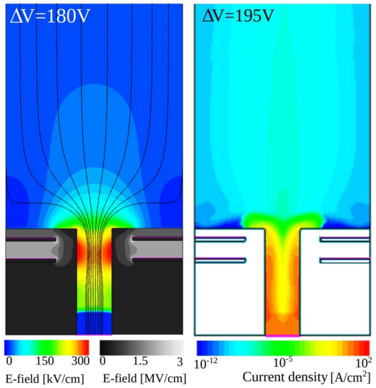
Develop mm-wave-based wireless communication as an alternative to optical and wired links in a HEP-like environment to reduce the material and optimize the read-out.

Silicon Electron Multiplier (SiEM) principle

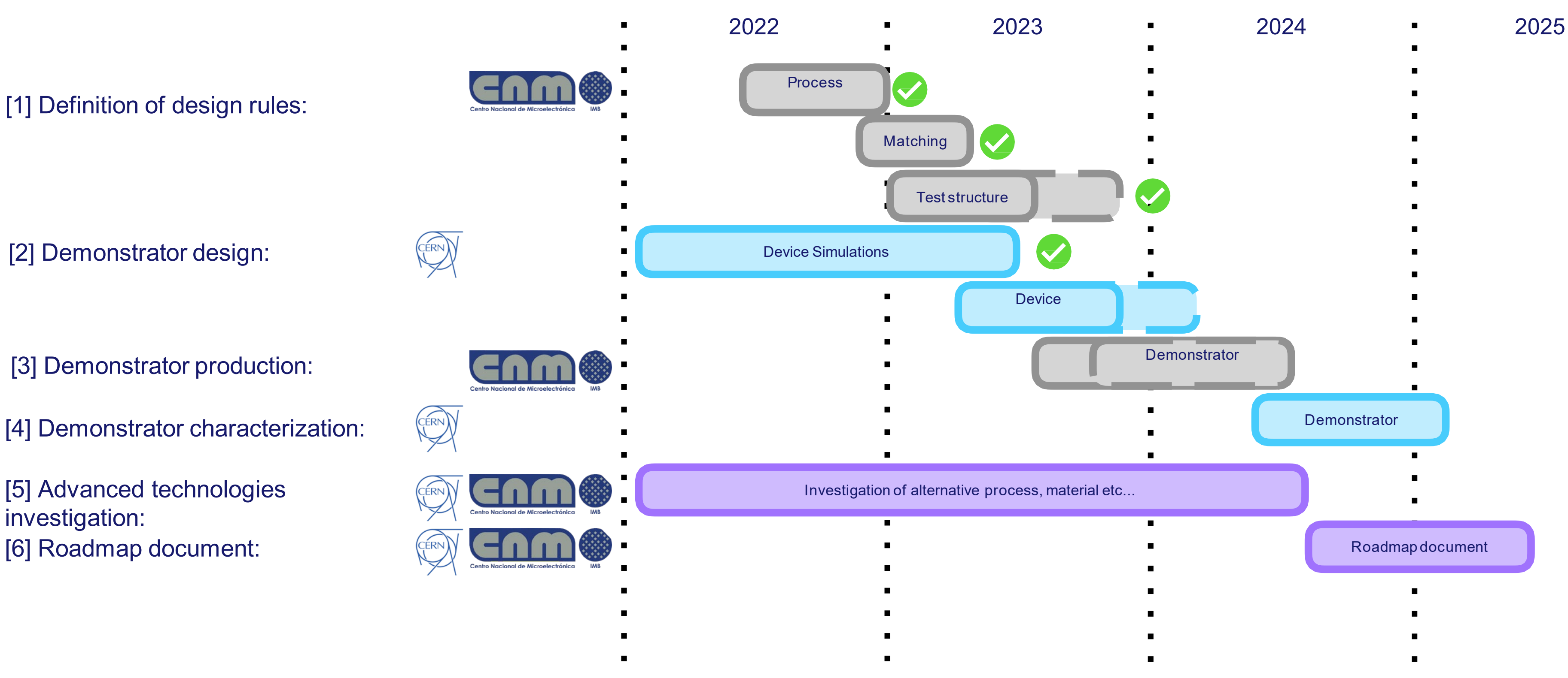
- The Silicon Electron Multiplier (SiEM) is a novel sensor concept.
- Internal gain and fine pitch --> excellent time and spatial resolution.
- Divided in two regions: 1. conversion and drift layer, 2. amplification layer.
- Gain mechanism --> impact ionization applying a ΔV in embedded electrodes deposited in a trench, surrounding a Si pillar.
- No gain-layer deactivation is expected with radiation damage, expected to withstand fluencies up to 10^{16} neq/cm^2.







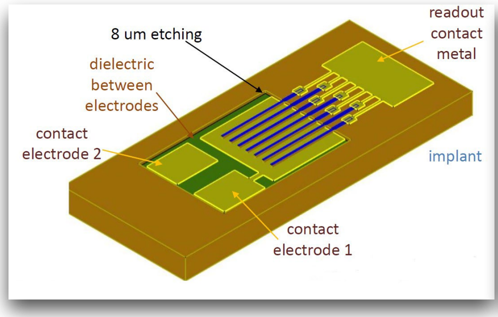
PLANNING TOWARDS DEMONSTRATOR

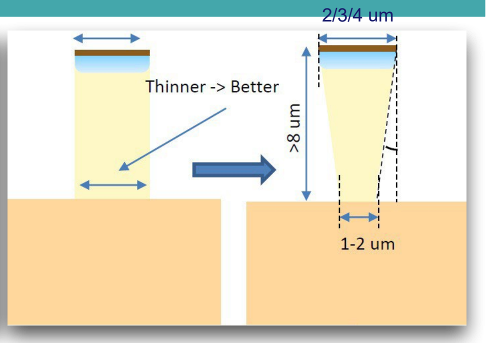


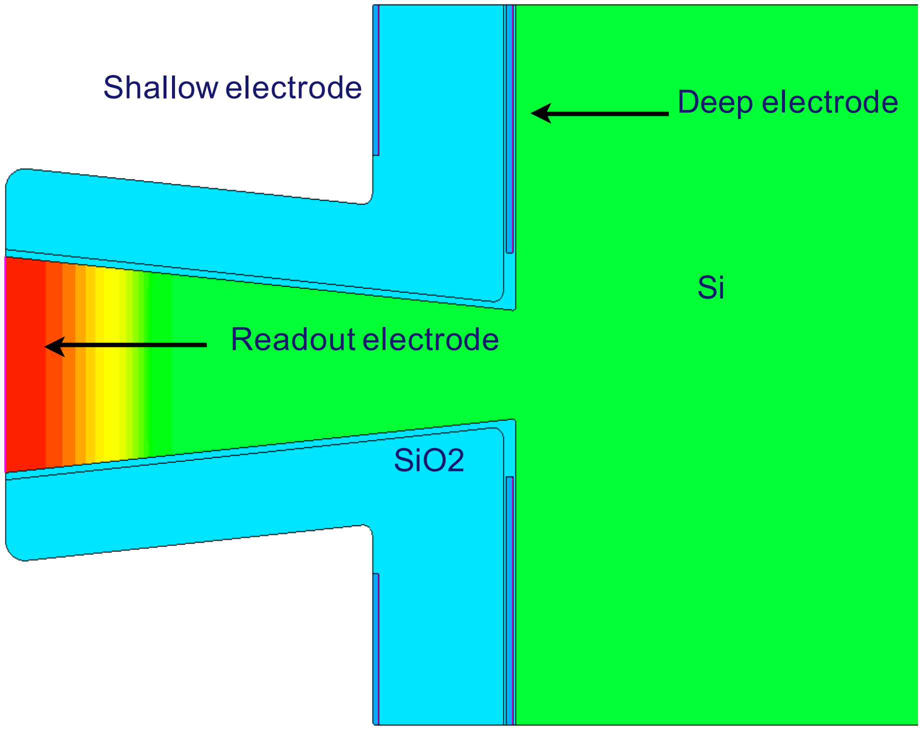
Demonstrator: process based on DRIE - Deep reactive ion etching

DRIE DEMONSTRATOR
(Deep reactive ion etching)

- **Demonstrator as a PoC manufactured by CNM.**
  - Strip with two embedded electrodes design, wire bond pads connect strips in parallel.
- **Trenches:**
  - Laser photolithography, Si trenches etched (DRIE - Deep reactive ion etching).
- **Electrode deposition:**
  - ALD 50 nm HfO_2, metal deposition, ALD 50 nm HfO_2, SiO_2 deposition, electrode 2.
- **Challenges:**
  - The oxide layer can induce stress, limiting the gap between electrodes 1 and 2.
  - Etching limited in width depending on the patterning process used:
    - Laser photolithography down to 2 um.
      - Fast prototyping and good flexibility.
      - *Require pyramidal profile to achieve best multiplication performance.*
    - Electron beam lithography (adjustment needed).

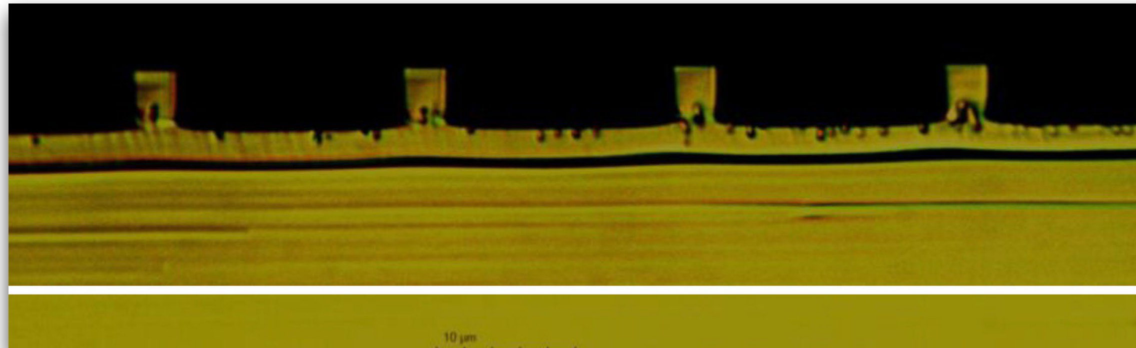


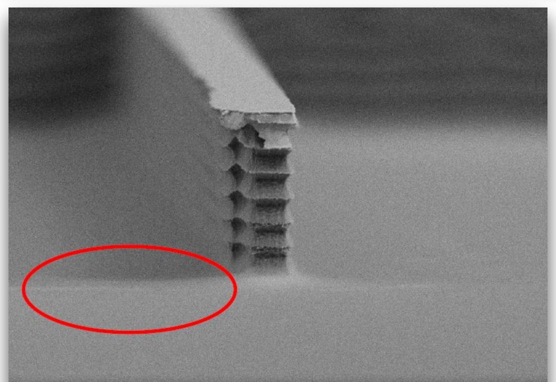


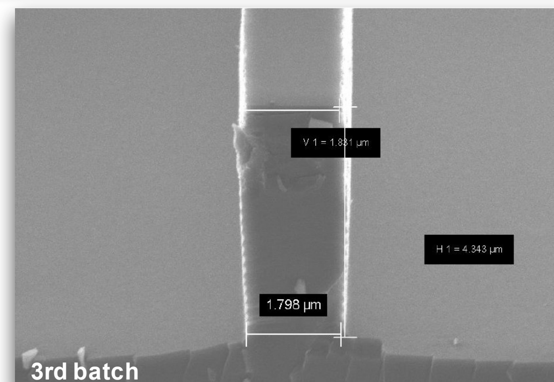


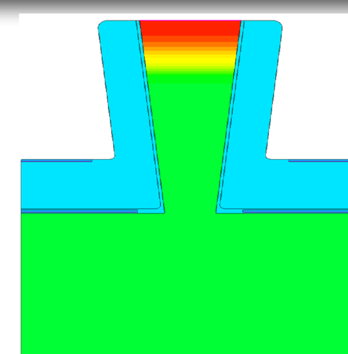
DRIE ITERATIONS

- **1st batch over etched:**
  - Trench 25 um instead of 8 um.
- **2nd batch improved etching:**
  - Test B: 9 um, test C: 8.41 um.
  - Pillars thinner than nominal 1.7 um, some were broken.
  - No pyramidal shape.
- **3rd batch closer to specs:**
  - Pyramidal shape achieved but rough walls.
  - Slightly over etched due to thin photoresist (unexpected).
  - Curved profile at the pillar base due to etching.
- **Recipes closer to the goal profile:**
  - May require minor adjustments.
  - Some curved profile in the base from etching process.
  - Goal is to achieve 2/3/4um on top and 1um on bottom.



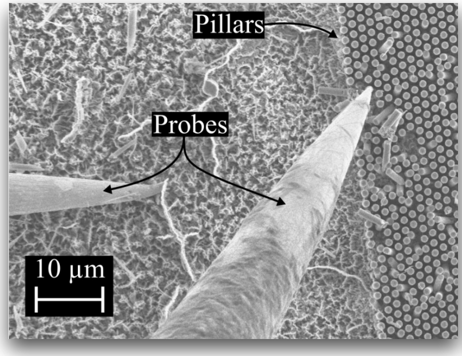


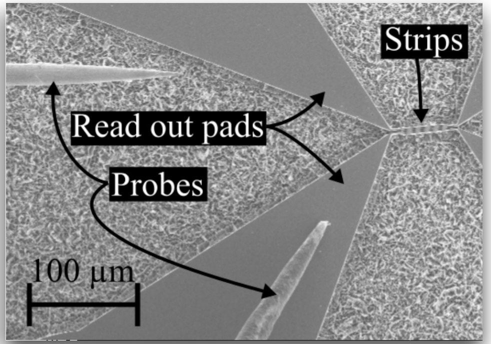


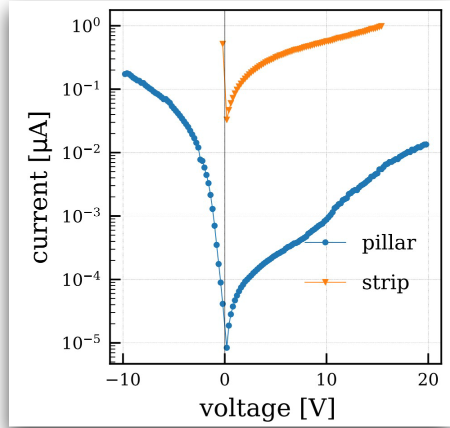


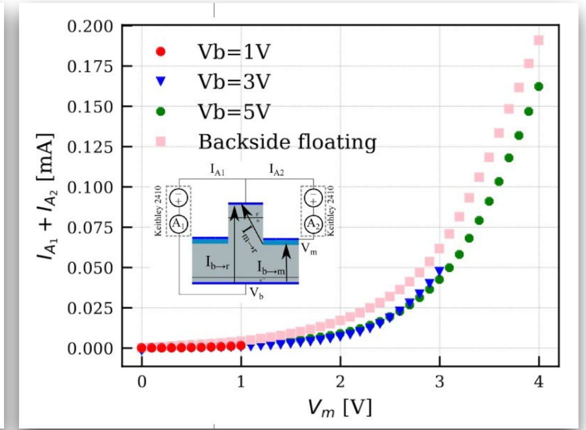
ADVANCED TECHNOLOGIES INVESTIGATION - MACETCH

- **Study possible use of Metal assisted etching:**
  - Parallel project between CERN and PSI, based on AdEM 22 (2020) 2000258.
  - Very different process constraints (cheap, high aspect ratio, first electrode deposited while etching).
  - Fast development.
  - Samples manufactured on n on p wafers
  - One gain electrode structure with metal in contact with Si (no SiO2).
  - Strips and pillar geometries.
  - Published NIM A 1060 [2024] 169046









- **Testing the structures:**
  - IV just after production with probe station pn junction conserved.
  - Bonding of test structures to a carrier board.
  - IV done in the lab using 16 Channel board V1 from backside electrode and multiplication electrode.
  - Preparing setup for laser/test beam.

SiEM: SUMMARY AND OUTLOOK

- Electron Multiplier concept on Silicon Radiation allows charge multiplication, not relying on high doping implantation.
- Mechanism depends on geometry only --> not sensitive to acceptor removal.
- Additional geometries under simulation to match CNM production process.
- CNM DRIE demonstrator production is ongoing, the first samples expected in a few months.
- Alternative approaches to the SiEM geometry are being studied using metal assisted etching.
- Lab characterization setup to be prepared and commissioned (laser and 16 channel boards).
- Integration with TimePix4 telescope under study.

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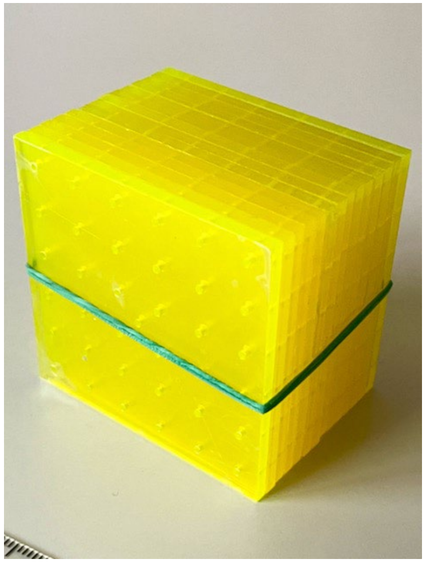
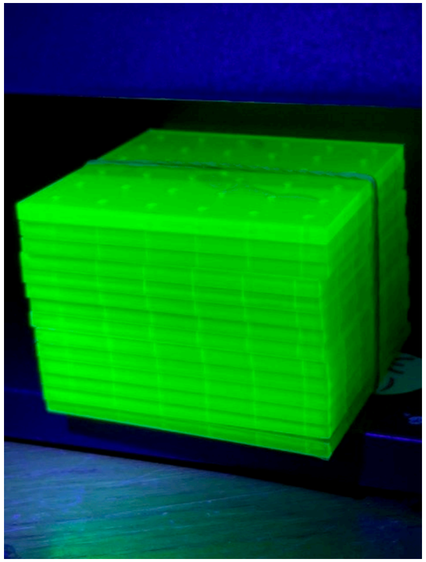
Nanomaterial composites (NCs)





Semiconductor nanostructures can be used as sensitizers/emitters for ultrafast, robust scintillators:

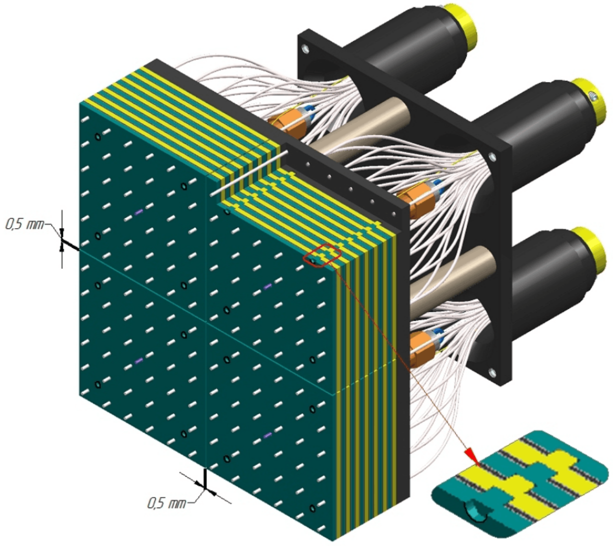
- Perovskite (ABX_3) or chalcogenide (oxide, sulfide) nanocrystals
- Cast with polymer or glass matrix
- Decay times down to O(100 ps)
- Radiation hard to O(1 MGy)

Despite promise, **applications in HEP have received little attention to date**

No attempt yet to build a **real calorimeter with NC scintillator** and **test it with high-energy beams**

Shashlyk design naturally ideal as a test platform:

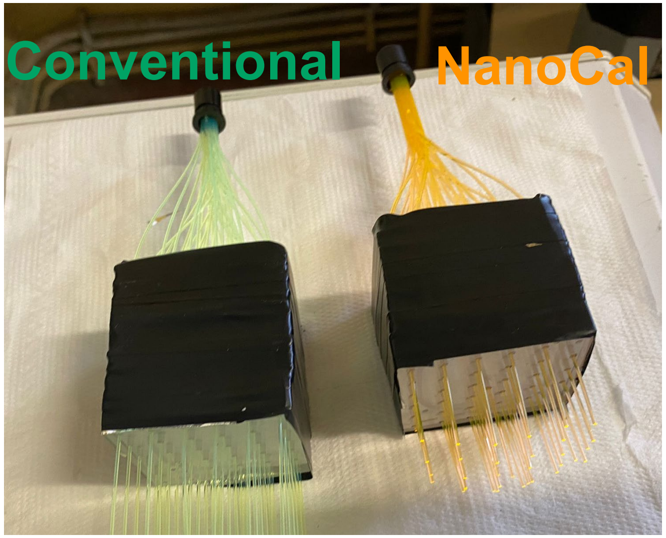
- Easy to construct a shashlyk calorimeter with very fine sampling
- Primary scintillator and WLS materials required: both can be optimized using NC technology



KOPIO/PANDA design
Fine-sampling shashlyk

Schedule:

- **Oct 2022: First shashlyk component test at CERN: fibers/tiles/SiPMs**
- **2023**: Further iterations to improve performance of NC scintillator prototype
- **2024:** Construction of full-scale shashlyk modules; performance comparison



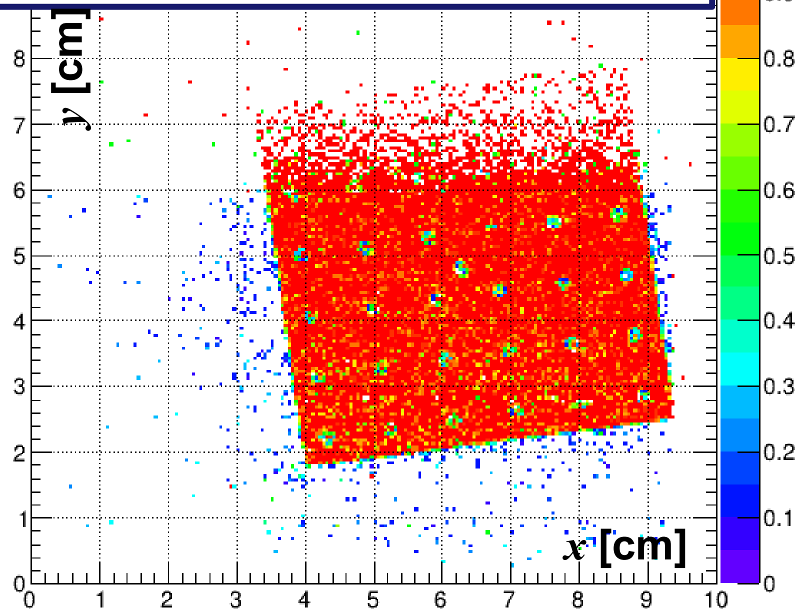
2 prototypes with 12 fine sampling layers

$1.3X_0$ in depth: MIP deposit = 10 MeV

Known formulation for NC scintillator:

- 0.2% $CsPbBr_3$ in UV-cured PMMA
- 50% of light emitted with $\tau < 0.5$ ns

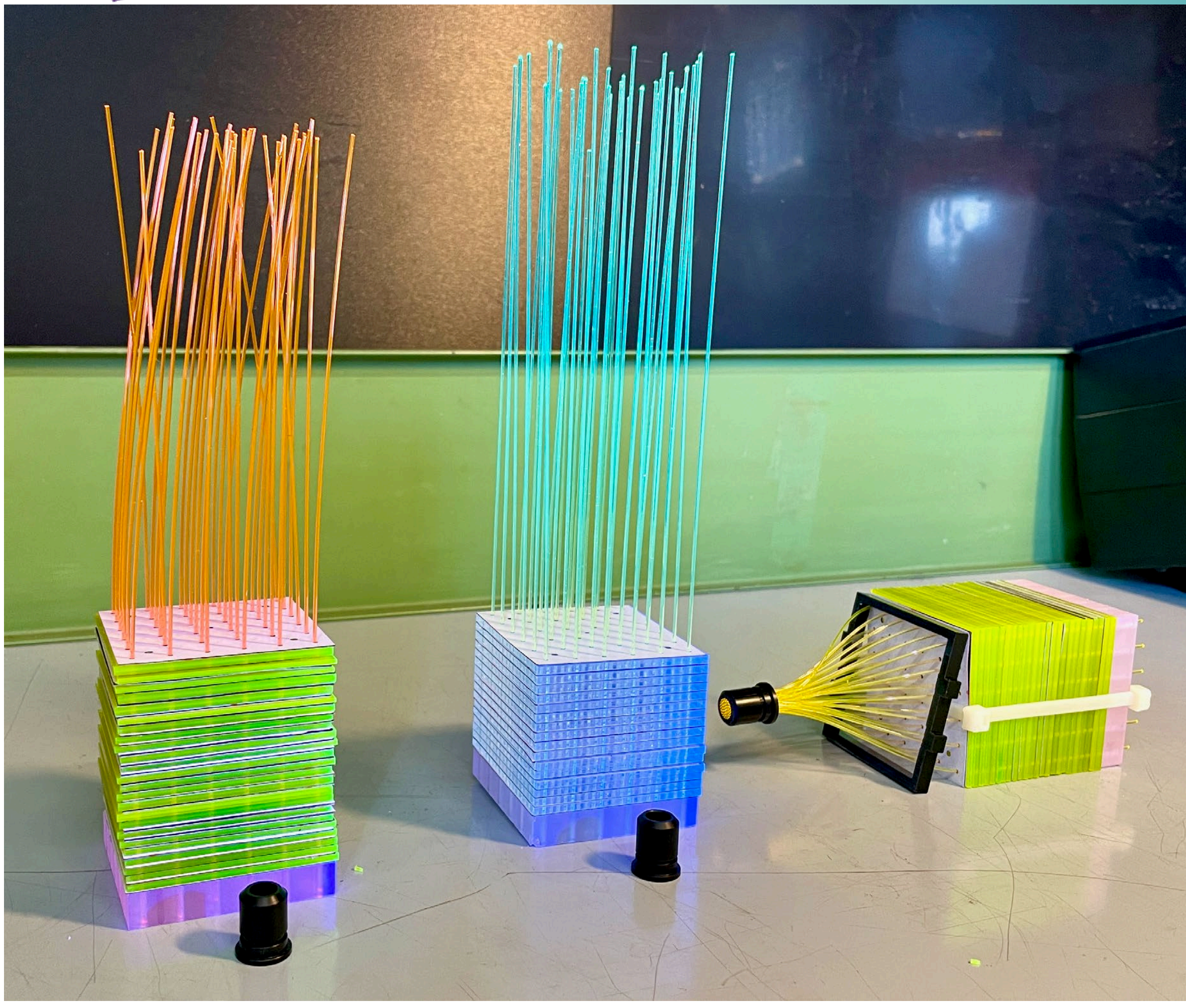
Oct 2022 test: SPS H2 beamline
e^- and π^+ with beam tracking



Conclusion of 2022 test:

NC prototype seems to work but with low light yield and many open questions

New prototypes for summer 2023 tests



Prototypes tested in PS T9, June 2023:

- Conventional scintillator (Protvino), Y-11 fibers
- Conventional scintillator (PVT + BTP 0.02%), Y-11 fibers
- PMMA + $CsPbBr_3$ 0.2%, O-2 fibers
- PMMA + $CsPbBr_3$ 0.2%, custom NCA-1 fibers
- PMMA + $CsPb(Br,Cl)_3$ + coumarin-6, NCA-1 fibers

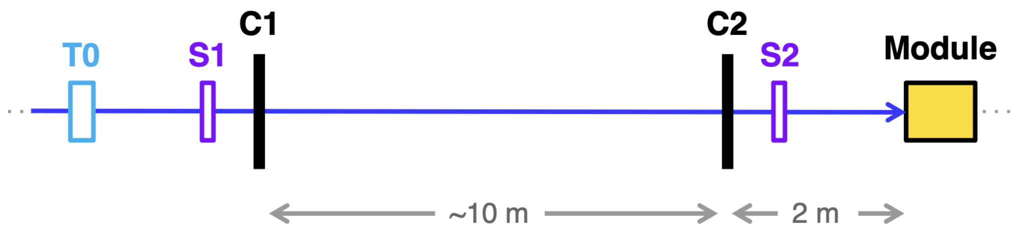
NanoCal setup and T9 test results

Electron beam, 1, 2, 4 GeV
MIP beam (μ^- or π^-), 10 GeV
Cerenkov ID for $e/\mu\pi/p$

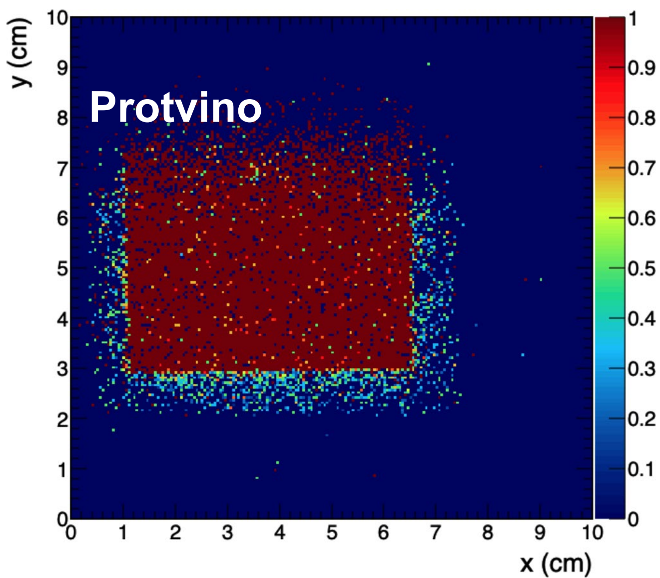
For each prototype:

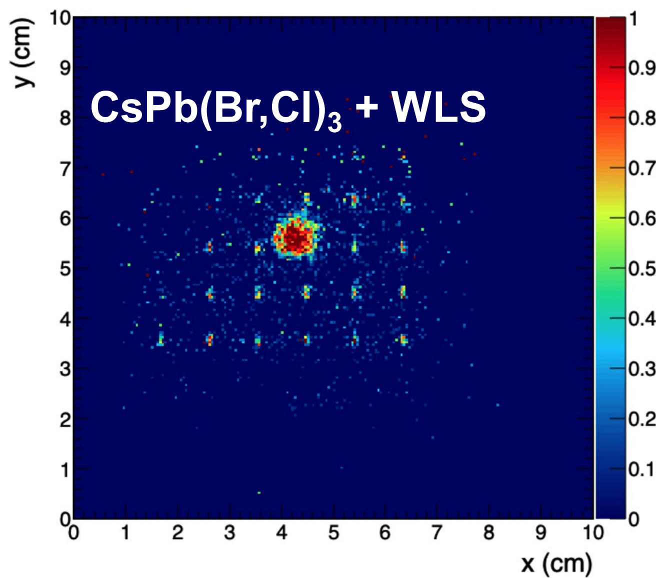
- MIP response, efficiency
- e^- response
- Time resolution

T0	Time reference detector
S1, S2	Trigger scintillator paddles
C1, C2	Si strip tracking chambers, 10×10 cm^2
Module	Module to be tested



Efficiency maps with 10 GeV μ, threshold = $5\sigma_{noise}$
Disappointing result from new nanocomposite: only light is from readout fibers!



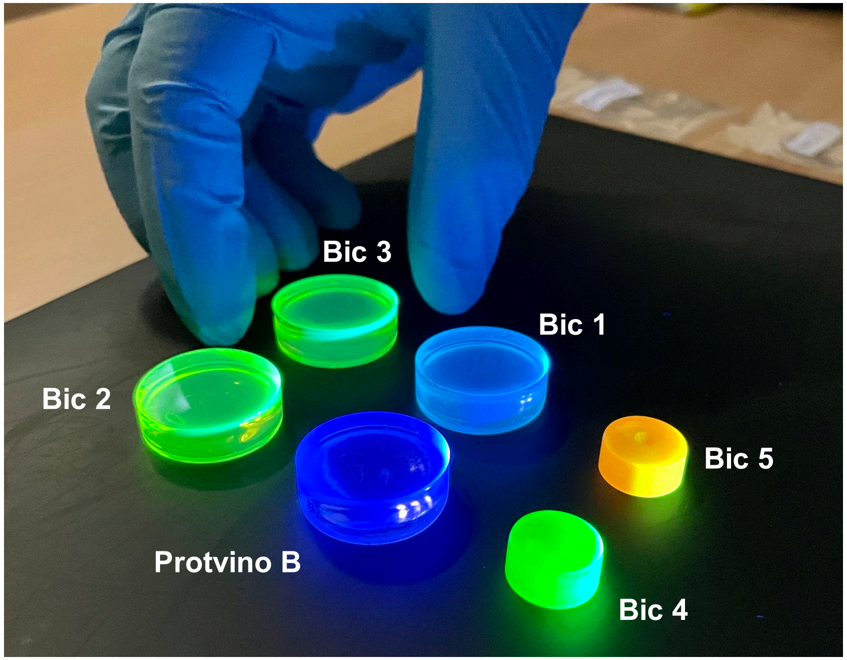


New samples for fall 2023 tests

Still many good ideas for the next steps

- Direct synthesis of $CsPb(Br,Cl)_3$ to preserve surface passivation
- Use of an aromatic matrix material, e.g., PVT as in conventional scintillator
  - First formulations use PMMA: gives no primary scintillation contribution
  - Now have new protocol to use perovskites with thermally polymerized matrix, with or without additional WLS

New samples synthesized and tested in fall 2023:



All samples 90:10 PVT/DBV matrix with 1.5% PTP as primary dye

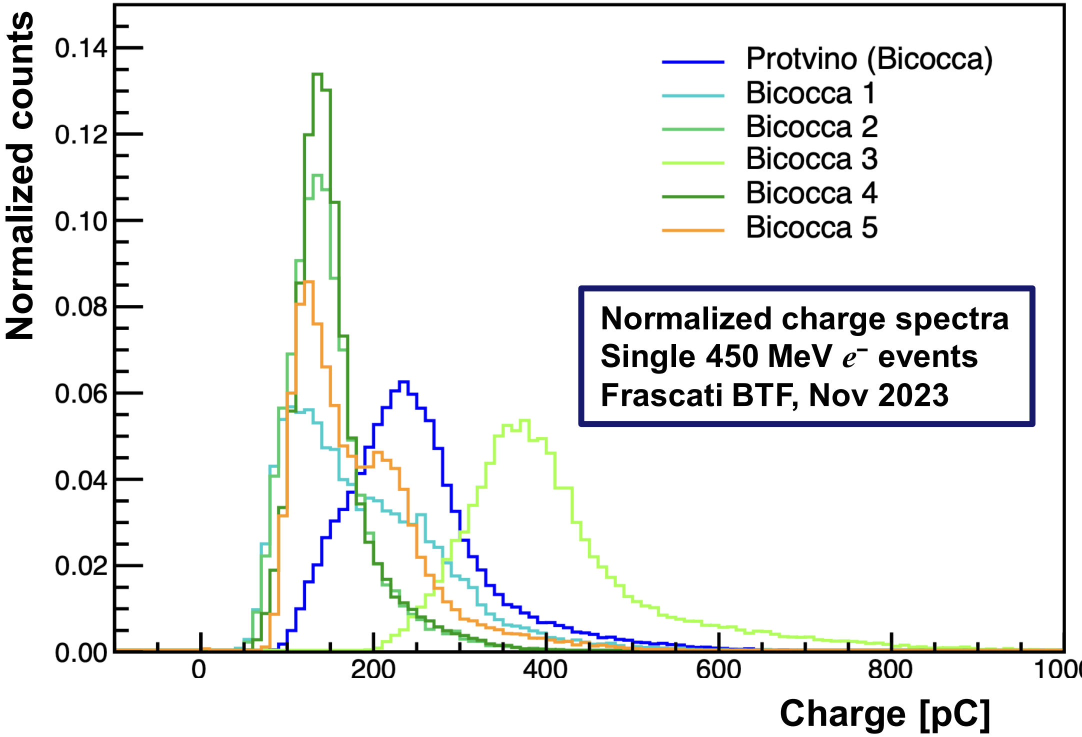
Protvino B	0.04% POPOP
Bicocca 1	0.04% benzothiophene (BTP)
Bicocca 2	0.04% coumarin-6
Bicocca 3	0.04% BTP + 0.04% coumarin-6
Bicocca 4	1% Yb:CsPbBr3
Bicocca 5	1% Yb:CsPbBr3 + perylene dyad

Light yield tests with new samples

- Reference sample:
  1.5% PTP + 0.04% POPOP in PVT ("**Protvino**")
- Bicocca **4**, **5**: $CsPbBr_3$:Yb in PVT
  ~50% ILY of ref. sample
  Our first nanocomposites with good mip response!
- Bicocca **3**: Coumarin-6 in PVT with PTP + BTP
  ~160% LY of ref. sample!

Tests with mip and e^- beams:

CERN T9	6, 10 GeV electrons
Oct 2023	10, 15 GeV hadrons/mips
Frascati BTF	450 MeV electrons
Nov 2023	Similar to mips for small samples



NanoCal: Outlook

By summer, we should have complete results from spectroscopy, cosmic rays, sources, and Frascati BTF electrons for *all* samples

Better setup for measurements with cosmic rays and beams:

- New laboratories in Frascati and Napoli, new sample holders with better optical coupling, easier sample handling, electronics with reduced noise, new DAQ system for digitizers, addition of Medipix-2 pixel detector to BTF setup for multiplicity counting

The survey will allow us to identify the best candidate(s) for a small prototype to be tested with mips and electrons in CERN PS T9 in September 2024:

- Isolation of contributions from nanocrystals and dyes and a better understanding of how NC scintillators work

Survey now in progress with cosmic rays, sources, and mip and electron beams, with improved measurement setup, to obtain:

- **Identification of most promising candidates for prototyping**
- **Better understanding of how NC scintillators work**

Project: WADAPT

- Thin Silicon Sensors for Extreme Fluences

Make Si sensors radiation tolerant by using a thin bulk, internal amplification and using a gain implant that would withstand a factor of 50 higher fluences than what is presently available.

- The Silicon Electron Multiplier, a new approach to charge multiplication in solid state detectors

Make Si sensors radiation tolerant by a novel biasing method – electrodes embedded in silicon.

- Development of fine-sampling calorimeters with nanocomposite scintillating materials

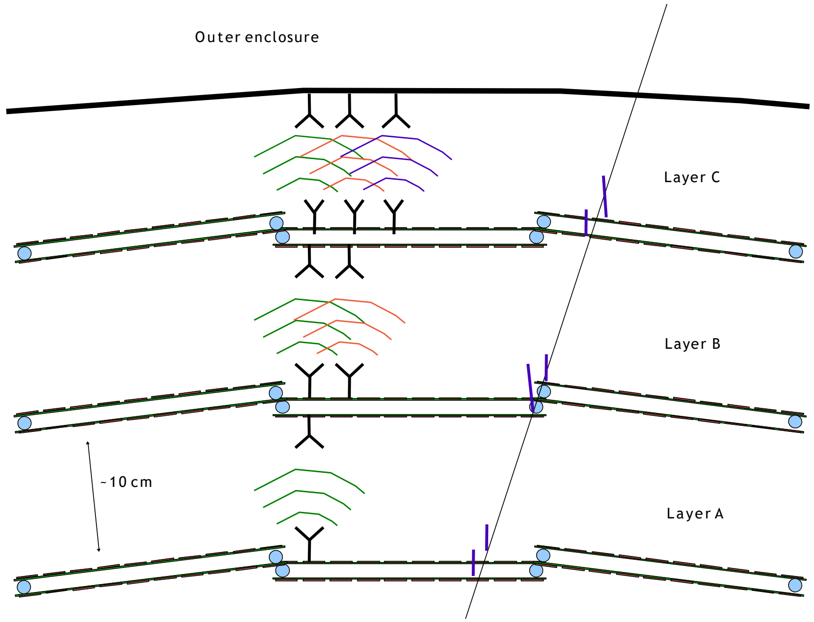
Develop a new generation of fine-sampling calorimeters that use innovative scintillating materials based on perovskite nanocrystals dispersed in a plastic matrix to form fast (~100ps) and radiation resistant (~1 MGy) scintillators.

- **Wireless Data Transfer for High-Energy Physics Applications**

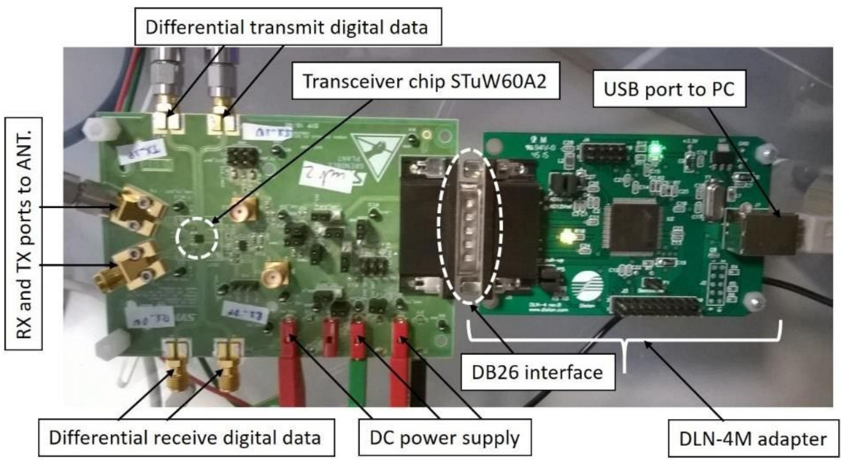
Develop mm-wave-based wireless communication as an alternative to optical and wired links in a HEP-like environment to reduce the material and optimize the read-out.

Wireless Data Transfer for HEP Applications

- Study of components and antennas integration
- Full link demonstrator(s) from 1 tile to 2 and 3 tiles – several mock-ups to be tested
- Use and integrate commercially available components
- Study the performance of the system (data rate, bit error rate, modulation schemes, usage of bandwidth, crosstalk in repeater, etc.)



Debit 1 Gbps per layer and is cumulative, thus it will be reaching 3 Gbps at the outer enclosure.

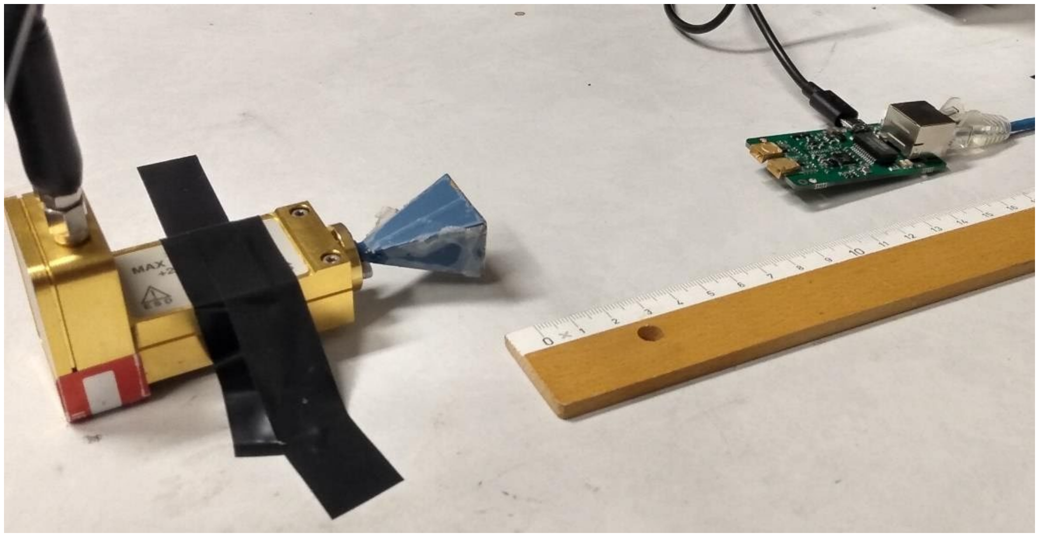


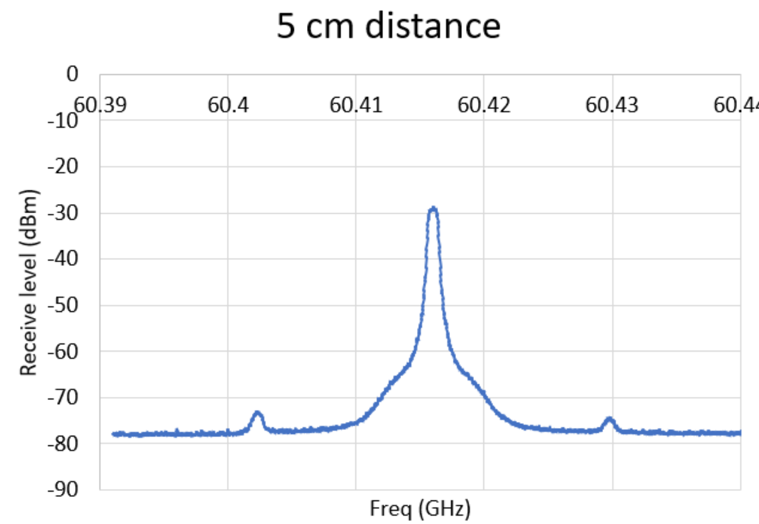
Courtesy of CEA-Letti and STMicroelectronics

SK202 boards (employing ST-60 GHz transceiver chip)

Board outlook:

SK202: radiation power measurements





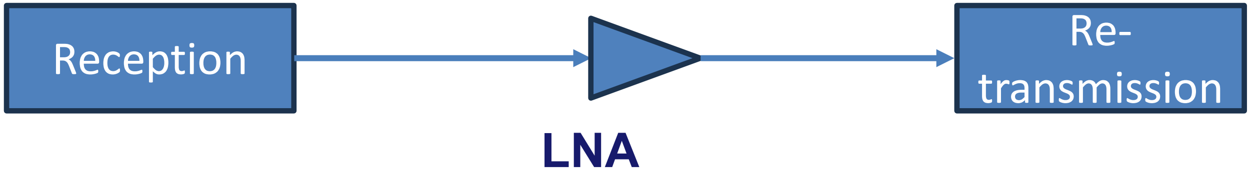
Peak value: -28.7 dBm

- Power measurements of the SK202 board to horn antenna harmonic mixer with a 20 GHz spectrum analyser.
- Measurements are done at different distances, i.e., 5 cm, 10 cm, 15 cm and 20 cm

distance	5	10	15	20	cm
received power	-28.7	-31.9	-34	-37.8	dBm

- The SK202 boards don't communicate at distances higher than 5 cm, as the receive power is not enough which is needed for the down-conversion.

Plan now is to integrate an LNA (low noise amplifier) on a new repeater mm-wave board to extend this range to 20 cm.



Two amplifiers:

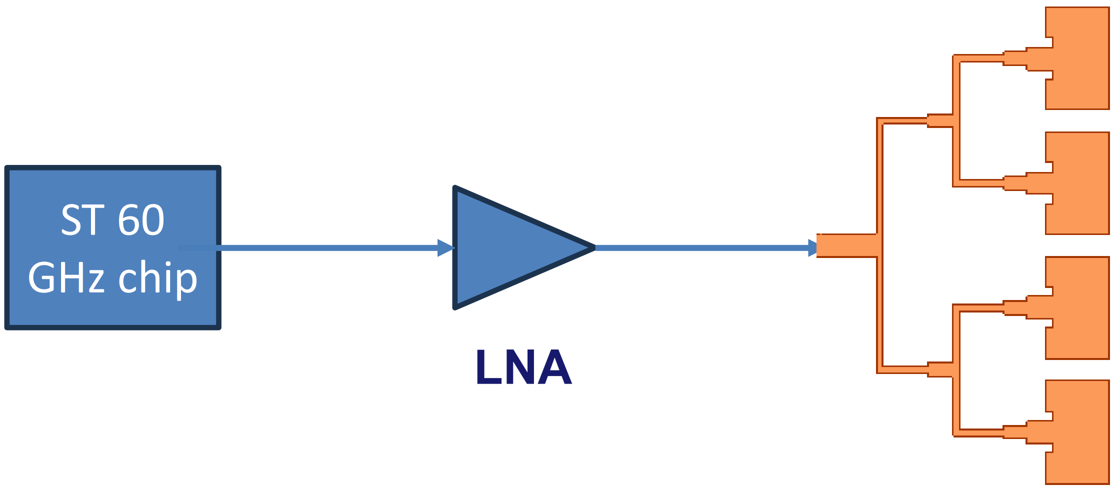
1. Gotmic gANZ0031 C V-band LNA MMIC 57-66 (52 - 72) GHz
2. Hittite HMC-ALH382 LNA 57-65 GHz

- Both to be implemented with stud bumps as well as with wire-bond configurations

- ACB Group CIBEL, France: PCB fabrication; TAI-PRO Engineering, Belgium: amplifier assembly using stud bump; Note, Norrtälje: wire bonding

WADAPT: outlook

- Measurements for newly fabricated boards are to start end of March.
- Make a prototype where the LNA is integrated between the 60 GHz transceiver chip and the antenna/antenna array.



WP13 Prospective and Technology -driven Detector R&D: summary

Summary and outlook

- The four projects are well underway.
- They have seen a lot of progress.
- All of them have also encountered problems, but have good ideas on how to mitigate them
- Planning to wrap up the projects in the final year.
- All of them would find an extension of 6 months very useful.

Backup slides