Advancement and Innovation for Detectors at Accelerators

Second Project Review meeting

Thursday 20 June 2024
CERN

WP 13

Prospective and Technology-driven Detector R&D

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004761.

Objectives

WP13 Prospective and Technology-driven Detector R&D:

→ support blue-sky research

following a strong motivation for such an alternative approach to detector R&D during the European Strategy discussions for particle physics in 2019

Call for projects carried out in the early stage of AIDAinnova

- 4 projects
- 3-year projects
- Require modest matching funds
- Single institutes or small consortia, industrial partner welcome

Four projects selected out of 15.

Objectives

- 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

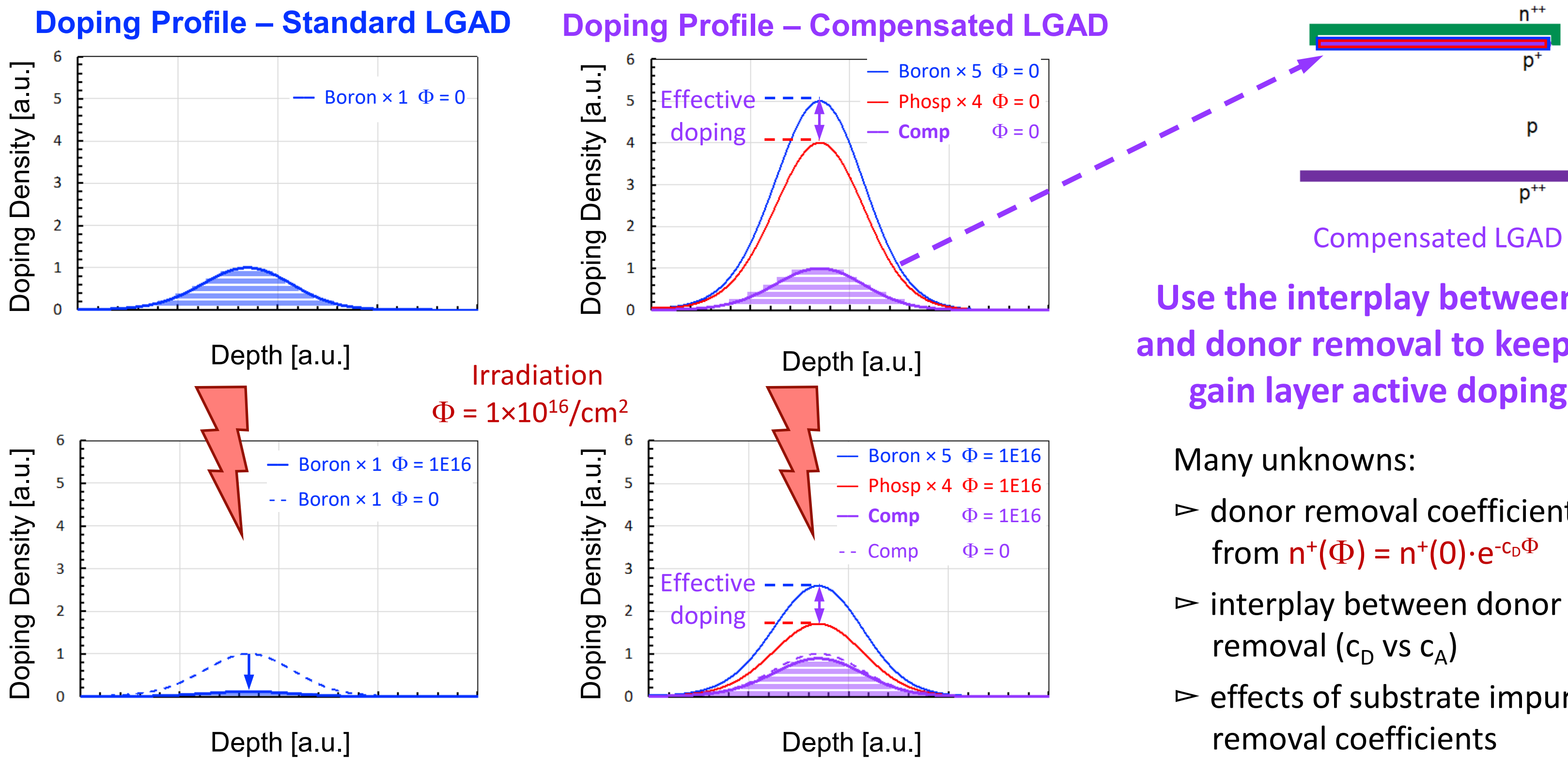
Develop a new generation of fine-sampling calorimeters that use innovative scintillating materials based on perovskite nanocrystals dispersed in a plastic matrix to form fast (~100ps) and radiation resistant (~1 MGy) scintillators.

- 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.

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.



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

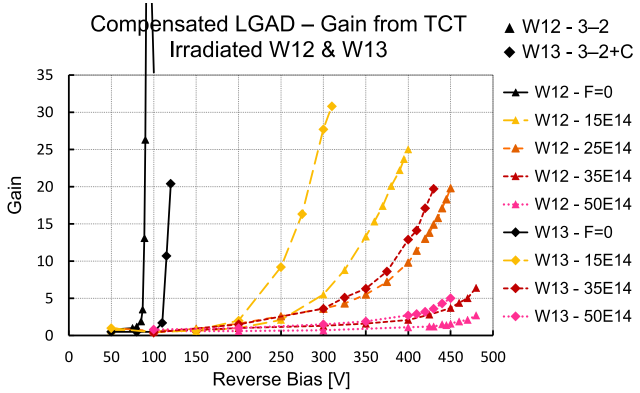
Many unknowns:

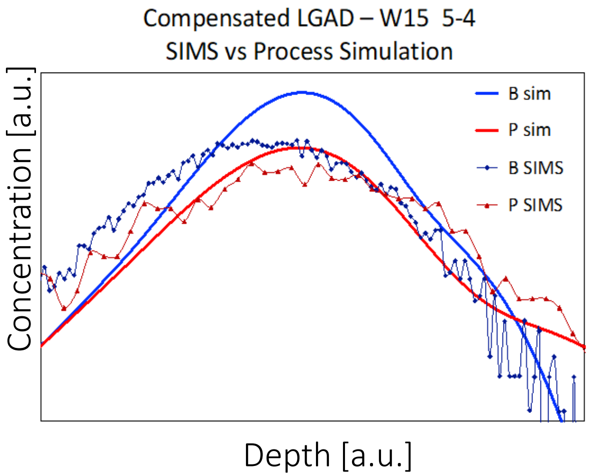
- donor removal coefficient, from $n^+(\Phi) = n^+(0) \cdot e^{-c_D \Phi}$
- interplay between donor and acceptor removal (c_D vs c_A)
- effects of substrate impurities on the removal coefficients

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.

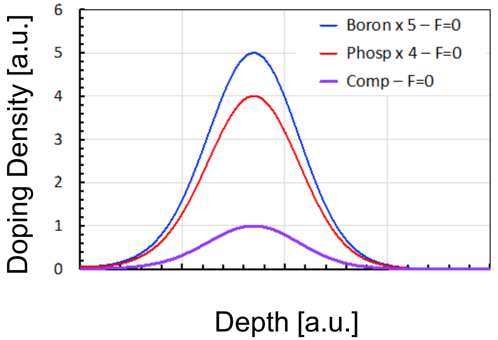
Neutron irradiation of compensated sample
- TCT studies and I-V measurements
→ Good gain behaviour of the compensated LGAD sensors
→ Even in compensated LGADs, the usage of carbon mitigates the acceptor removal





Challenging doping with both components
Boron peak is shallower than phosphorus (profiles are not aligned)
Boron peak is lower than predicted from simulation
Adjustment needed for the next iteration

Doping Profile – Compensated LGAD



Results/highlights

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 status

- ▻ The p^+–n^+ design has been completed
- ▻ The p^+–n^+ production batch has been completed
- ▻ The characterisation and testing on the p^+–n^+ sensors is almost complete
- ▻ The p-in-n LGAD batch (study of donor removal) is about to start ⌛

→ **Some delay in activities**

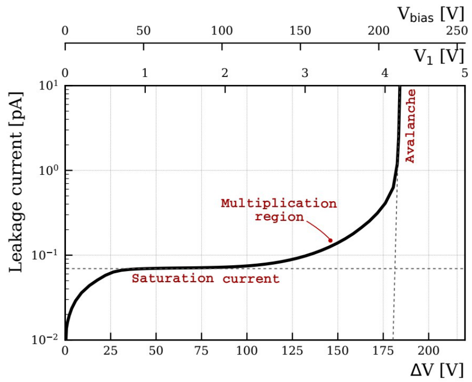
An ERC Consolidator Grant awarded to the PI for a further development of compensated LGAD sensors

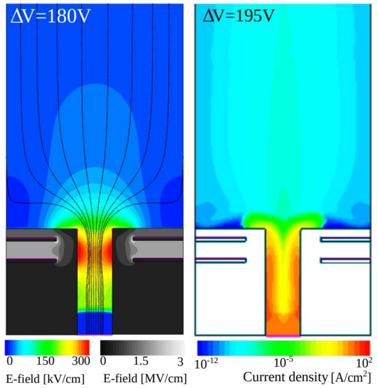
Doping Compensation in Thin Silicon Sensors: the pathway to Extreme Radiation Environments - CompleX

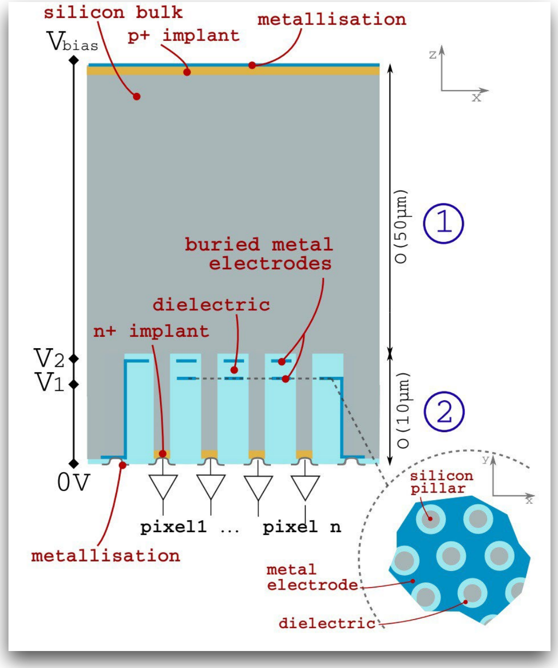
The Silicon Electron Multiplier, a new approach to charge multiplication in solid state detectors

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

- 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, 2. amplification layer.
- Gain mechanism --> 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.



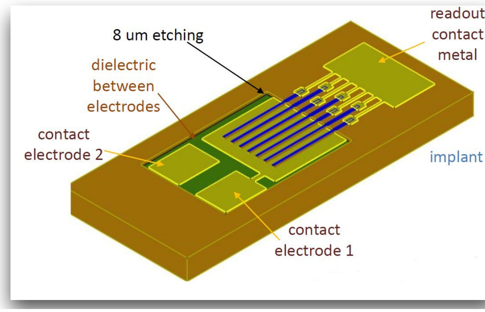


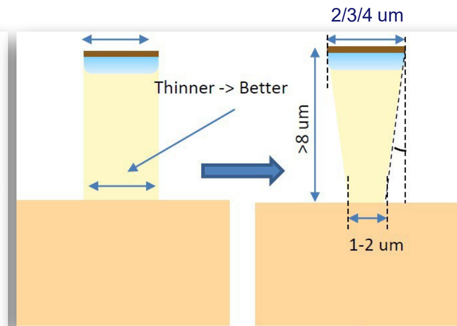


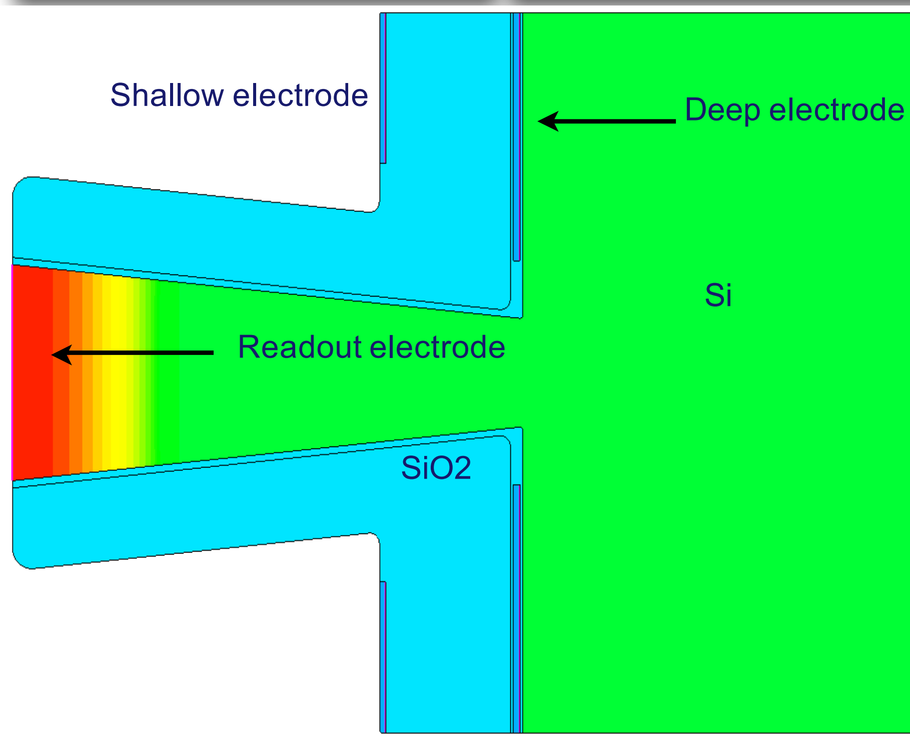
The Silicon Electron Multiplier, a new approach to charge multiplication in solid state detectors

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

- **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 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).





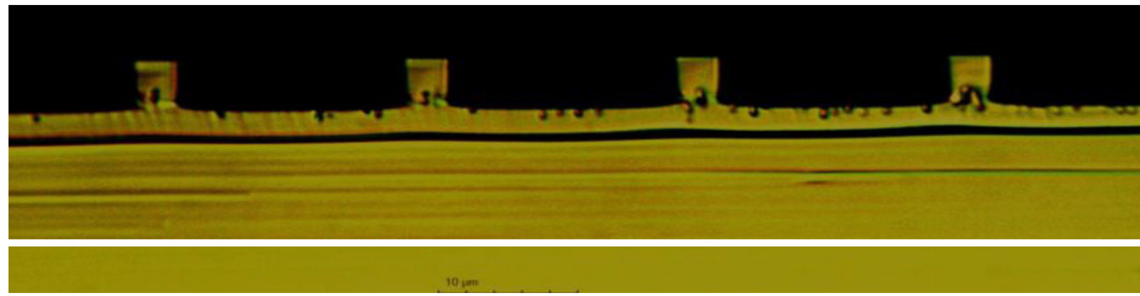


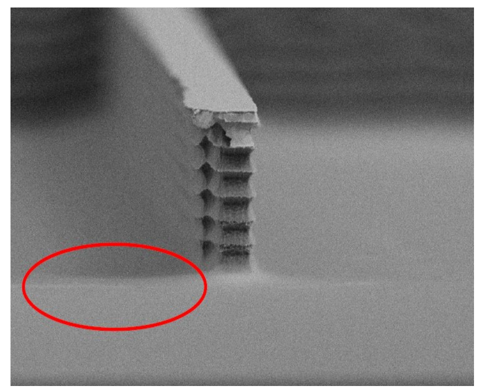
Results/highlights

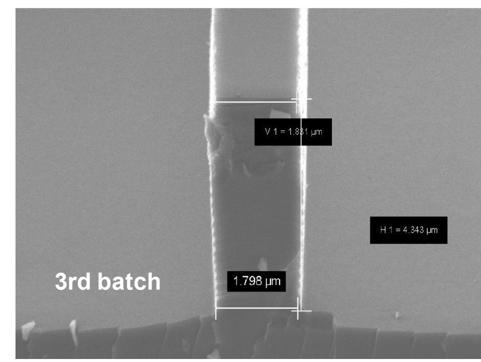
The Silicon Electron Multiplier, a new approach to charge multiplication in solid state detectors

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

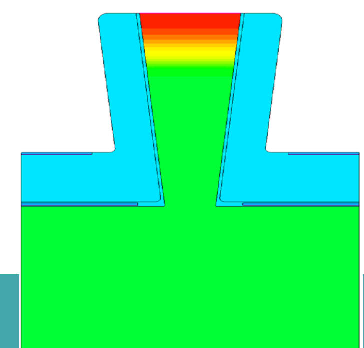
- **1st batch over etched:**
  - Trench 25 um instead of 8 um.
- **2nd batch improved etching:**
  - Test B: 9 um, test C: 8.41 um.
  - Pillars thinner than nominal 1.7 um, some broken.
  - No pyramidal shape.
- **3rd batch closer to specs:**
  - Pyramidal shape achieved but rough walls.
  - Slightly 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.



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

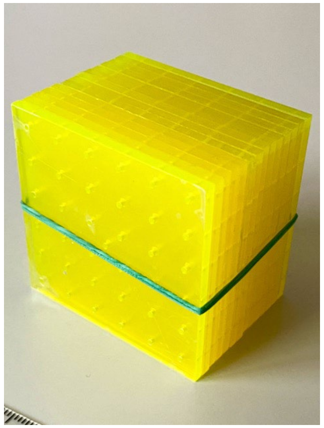
Make Si sensors radiation tolerant by a novel biasing method – electrodes embedded in silicon

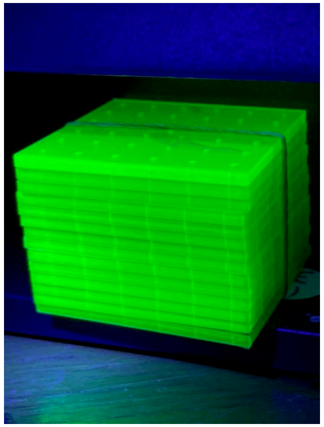
- Electron Multiplier concept on Silicon Radiation allows charge multiplication, not relying on high doping implantation.
- Mechanism depends on geometry only --> not sensitive to acceptor removal.
- Additional geometries under simulation to match CNM production process.
- CNM DRIE demonstrator production 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.

Results/highlights

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 and radiation resistant scintillators.

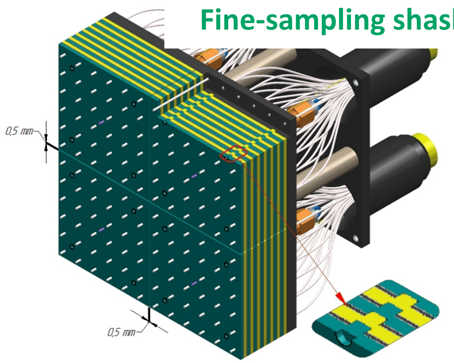




Semiconductor nanostructures can be used as sensitizers/emitters for ultrafast, robust scintillators:

- 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)

KOPIO/PANDA design
Fine-sampling shashlyk



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

Results/highlights

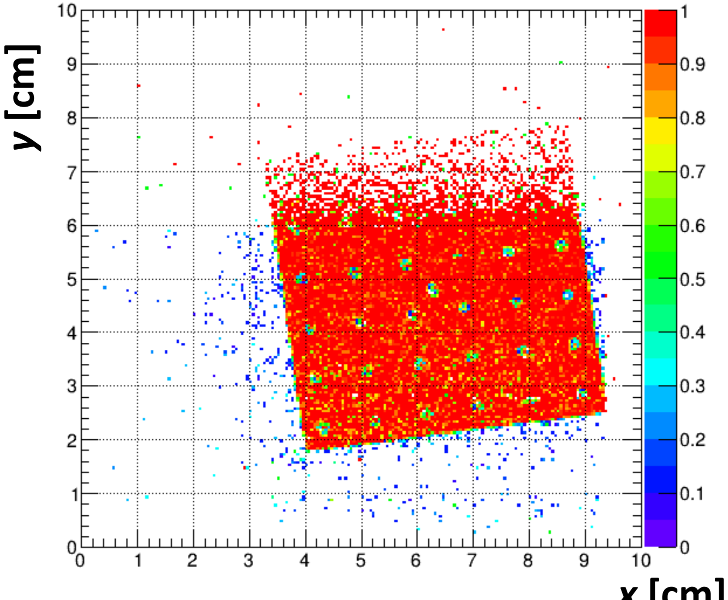
Development of fine-sampling calorimeters with nanocomposite scintillating materials

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 and radiation resistant scintillators.

- **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, NC scintillator:

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



Conclusion of 2022 beam test: NC prototype seems to work but with low light yield and many open questions

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Results/highlights

Development of fine-sampling calorimeters with nanocomposite scintillating materials

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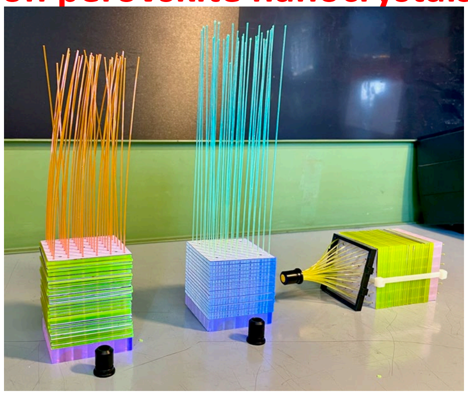
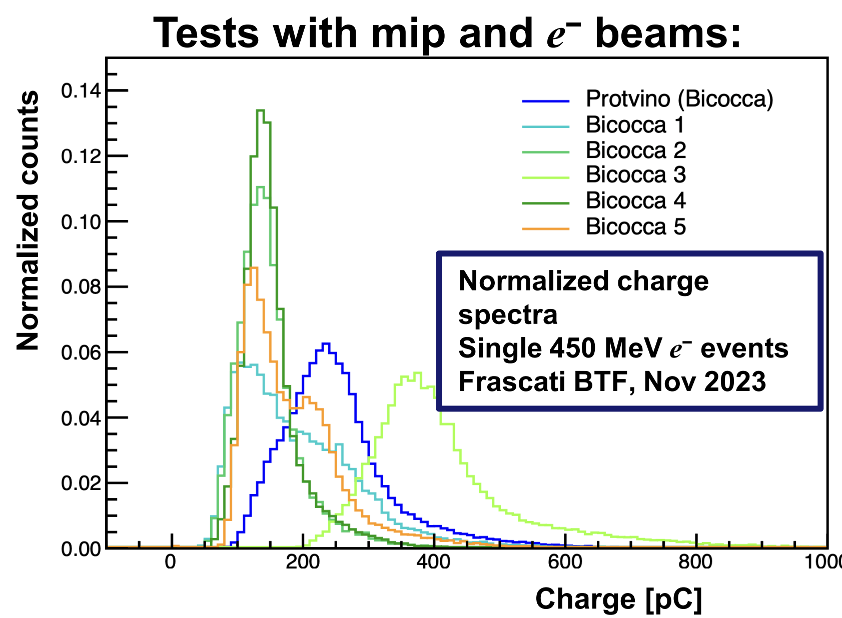


Prototypes tested in June 2023: Disappointing result from new nanocomposite: only light is from readout fibers!
Fall 2023: new ideas for nanocomposites, synthetised



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

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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 and radiation resistant scintillators.

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

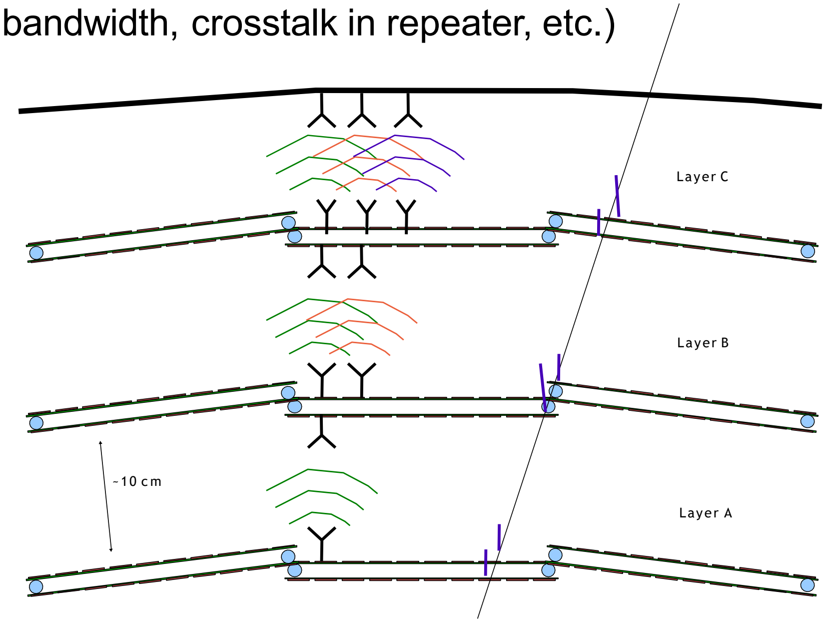
The survey will allow us to identify the best candidate(s) for a small prototype to be tested with mips and electrons in CERN PS T9 in September 2024:

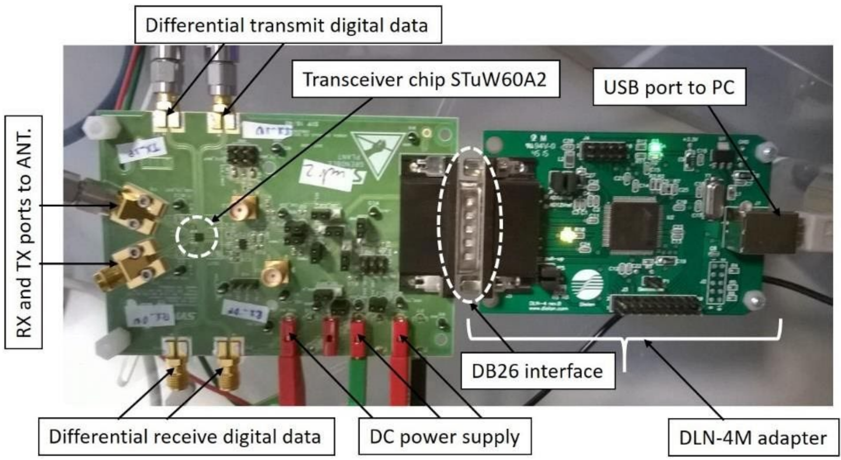
- Isolation of contributions from nanocrystals and dyes and a better understanding of how NC scintillators work

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.

- 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.

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.

Board outlook:

Wireless Data Transfer for High-Energy Physics Applications

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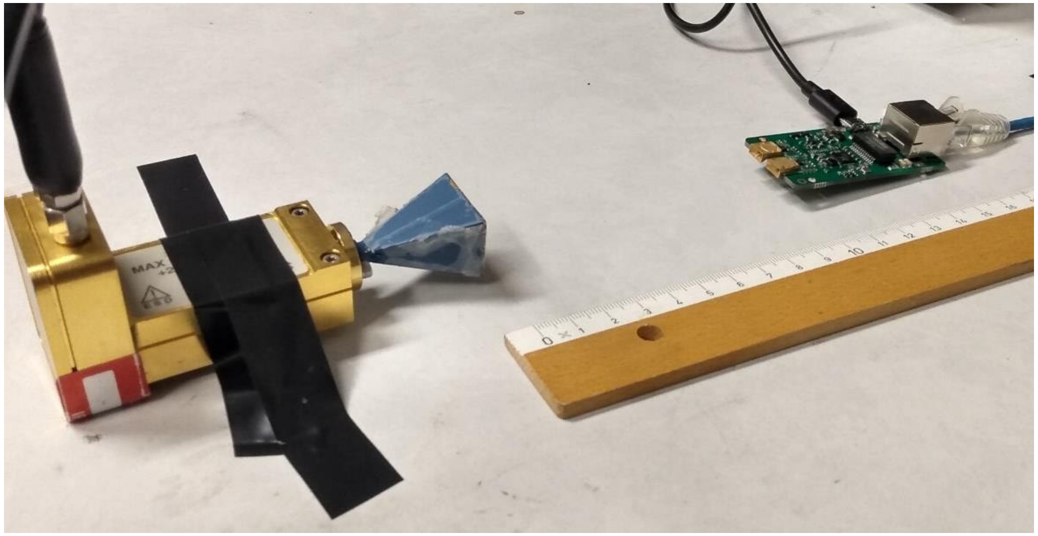
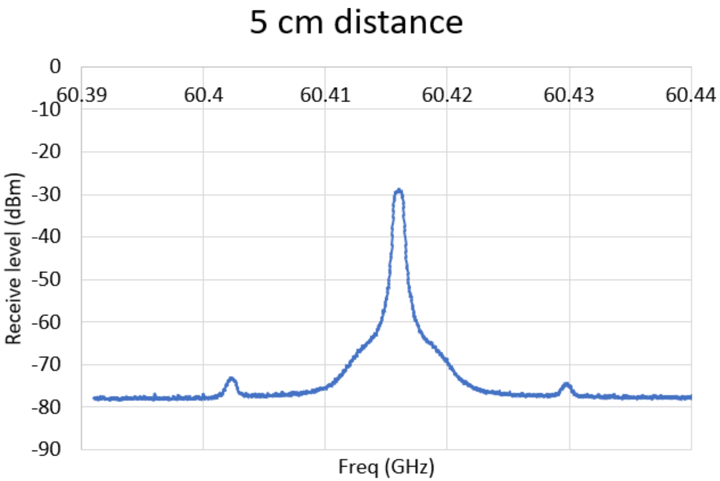




Peak value: -28.7 dBm

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

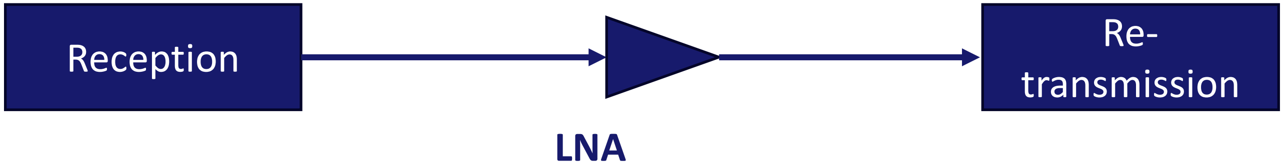
distance	5	10	15	20	cm
received power	-28.7	-31.9	-34	-37.8	dBm

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.

The SK202 boards do not 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 amplifier candidates, both to be implemented with stud bumps as well as with wire-bond configurations

Deliverables/Milestones

Milestones

- MS51: Generic R&D projects selected M8 01/02/2022 Achieved
- MS52: Mid-term review of selected projects M21 20/02/2023 Achieved

Deliverables

- D13.1 Summary report of generic R&D projects and evaluation of the approach M46

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
- Wrapping up the projects in the final year.
- All of them would find an extension of 6 months very useful.