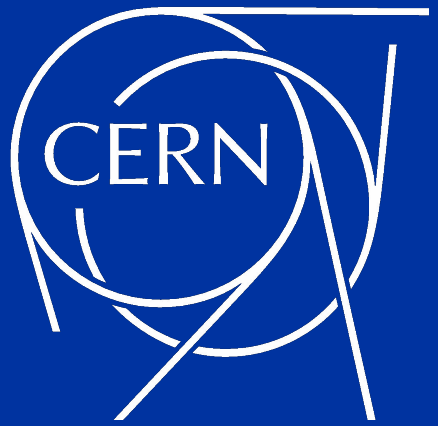


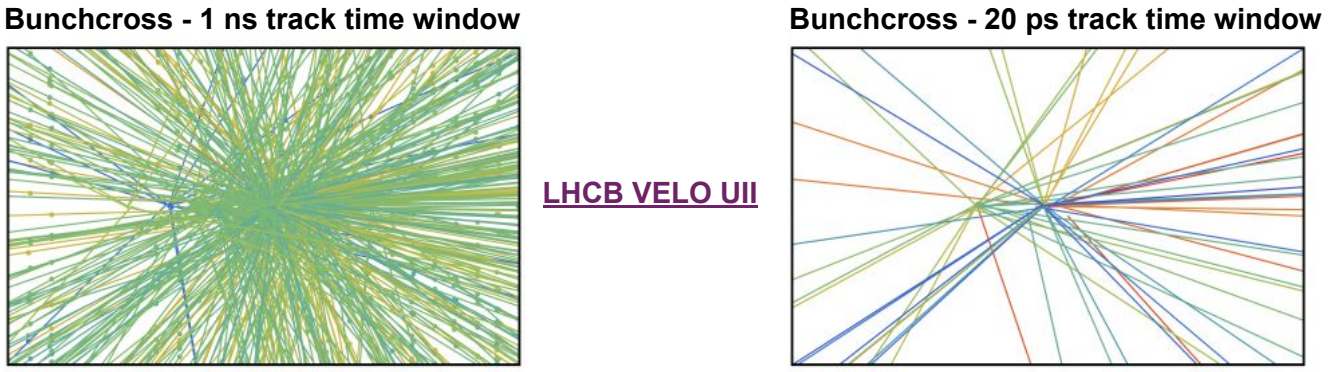
Characterisation of the First Silicon Electron Multiplier Demonstrators

Federico De Benedetti
Paula Collins, Victor Coco, Sara Cesare, Edgar Lemos Cid, Alfonso Puicercus Gomez, Janina Nicolini, Efren Rodriguez Rodriguez, Lotte Sikkema, Morag Williams, Giulio Pellegrini, Ivan Lopez Paz, Gemma Rius.

TIPP, Mumbai, 2-6 February 2026

Introduction

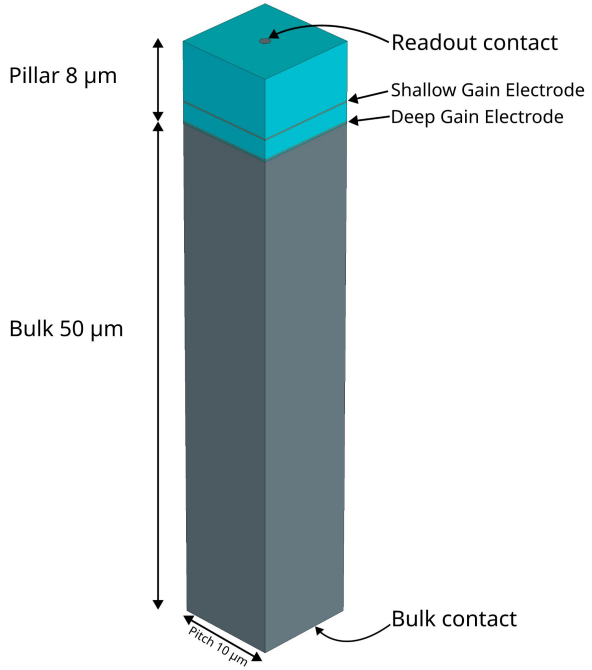
- **Future detector upgrades for FCC and HI-Lumi LHC will face new challenges:** ECFA Detector R&D Roadmap
  - Increased radiation tolerance.
  - Fine space resolution.
  - Introduction of timing to cope with increased pileup (4D tracking).
- **Current technological limitations in silicon:**
  - Very thin planar sensors → signal too small.
  - LGADs → Segmentation and maintaining stable gain at very high fluence is challenging.
  - 3D sensors → Small pitch difficult to achieve.
- **This motivates the search for a new approach to MIP detection in silicon.**

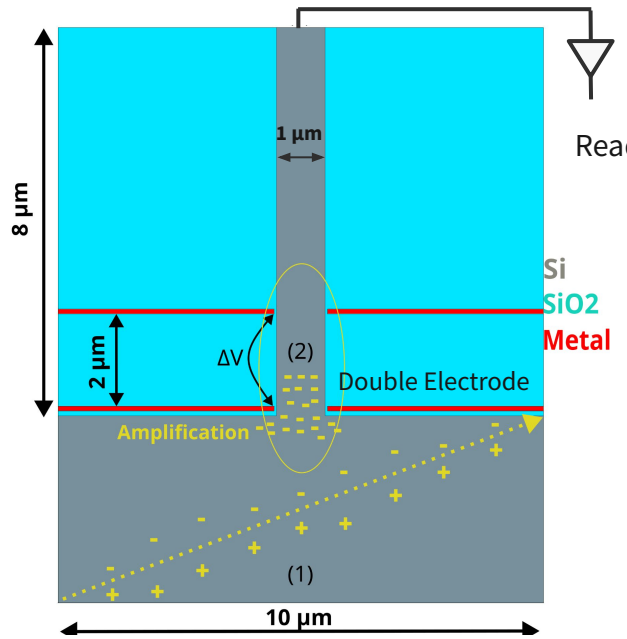


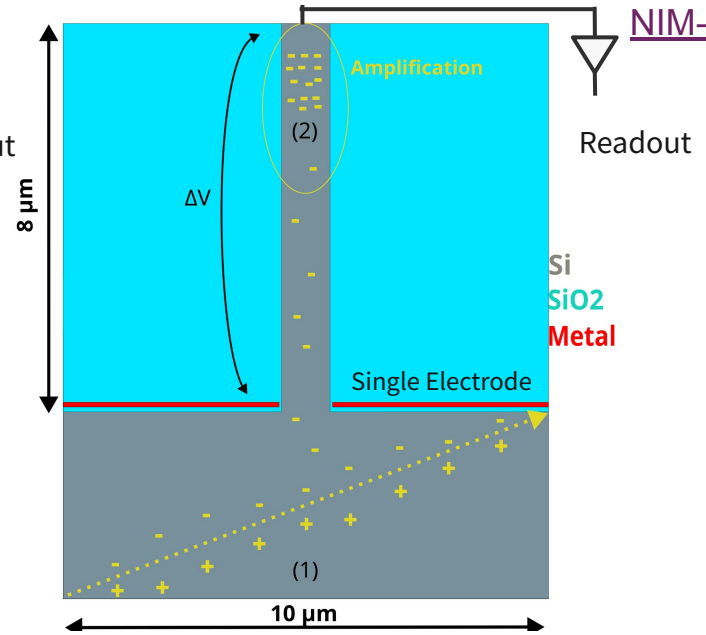
The Silicon Electron Multiplier (SiEM)

Working Principle

- **The SiEM sensor aims to achieve internal gain with fine pitch, and excellent radiation hardness.**
  - e/h pair production occurs in a planar bulk region (1).
  - Embedded metal electrodes for high electric field (2).
  - Charge multiplication obtained via electrostatic potential (no doping).
- **No gain deactivation is expected (gain mechanism based on electrodes dV).**
- **Initial TCAD simulations show gain > 10 and time resolution of tens of picoseconds based on the geometry.**

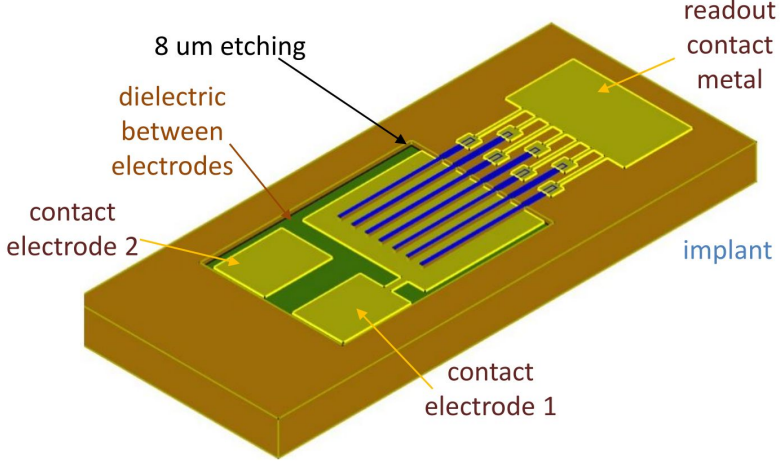


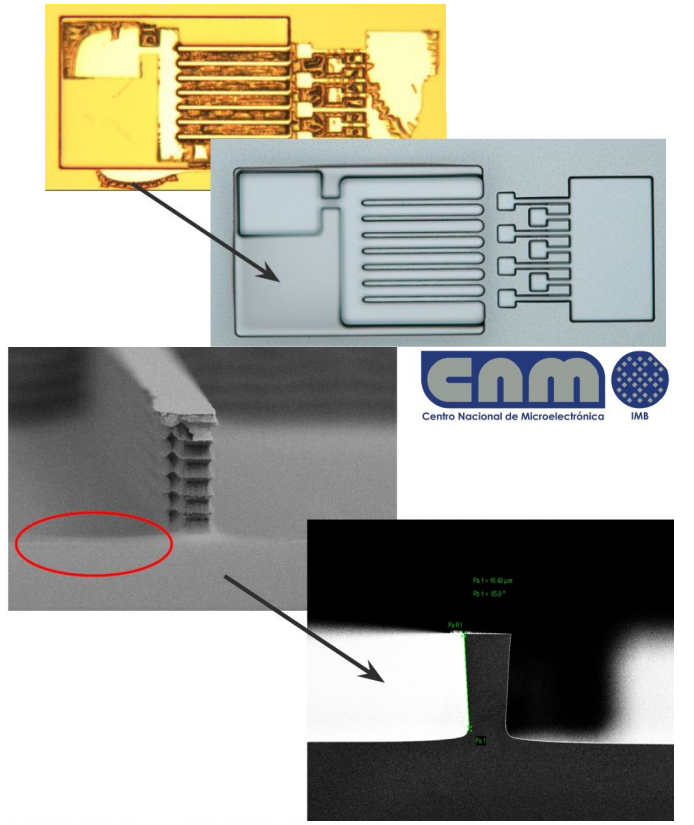




CNM Strip SiEM demonstrators

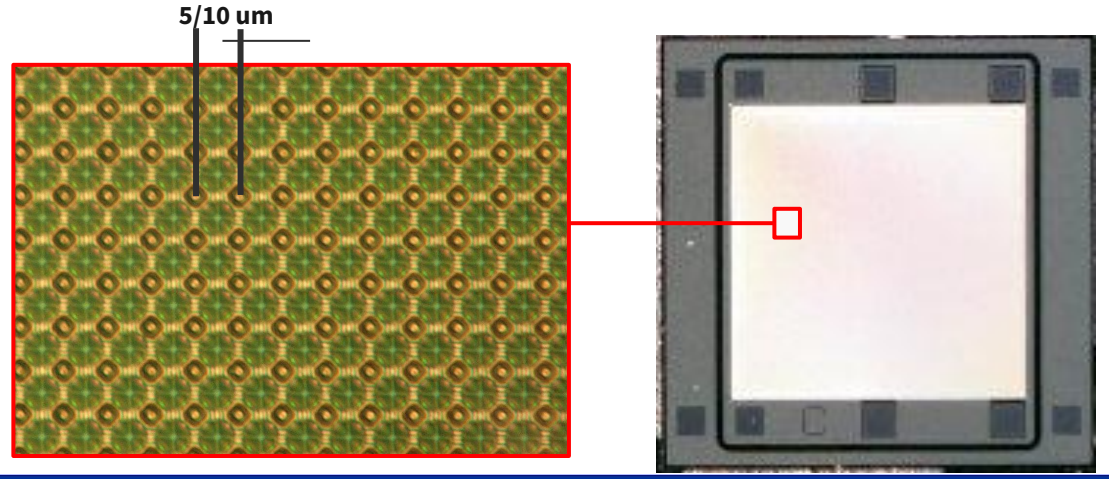
- **AIDA-Innova blue sky R&D project with IMB-CNM**
- **Production process is DRIE based:**
  - Targeting strip sensor with two electrodes configuration.
- **Investigating photolithography process:**
  - Laser lithography process can limit pillar dimensions → slant.
  - CMOS compatible stepper photolithography.
- **Optimization of DRIE parameters:**
  - Smooth pillar after DRIE optimization.
- **Investigating metallization procedure for gain electrodes:**
  - Using RIE after metallization to remove metal from the pillar walls.
- **Status:**
  - Produced 4 mechanical wafers with good etching.
  - Doping of the wafers.
  - Waiting for problem on stepper machine.





HPK Pixel SiEM demonstrators

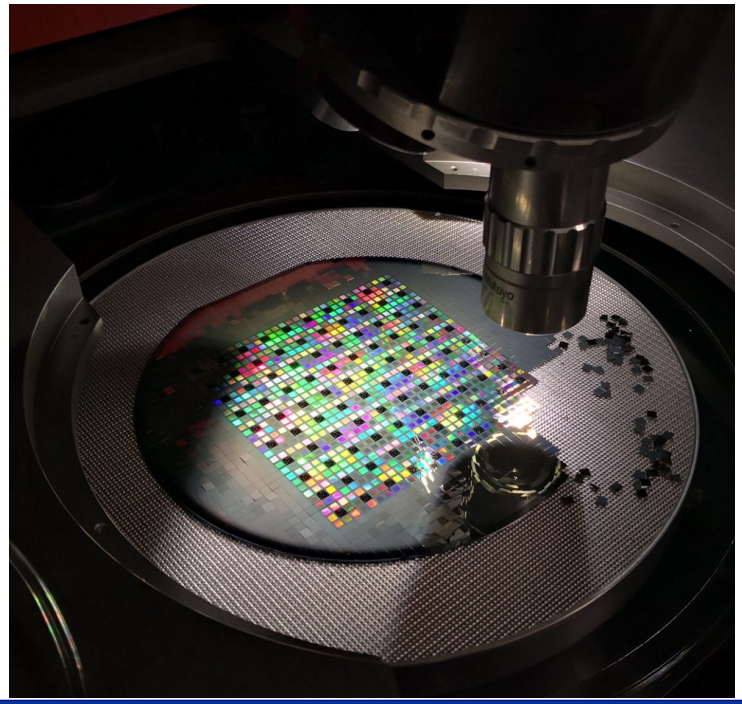
- **HPK R&D team evolved the idea to produce pixelated demonstrators.**
- **New approach on the embedded electrodes, single electrode configuration.**
- **1 wafer received in April 2025:**
  - 50 µm thickness.
  - 2x2 mm active area with 10x10 µm and 5x5 µm pitch.
  - All pixels are interconnected.
  - Various flavours in pillar diameter.
- **Systematic IV on all flavours at different temperature.**
- **Test beam to evaluate gain on specific structures.**



Device design and development: H. Sonobe (HPK).

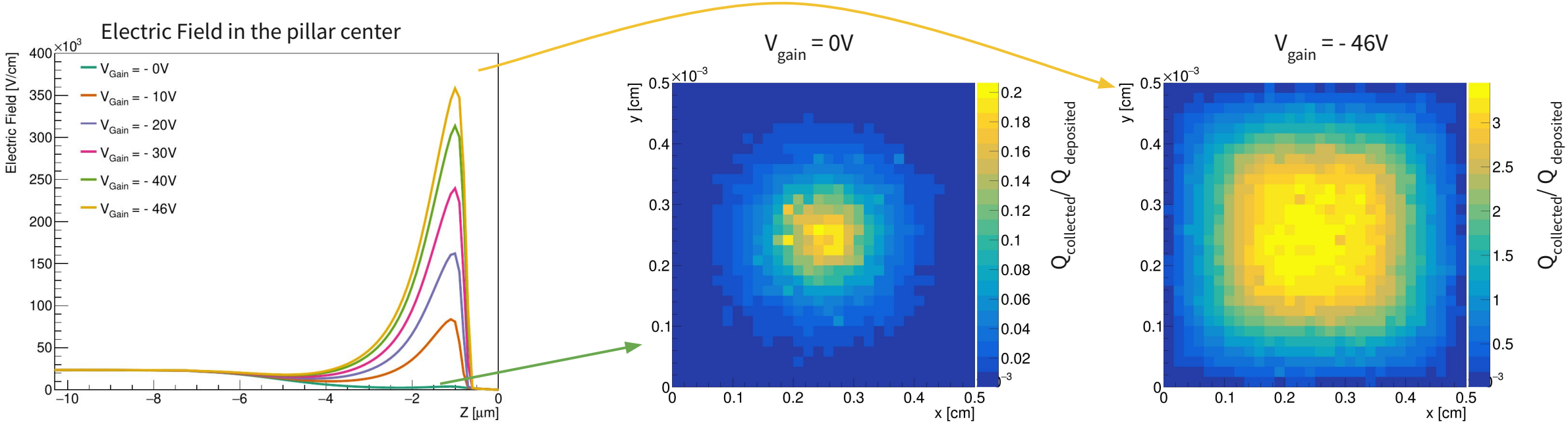
HAMAMATSU

PHOTON IS OUR BUSINESS



Simulated Gain And Pixel Efficiency

- **Simulated MIP response using Garfield++ on HPK structure, single pixel @ V_{Bulk} = -100V.**
- **Localized charge multiplication in the center (pillar).**
- **Expected effective gain of O(3.5).**
- **Transport efficiency depends on the gain electrode voltage and charge generation position.**
  - Low CCE at low V_{Gain}, Low CCE far from the pillar center.



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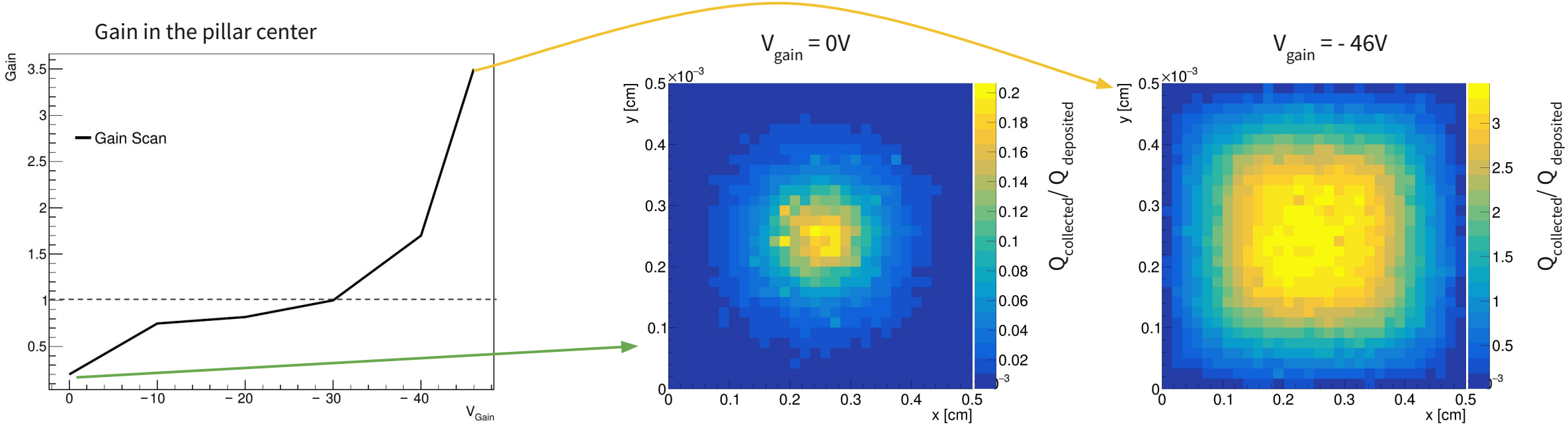
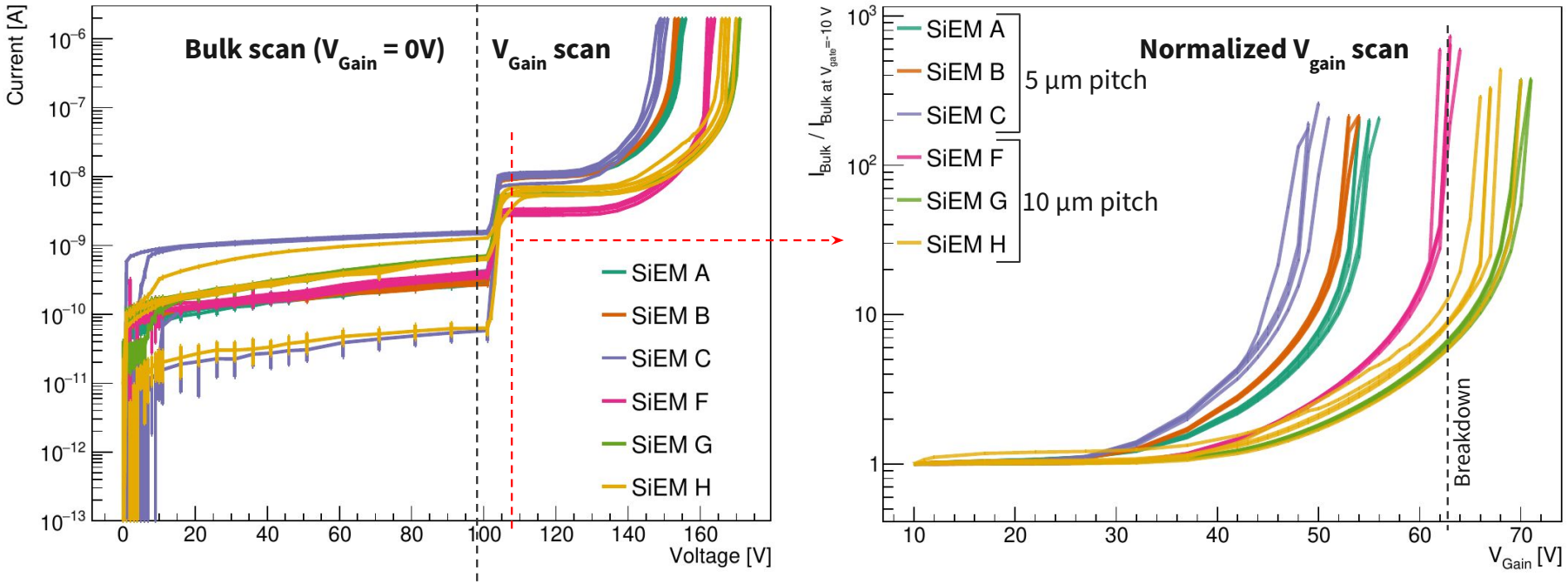


Systematic IV Measurements

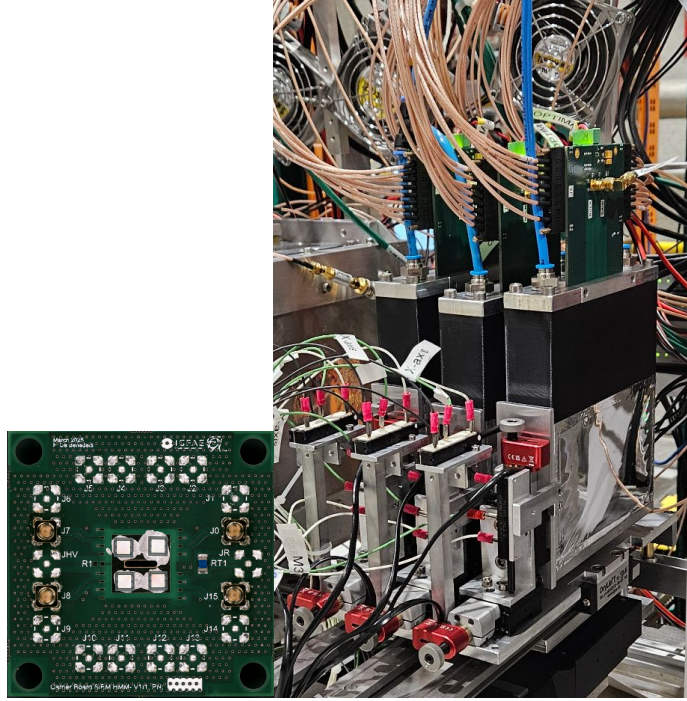
- **Performed systematic IVs on all flavours with needle setup.**
- **Bulk voltage scan:** Standard pn-junction behaviour and clear depletion.
- **Gain voltage scan:** Controlled current increase associated to charge multiplication.
- **Excellent uniformity among devices of the same flavour.**
- **Observed current step when gain is activated: compatible with surface or interface-related effects.**

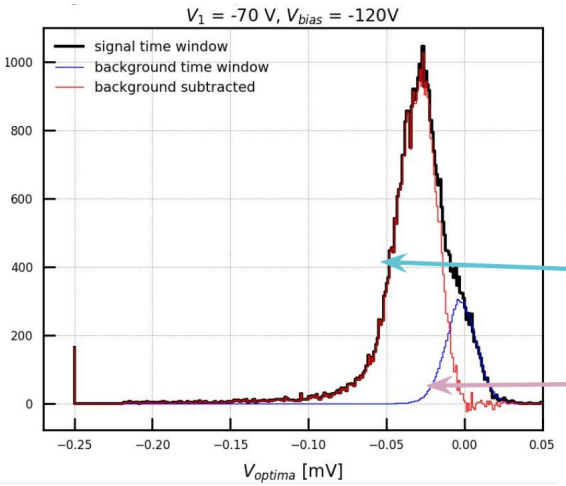


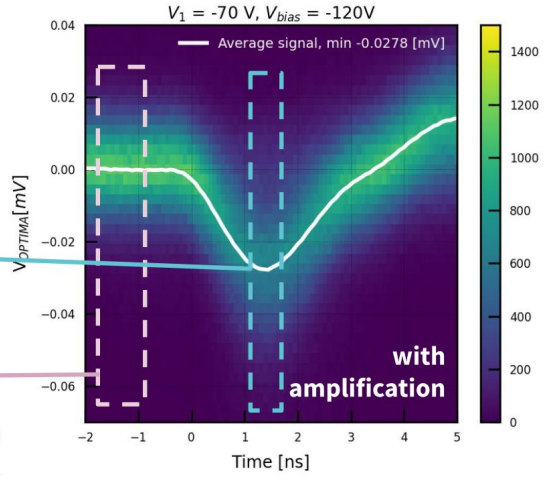
HPK Structure Characterisation

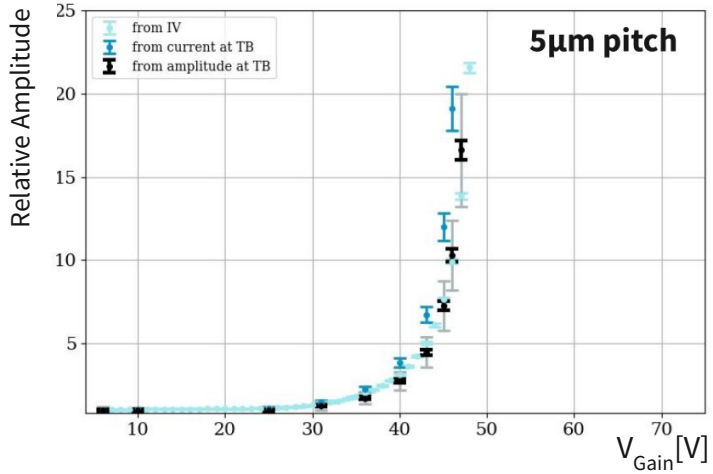
Relative amplitude from test beam

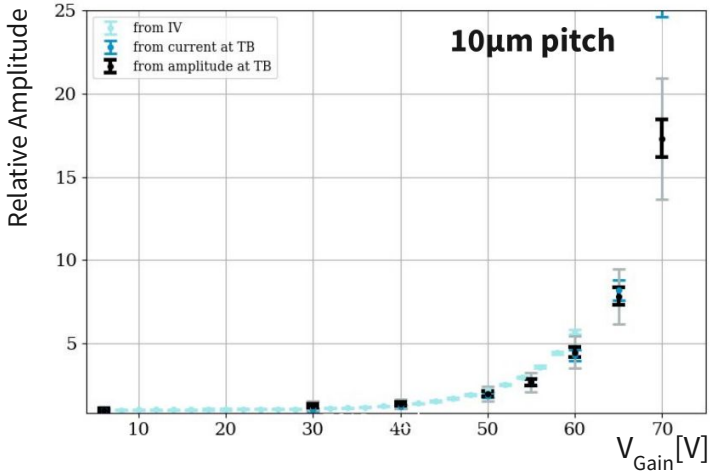
- **OPTIMA as analog front-end board (arxiv 2601.15937):**
  - Multichannel board with discrete amplifier + oscilloscope.
  - 3 stages setup with Region Of Interest (ROI) trigger.
- **Performed IVs and compared with signal amplitude:**
  - Amplitude distribution is proportional to IV-characteristic curve.
  - First hints of gain in the structure.
- **For absolute gain, a calibration of the front-end electronics is needed.**







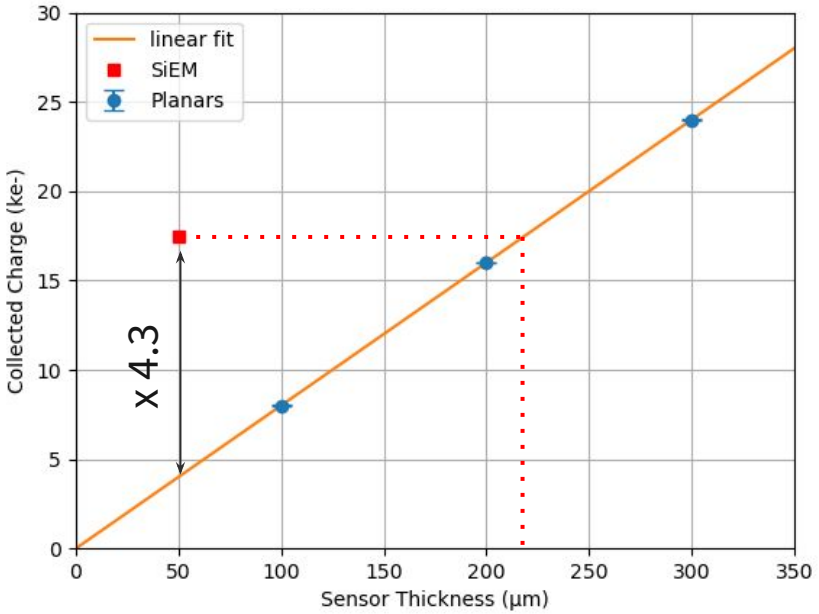


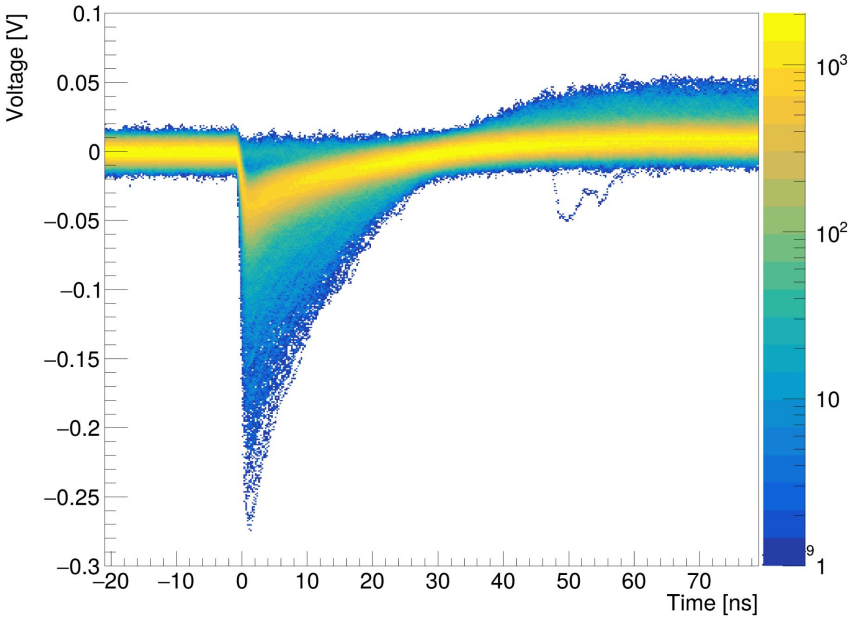


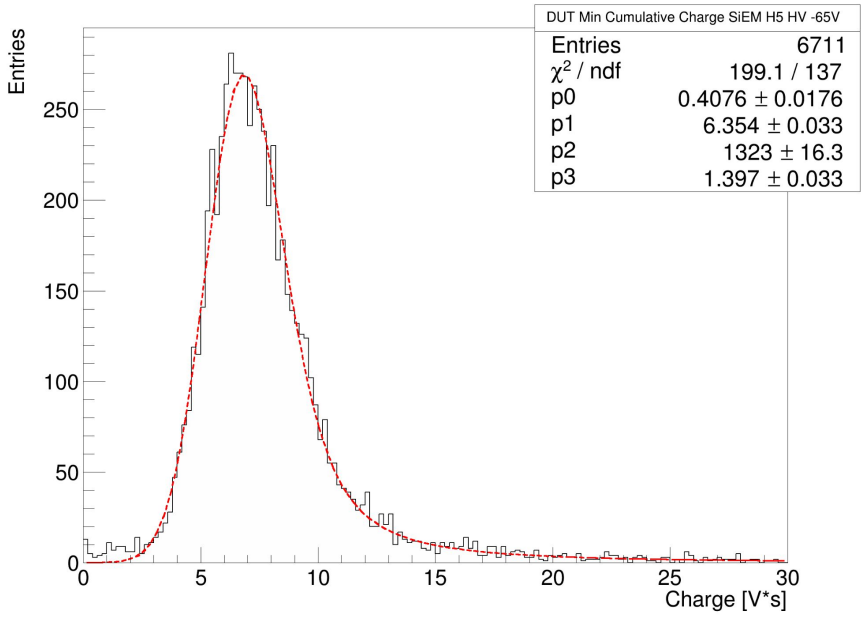
HPK Structure Characterisation

Absolute gain from test beam

- **Charge calibration performed using planar sensors of known thickness.**
  - Integrated signal used to extract the calibration curve.
- **SiEM landau distributions extracted from calibrated charge.**
- **Absolute gain measured for SiEM devices:**
  - Gain ≃ 4.3 (≈ 17 ke⁻) wrt planar 50 µm at max V_{gain}
  - Equivalent to a ~220 µm planar sensor response



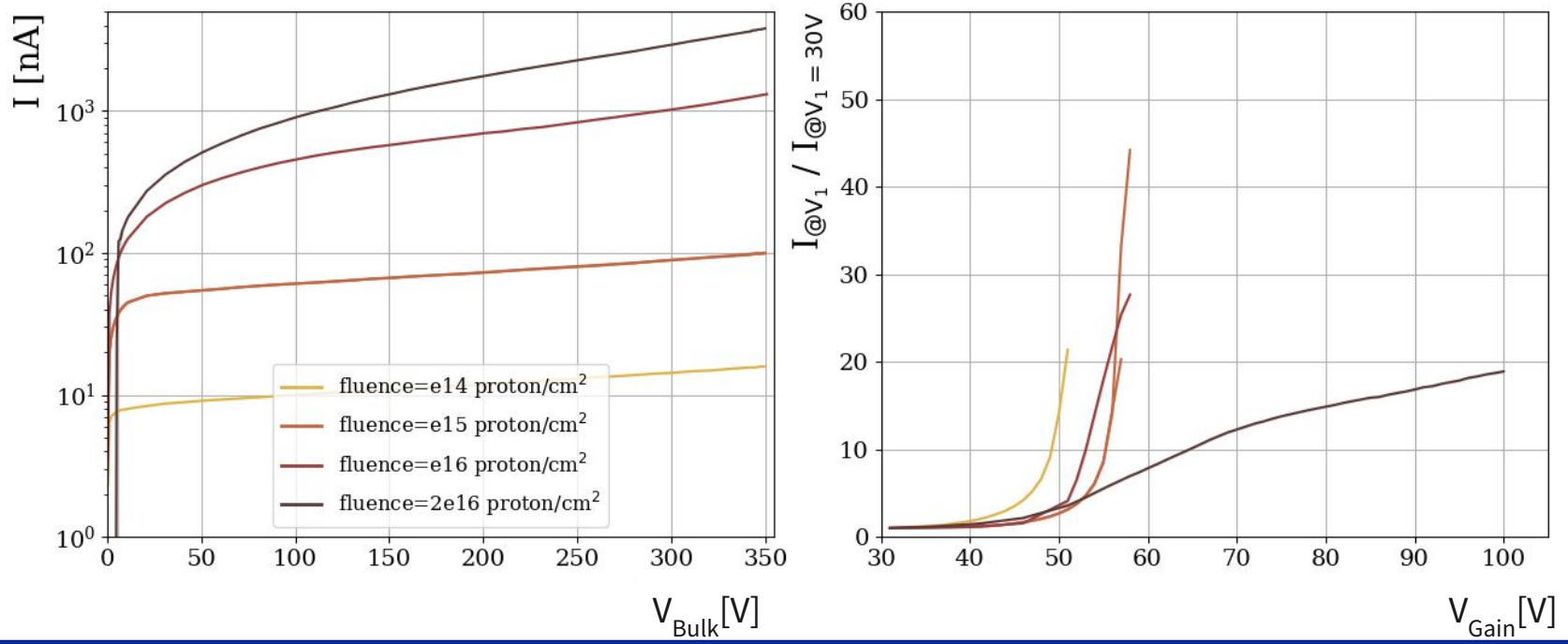




IV Measurements of Irradiated Samples

- **Irradiated samples with protons at different fluence:** 10^{14}, 10^{15}, 10^{16}, $2*10^{16}$ n_{eq}/cm^2
- **Bulk current increase, gain curve still visible at $2*10^{16}$ n_{eq}/cm^2**
  - Clear dependance with bulk depletion voltage
- **More systematic studies with beam are needed to validate gain mechanism of irradiated samples**

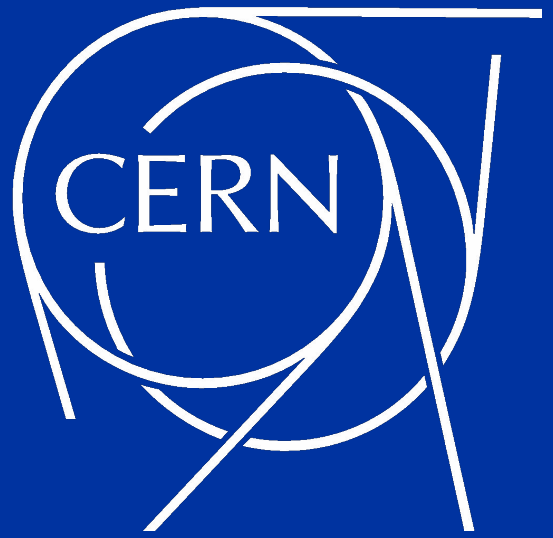
C structures irradiated, V_{Gain} scan @ V_{bulk} = 350V



Conclusions and Future Development

- **A novel Silicon Electron Multiplier (SiEM) concept has been presented.**
- **First HPK pixelated devices have been manufactured in single electrode variant.**
- **These demonstrators exhibit a signal equivalent to a ~220 µm planar sensor (gain ~4.3).**
- **Proton irradiation campaign is completed up to $2*10^{16}$ n_{eq}/cm^2.**
  - Gain curve is still visible up to $2*10^{16}$ n_{eq}/cm^2.
- **SiEM is a promising candidate for fine-pitch, radiation-tolerant detectors.**

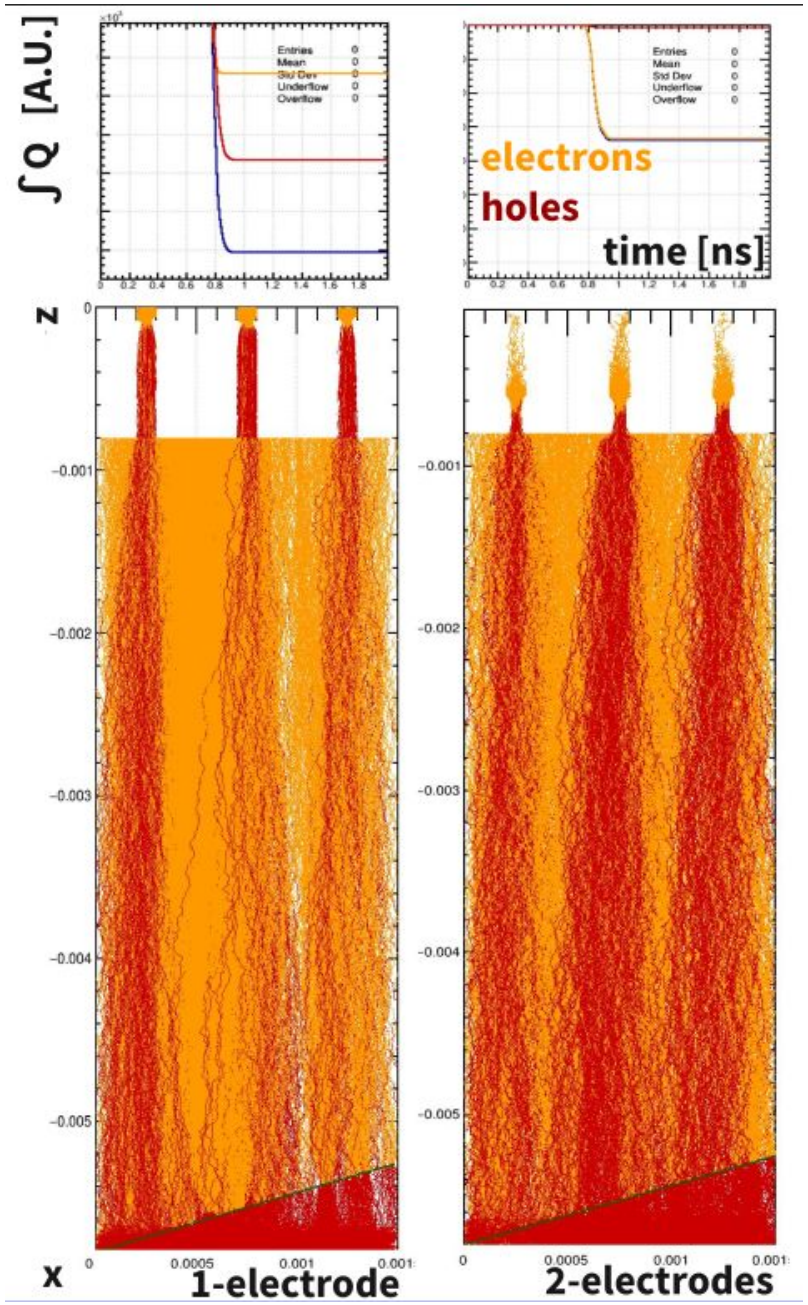
- **Test setup integrated in Timepix4 telescope will enable detailed pixel-level efficiency and time resolution.**
  - Analysis in progress.
- **Dedicated test beams to study intrinsic gain of irradiated samples.**
- **Discussing with HPK to make a version compatible with Timepix4/Picopix ASICs**


CERN

BACKUP

Signal Formation

- **Amplification electrodes tend to shield the induction from charge in the drift region**
- **Double electrode operation mode:**
  - signal is almost uniquely from amplified electrons drifting in the pillar
- **Single electrode operation mode:**
  - electron contributes briefly after amplification
  - holes drifting back out of the pillar dominates the signal
- **Timing properties**
  - double vs. single electrode impact the signal shape
  - “pitch” impact variation on the drift distance
  - like for LGAD, the thinner the better $\sigma t \propto d$ [JINST 12 (2017)P11017]
- **further work on going to systematically check the various configuration with Garfield++**



BACKUP

H Structure Irradiation IV