From Single Particles to Clinical Beam Rates: A Wide Dynamic Range Beam Monitor

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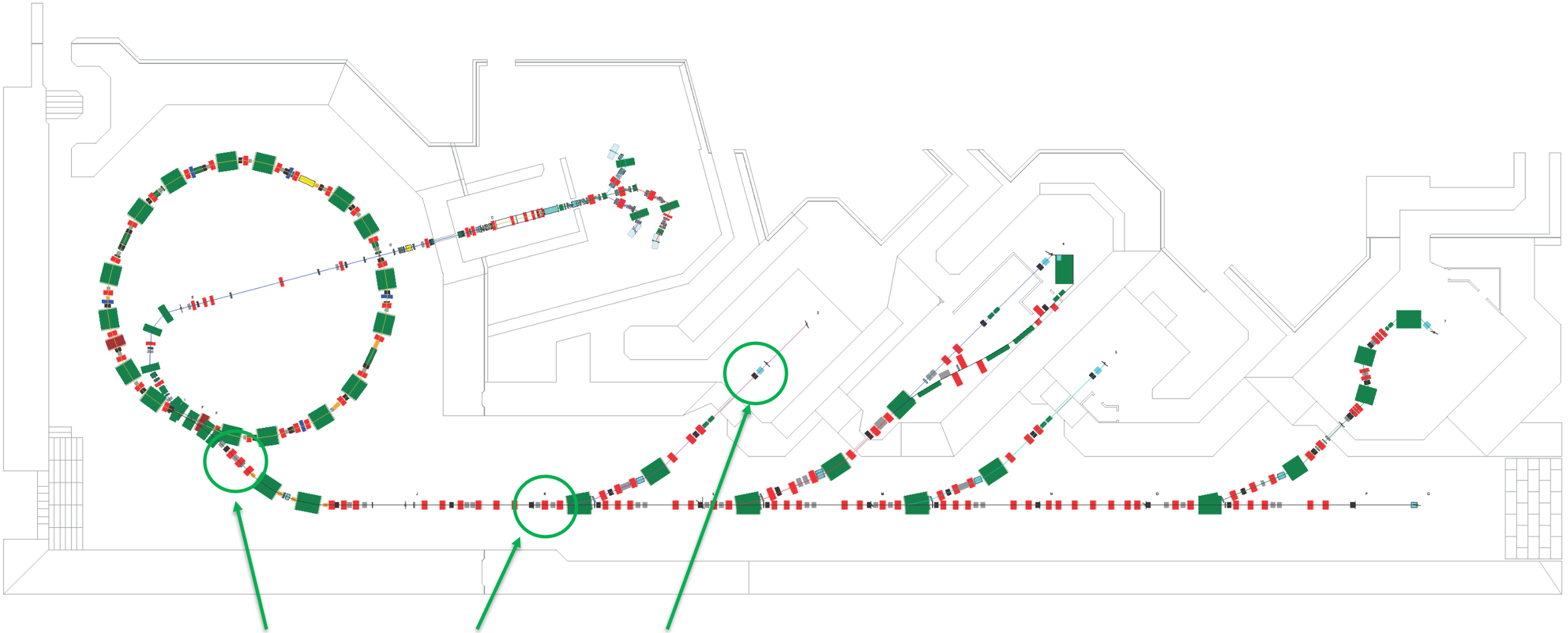
Outline

- Motivation
- Advantages of Silicon Carbide
- Results
- Summary/Conclusion

Motivation

- We use the Medaustron accelerator in Wiener Neustadt for sensor tests in a “low-flux” mode.
- The accelerator was designed for cancer treatment (similar to CNAO).
- Current beam detectors are blind to particle fluxes we use for sensors.
- Need for beam monitors capable of working in “low-flux” mode while ideally covering clinical intensities too.

Requirements



Add beam monitors for single particle detection:

- 6.4 x 6.4 cm² active area.
- 0.5 mm lateral resolution
- At least 25 frames per second

Implementation

Typical circuit for single particle detection. Current pulses are detected, dark current is suppressed.

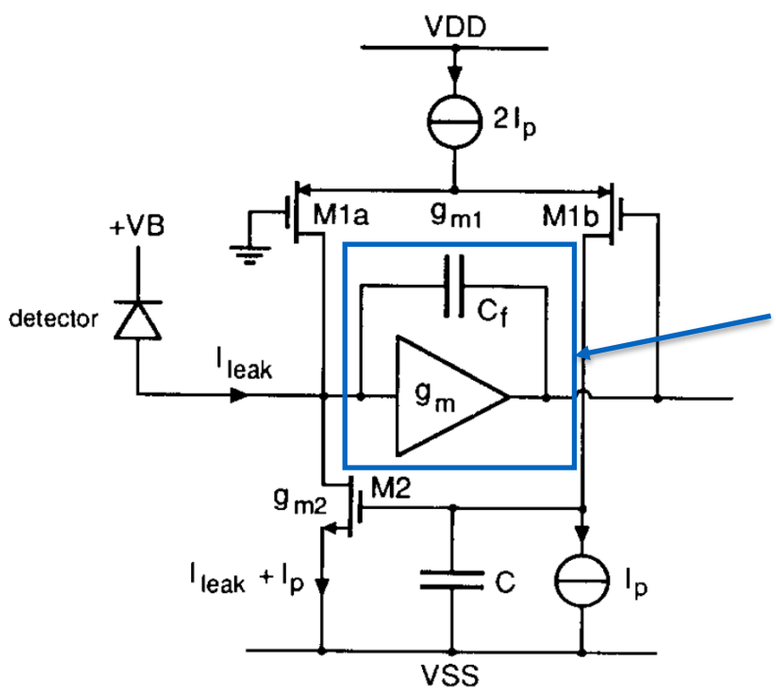
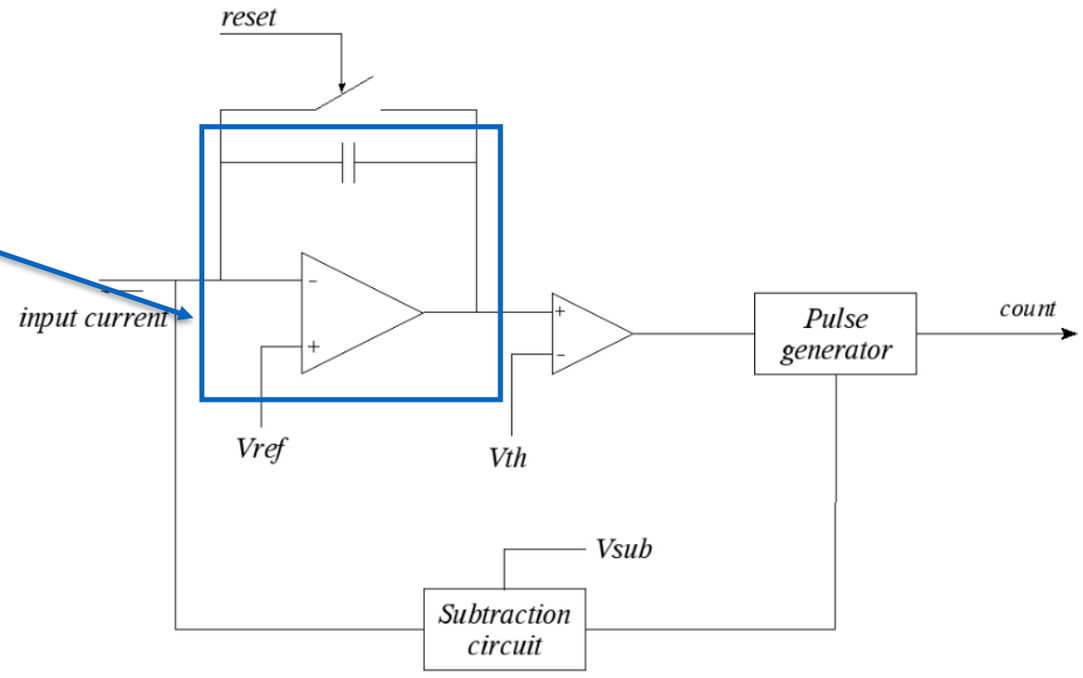


Fig. 2. Example of a CSA with a dc feedback circuitry which automatically compensates for the detector leakage current.

F. Krummenacher, "Pixel detectors with local intelligence: an IC designer point of view," *NIM A* vol. 305, no. 3, pp. 527–532, Aug. 1991, doi: 10.1016/0168-9002(91)90152-G.

Circuit used for ionization chambers at clinical rates: DC current is measured using a current-to-frequency converter.

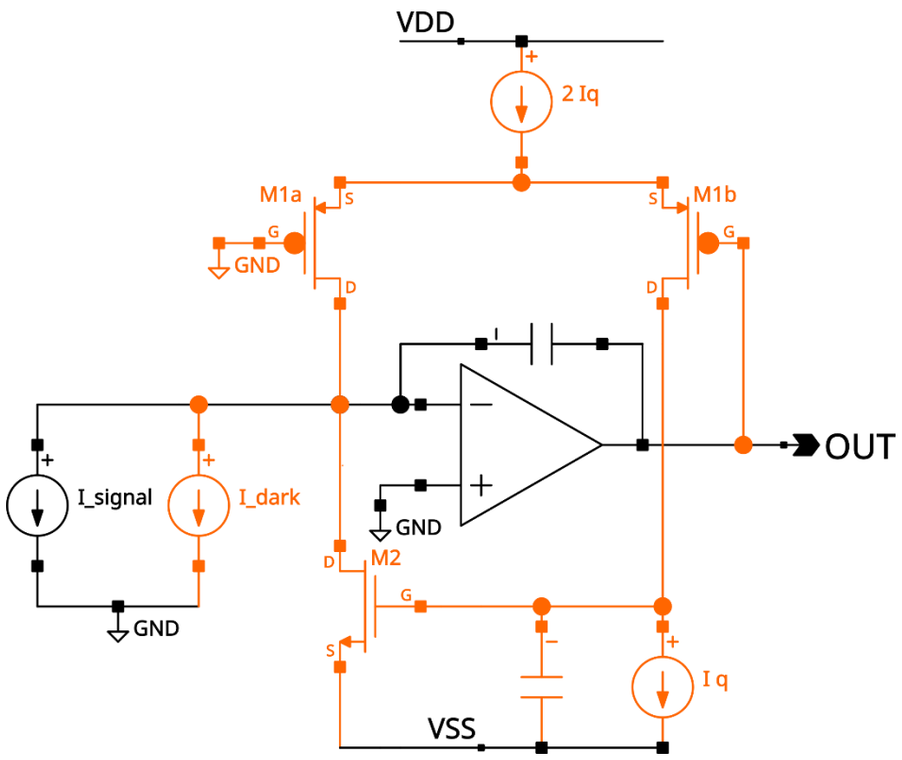
Integrator



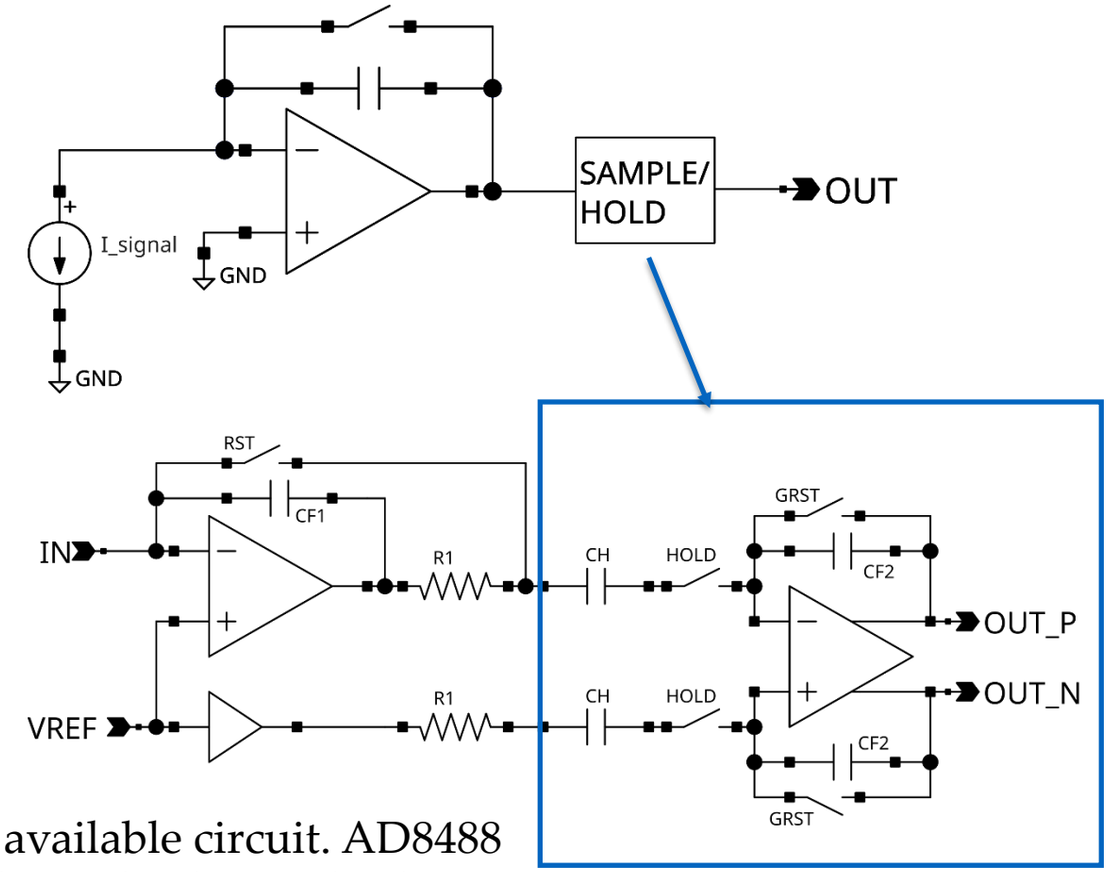
G. Mazza *et al.*, "A 64-channel wide dynamic range charge measurement ASIC for strip and pixel ionization detectors," in *IEEE Symposium Conference Record Nuclear Science 2004.*, Oct. 2004, pp. 964-968 Vol. 2. doi: 10.1109/NSSMIC.2004.1462367.

Implementation

Orange parts are for dark current compensation. Can we get rid of the dark current of our sensors?

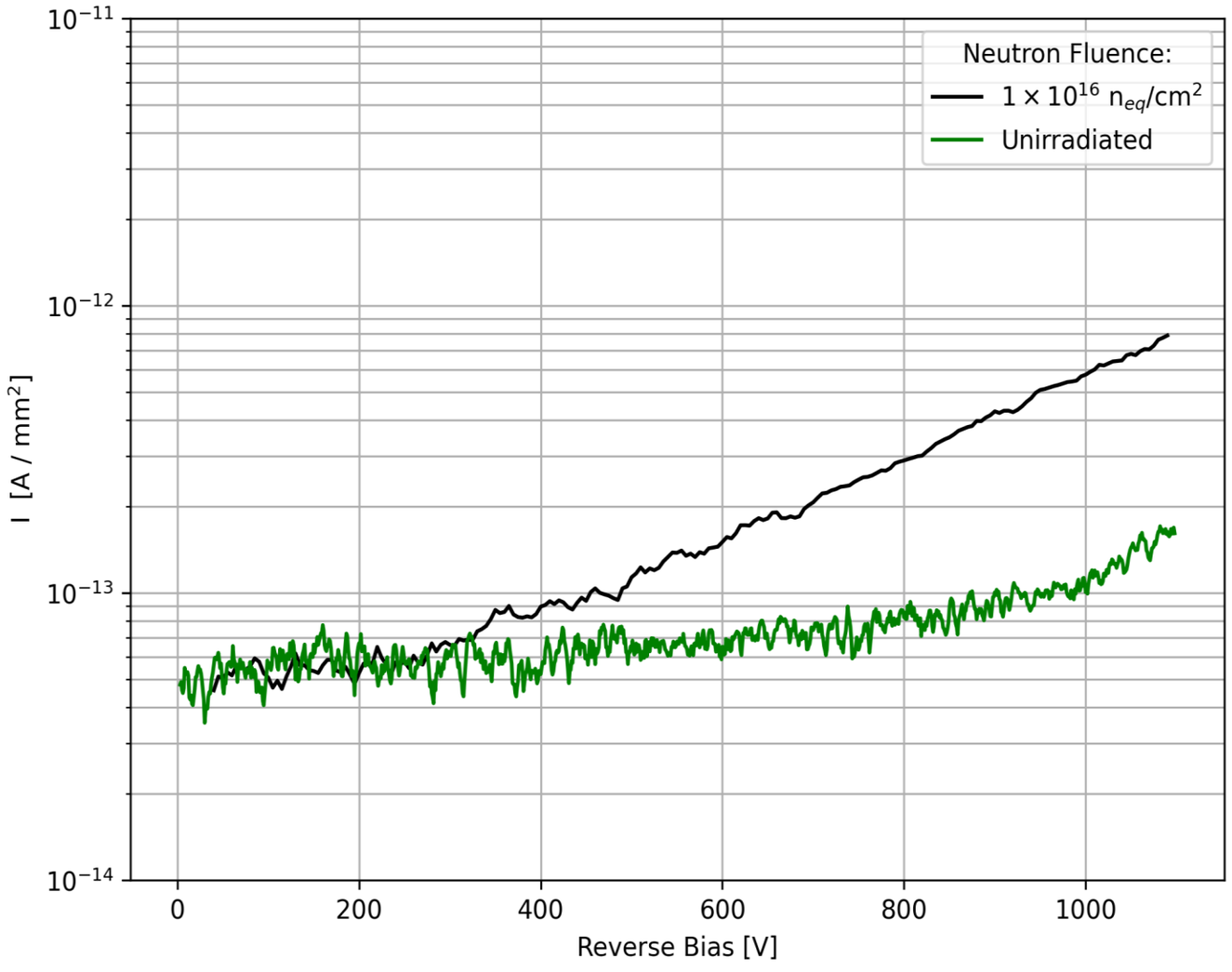


Without dark current, we can use the same circuit for single particle detection and current measurements.



Commercially available circuit. AD8488 contains 128 channels plus multiplexer.

How to eliminate the dark current? Use SiC!

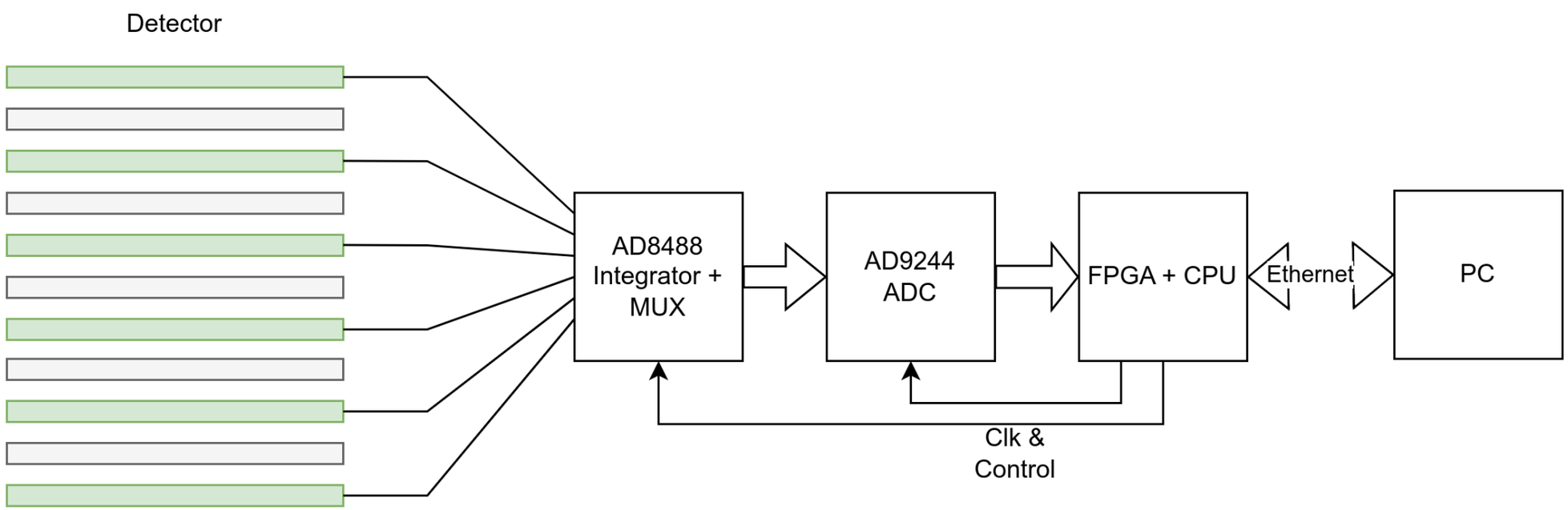


Current measured using a 3x3 mm², 50 um thick SiC detector obtained from CNM

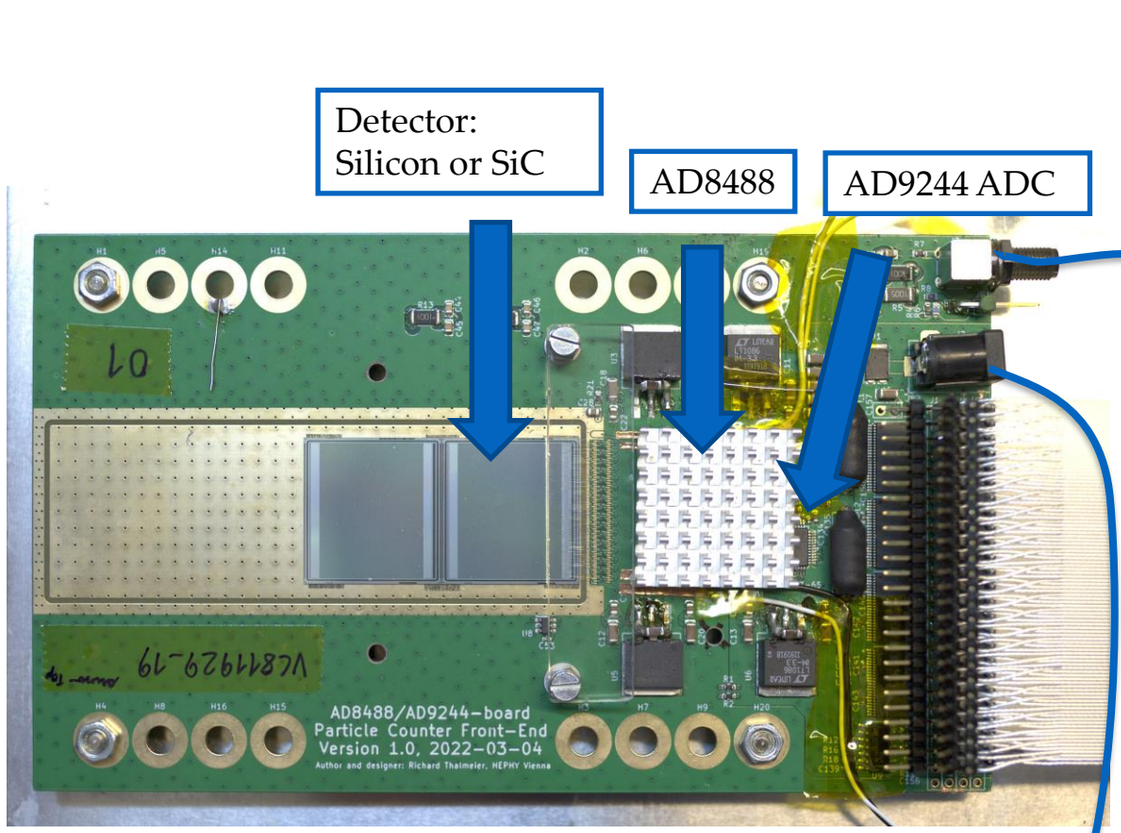
For 1 MeV equivalent Neutron fluences up to 10^{16} SiC has a darkcurrent is below 1pA/mm²

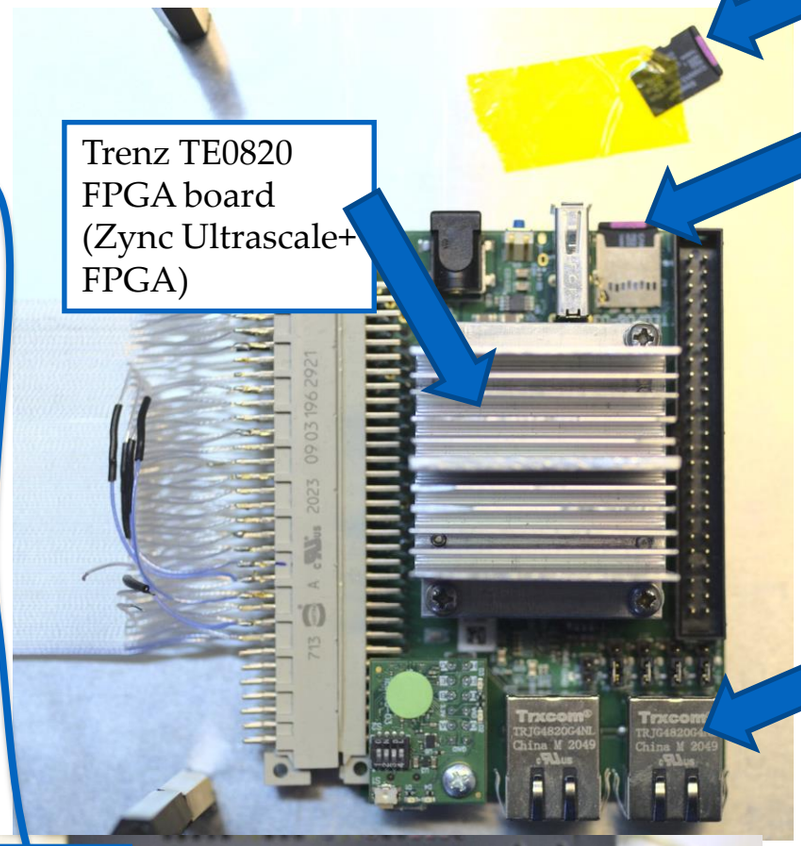
No Need for an ASIC: AD8488 as Frontend

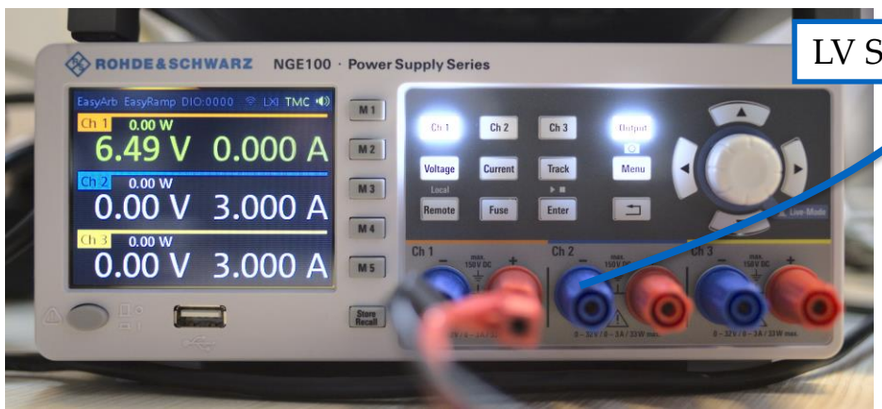
- Input referred noise: 993 electrons/sample (at 38pF input capacitance)
- 128 input channels integrator with integrate/hold and MUX elements
- Up to 37 kHz sampling rate (> 12µs integration, 15µs readout)
- Selectable amplification. Full range current from +/- 3.6 nA To +/- 1.8 µA



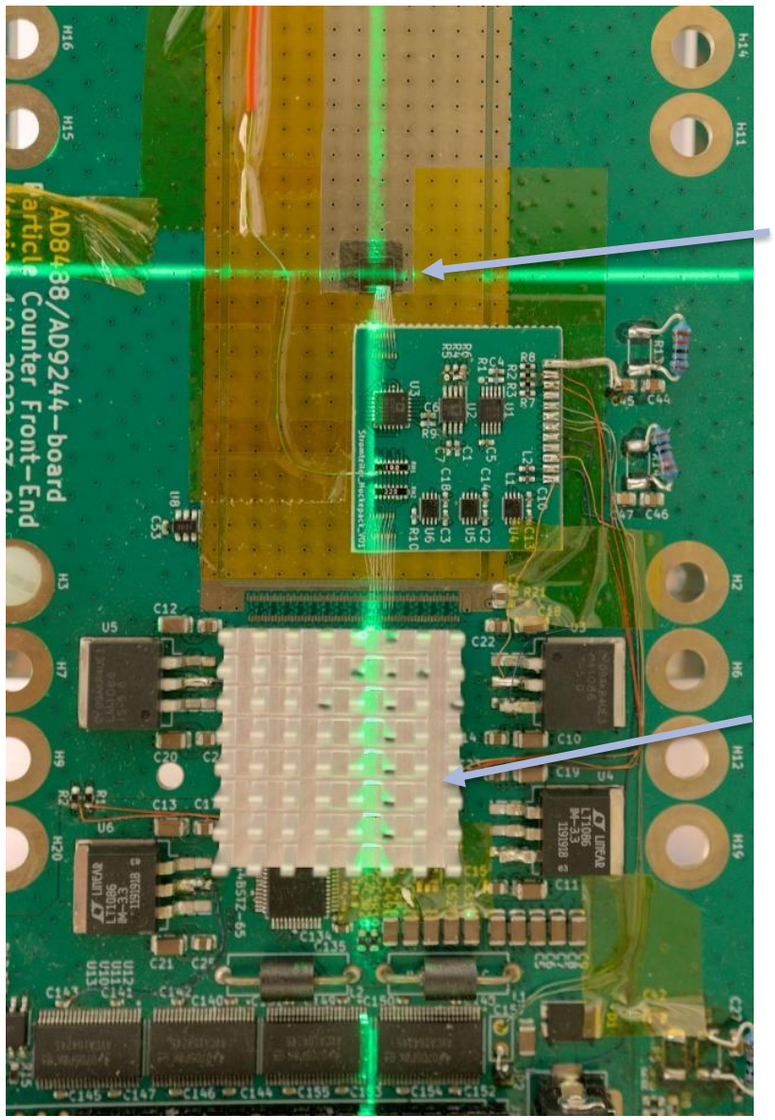
Prototype Measurement Setup



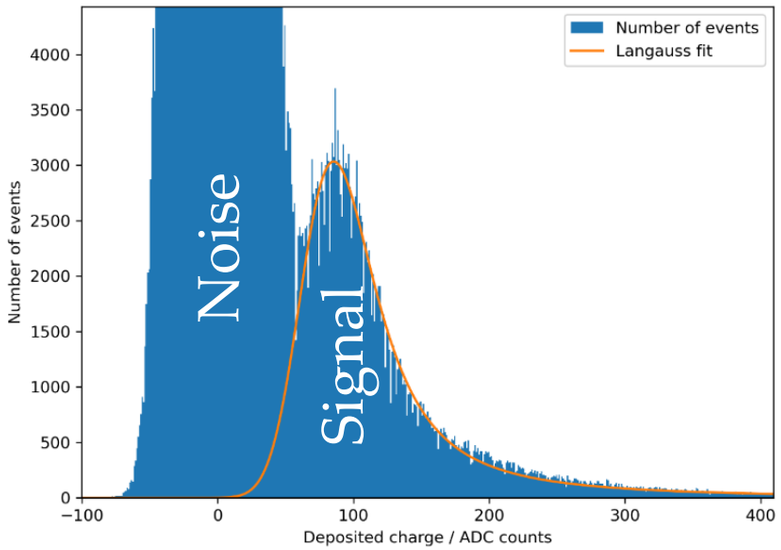




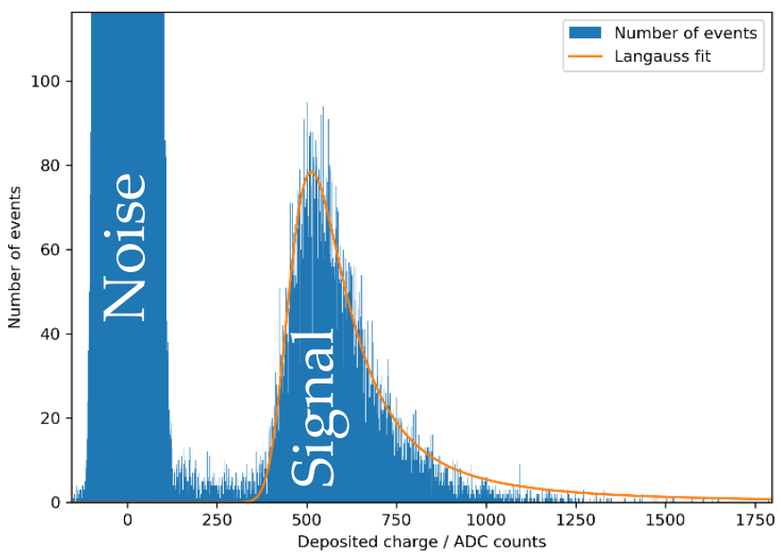
Single Particle Detection



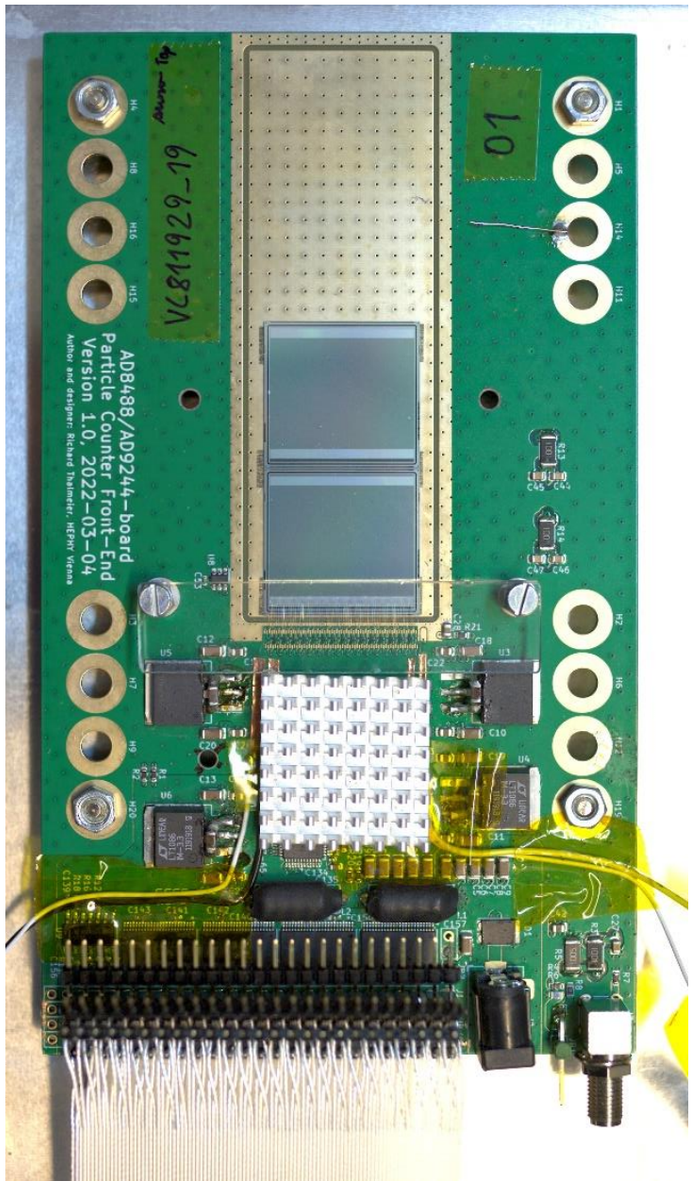
800 MeV protons single particle detection using SiC detector with 50 µm epi. SNR: 4.7
Improvement is expected from the new wafer run using SiC with 100 µm epi.



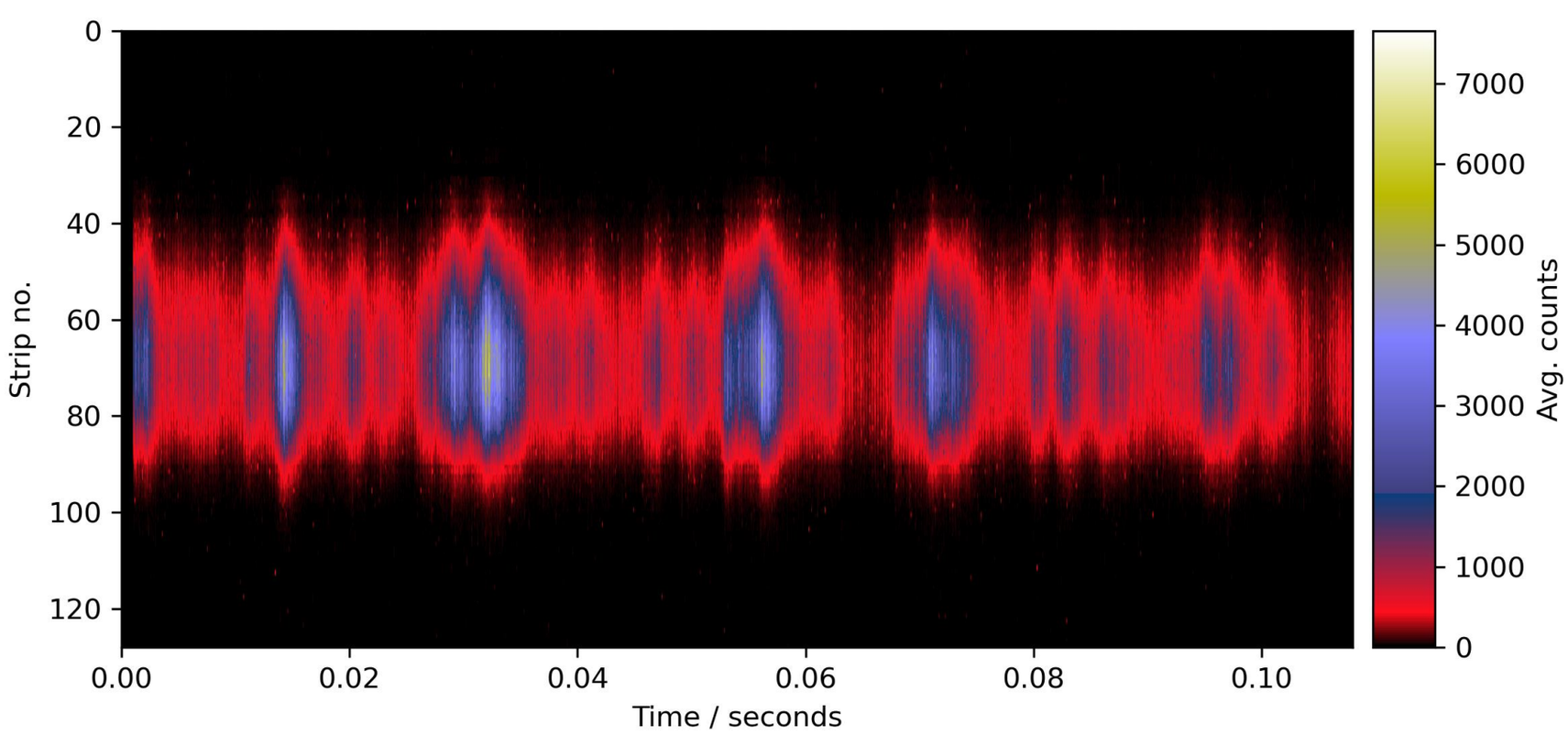
62.4 MeV protons single particle detection



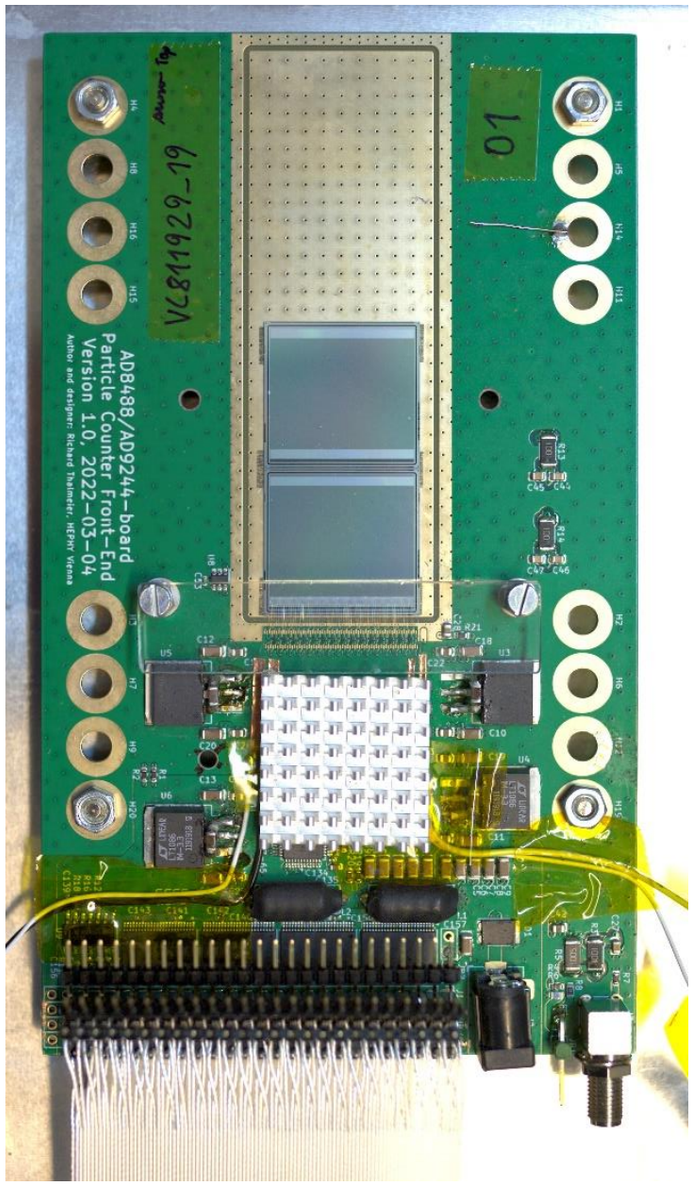
Clinical Beams: Cross-Section



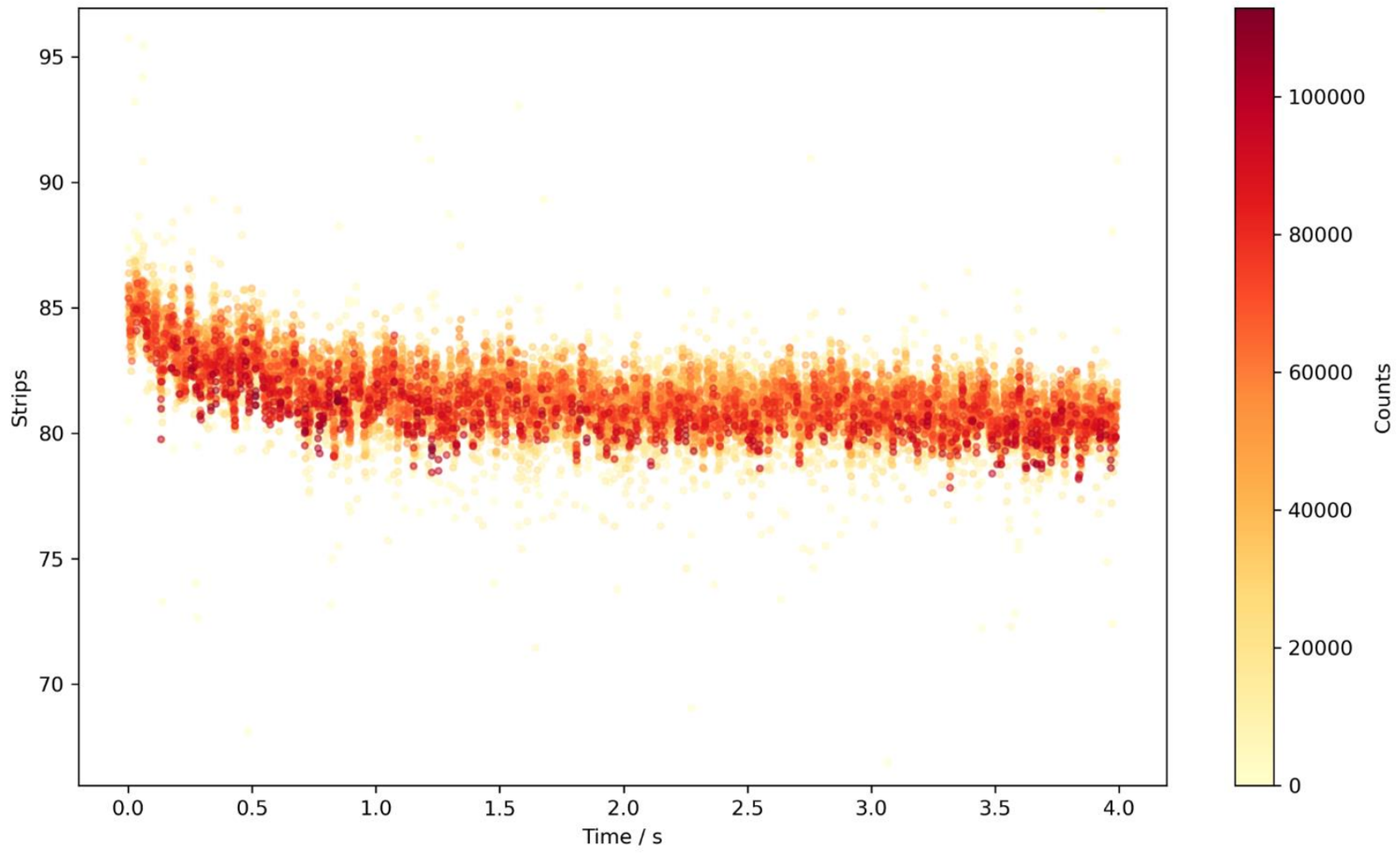
Proton 252.7 MeV, full rate
Using a silicon sensor due to lack of large SiC sensors



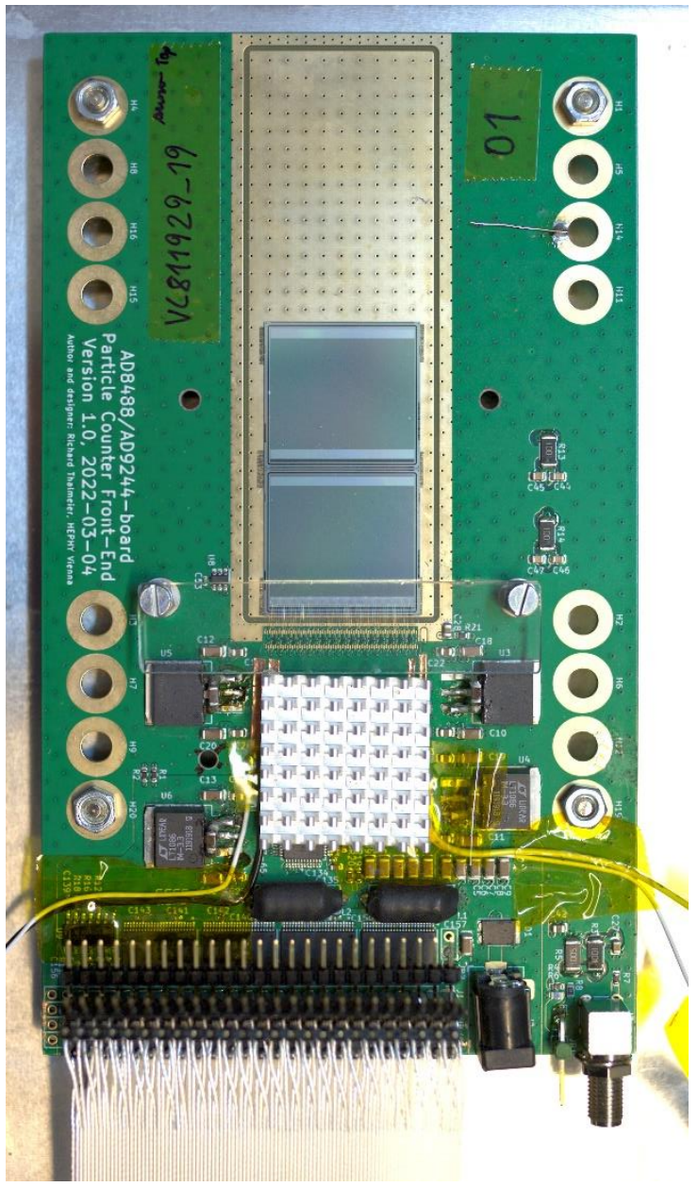
Clinical Beams: Center of Mass



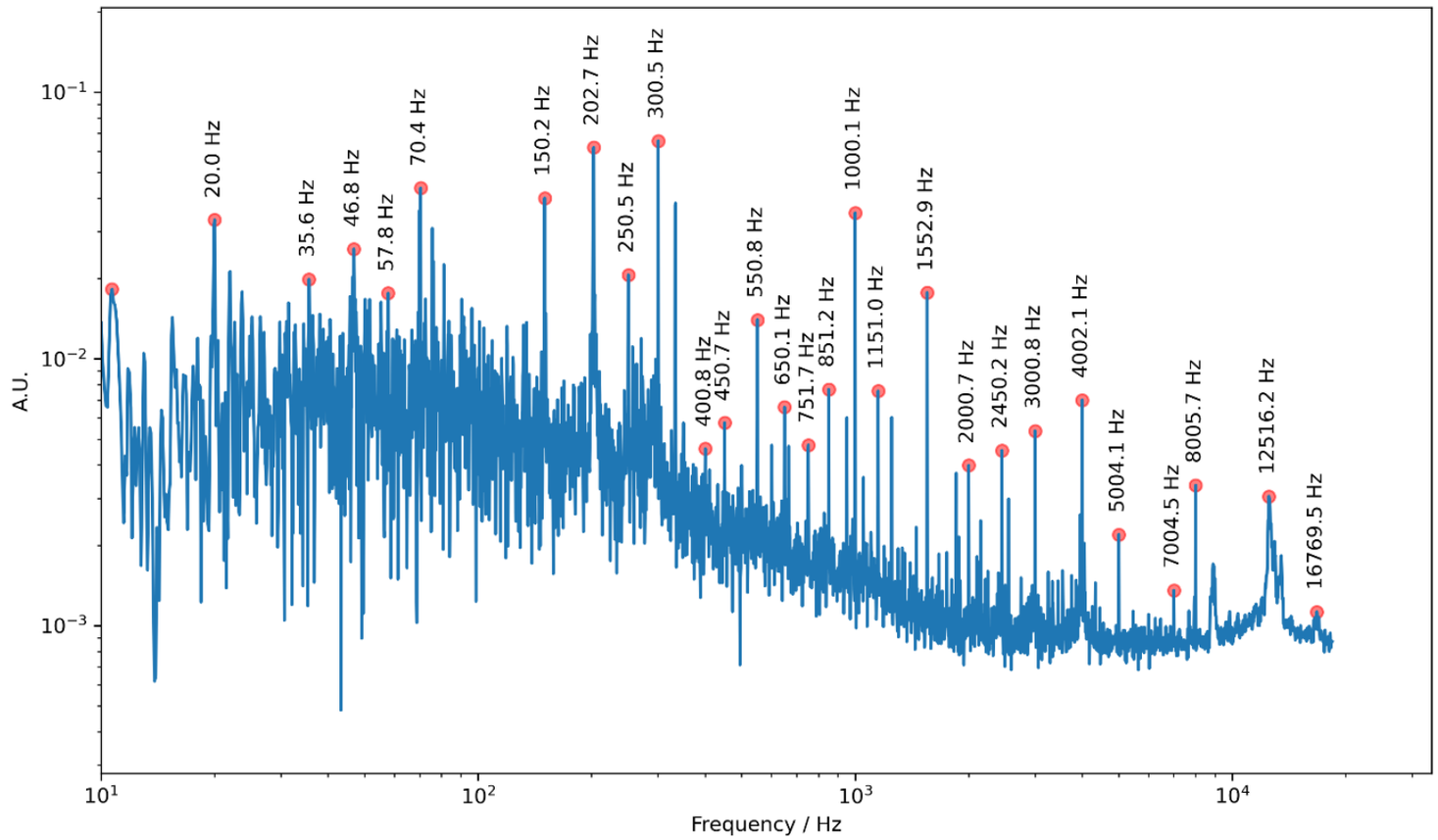
Center of mass, 402MeV carbon, resampled to 3.7kHz
Using a silicon sensor due to lack of large SiC sensors



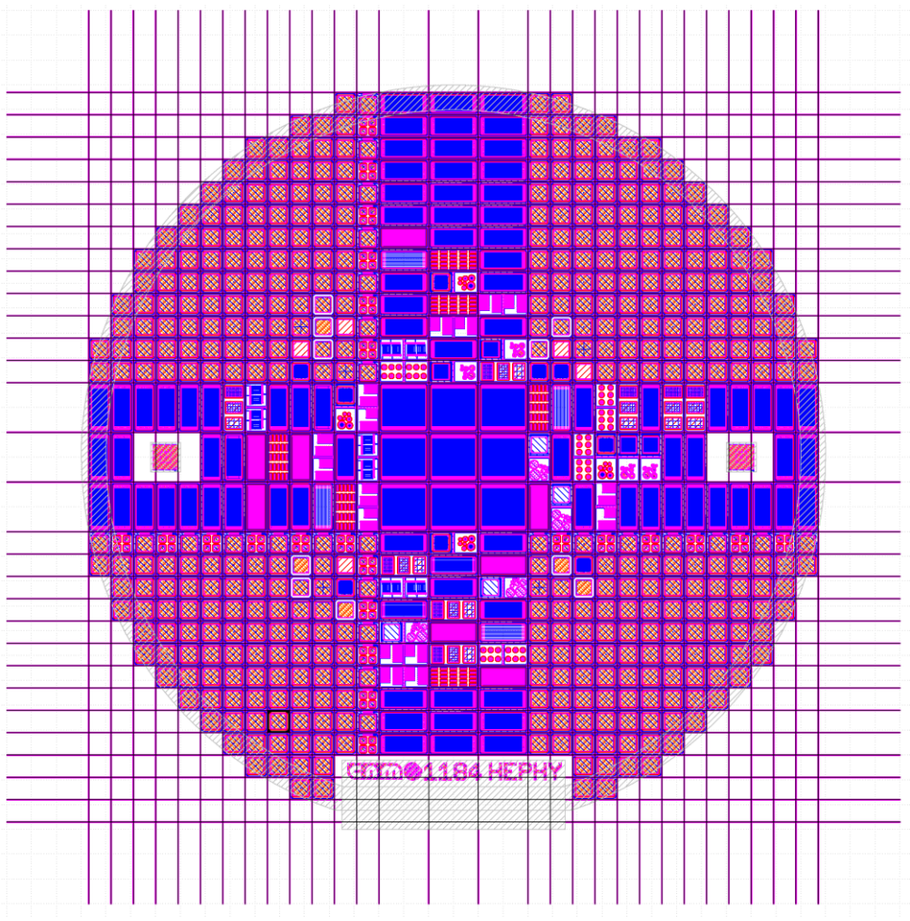
Clinical Beams: Center of Mass, FFT



Fourier transform of the center of mass,
Protons 62.4 MeV, full rate



Prototype SiC Production Run



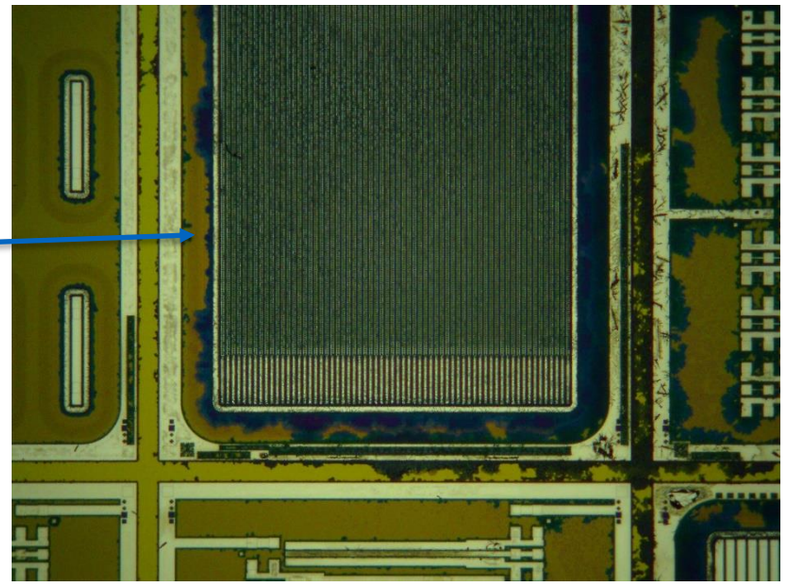
- ~300 pcs. pad detectors (various shapes): main vehicle for radiation hardness tests.
- 9 strip detectors 1x1 cm²
- ~70 smaller strip detectors 1x0.45 cm² in various shapes.
- Structures for characterizing the process.

Sensor Demonstrator:

- 35 strips
- Pitch: 250µm
- Die area 1x1cm².
- Guard structure has been optimized for high voltages using TCAD.

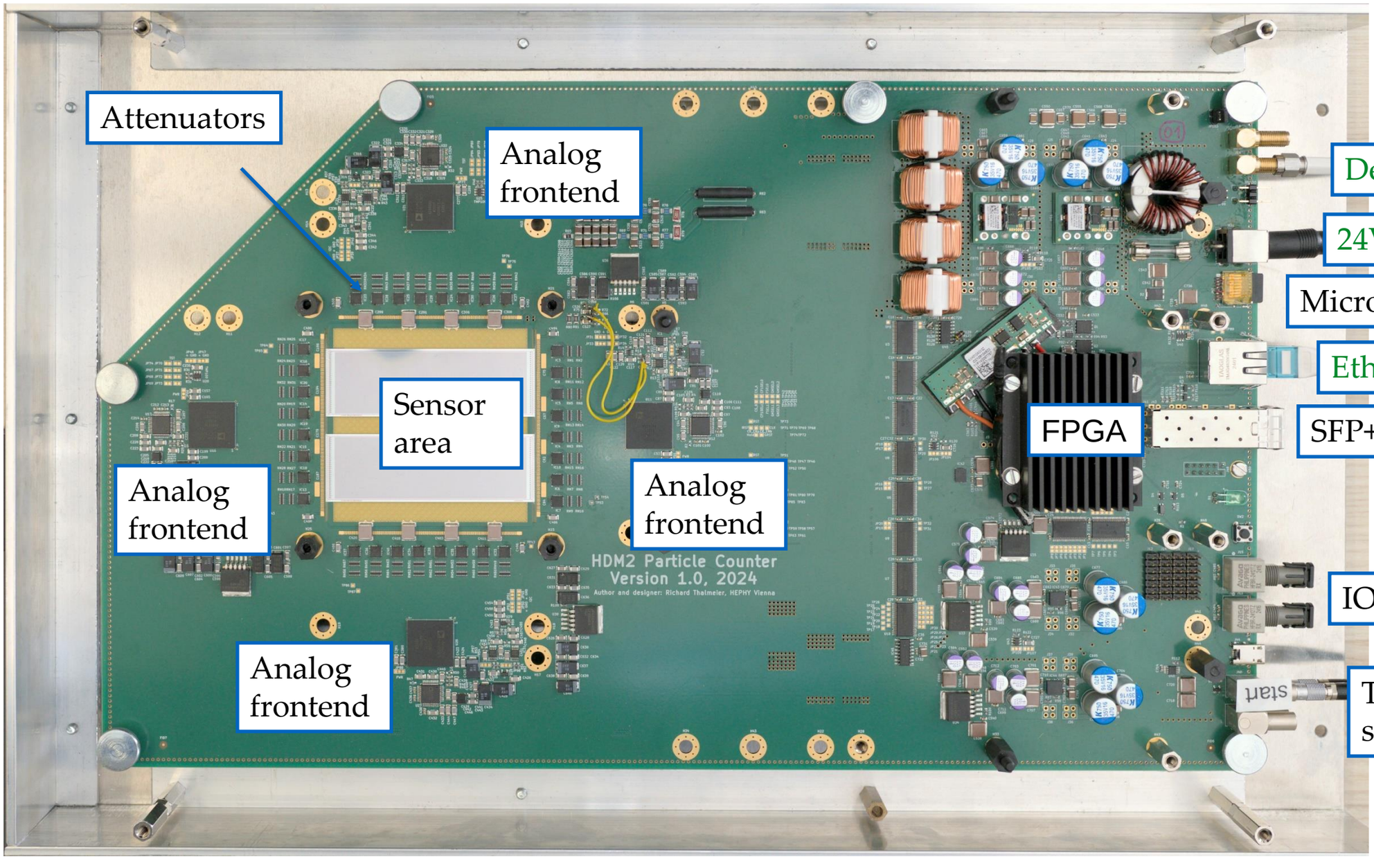
Prototype SiC Production Run

- Tapeout in May 2023
- Production by CNM
- The first production run finished in the spring of 2024. No strip sensors were working due to metallization issues.
- Process was modified adding an additional mask.
- A second production run is ongoing.

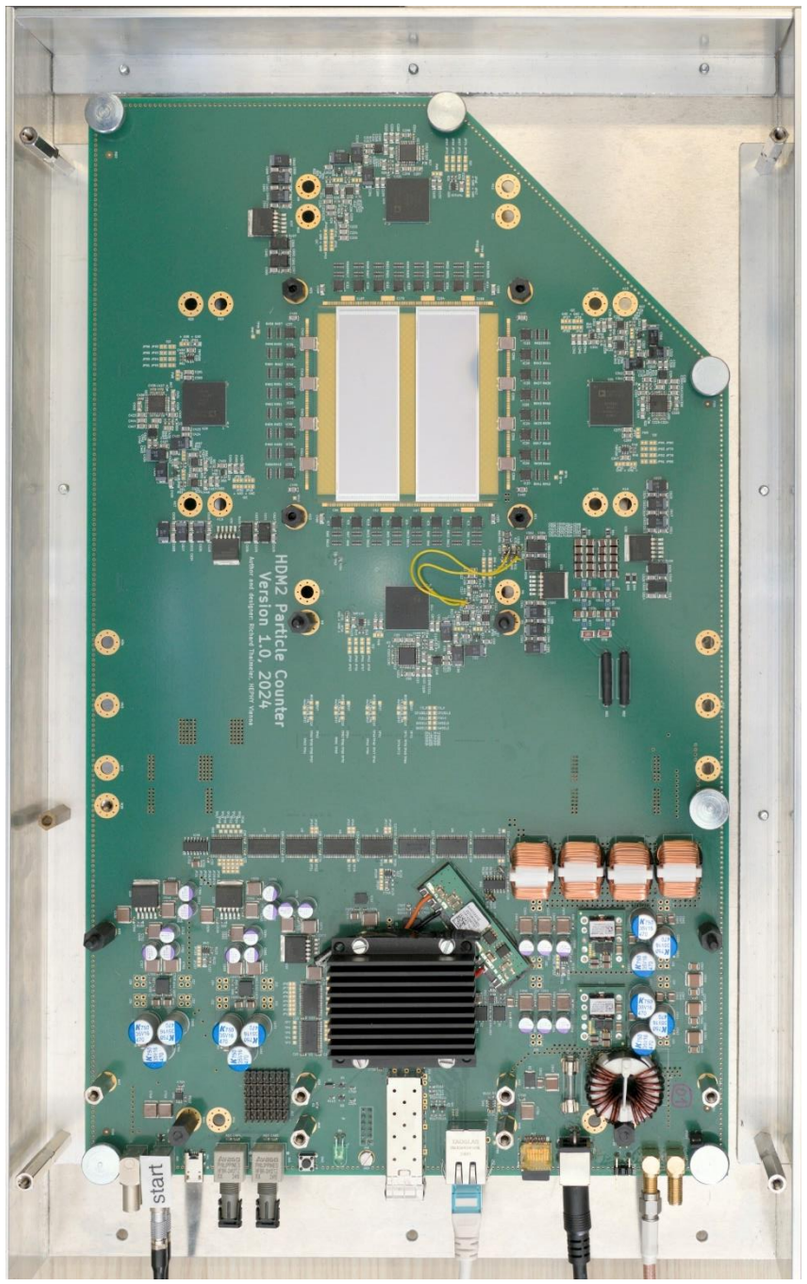


Appeal to the community:
There is a lack of SiC manufacturing capacity!

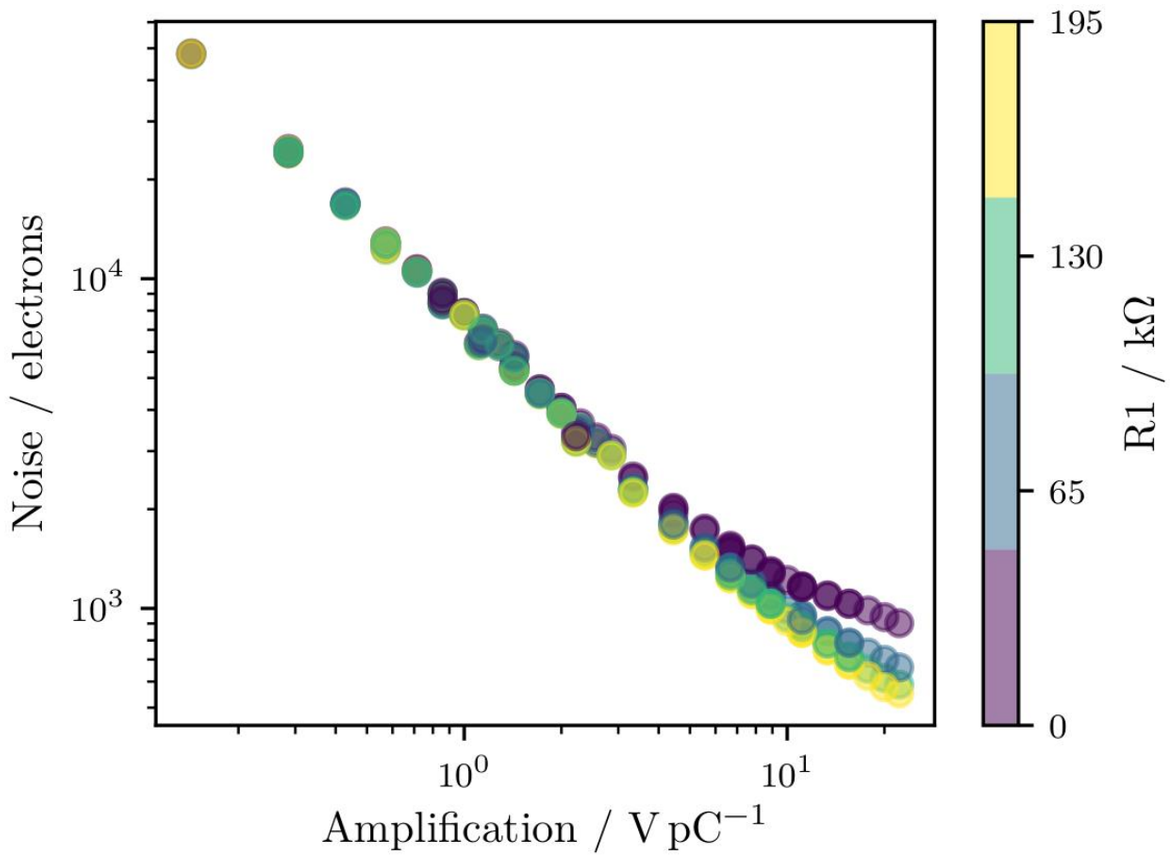
Full size device



Full Size Device: Noise Performance



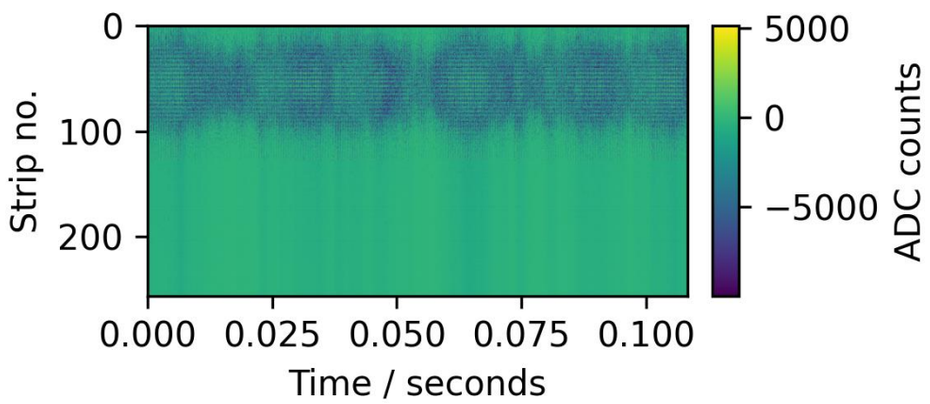
- Can reach the same noise performance as 1st prototype.
- ENC down to 600 e- allows for single particle detection
- Attentuator array should extends input currents up to around 36 µA (To be tested).

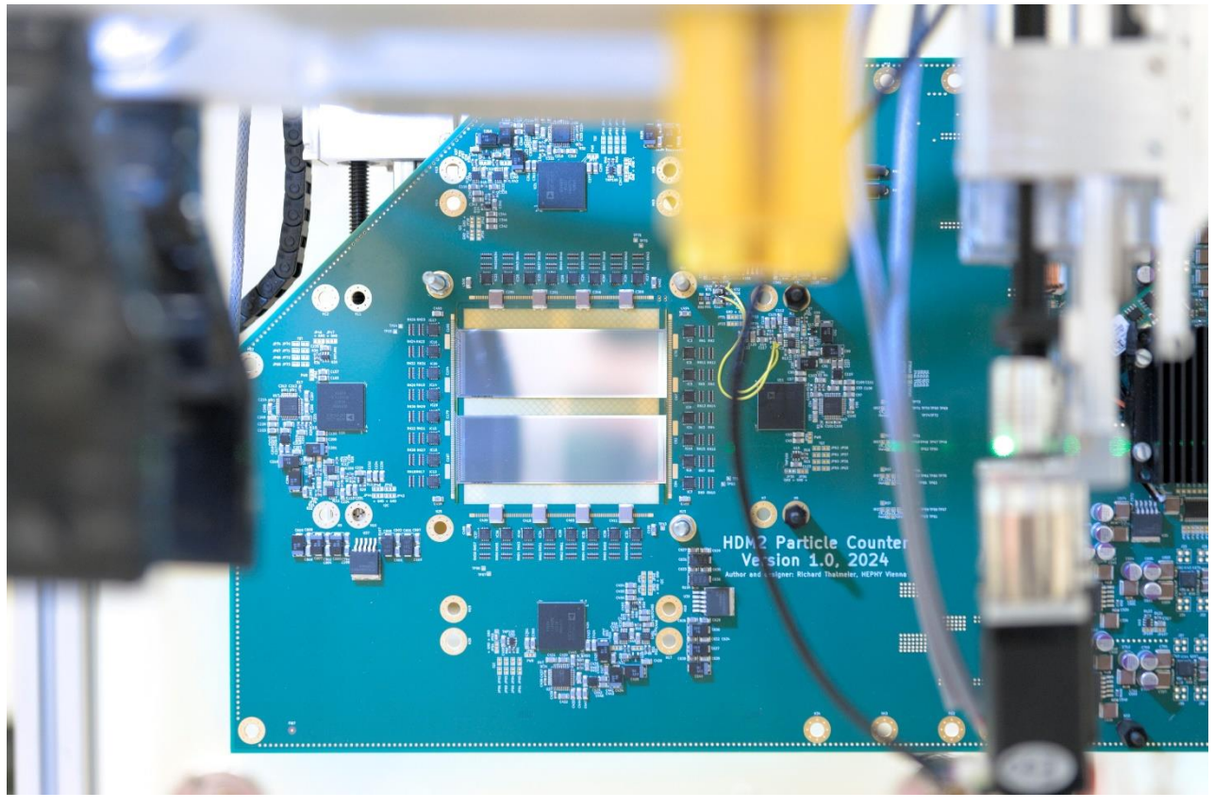


Full size device

- First beam tests successful (using silicon sensors).
- Some tweaking of the biasing circuit and improved software are still needed.
- Need SiC sensors!

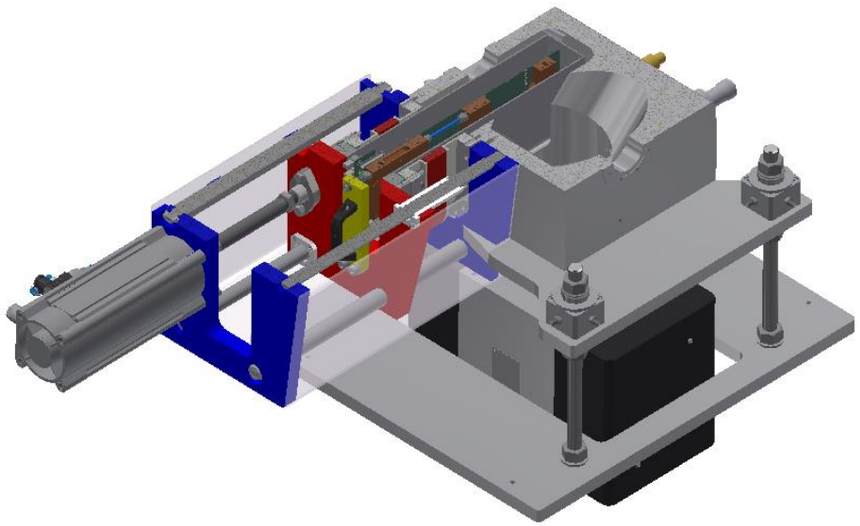
Below a 120 MeV carbon ion beam.





Full-size device mounted for testing at the MedAustron facility.

Feature Summary



- 512 channels readout (256 per direction)
- 0.25 mm channel pitch, total area 6.4 x 6.4 cm²
- Configurable frontend amplification:
  - Odd channels: Full range current from +/- 3.6 nA to +/- 1.8 µA
  - Odd channels: ENC down to 600 e- for single particle detection
  - Even channels: Full range current up to +/- 36 µA
- 37 kHz sampling in synchronous, 74 kHz in interleaving mode
- Data and control signals transferred via TCP/IP for easy accelerator integration
- Loss-less compression in FPGA reduces data rate
- Insertion mechanism is being designed

Conclusions

- The low dark current of Silicon Carbide simplifies the sensor readout circuit.
- Using commercial off-the-shelf (COTS) components an ENC down to 600 e- and full range up to +/- 1.8 μA or even +/- 36 μA was attained.
- Single particle detection was demonstrated, and beams at clinical rates were characterized.
- Full-size demonstrator available. Beam-line insertion mechanism is being designed.
- The unavailability of SiC sensors currently prevents the final device from being manufactured in the facility.

There is a lack of SiC manufacturing capacity!

Thank you for your attention!

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