SiC Based Beam Monitoring System for Particle Rates from kHz to GHz

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Introduction

The Medaustron particle accelerator, located in Wiener Neustadt serves as cancer treatment center and research facility. Its beam monitors have been optimized for beam intensities useful for cancer treatment. However, for research purposes lower beam fluences are required. These fluences include particle rates down to 2 kHz [1]. For cancer treatment fluences in the GHz range are employed.
Beam monitors integrated into the accelerator are optimized for clinical rates and currently blind to particle rates in the kHz range. We have developed a beam monitor that can detect single particles and thus particle rates of a few kHz, while still enabling beam measurements at clinical rates.

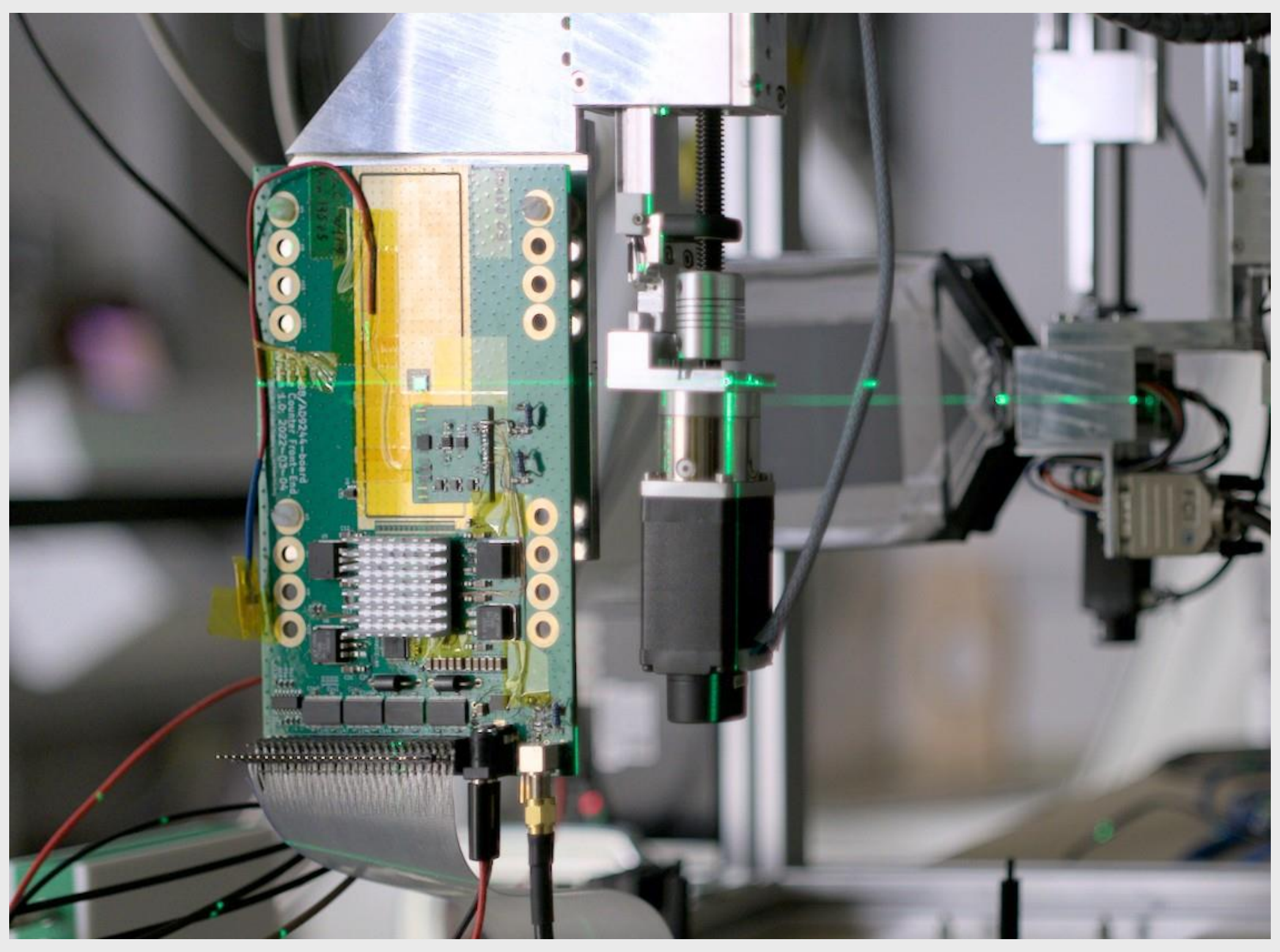
Hardware

4H-SiC was chosen as detector material. In contrast to Si, SiC does not show an increase in dark current when exposed to radiation. Detectors exposed to a dose equivalent to up to 1E15 1MeV neutrons were previously shown to exhibit dark currents below 6pA/cm² [2]. Thus, in contrast to Si, DC current measurements can be performed even with irradiated detectors.

4H-SiC detectors were obtained from CNM and had a thickness of 50 µm. More details about the detectors are given in [2] and [3]. 4H-SiC detectors with a size of 3 x 3 mm² were employed for single particle detection.

For clinical particle rates, larger silicon strip detectors were employed. The employed silicon strip detectors had a thickness of 300 µm and a pitch of 100µm. Only every second strip was connected to the AD8488.

For reading of the detector, an Analog Devices AD8488 current to voltage converter was employed. In addition to the AD8488 the circuit consisted of an AD9244 14-bit ADC and a Xilinx Ultrascale+ FPGA SOC. The FPGA was employed for controlling the AD8488 and reading out the ADC. The CPU of the FPGA SOC was sunning Peta-Linux. A small C-program was interfacing the FPGA and providing a data-stream via a TCP socket. Part of the on-board RAM was used for buffering (1GB) enabling up to 10 s of data to be stored in case of a congested network.



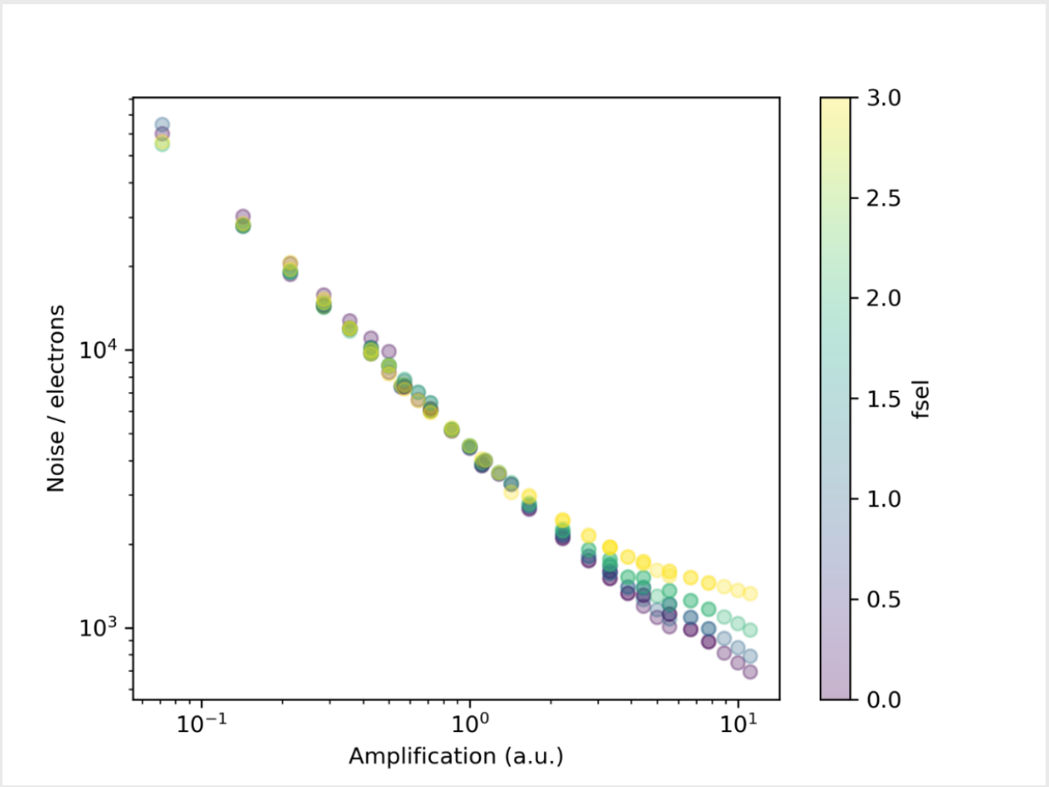
Setup employed for characterization measurements. The SiC detector can be seen at the center of the laser cross-hairs. The AD8488 is covered by the heat sink. The FPGA is located on a separate PCB.

Noise Performance

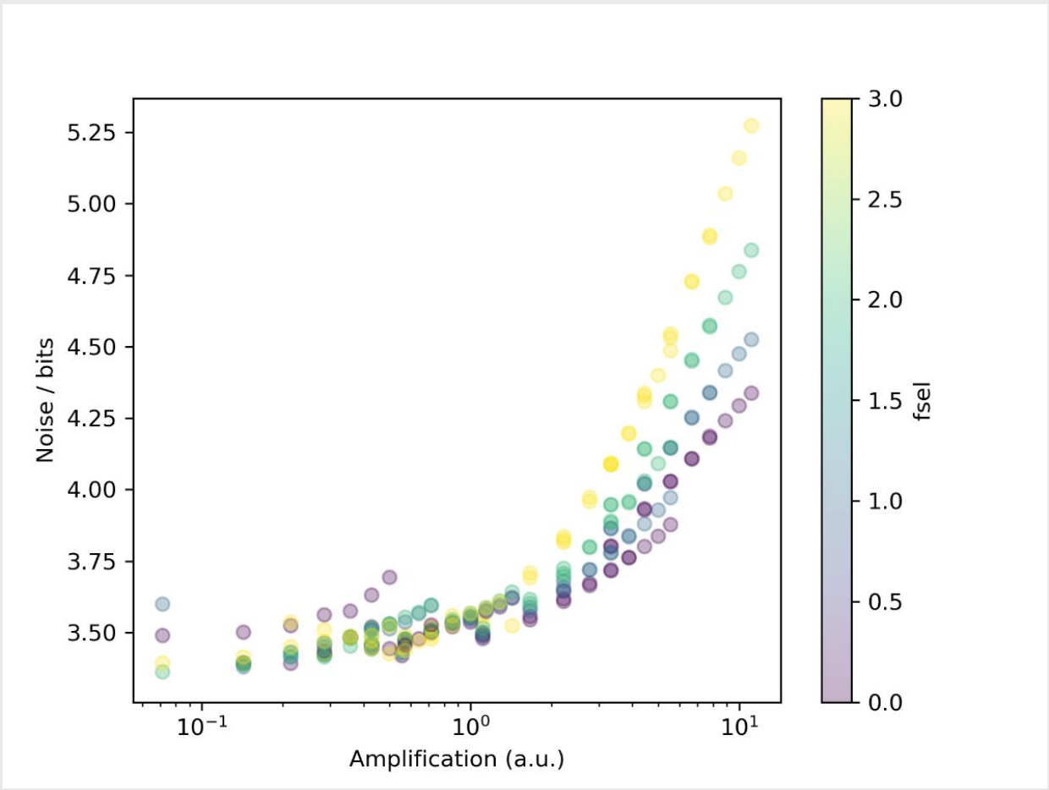
The gain of the AD8488 is selected via the CF1SEL and GNSEL inputs. A low pass can be enabled via the FSEL input. The low pass reduces the noise floor, however it also delays charging of the hold capacitor. This delay causes the reading at the output to become dependent on the moment of arrival of the particle.

For highest sensitivity the low pass needs to enable (FSEL=0). For accurate particle energy measurement, the low pass needs to be disabled.

Noise in electrons as a function of the amplification and FSEL. With a 0.5 pF detector attached a noise floor as low as 700 elections is attained.



Noise in ADC bits as a function of the amplification and FSEL. The ADC has 14 overall of which one is the sign.



References

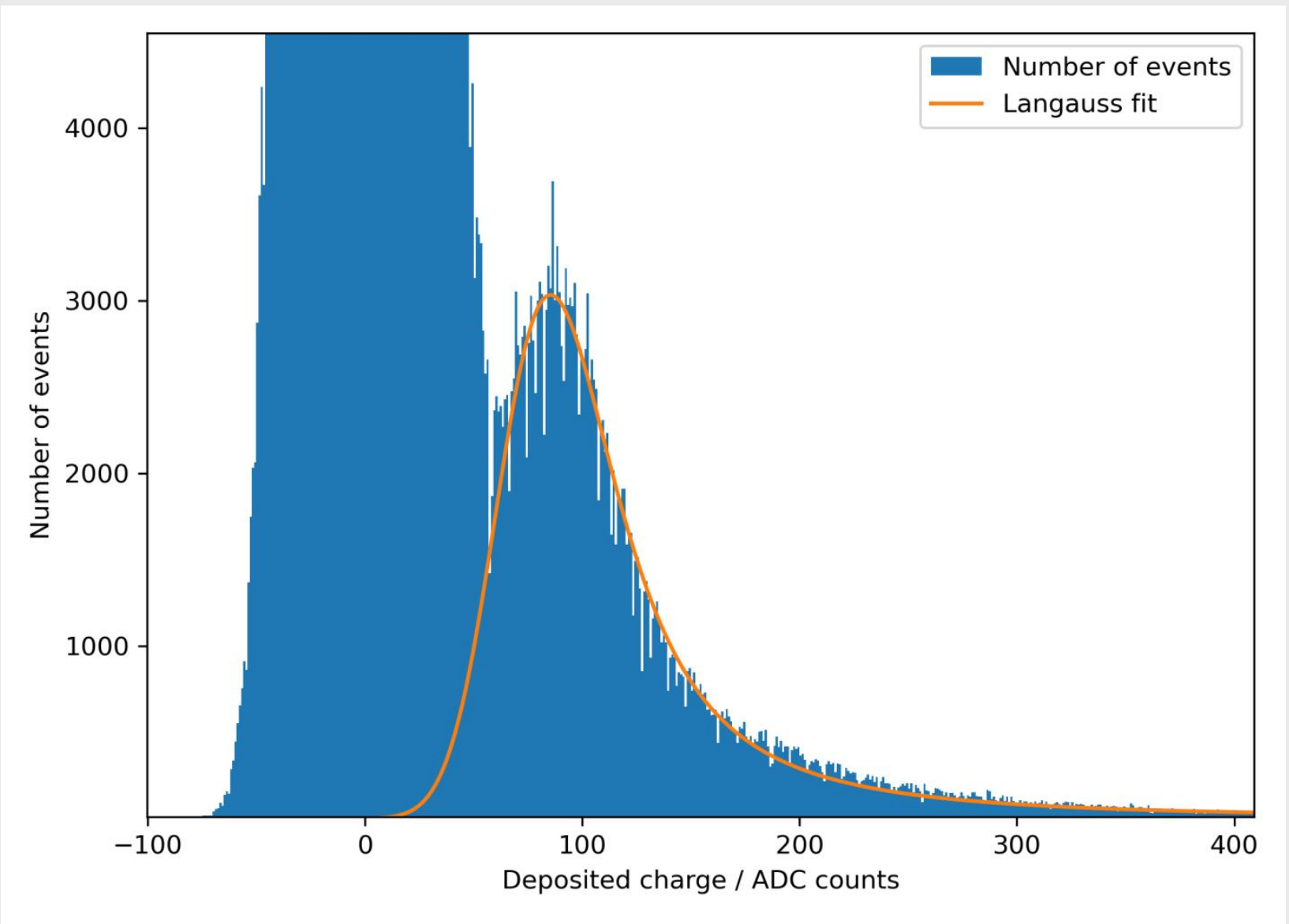
[1] F. Ulrich-Pur et al., doi: 10.1088/1748-0221/18/02/C02062.
[2] Gsponer et al., 42nd RD50 Workshop, Tivat, Montenegro
[3] J. M. Rafí et al., doi: 10.1109/TNS.2020.3029730.

Single Particle Detection

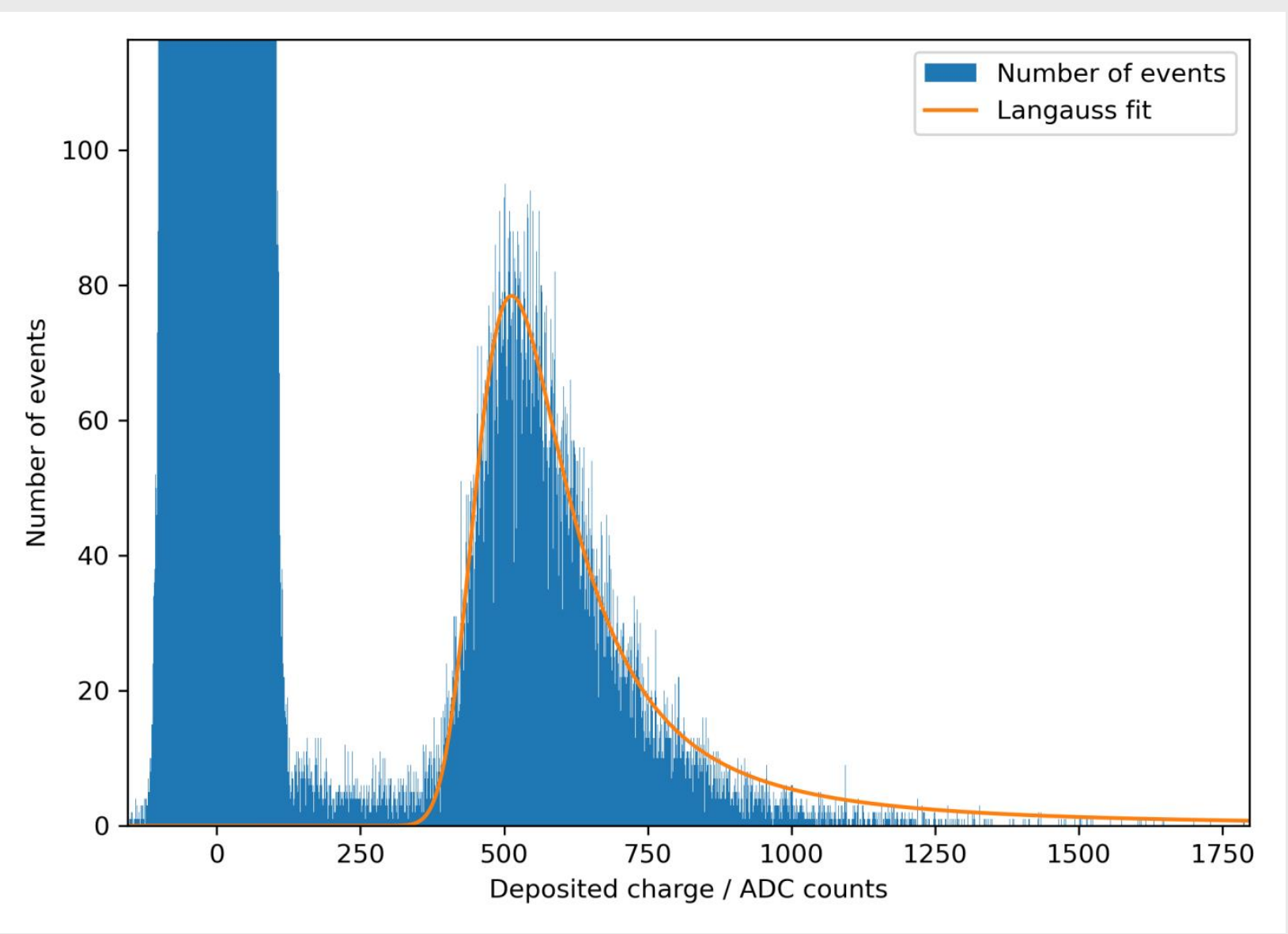
Single particle detection was using on a 50µm thick 4H-SiC detector using proton beams with energies from 62.4 MeV to 800 MeV. At 62.4 MeV (corresponding to 5.5 Minimum ionizing particle, MIP), without low pass (FSEL 3), the SNR was 19 (25 dB). At 800 MeV (1.2 MIP), with largest low-pass resistor (FSEL 0, the SNR was MeV is 4.7. The employed detector had a capacitance of 0.5 pF.

Currently, 4H-SiC detectors with a thickness of 100 µm are being manufactured. They are expected to increase the signal intensity by a factor of two. At the same time, due to the larger area covered, the capacitance will increase to 15 pF, increasing the noise level. This new detectors are expected to deliver a sufficiently large SNR to enable reliable discrimination between particles and noise even at MIP energies.

800 MeV protons (1.2 MIP) impinging on a 50µm thick, 0.5pF detector.
The low pass resistor on the AD8488 was set to maximum (FSEL 0).
The resulting SNR was 4.7.



62.4 MeV protons (5.5 MIP) impinging on a 50µm thick, 0.5pF detector.
The low pass resistor on the AD8488 was set to maximum (FSEL 0).
The resulting SNR was 19.



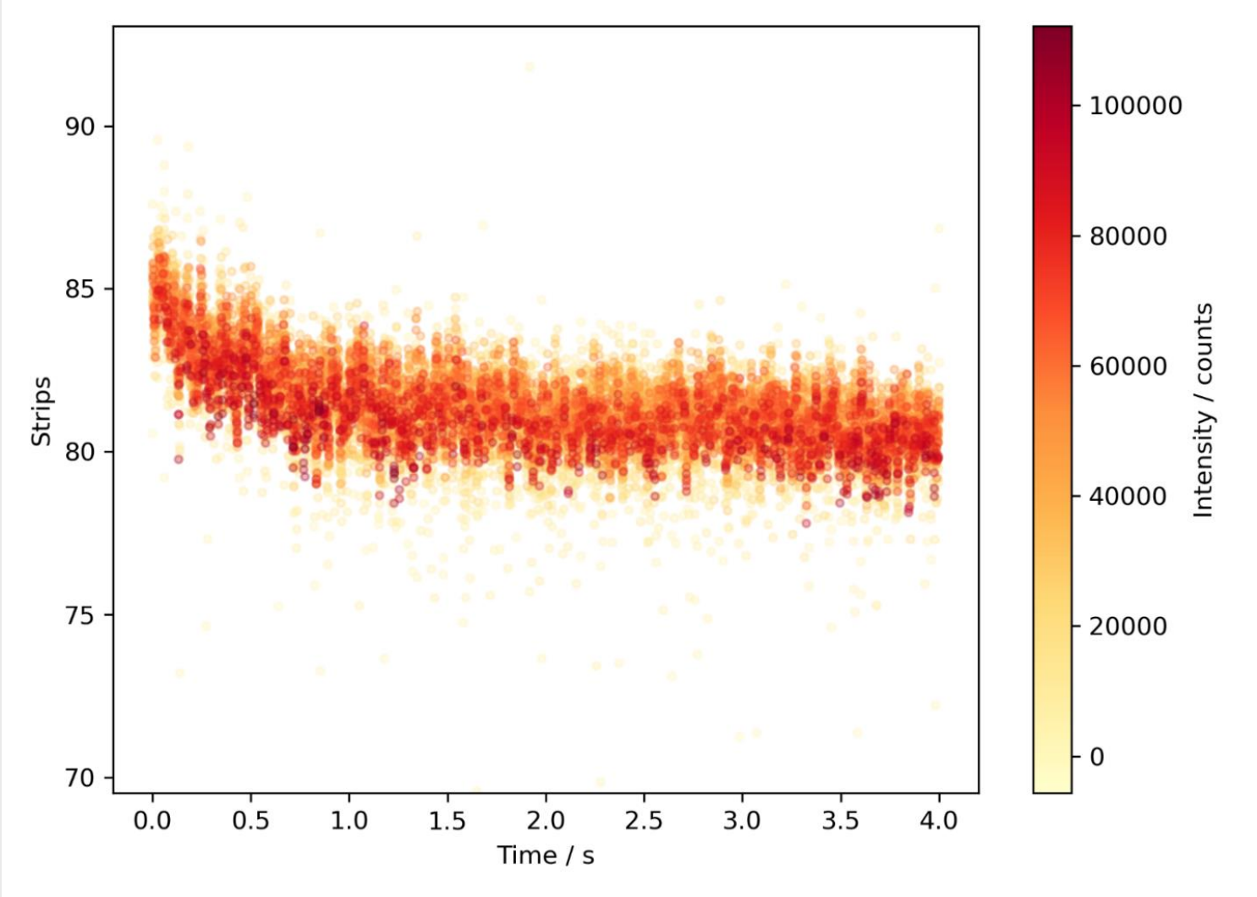
Monitor at Clinical Rates

Clinical rate tests were performed using a silicon strip detector. The strip width was 100 µm opposed to the 250 µm expected from the final HDM detector. The detector was 300 µm thick, opposed to the 100 µm expected from the final detector. Thus, the detector signal was 1.7 times larger than what is expected from future 4H-SiC detectors.

The beam monitor was tested using clinical proton and carbon beam parameters. The beam parameters were the following:

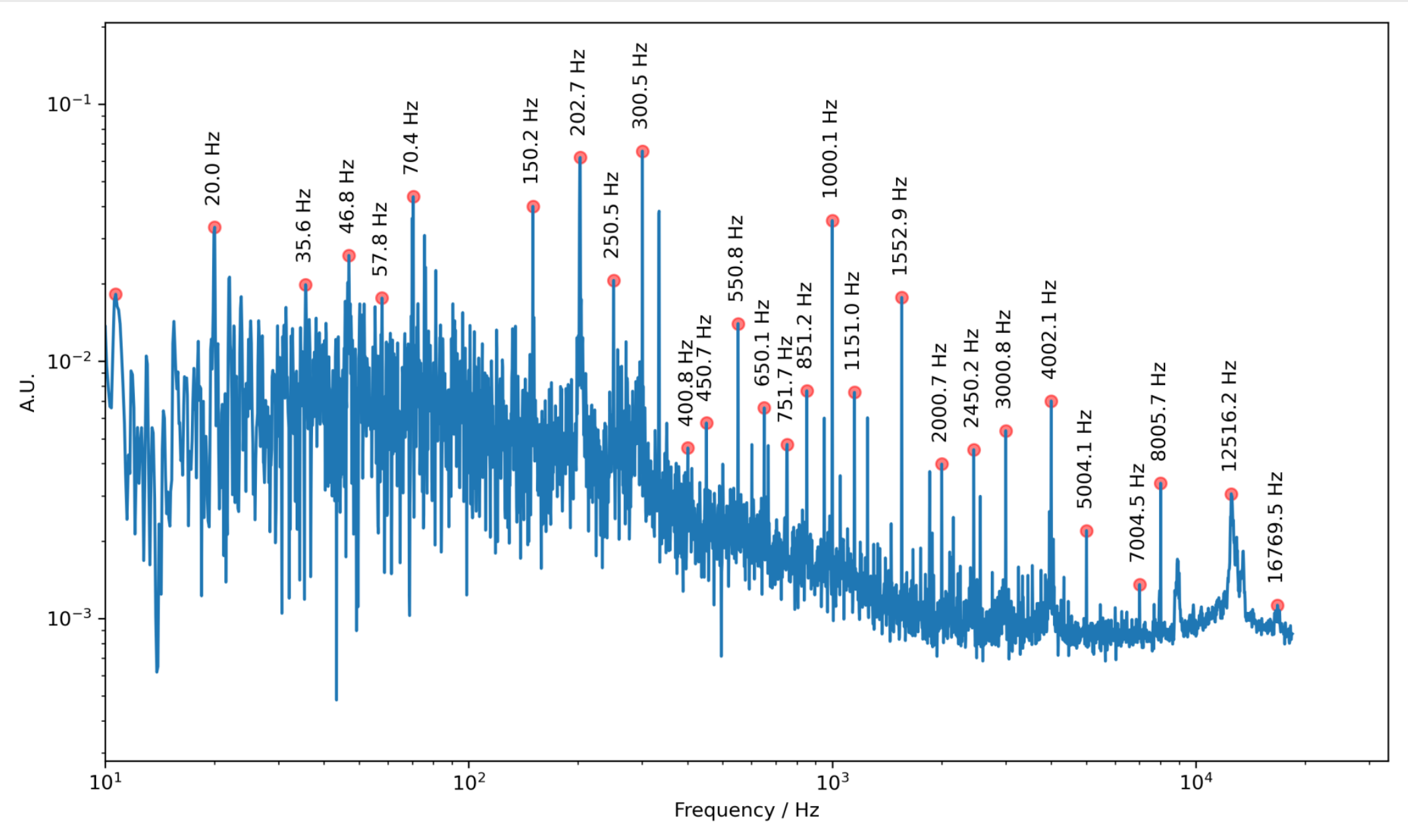
- Protons: 62.4 to 800 MeV, 10 s spills, 1E10 particles per spill
- Carbon 120 to 402 MeV, 4 s spills, 1E8 particles per spill

Saturation effects were observed for less than 1% of frames and could be filtered out using a χ^2 analysis. Work is ongoing to integrate an attenuator into the circuit, thus enhancing the dynamic range

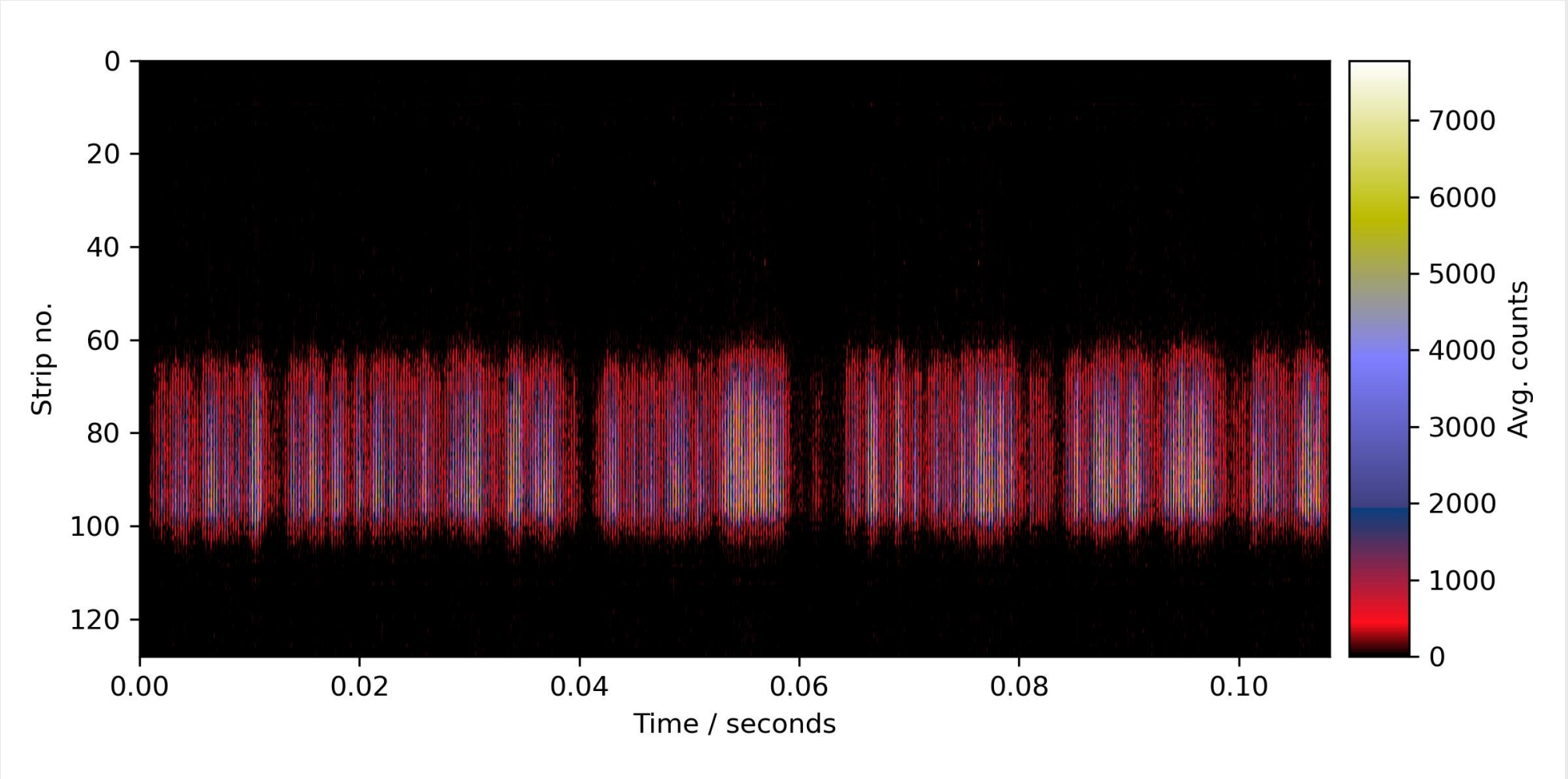


Center of mass of a 402 MeV carbon beam, down-sampled to 3.7 kHz.

Beam movement at the beginning of the spill as well as position oscillations can be observed.



FFT of the center of mass of a 62.4 MeV proton beam. The frequency components of beam position oscillations can be resolved.

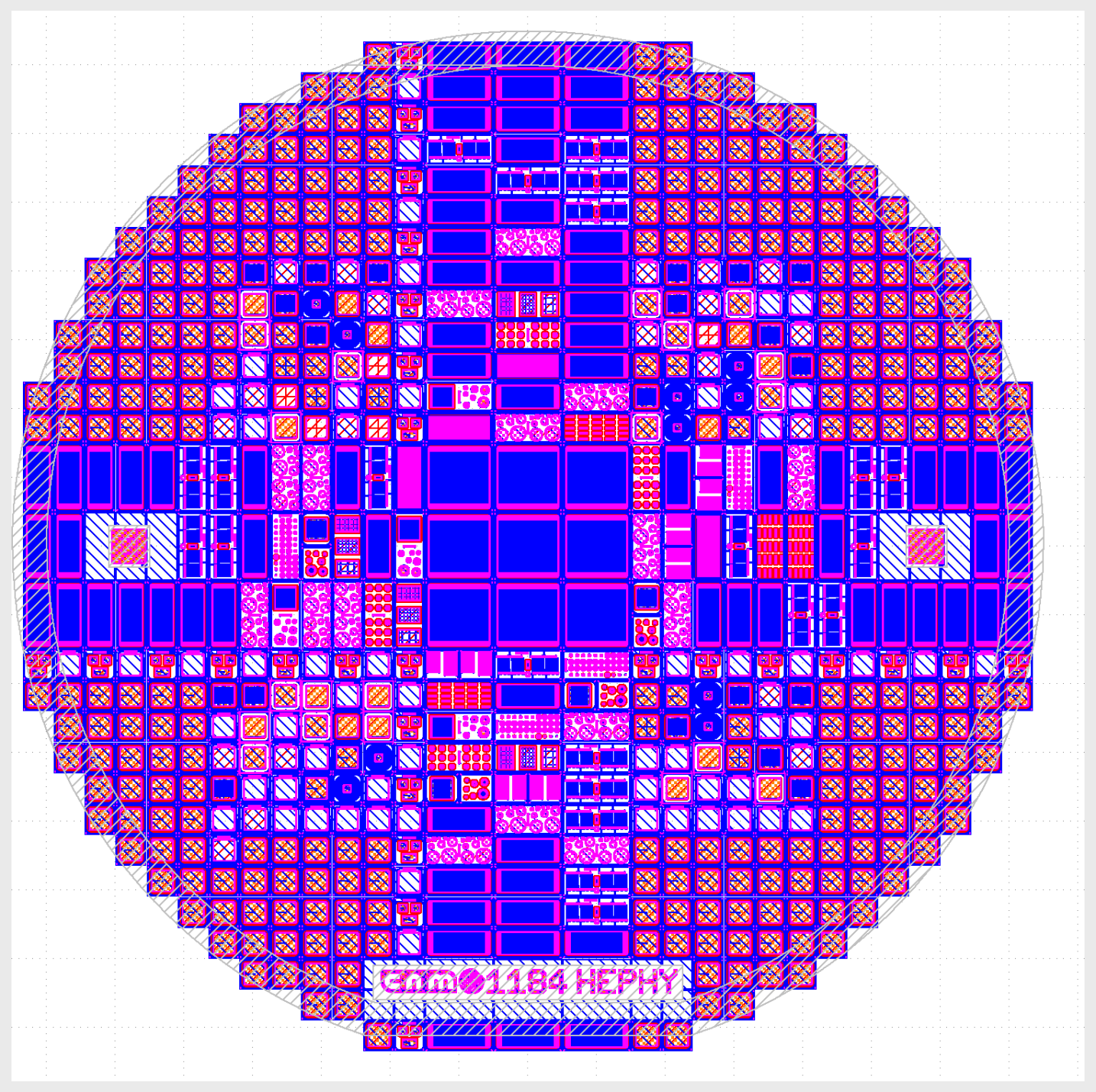


Frame by frame plot of a 402 MeV carbon beam. Shape and intensity oscillations are characteristic for carbon.

Conclusion and Outlook

- A prototype of a beam monitor being capable to detect single particles while being compatible with clinical rates was developed.
- For single particle detection, the system showed an SNR of 4.7 or better for all beams available at Medaustron.
- Operation at clinical rates was demonstrated. All beams could be resolved. However, the system partly operated close to the saturation limit.

- To improve the SNR for single particle detection a new detector is being manufactured. An improvement of the SNR close to of a factor of 2 is expected.
- To improve performance at high fluences, an attenuator is currently being tested. The attenuator circuit is expected to make the beam monitor compatible with FLASH beams.



Wafer layout of new production