SiPM Front-end for CTA

SMART2: a SiPM Multichannel ASIC for high Resolution Cherenkov Telescopes

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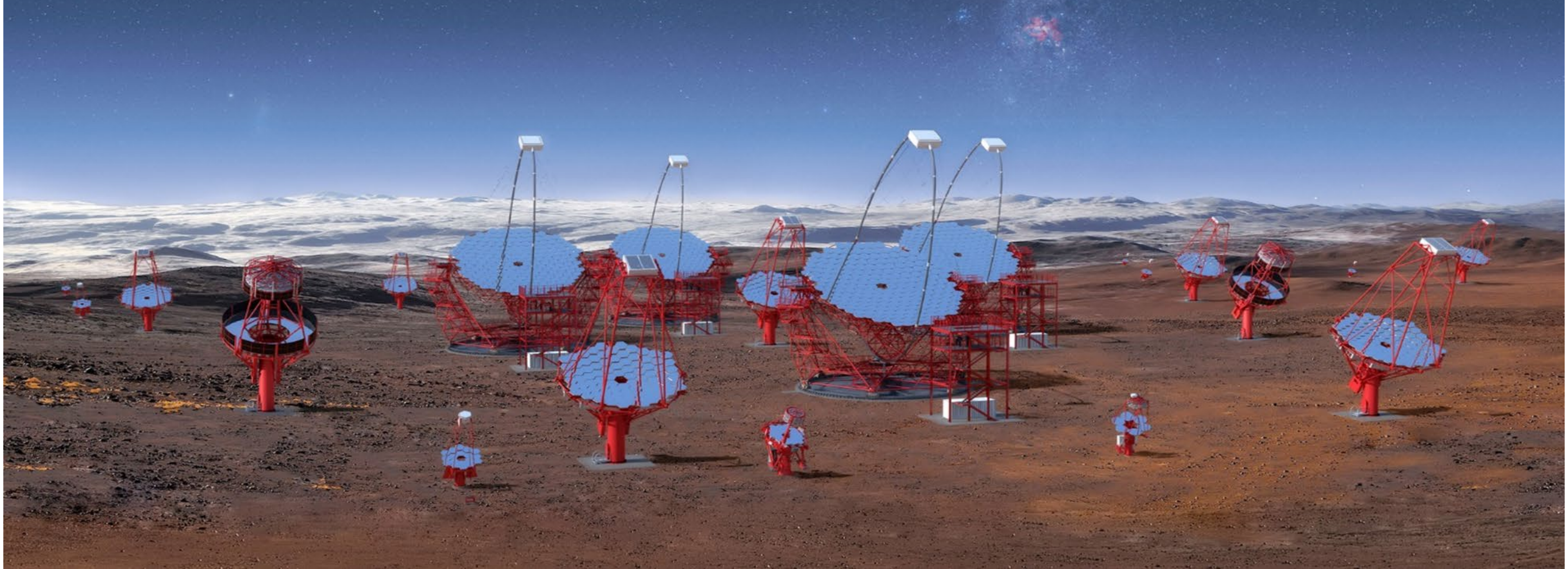
Outline

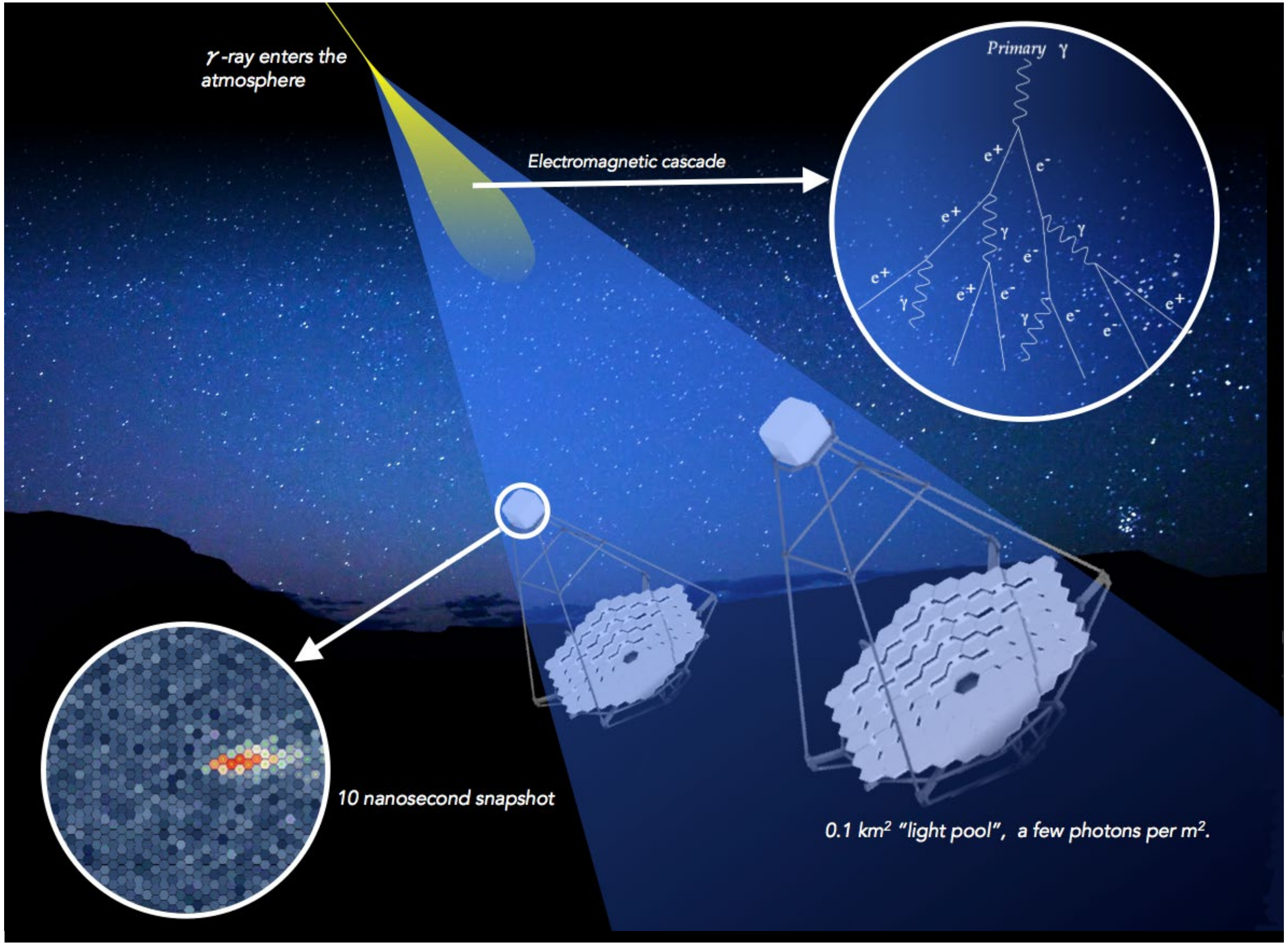
- The CTA experiment overview
- Silicon PhotoMultiplier overview
- SMART2: architecture, channel structure and measurements
- SMART3: a new channel prototype
- Future perspectives

The Cherenkov Telescope Array

- New generation of ground-based gamma-ray instrument to improve sensitivity in the range of 30 GeV - 300 TeV;
- Two sites: La Palma for the northern emiphere, Atacama Desert (Chile) for the southern observatory;
- 3 sizes of telescopes: large (PMT), medium (PMT single mirror, SiPM double mirror) and small (SiPM);
- For the medium size a candidate is the Schwarzchild-Couder Telescope (SCT): higher FoV, aberration corrections and high camera resolution - > SMART front-end development.



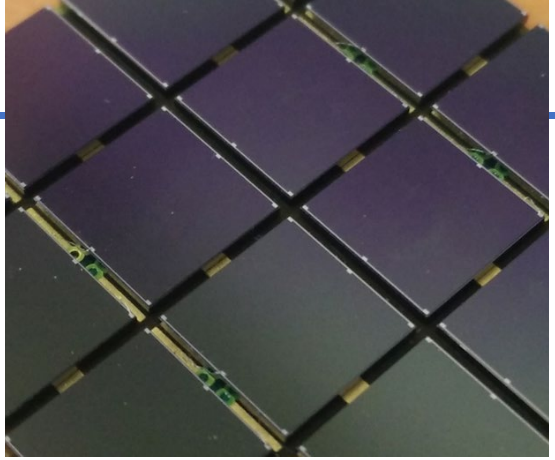
How CTA works



Basic physics:
- Gamma – ray interacts with atmosphere generating an electromagnetic cascade
- Cascade secondary products (charged particle) emit Cherenkov flashes
- Cherenkov flashes arrive on the camera with different times enlightening a small area of elliptical shape, event duration about 10 ns
- Other particles (hadrons, muons) can be observed and recognized analysing the detected images

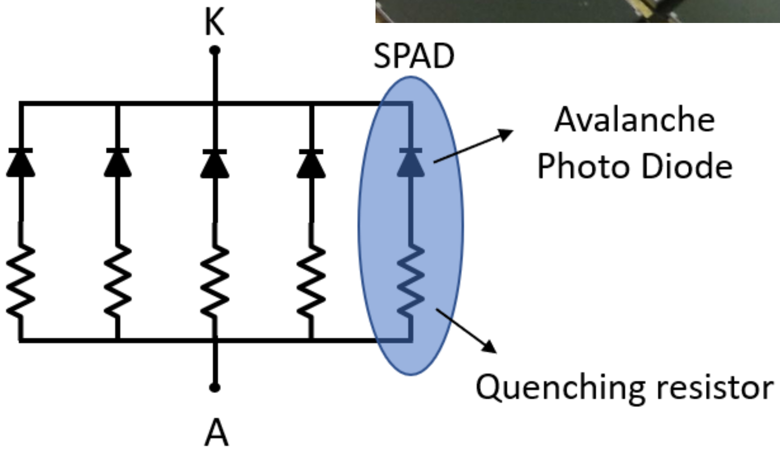
Electronics requirements for the physics:
- Photon counting: 1 – hundreds photon/pixel
- Signal time evolution recording: about 10 ns -> sampling at 1 Gsps
- Event separation: possibility to avoid pile-up with noise due to other sources (stars, moon light) -> Night Sky Background (NSB) in the order of tens of MHz

Silicon Photo-Multiplier



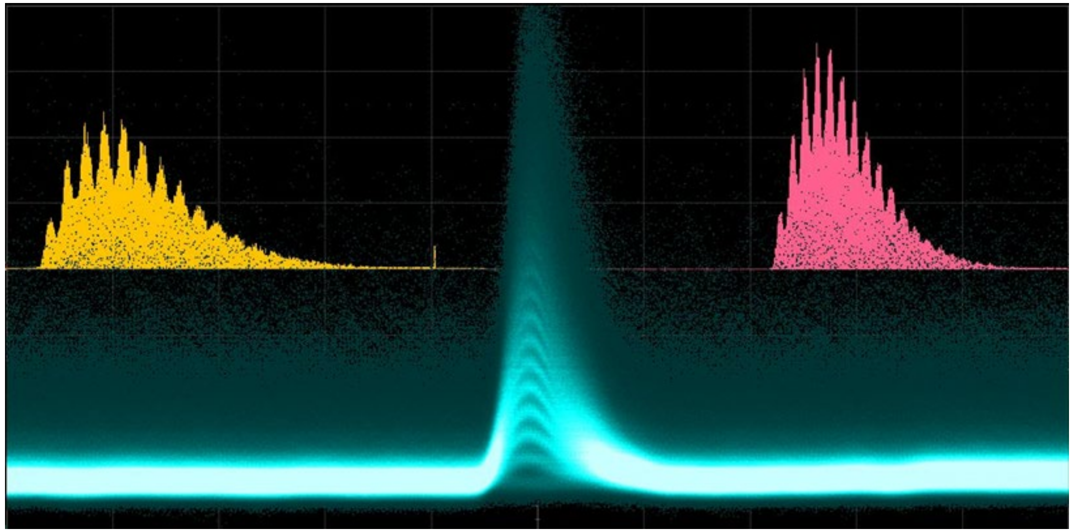
Silicon PhotoMultiplier (SiPM):

- Matrix of parallel connected microcell (SPADs);
- Microcell: SPAD (Single Photo Avalanche Diodes) operating in Geiger mode;
- SPAD: capable to detect the single photon generating a current pulse whose charge is controlled by the SiPM bias point;
- SiPM output is a fast rising edge current pulse whose charge is proportional to the number of detected photons.



Pro:
- Single photon resolution
- NSB tolerant: can operate in full moon condition
- High PDE: > 50% in the NUV range
- Low bias voltage: < 100 V

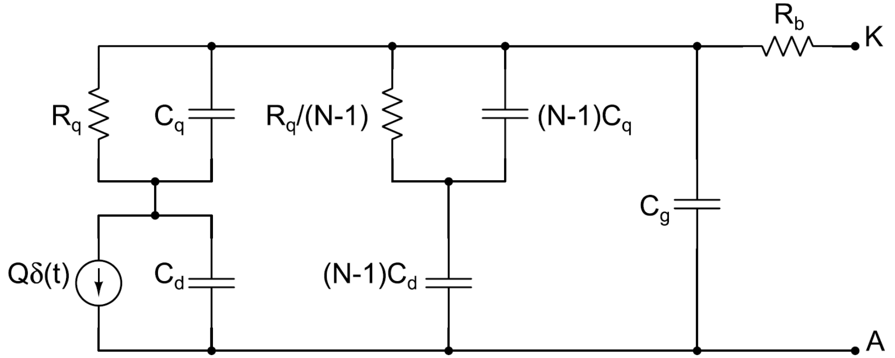
Cons:
- Correlated noise (crosstalk and afterpulsing)
- High sensitivity to NSB
- High Dark Count Rate (DCR), usally lower than NSB



SiPM modelling

SiPM equivalent circuit:

- N microcell detector: 1 cell is fired and N-1 pixels as load effect
- C_d: detector capacitance
- R_q: quenching resistor
- C_q: R_q parasitic capacitance
- C_g: microcell interconnection grid parasitic capacitance
- R_b: substrate Ohmic resistance
- Current generator: models the charge produced by the avalanche discharge by means of a Dirac's delta of area Q



SiPM Pulse charge:

- $Q = (C_d + C_q) \times (V_{bias} - V_{BD})$, where V_{BD} is the breakdown voltage

SiPM Capacitance:

- $Ceq = (C_g + N\ C_d)$

SiPM Pulse duration:

- SiPM recovery time constant: $\tau_R = (C_d + C_q)\ R_q + (C_g + N\ C_d)\ (R_b + R_i)$, where R_i is the front-end input resistance

SiPM FBK NUV HD 6x6 mm2

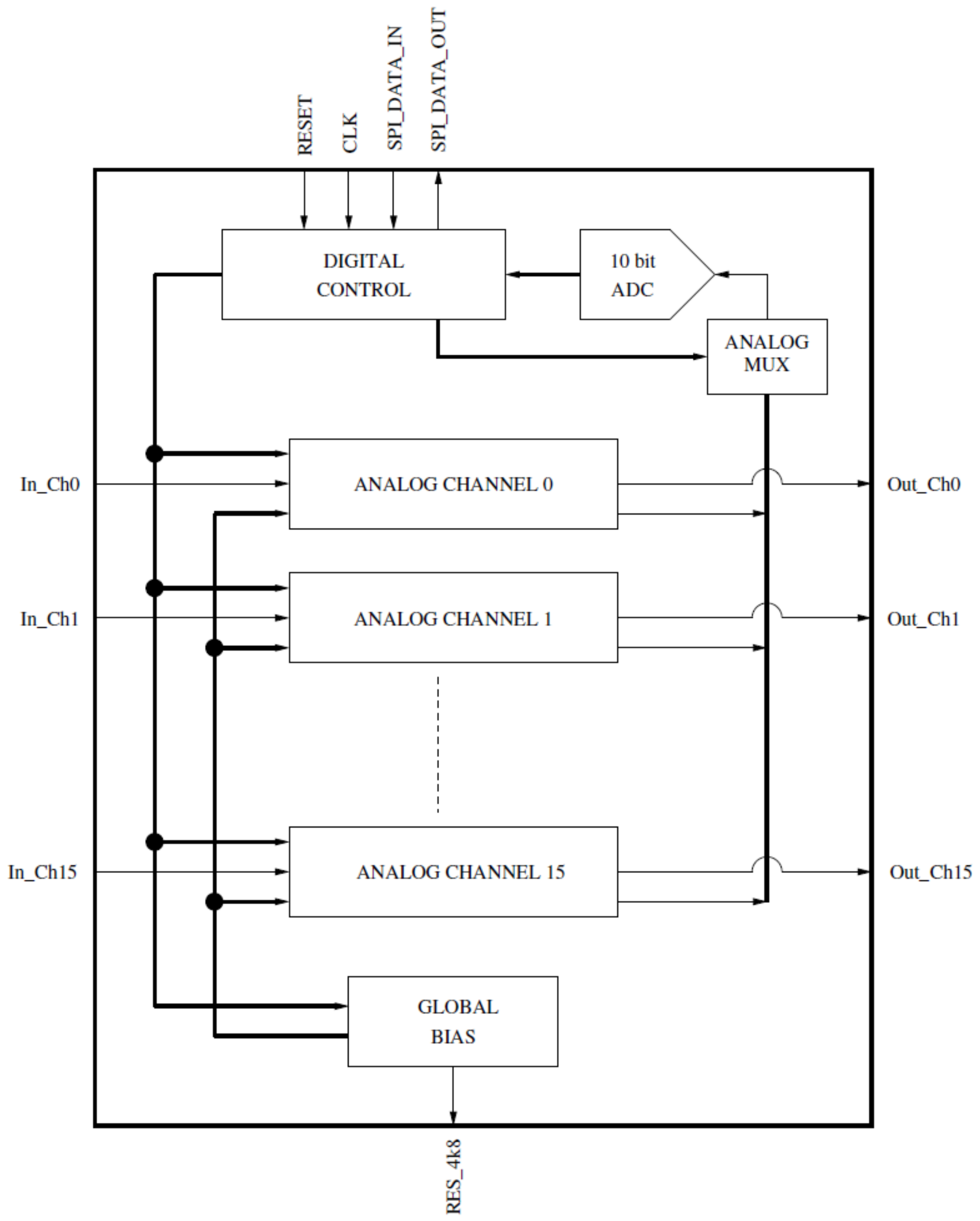
- Q = from 150 fC (old SiPM) up to 750 fC (new SiPM)
- Ceq = 2 nF
- τ_R = 200 ns – 250 ns with Ri = 50 Ohm
- DCR = 2.5 MHz

"Modelling a silicon photomultiplier (SiPM) as a signal source for optimum front-end design";
F. Corsi, A. Dragone, C. Marzocca, et. Al; NIMS A; Volume 572, Issue 1, 1 March 2007, Pages 416-418

Front-end requirements

- Single photon resolution
- Detector capacitance: 2 nF
- Single photo-electron charge: 150 fC
- Linearity range: up to hundreds of photons
- DCR + NSB in the order of tens of MHz -> a circuit to suppress the recovery tail is need to avoid pile-up
- Signal sampled at 1 Gsps (sampling done by a dedicated ASIC) -> output signal FWHM about 10 ns
- Possibility to fine adjust the SiPM bias voltage to compensate the gain mismatches among SiPMs
- Slow monitoring for SiPM mean current measurements (high luminosity enlightening, SiPM aging, telescope pointing)

SMART2: ASIC architecture overview



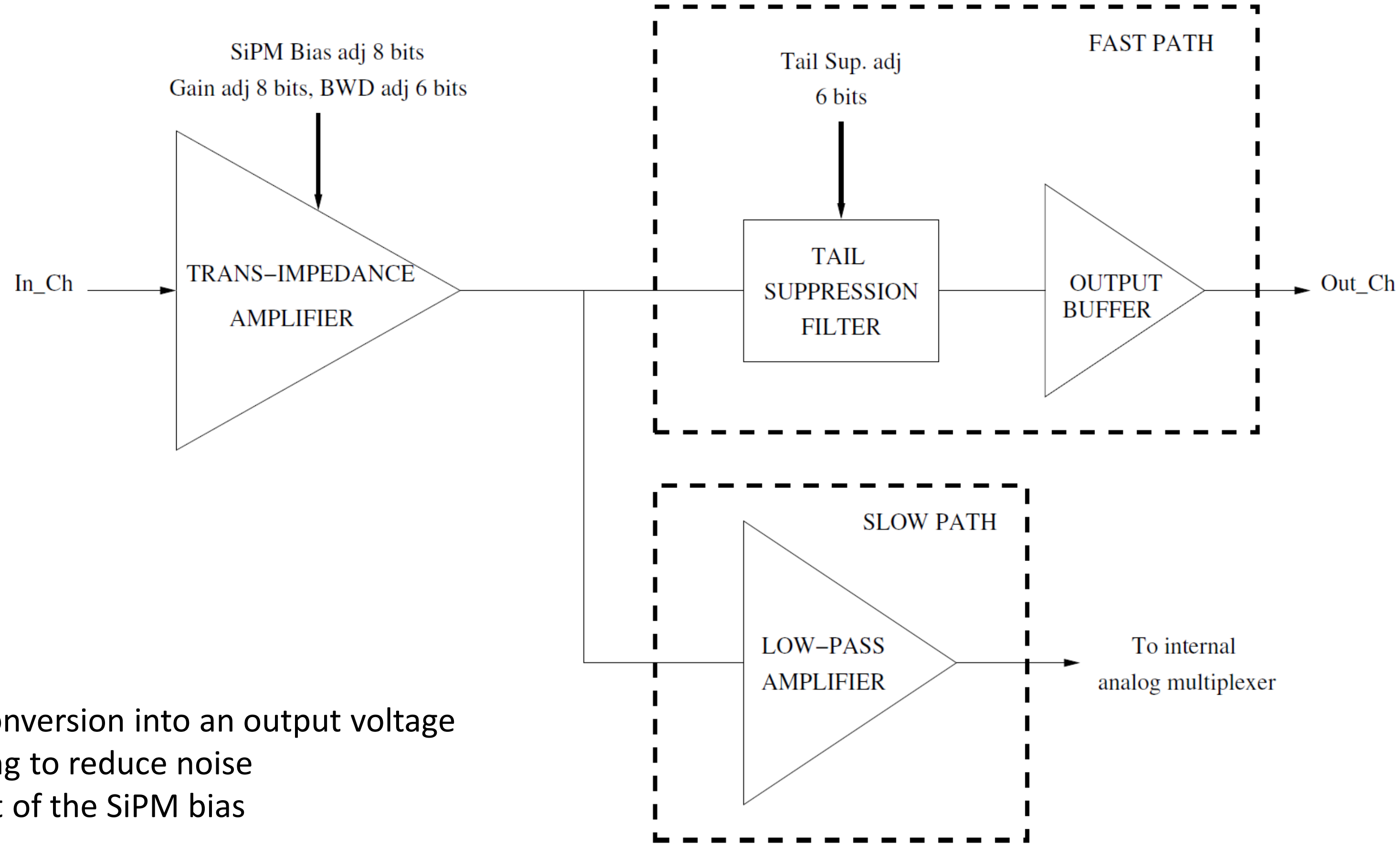
Analog Section:

- 16 Front-end channels:
  - Direct output: designed for photon-counting
  - Internal output: SiPM mean current measurement
- Global Bias: temperature and power supply independent
- 10 bit 1 MHz SAR ADC for channel internal output conversion

Digital Section:

- Control Unit:
  - 1 MHz SPI LVDS link
  - Channel & Global bias adj. bits
  - ADC control

SMART2: Channel architecture overview



Z-Amplifier:

- Input current conversion into an output voltage
- Low pass filtering to reduce noise
- Fine adjustment of the SiPM bias

Fast Path

Tail suppression filter:

- Filters the output pulse tail due to the SiPM recovery

Output buffer:

- Drives the output path providing the current to a low impedance load

Slow path:

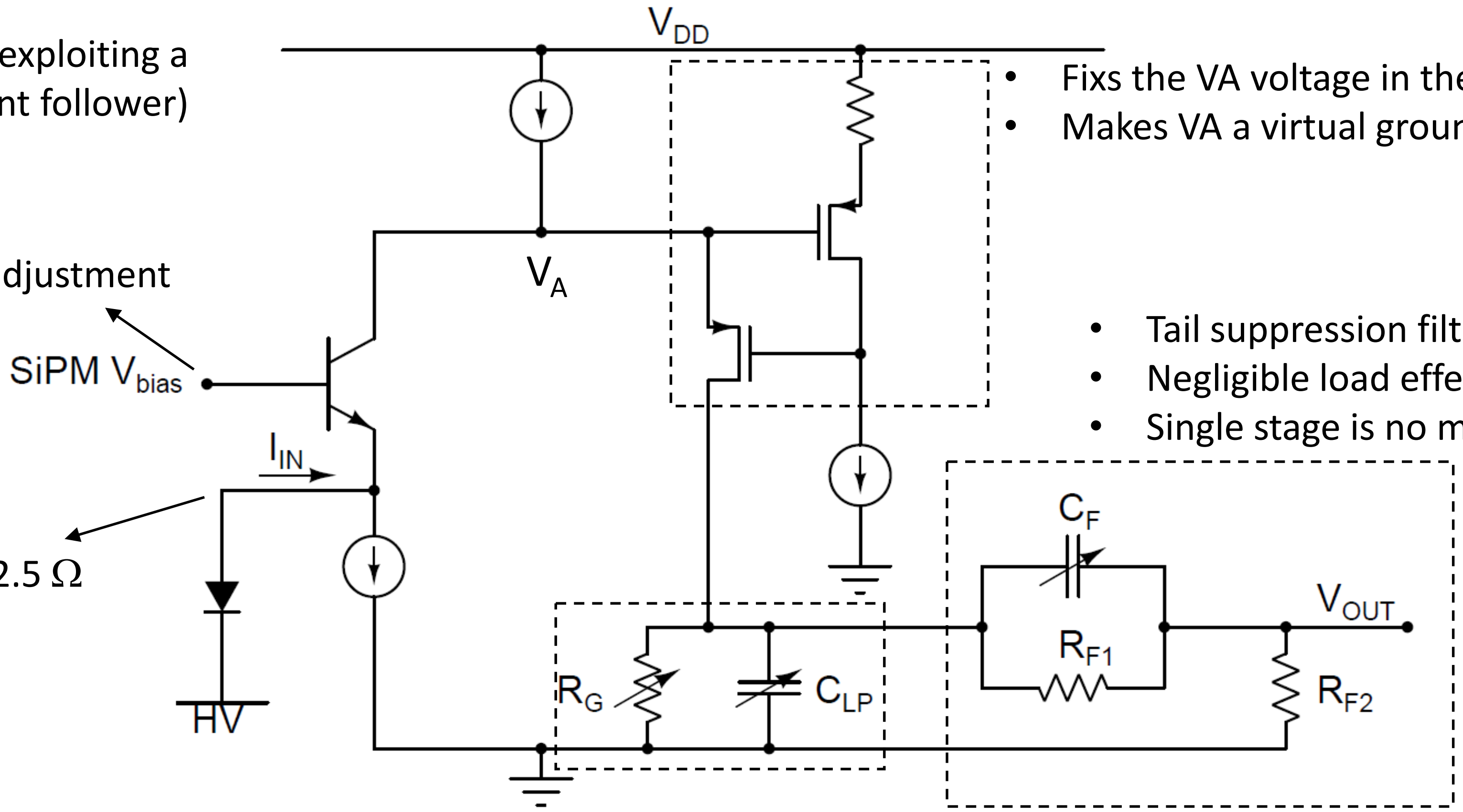
- Ultra low-pass voltage amplifier
- Output voltage proportional to the mean value of the SiPM current

Trans-impedance stage and tail suppression filter circuit

Open loop structure exploiting a common base (current follower) SiGe HBT

SiPM bias fine adjustment

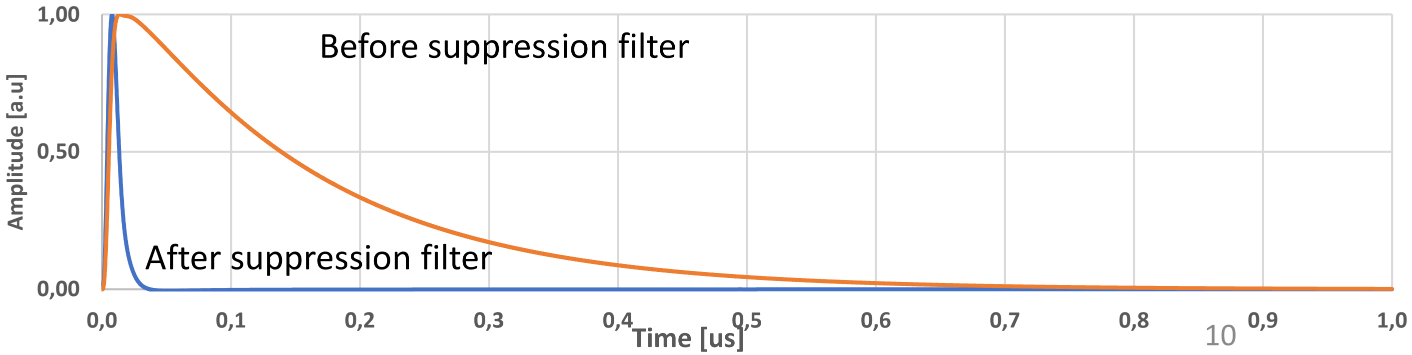
Input resistance ~ 12.5 Ω



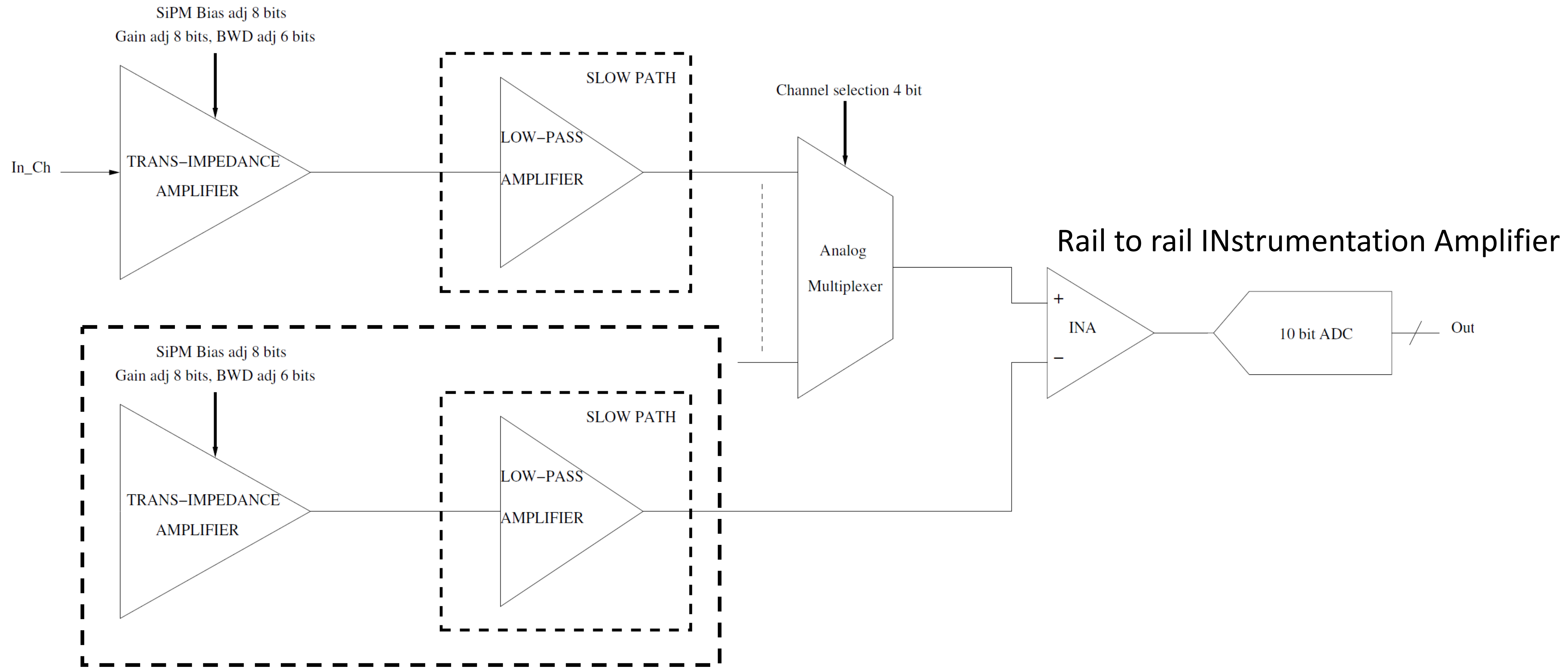
- Fixes the VA voltage in the bias point
- Makes VA a virtual ground

- Tail suppression filter
- Negligible load effect on transimpedance stage
- Single stage is no more effective on new SiPMs

- R_G and C_{LP} control the gain and filtering for noise reduction
- C_{LP} and C_F control the FWHM



Slow monitoring circuit



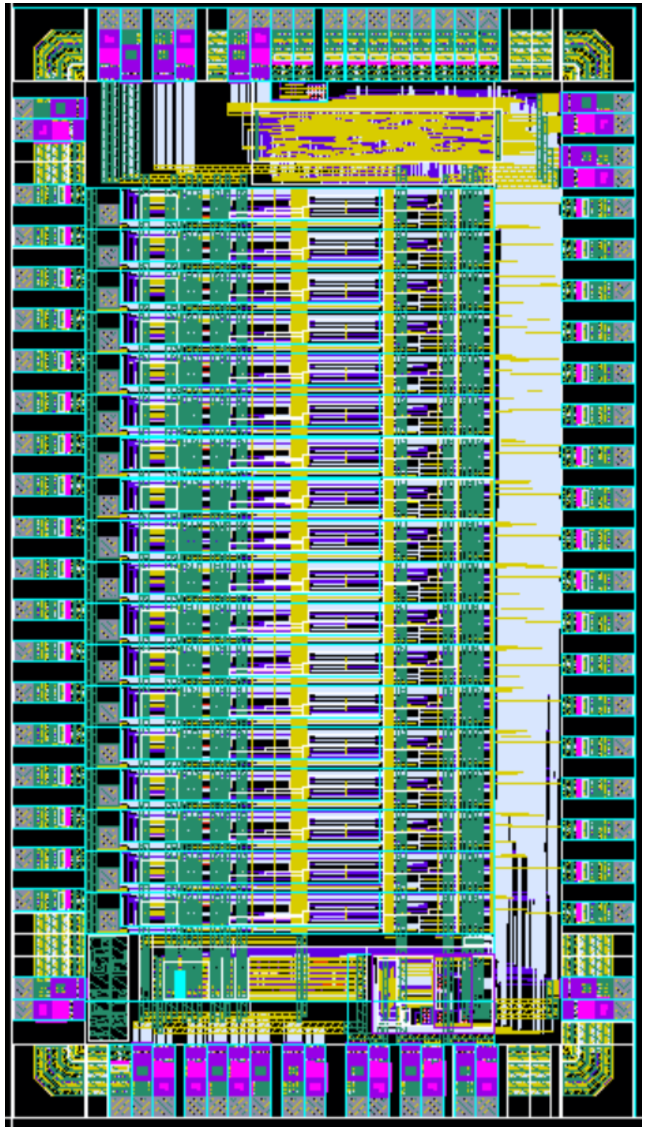
17° channel:

- Not connected to input pad
- Biased as the 16 read-out channels
- SiPM Bias adjustment used for slow monitoring calibration

SMART2 features

- AMS 0.35 μm SiGe technology node
  - 3.3 V power supply
  - Die size: 2.9 mm x 5.1 mm
- 16-channel trans-impedance amplifier
  - Input impedance ≈ 12.5 Ω
  - Current consumption: 5.5 mA
- 20-bit global adjustment: gain (8 bits), bandwidth (6 bits), PZ (6 bits)
  - Gain at the Fast Path output: 0.5 mV/pe ÷ 3.5 mV/pe
  - FWHM at the Fast Path output: 8 ns ÷ 20 ns
- 8-bit DAC for SiPM bias adjustment (one per channel):
  - 1.2 V adjustment range
- Slow monitoring of SiPM mean current (16 channels multiplexed)
  - Rate resolution: 20 kHz/LSB ⇔ Current resolution: 25 nA/LSB
- 10-bit ADC
- 1 MHz SPI LVDS interface
- 330 mW power consumption

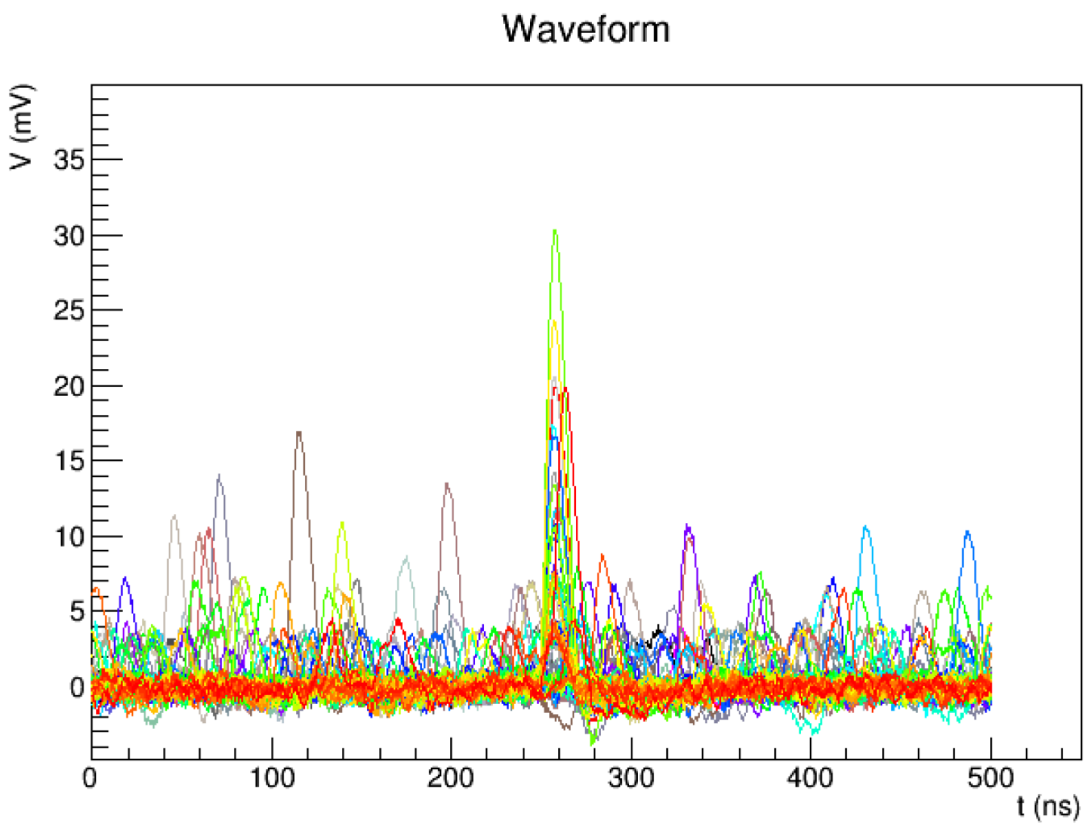
Designed for old SiPMs, no more suitable for new ones. An external filter is needed to fully compensate the SiPM recovery tail.



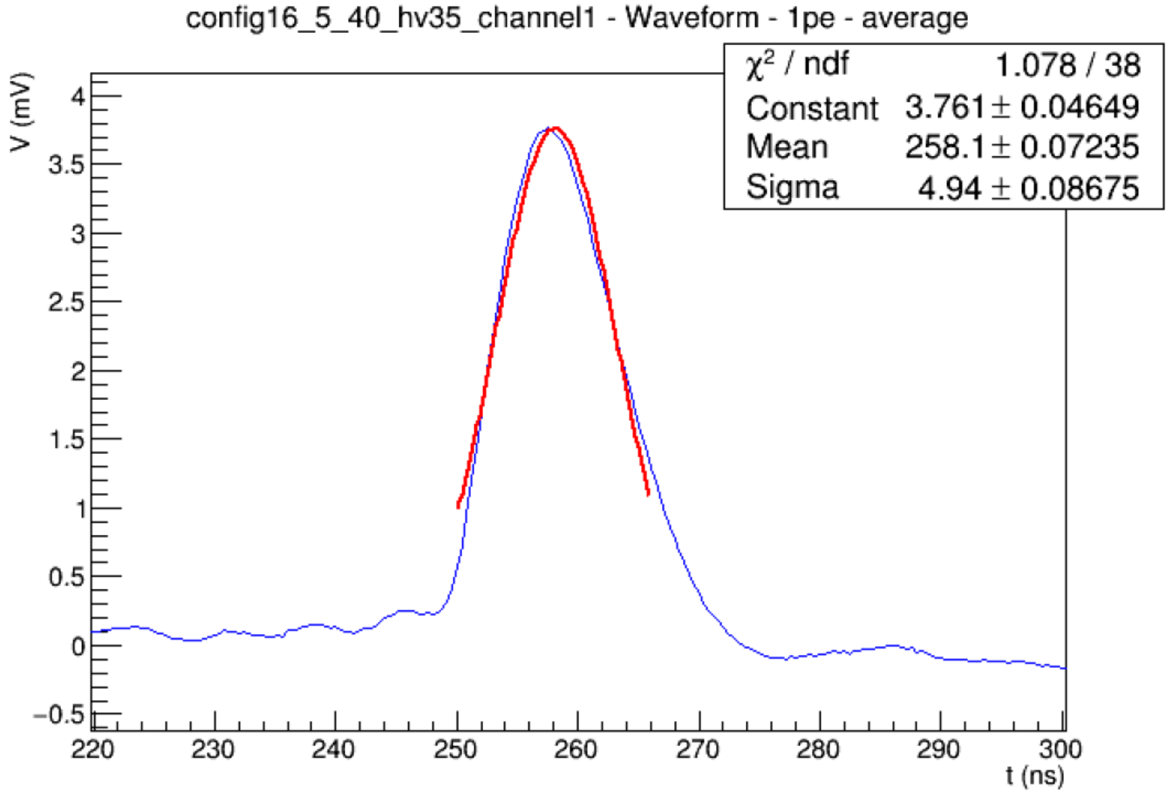
SMART2 layout

SMART2 characterization tests: Fast Path

Measurement conditions: SiPM FBK NUV-HD 6x6 mm^2, 35 V bias voltage, SMART2 conf. R = 16, C = 5, PZ = 40, laser pulse mode



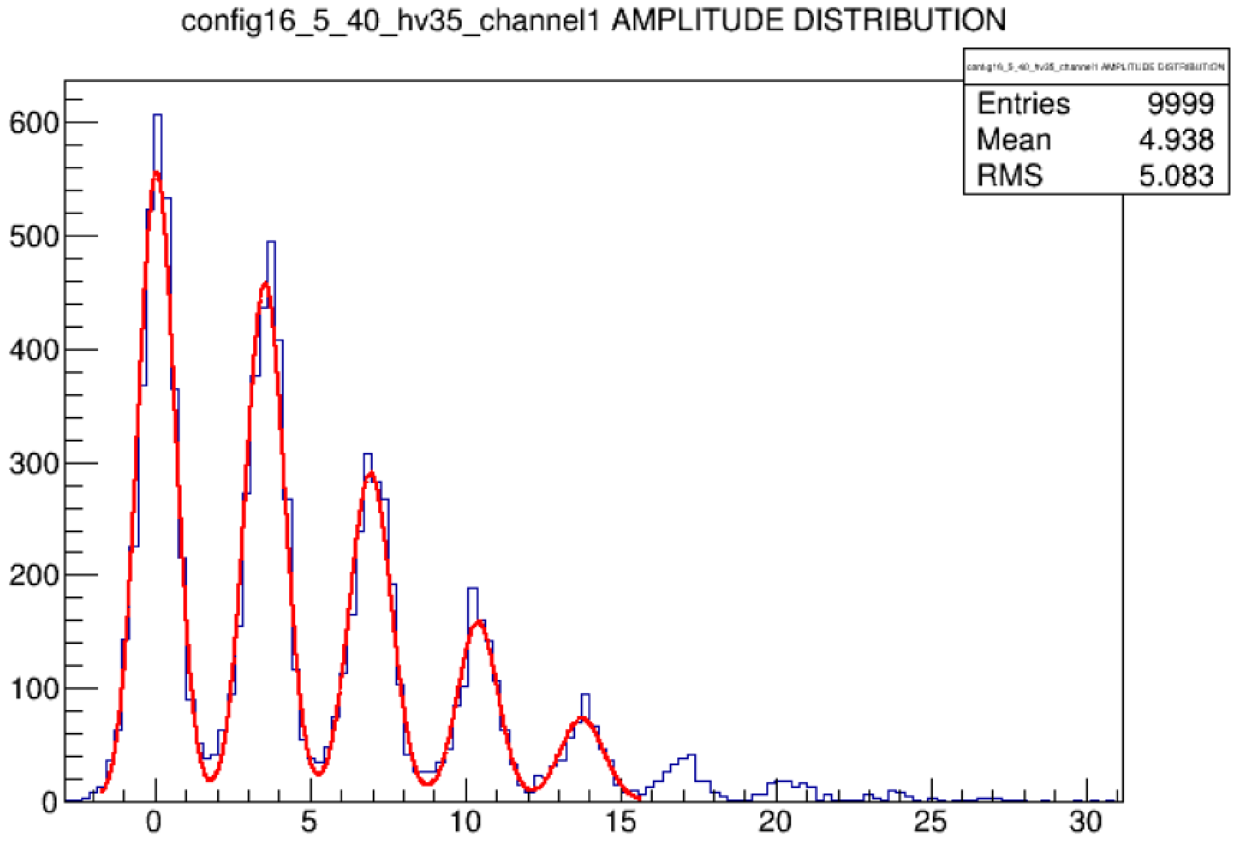
Fast-path output waveforms
(oscilloscope acquisition)



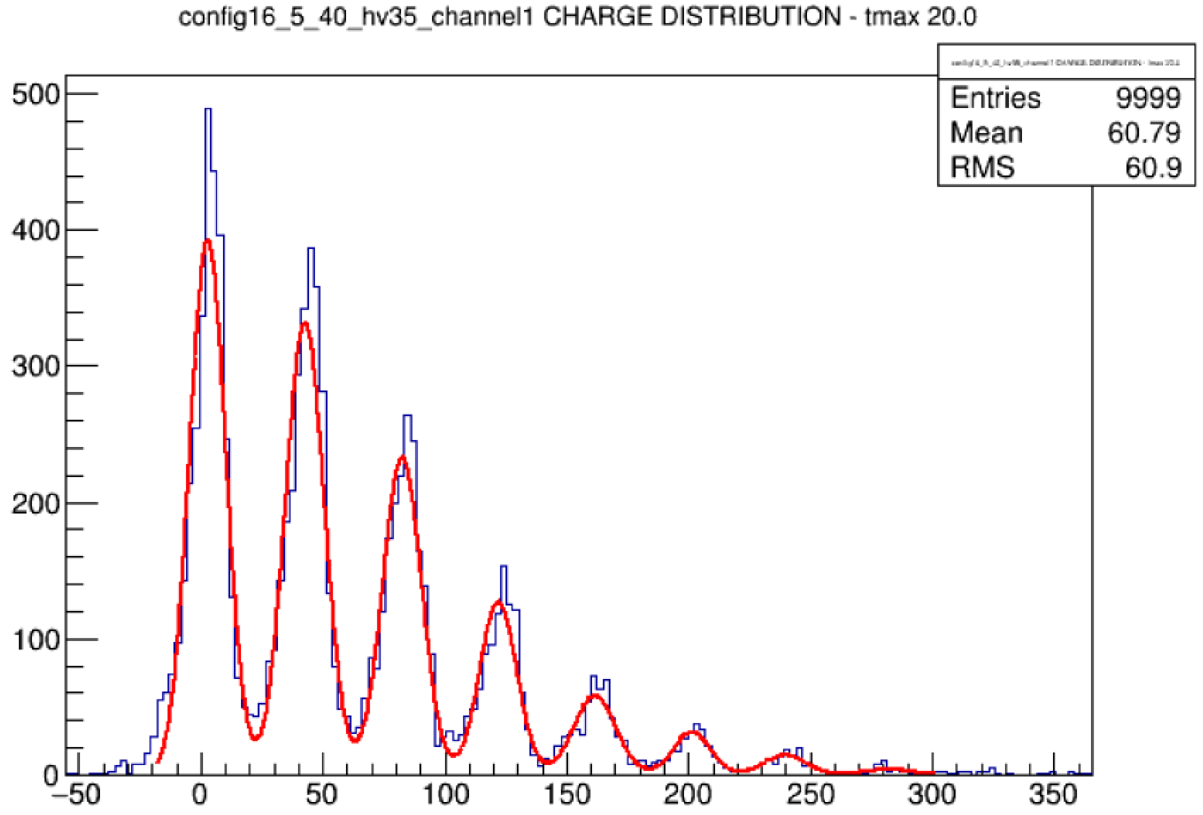
Single photo electron average waveform
FWHM = (11.61 ± 0.20) ns

SMART2 characterization tests: Fast Path

Measurement conditions: SiPM FBK NUV-HD 6x6 mm^2, 35 V bias voltage, SMART2 conf. R = 16, C = 5, PZ = 40, laser pulse mode



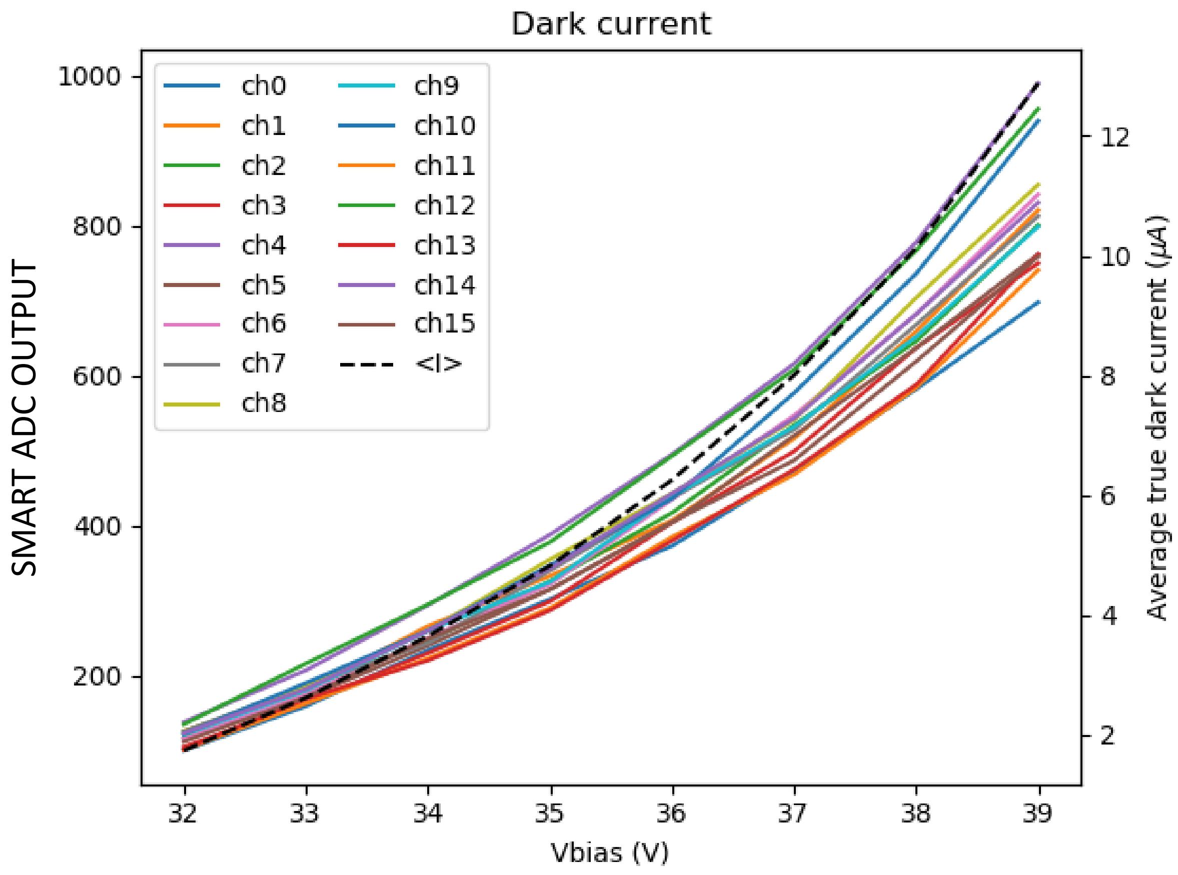
Amplitude distribution: Gain= (3.44 ± 0.01) mV/pe
SNR= 5.64 ± 0.09



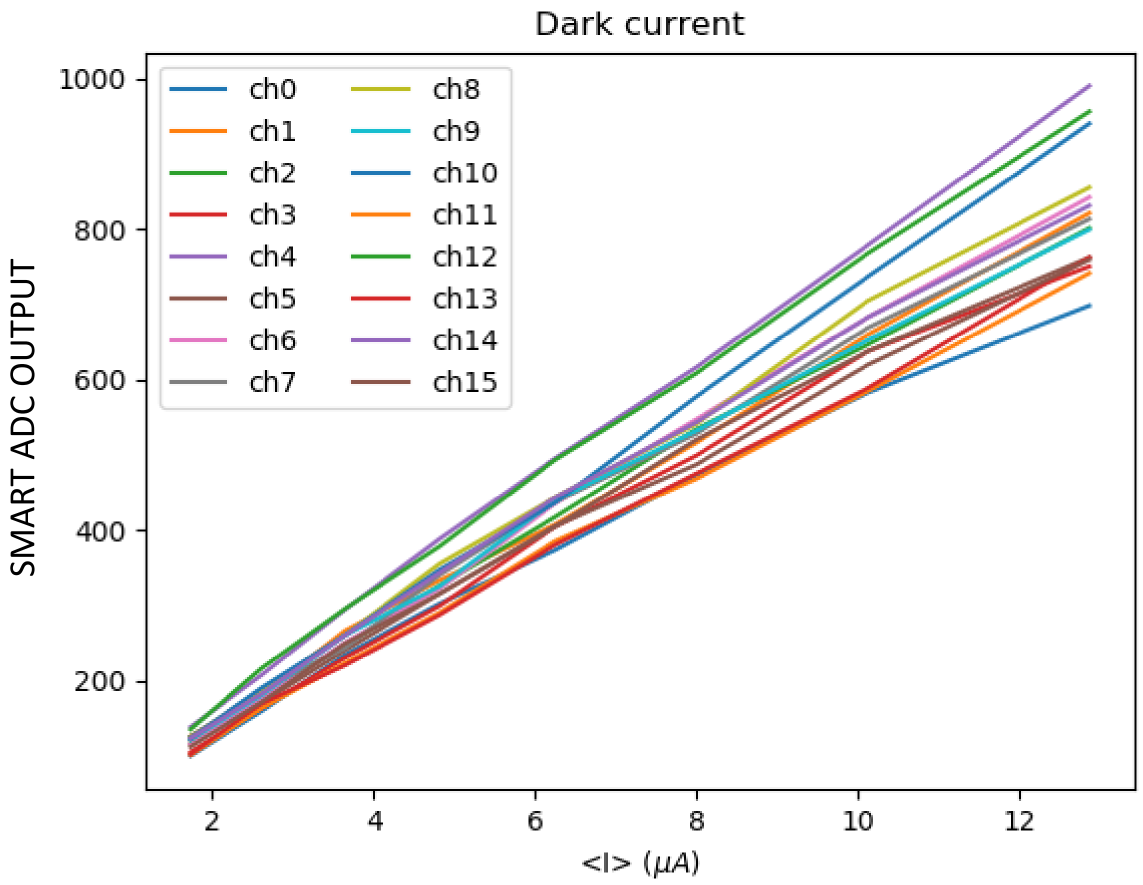
Gain= (39.72 ± 0.12) mV*ns/pe
SNR= 5.30 ± 0.07

SMART2 characterization tests: Slow Path

- **Measurement conditions**: 4x4 matrix of SiPM FBK NUV-HD 6x6 mm^2, SMART2 conf. R = 16, C = 5, PZ = 40
- **Measurement:** mean dark current as function of SiPM bias voltage
- Comparison between the SMART2 slow-monitoring output and the average dark current measured by the HV power supply pico-ammeter



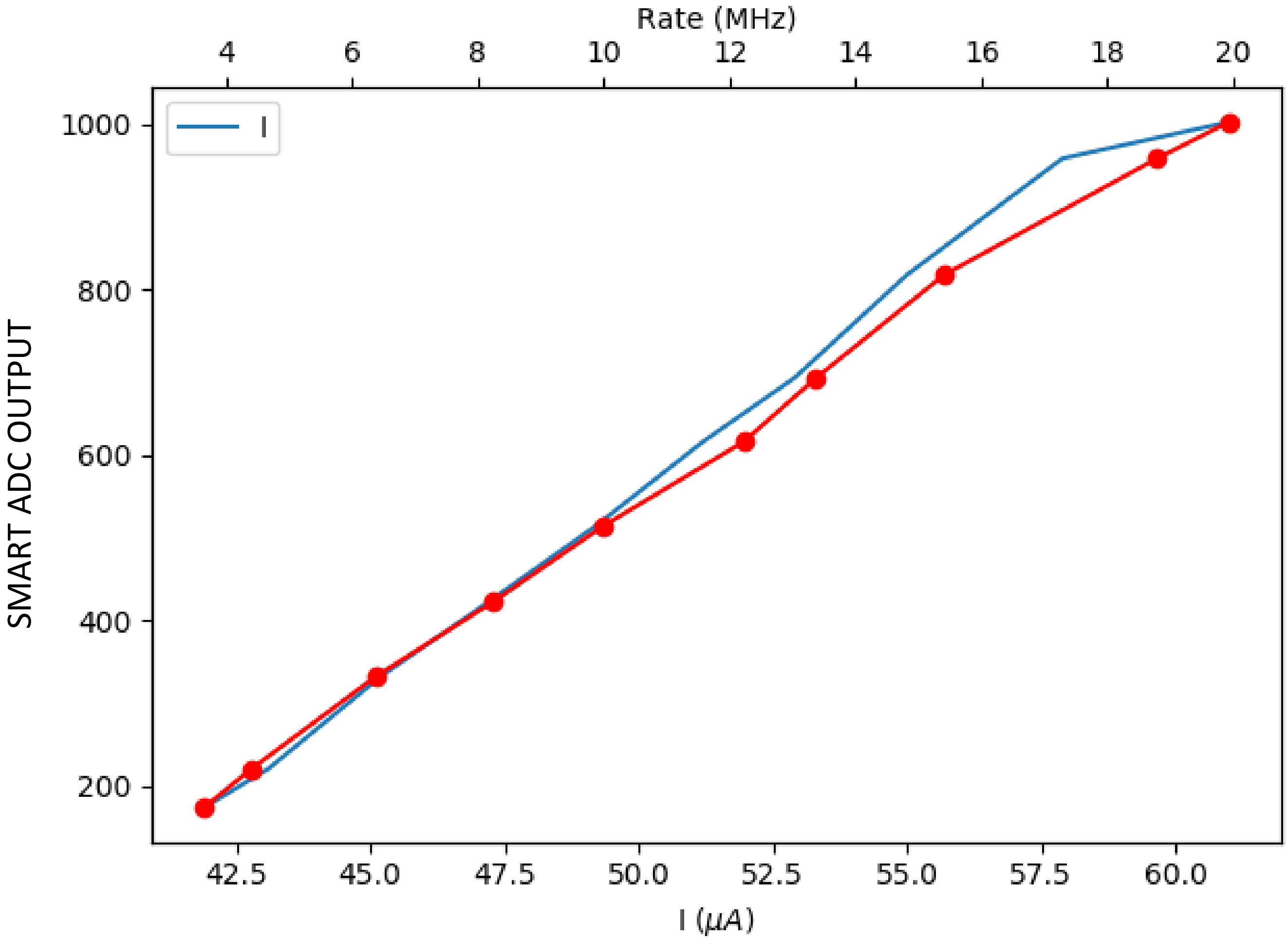
- Left y-axis: SMART2 slow-monitoring ADC output
- Rigth y-axis: current measured by pico-ammeter divided by 16 (dashed line)



- y-axis: SMART2 slow-monitoring ADC output
- x-axis: current measured by pico-ammeter divided by 16

SMART2 characterization tests: Slow Path

- **Measurement conditions**: 4x4 matrix of SiPM FBK NUV-HD 6x6 mm^2, 35 V bias voltage, SMART2 conf. R = 16, C = 5, PZ = 40, laser continuous mode
- Measurement: mean current as function of incoming pulse rate (laser in continuous mode and change the intensity)
- Rate is measured by the acquisition of the SMART2 fast-path output
- Rate values are compared with the current measured by the pico-ammeter of HV power supply

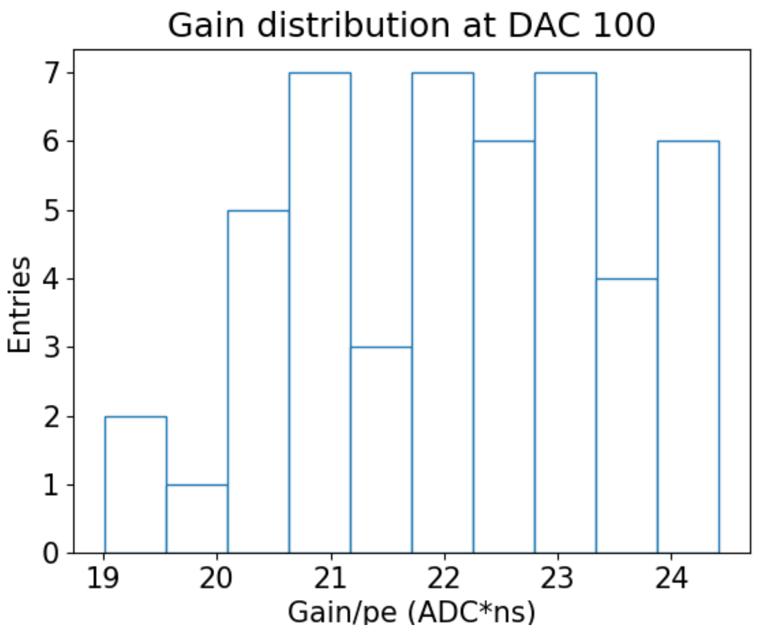


Slow-path measurements for a single channel, laser in continuous mode: max pulse rate: 20 MHz

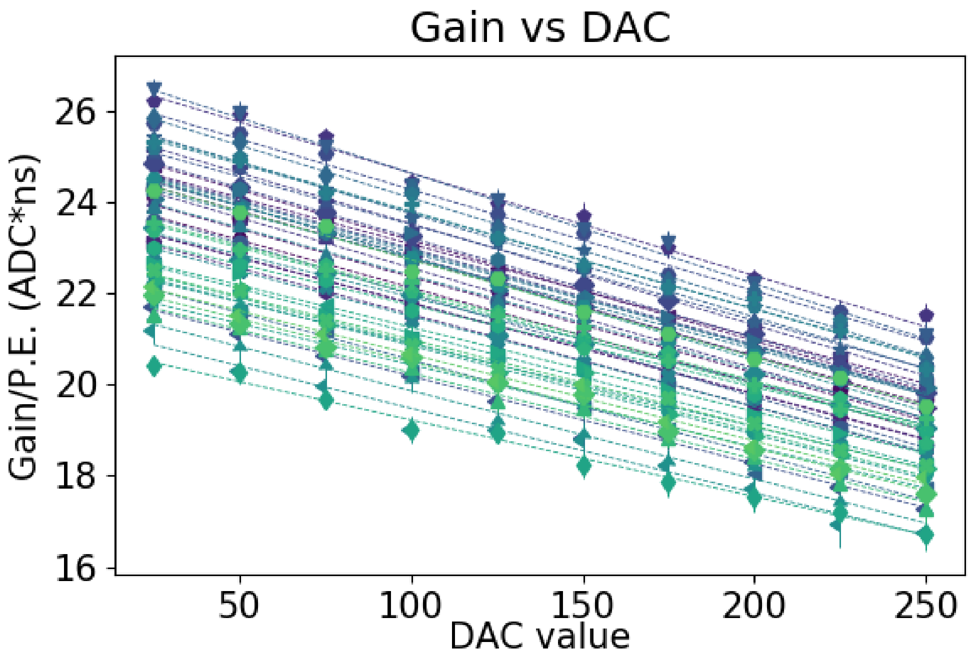
Bottom x-axis has an offset that corresponds to the overall matrix dark rate

SMART2: SiPM fine bias adjustment

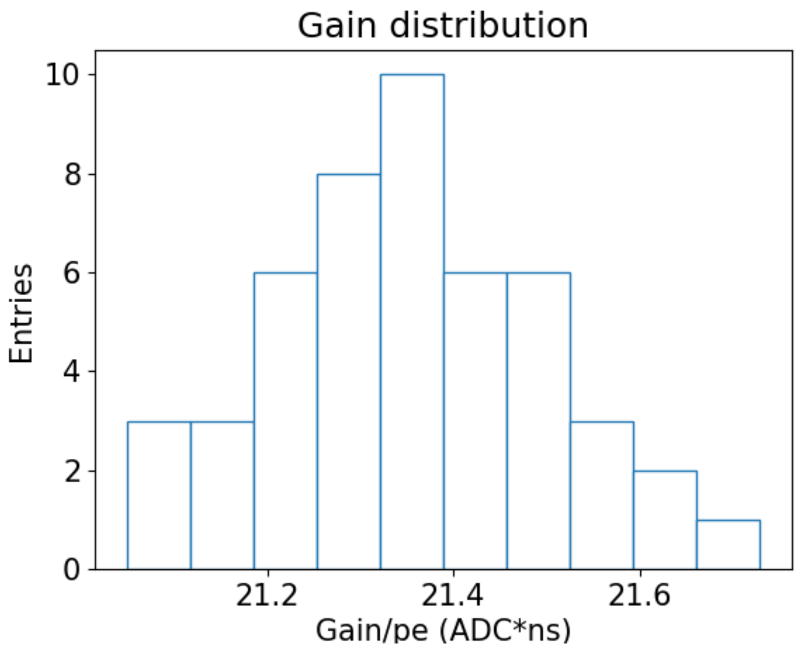
- **Measurement conditions**: four 4x4 matrices of SiPM FBK NUV-HD 6x6 mm^2, laser pulse mode



Gain measured at a fixed fine bias voltage DAC value (100) equal for all the channels.
Gain variation ±11,7%



Gain vs SiPM fine bias DAC characteristics measured for all the SiPMs



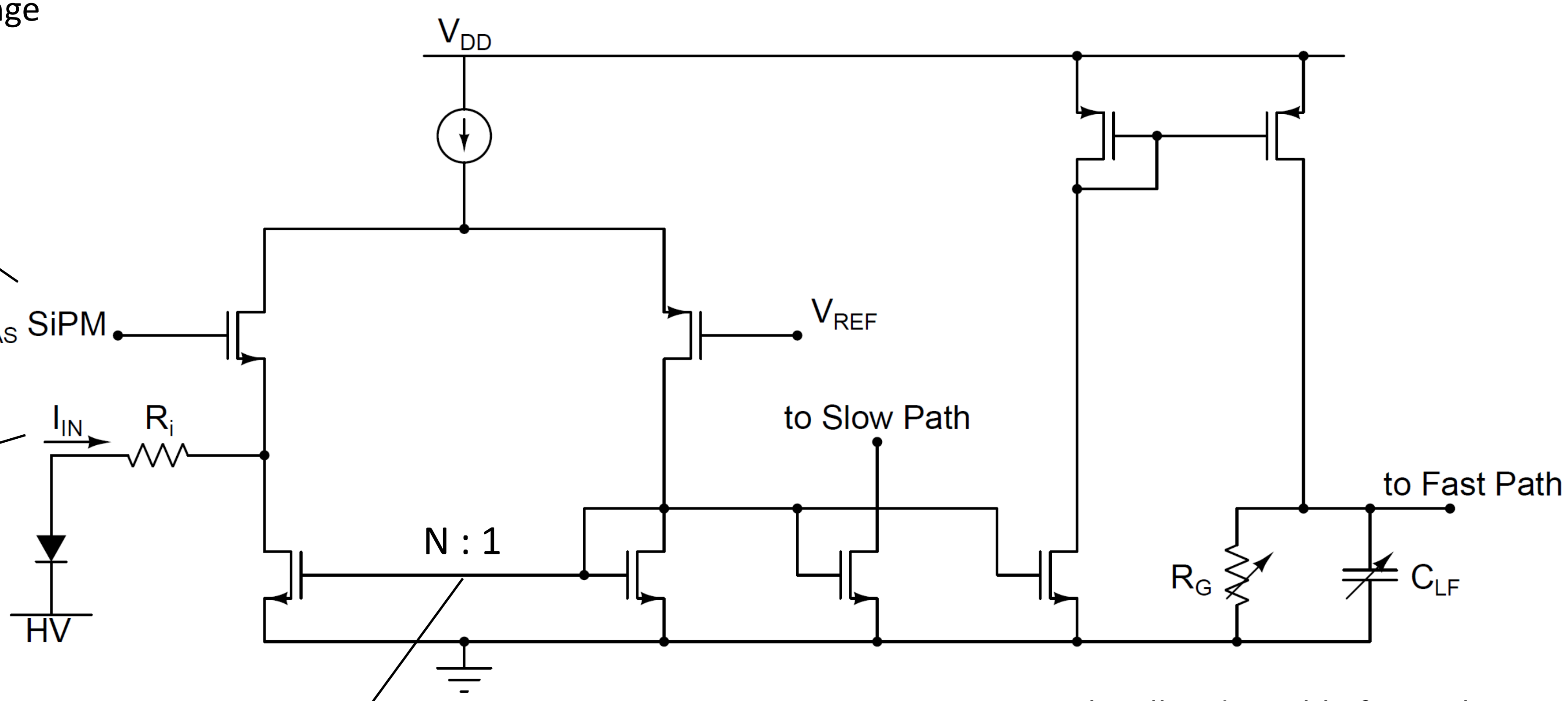
Gain measured after equalization.
Gain variation ±1,6%

SMART3 front-end architecture

Why? SMART2 issues:

- Pole-zero suppression not matched with the new SiPMs recovery tail -> a further external filter needed
- Limited fast-path output dynamic range
- Limited slow-path input dynamic range

SiPM fine bias adjustment

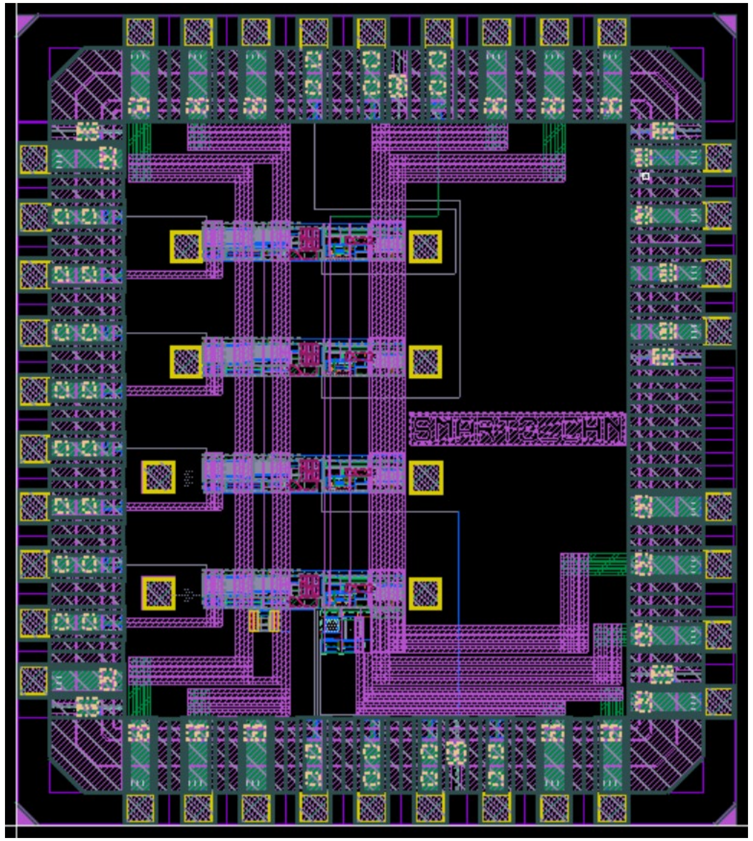


- Equivalent input resistance ~ 35 Ω
- R_i introduces a zero that improves loop stability
- R_i reduces both input transistor noise and input signal amplitude

N and the bias current control the input dynamic range

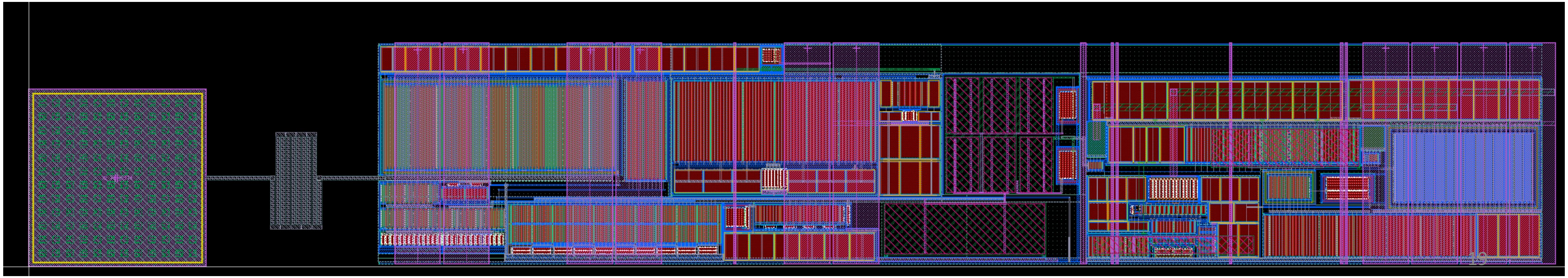
- R_G is locally adjustable for each channel to be combined with SiPM bias fine adjustment to improve gain equalization

SMART3: channel prototype



New channel prototype:

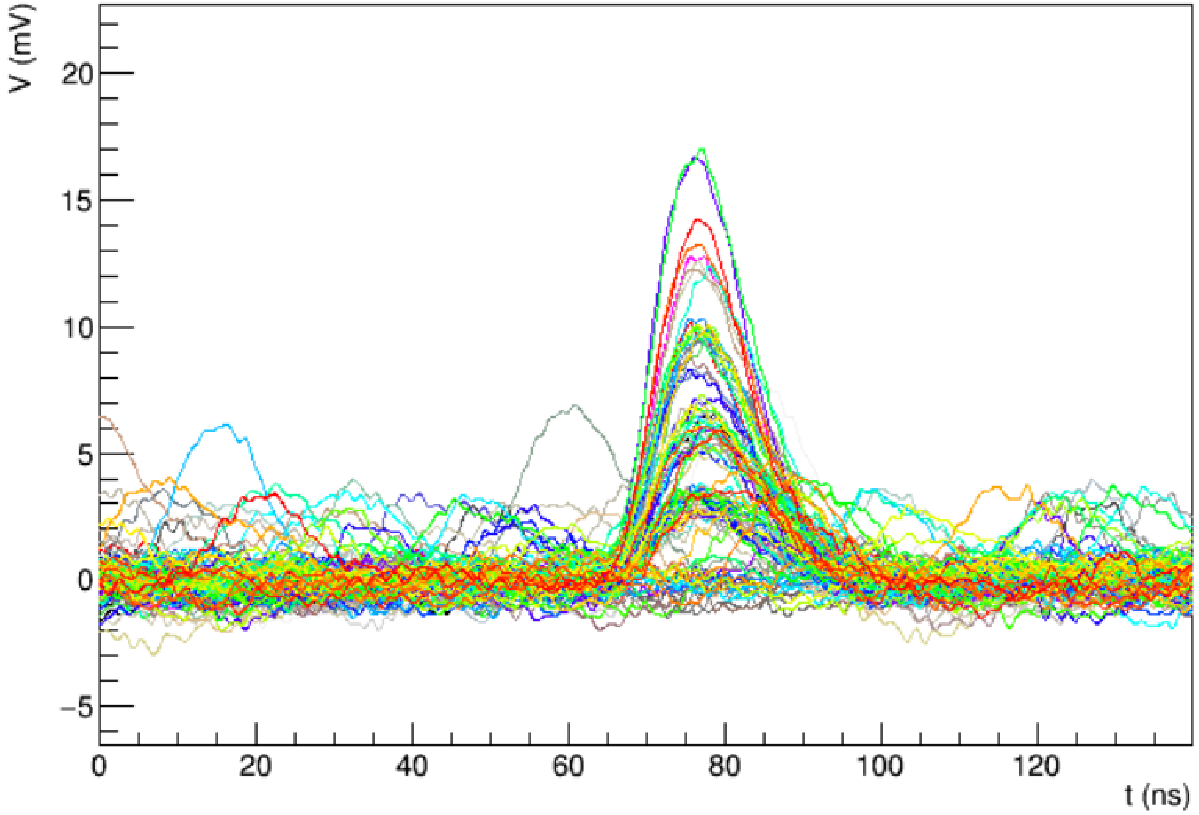
- New technology node: LF110nm
- New front-end architecture
- No programmable features (fixed gain, band-width and filter)
- Slow-monitoring not included
- First characterization tests in March 2022



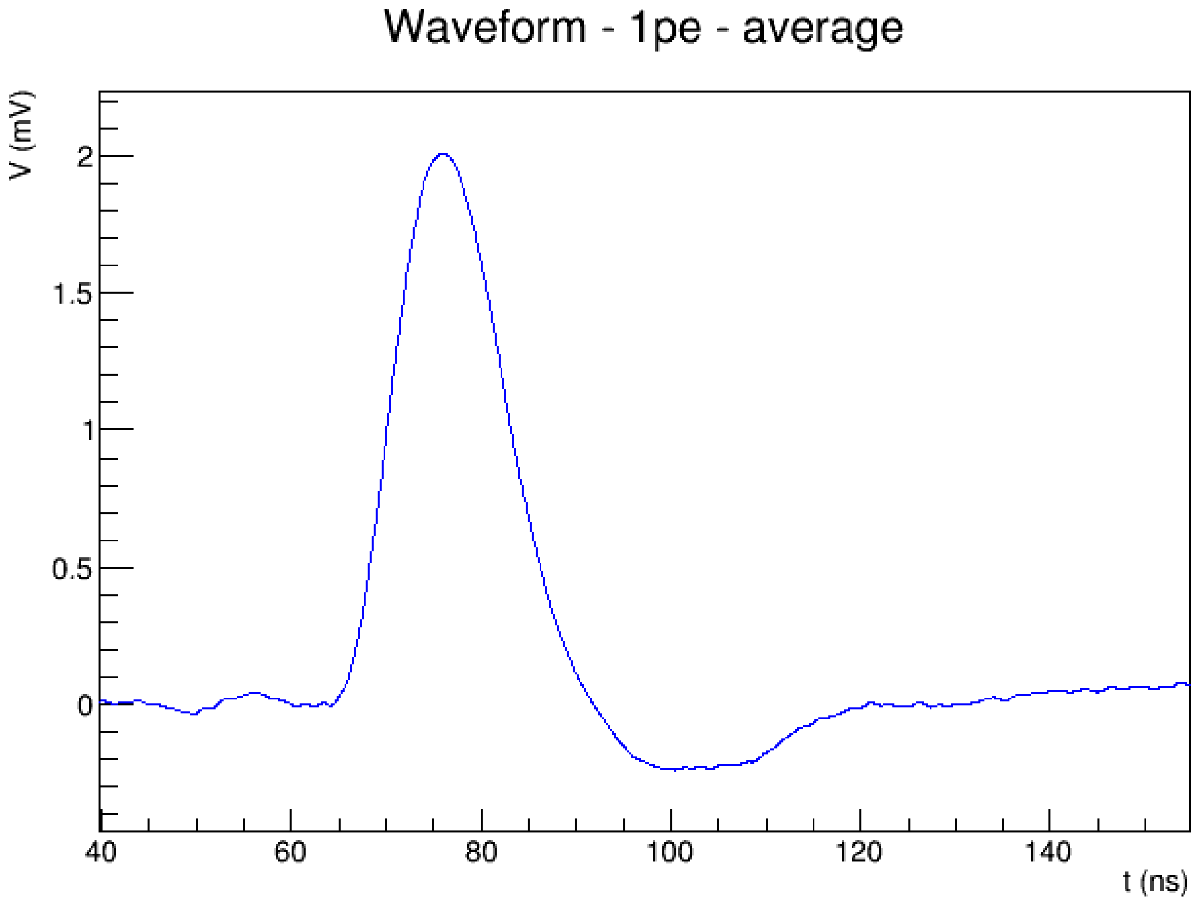
SMART3 channel prototype test: fast-path output waveforms

Measurement conditions:

- SiPM NUV HD3-5 - produced by FBK
- HV = 41 V -> OV = 13.5 V
- Laser pulse mode



Fast-path output waveforms (oscilloscope acquisition)

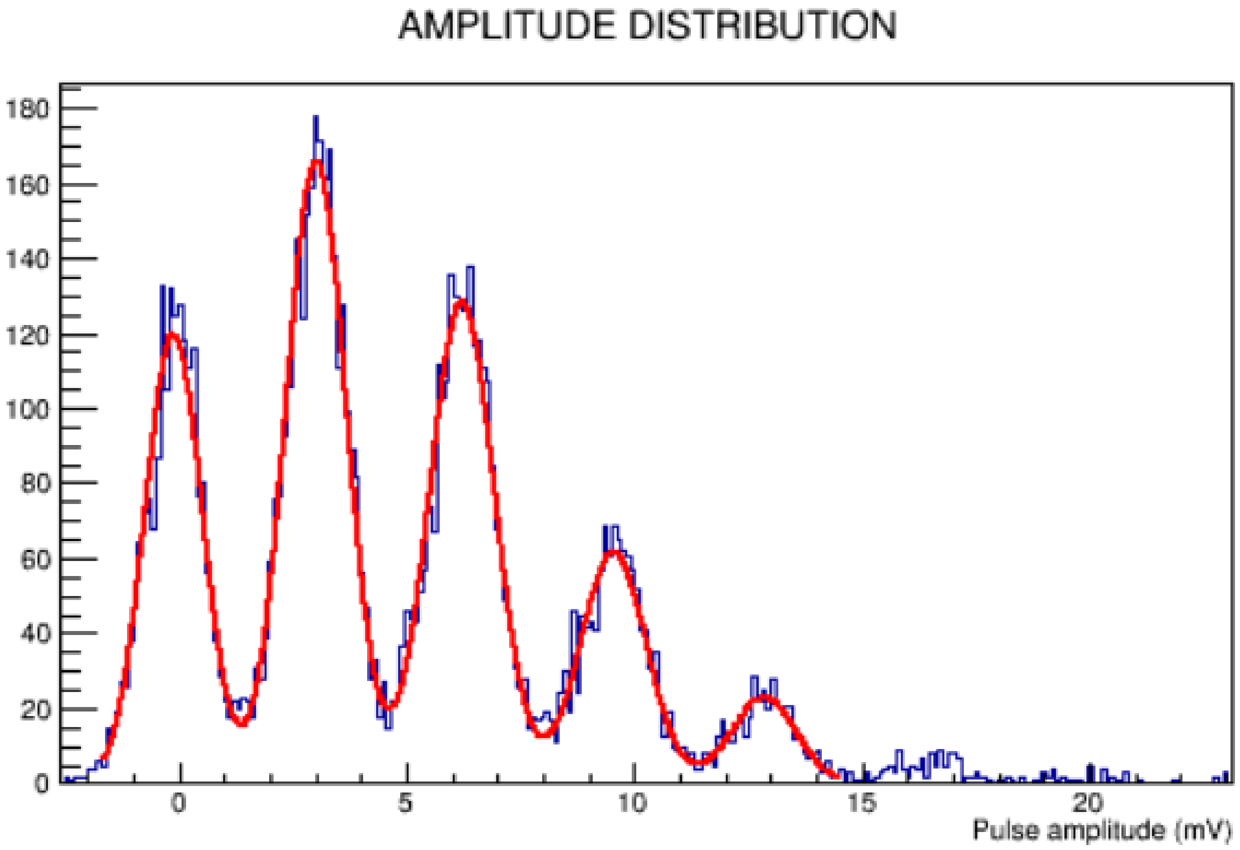


- Full SiPM recovey tail compensation with internal network
- FWHM about 13 ns

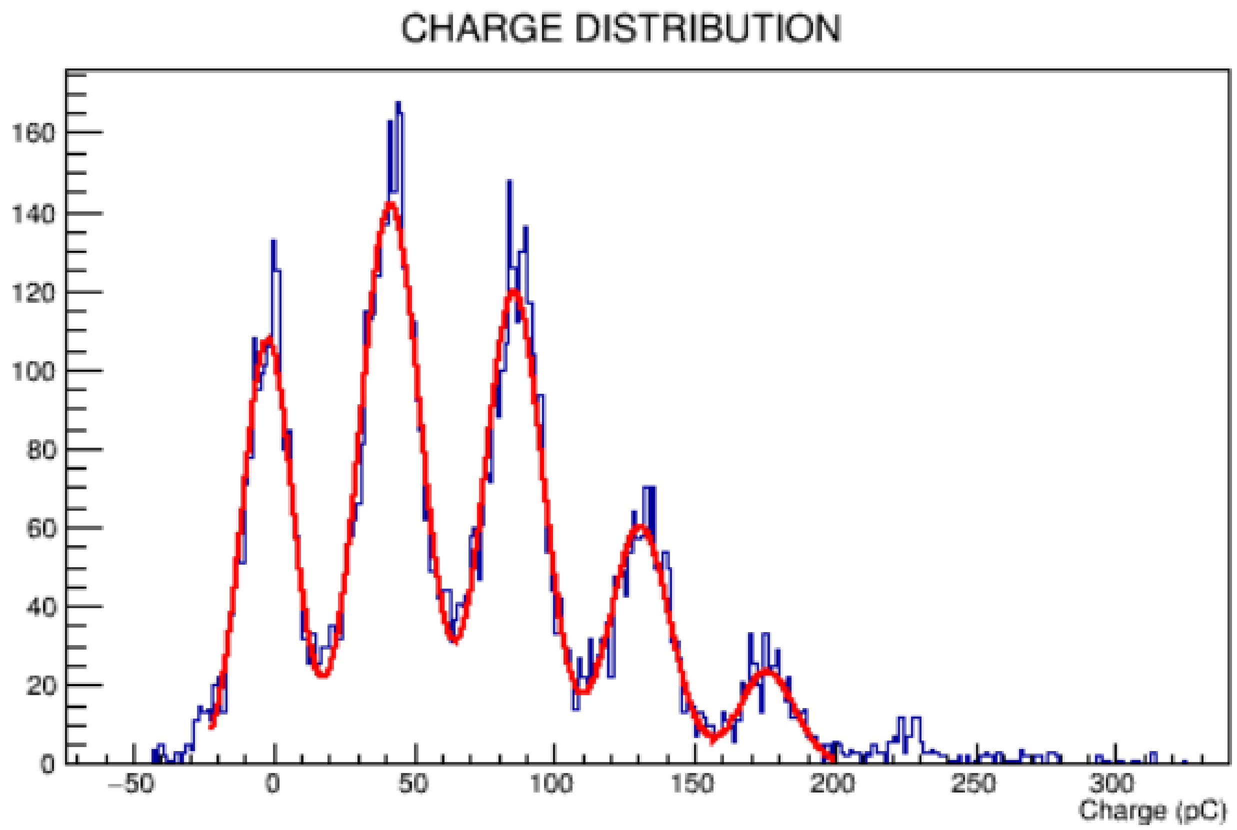
SMART3 channel prototype test: fast-path photon-counting

Measurement conditions:

- SiPM NUV HD3-5 - produced by FBK - same as those installed on pSCT camera
- HV = 41 V -> OV = 13.5 V
- Laser pulse mode

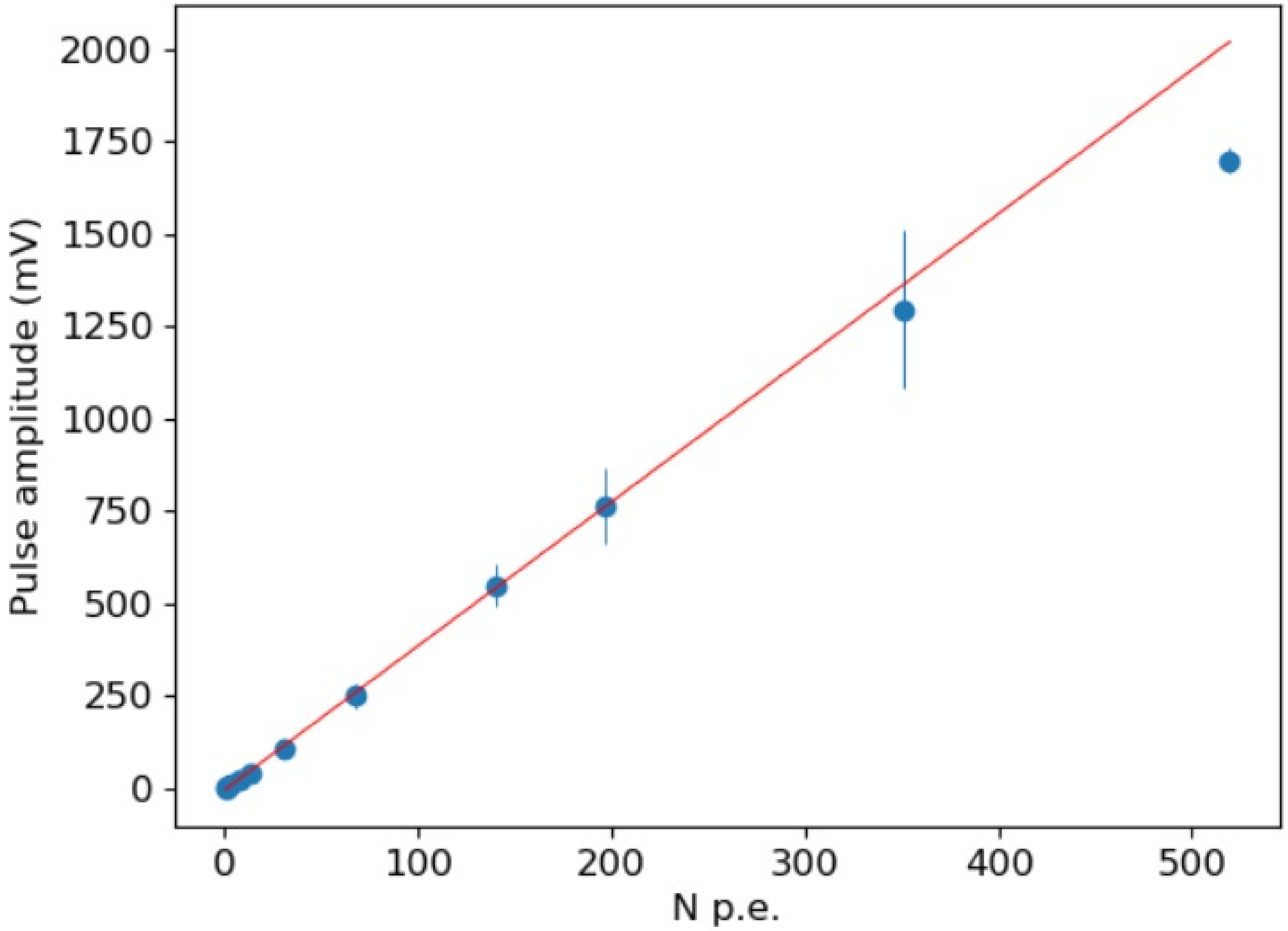


SNR = 4.85



SNR = 4.39

SMART3 channel prototype test: fast-path output dynamic

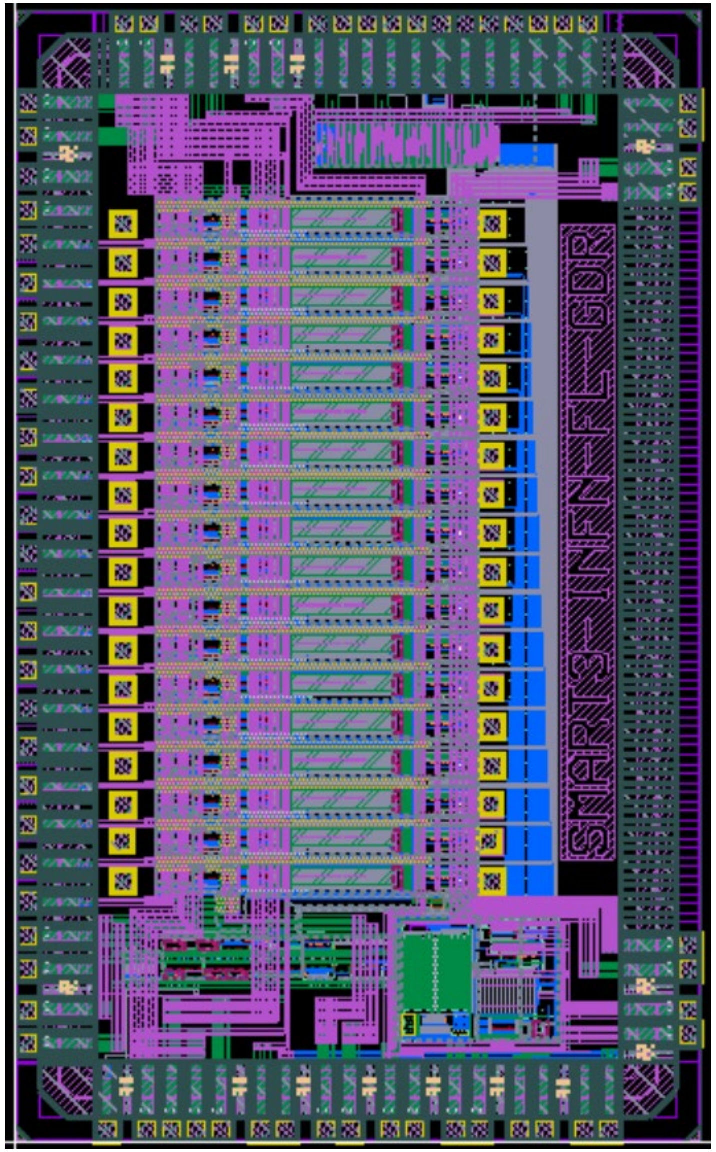


- Fast-path output dynamic up to 1.7 V on 50 Ohm load

Coming soon…

SMART3:

- 16 channel front-end ASIC
- LF110nm technology node
- 3.3 V & 1.2 V power supply
- SiPM fine bias adjust range: 1.7 V
- Channel current consumption 3.6 mA
- Fast-path output dynamic range: up to 1.7 V on 50 Ohm load (AC coupled)
- Slow-path input dynamic range: up to 2 mA of mean SiPM current (1 pC/pe at 2 GHz)
- Programmable gain, bandwidth and tail suppression



Tape-out: 7th November 2022

Currently in packaging

First tests expected for September 2023

Thanks