A 32-channels mixed-signal processor for the tracking system of the GAPS experiment

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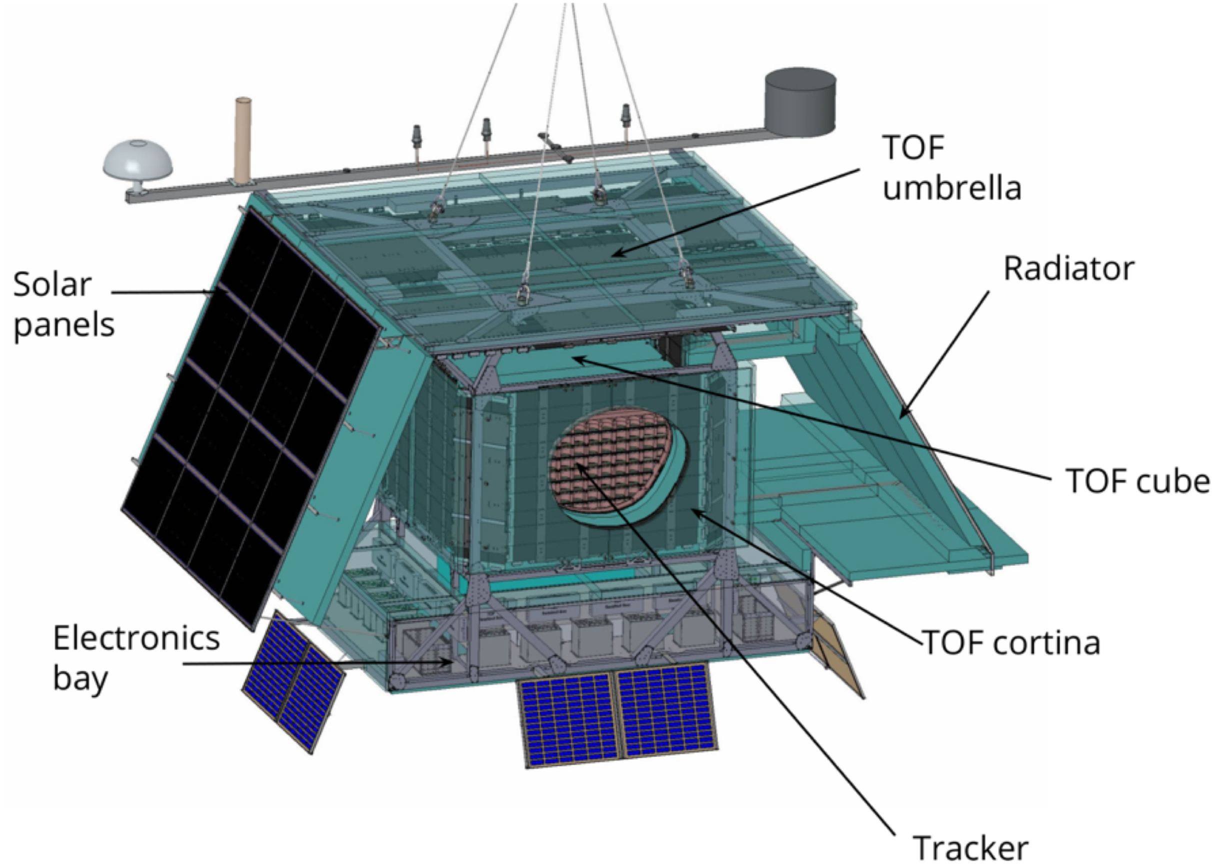
The GAPS experiment

The General Antiparticle Spectrometer (GAPS) is an Antarctic balloon experiment designed to detect low-energy cosmic antinuclei as an indirect signature of dark matter



GAPS will deliver:

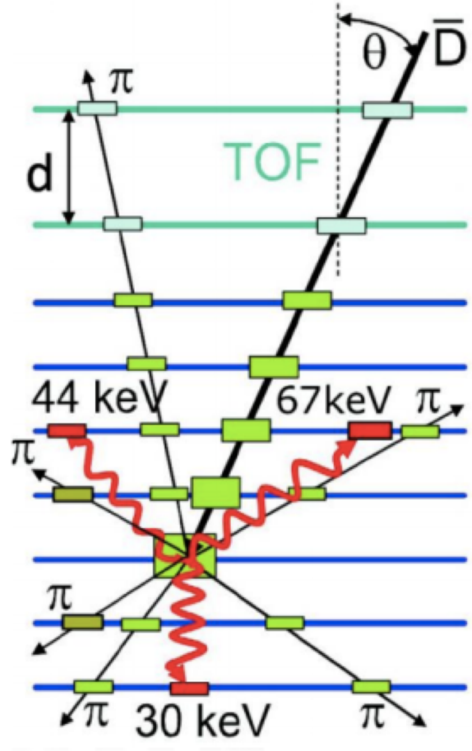
- a precision antiproton measurement in an unexplored energy range < 0.25 GeV/n
- antideuteron sensitivity 2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
- leading sensitivity to low-energy cosmic antihelium nuclei

GAPS is under construction, preparing for first Antarctic Long Duration Balloon flight

The GAPS instrument consists of a large-area (~ 50 m^2) scintillator time-of-flight system, and of a 10-planes tracker with custom Si(Li) detectors with dedicated ASIC readout

The GAPS detection principle

- ToF measures energy deposition, velocity, timing of incoming low-energy cosmic antinuclei
- Antinuclei slow down in the Si(Li) tracker material, until captured by the target material forming an exotic atom, with the antinucleus orbiting the nucleus of target material.
- Exotic atoms de-excite emitting X-rays with characteristic energies that depend on the reduced mass of the nucleus-antinucleus system. Finally, the antinucleus annihilates with the target material, producing pions and protons.



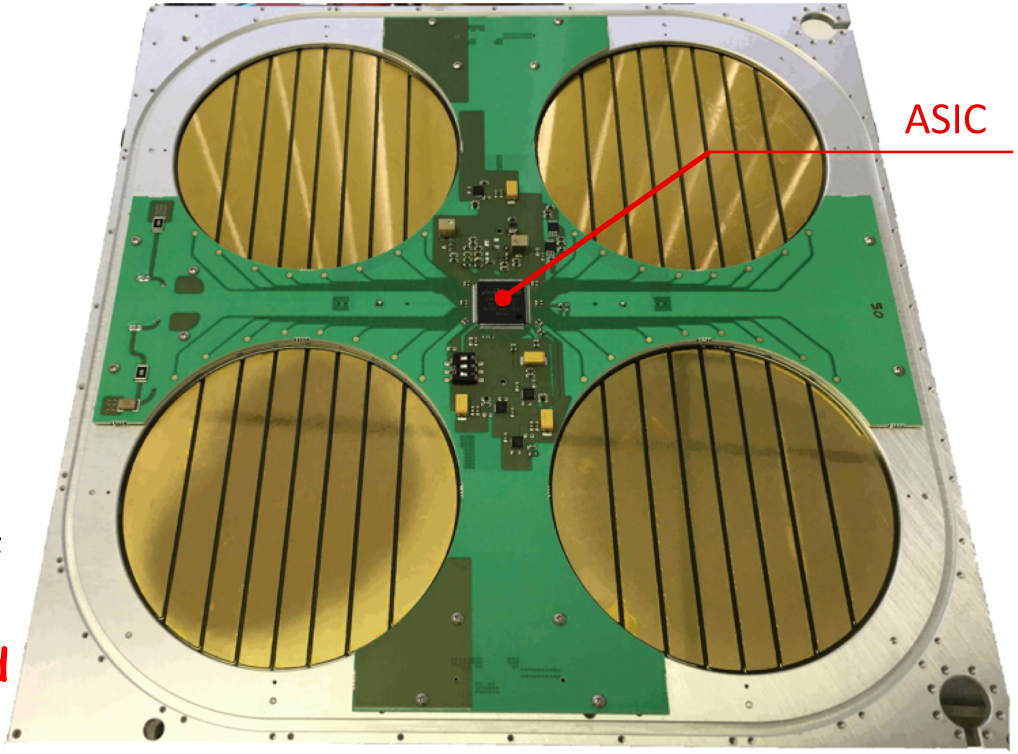
- Characteristic X-rays (20-100 keV) are detected by the Si(Li) detectors. Tracks from the charged annihilation products can be reconstructed using both the tracker and ToF, providing measurements of energy depositions and velocities.
- The GAPS detector uniquely identifies an antinucleus species while providing rejection power against protons and other non-antimatter cosmic-ray particles, which produce neither characteristic X-rays nor hadronic annihilation products.

The GAPS Si(Li) tracker

The Si(Li) Tracker, with active regions that can be made both large in area and deep in thickness, functions as

- **target** to slow an incoming antiparticle and capture it into an exotic atom in an excited state
- **spectrometer** for de-excitation X-rays (~4 keV (FWHM) energy resolution to distinguish X-rays from antiproton or antideuteron exotic atoms)
- **tracker** to measure antinucleus dE/dx and stopping depth, and annihilation products from nuclear decay

- Large area Si(Li) detectors developed by Columbia, MIT, ISAS/JAXA, produced by Shimadzu Corp.
- ~10 cm circular detectors, segmented in 8 strips with equal area and 2.5 mm thick
- module: 2x2 detectors, 6x6 module array in each plane, 10 planes vertically spaced by 10 cm
- Operation at relatively high temperature of – 35 °C to – 45 °C
- **Read out by a custom-designed front-end chip**



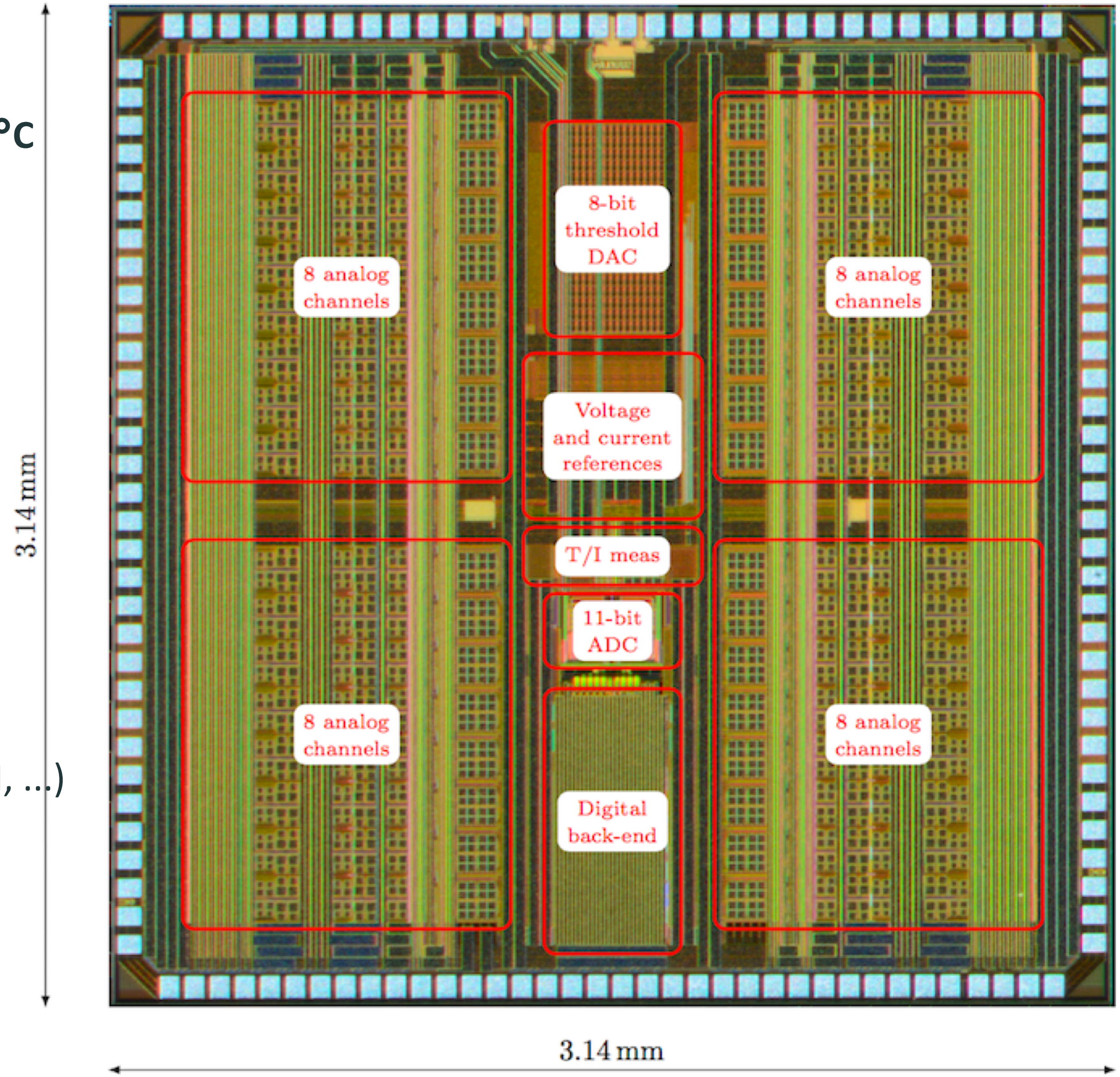
The GAPS Tracker readout chip

Front-end electronics requirements

- Channels per ASIC: **32**
- Nominal operating temperature: **-43 °C**
- Power dissipation: **≤ 10 mW/ch**
- Signal polarity: **electrons**
- Dynamic range: **10 keV-100 MeV**
- Analog Resolution: **4 keV (FWHM)** at detector capacitance 40 pF
- Threshold: **20 keV**
- Detector leakage current: **5 nA**
- Event rate: **100 Hz**

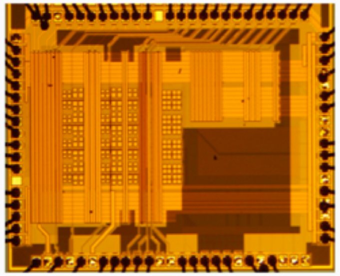
ASIC features

- 32 analog readout channels
- 11-bits ADC
- Digital Back End (registers control, SPI, ...)
- BGR with 3-bit DAC regulation
- 8-bit DAC for global threshold setting
- 3-bit DAC for threshold fine trimming
- Detector leakage current readout
- Temperature sensor readout

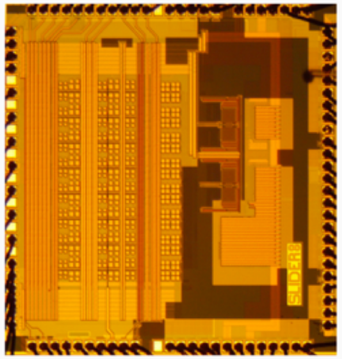


Developing the GAPS Tracker readout chip

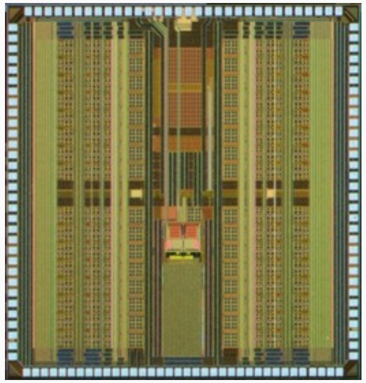
SLIDER: SiLI DEtector Readout



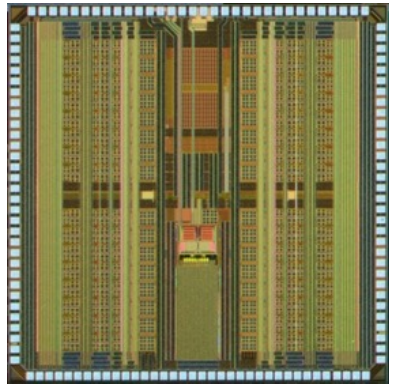
SLIDER4 (2018)
- 4 analog channels
- No digital back end
- 2 channels with analog output



SLIDER8 (2018)
- 8 analog channels
- digital back end
- 11 bit ADC
- No access to analog blocks

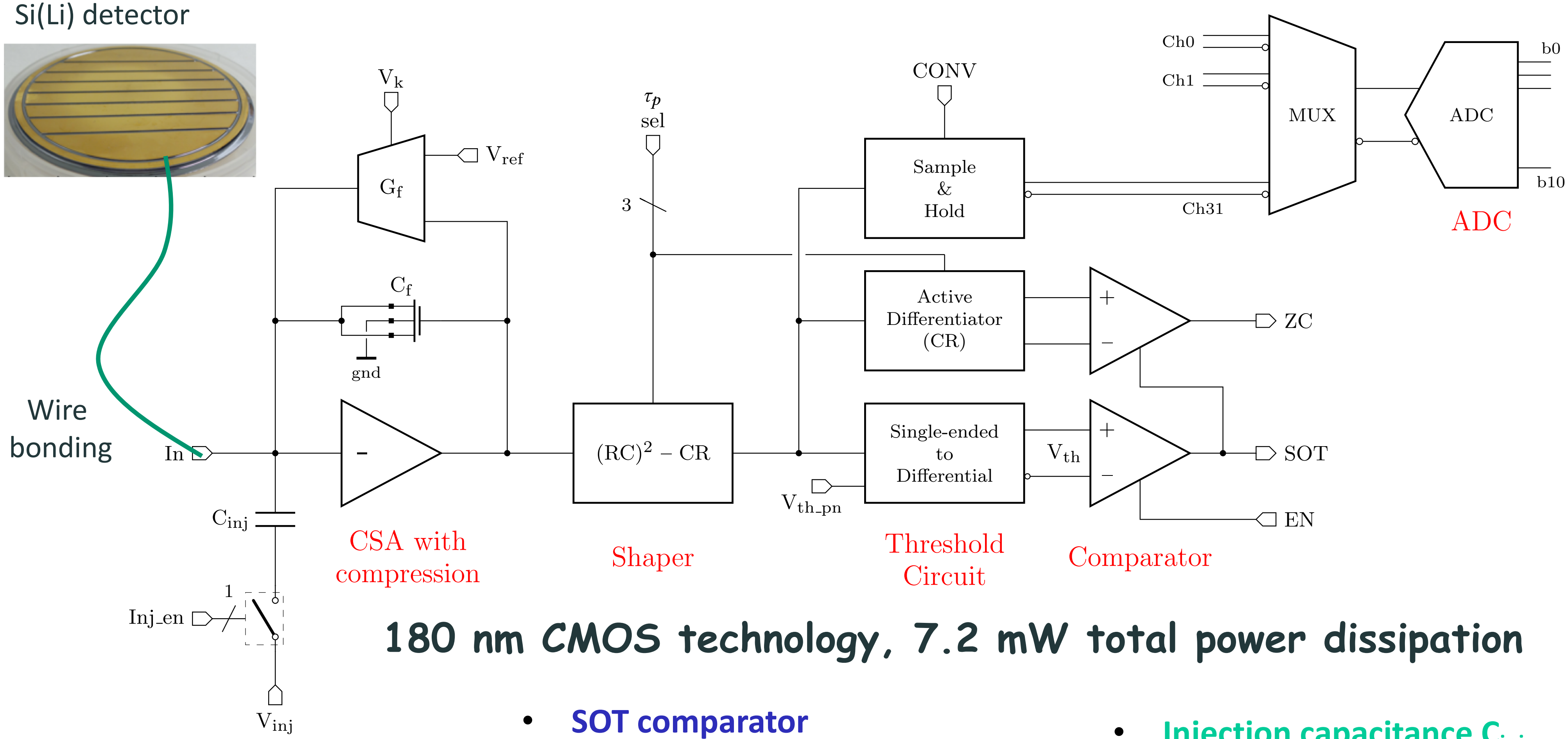


pSLIDER32 (2019)
- 32 analog channels
- digital back end
- 11 bit ADC
- 2 channels with access to analog blocks



SLIDER32 (2021)
- 32 analog channels
- Digital back end
- 11 bit ADC
- 1 channel with analog outputs
- Additional tests points

The analog readout channel



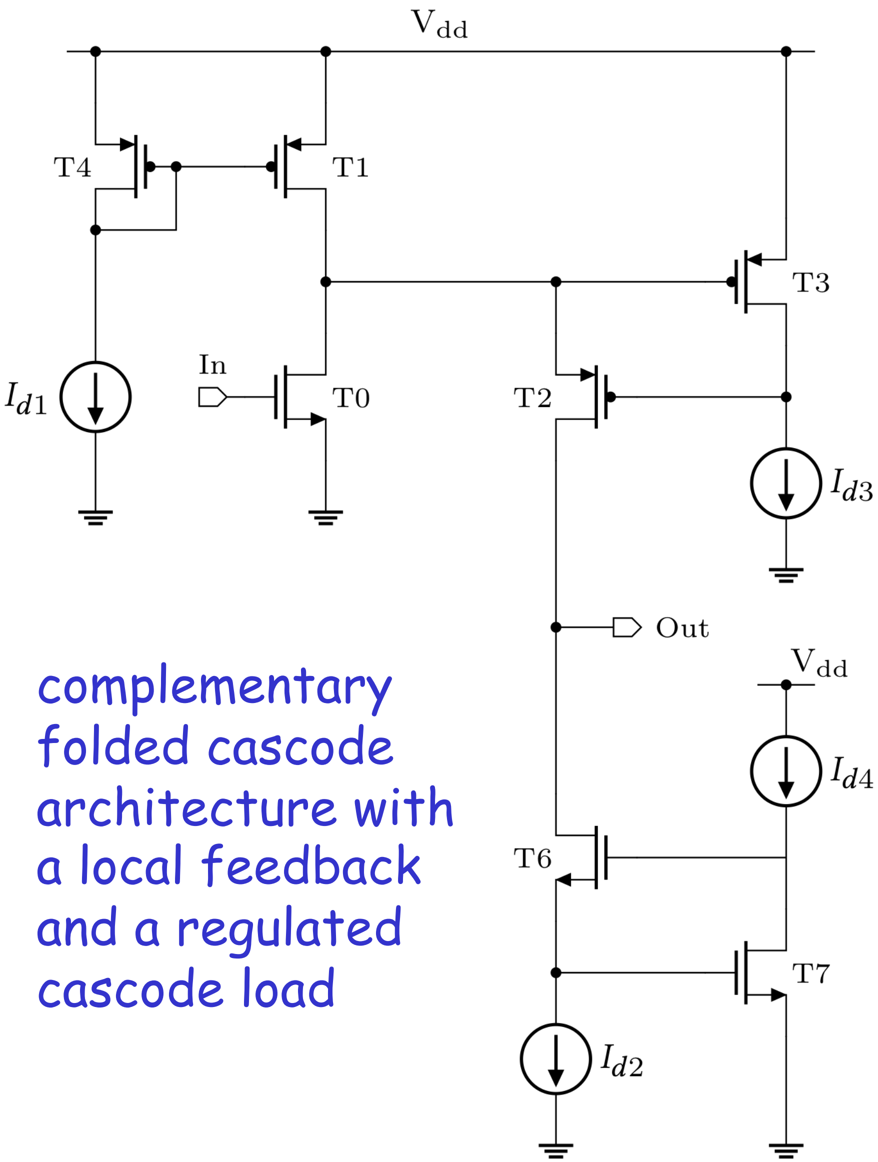
180 nm CMOS technology, 7.2 mW total power dissipation

Charge sensitive amplifier
with dynamic signal compression
CR-(RC)² filter
with 8 selectable peaking times
(from 300 ns to 1.8 μs)

- **SOT comparator**
  Signal Over Threshold identification
- **Active CR and ZC comparator**
  Shaper signal peak detection
- **Single-ended to differential S&H**
  Shaper signal peak storage

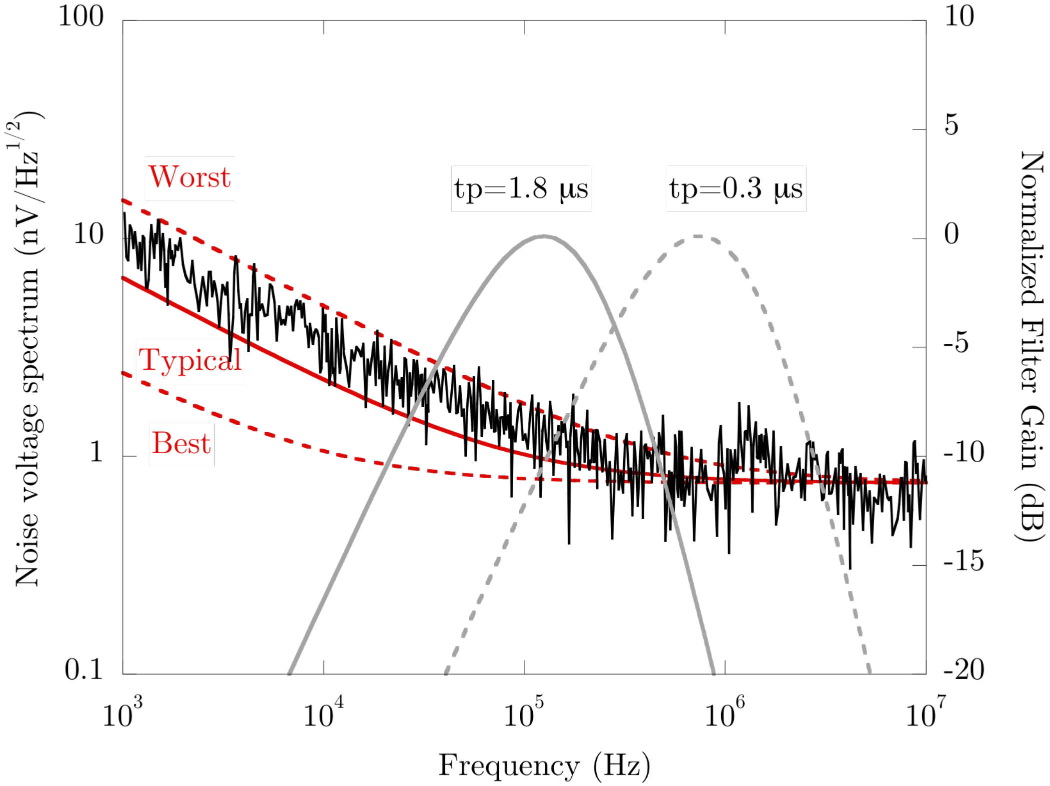
- **Injection capacitance C_{inj}**
  Calibration
- **11-bit hybrid SAR ADC**
  One per ASIC with 32:1 MUX

The charge-sensitive preamplifier

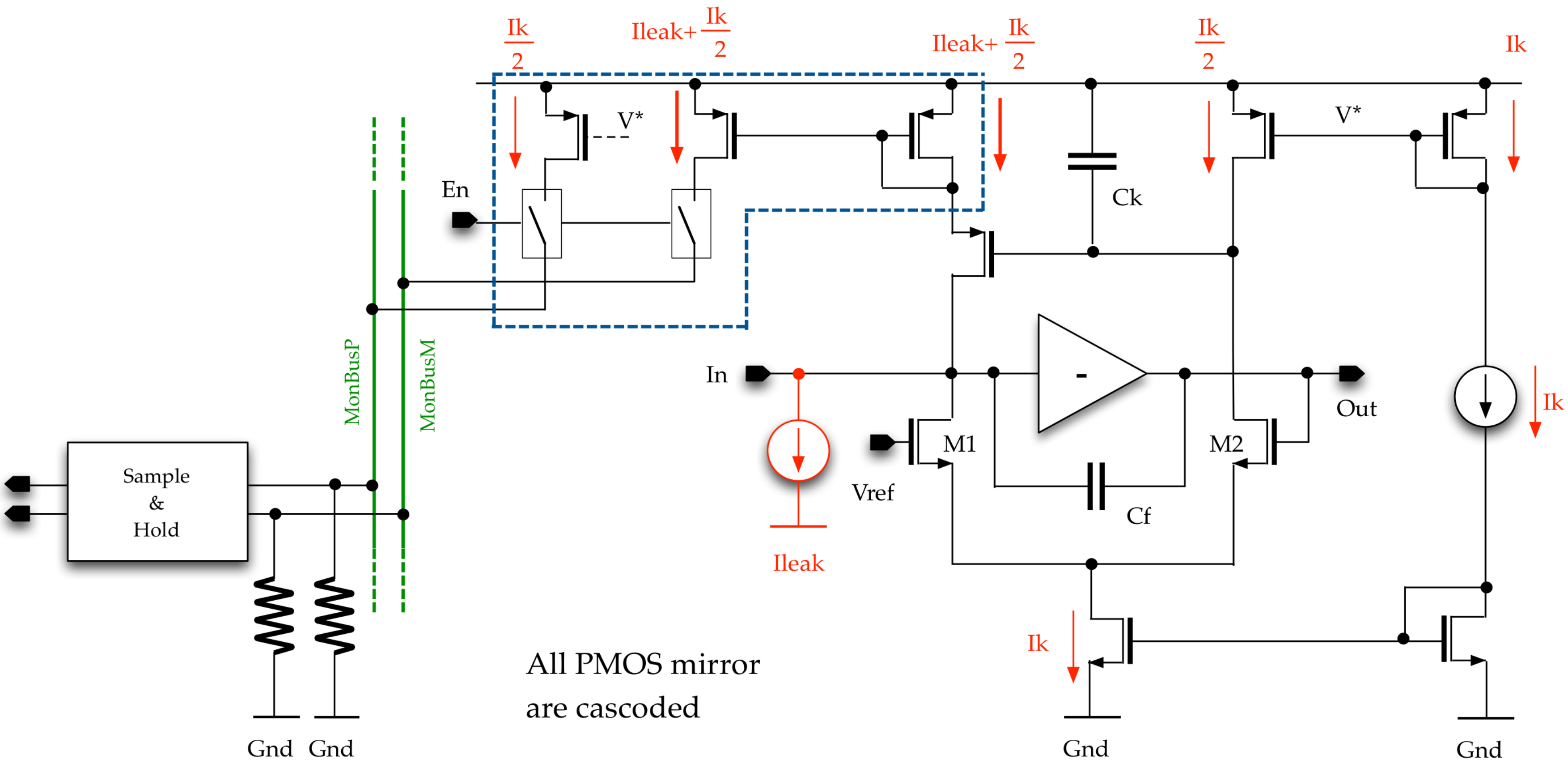


complementary folded cascode architecture with a local feedback and a regulated cascode load

Noise voltage spectrum of the preamplifier input device ($W/L = 2400/0.5$, $I_D = 1.6$ mA)



Preamplifier charge restoration network

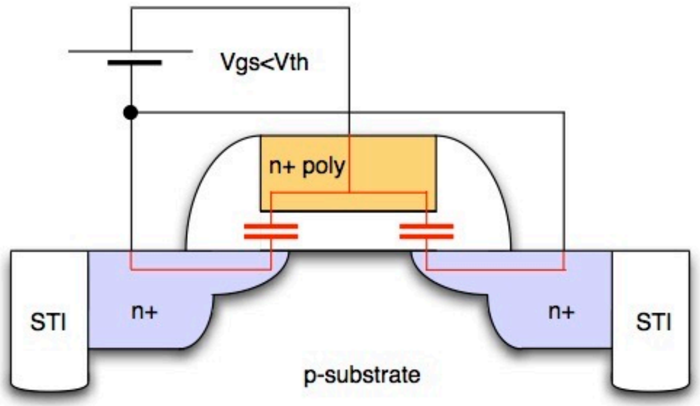


- Continuous-time Krummenacher feedback for sensor leakage current compensation (up to 50 nA for testing at temperatures higher than nominal), including a leakage current monitor
- Non-linear feedback capacitance for a dynamic compression of detector signals

Dynamic signal compression

It is based on the nonlinear behavior of a MOSFET capacitor operating in the inversion mode, with a suitable choice of W and L to set the gain in the low and high energy regime and dynamically change the gain of the preamplifier with the input signal amplitude

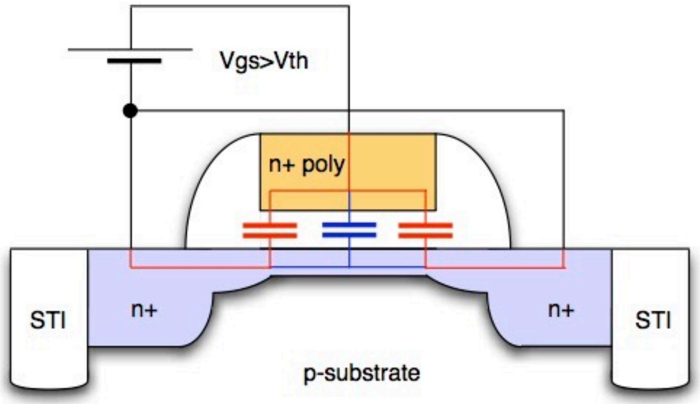
Drain and source shorted to form one capacitor terminal, the gate forms the other



$V_{G,SD} < V_{TH}$

gate/source, gate/drain overlap capacitance

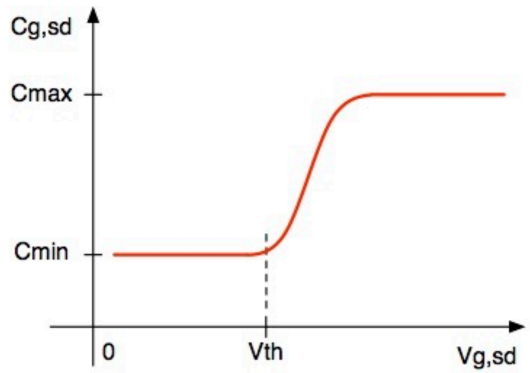
$C_{min} = W\Delta L C_{OX}$



$V_{G,SD} > V_{TH}$

gate/channel capacitance

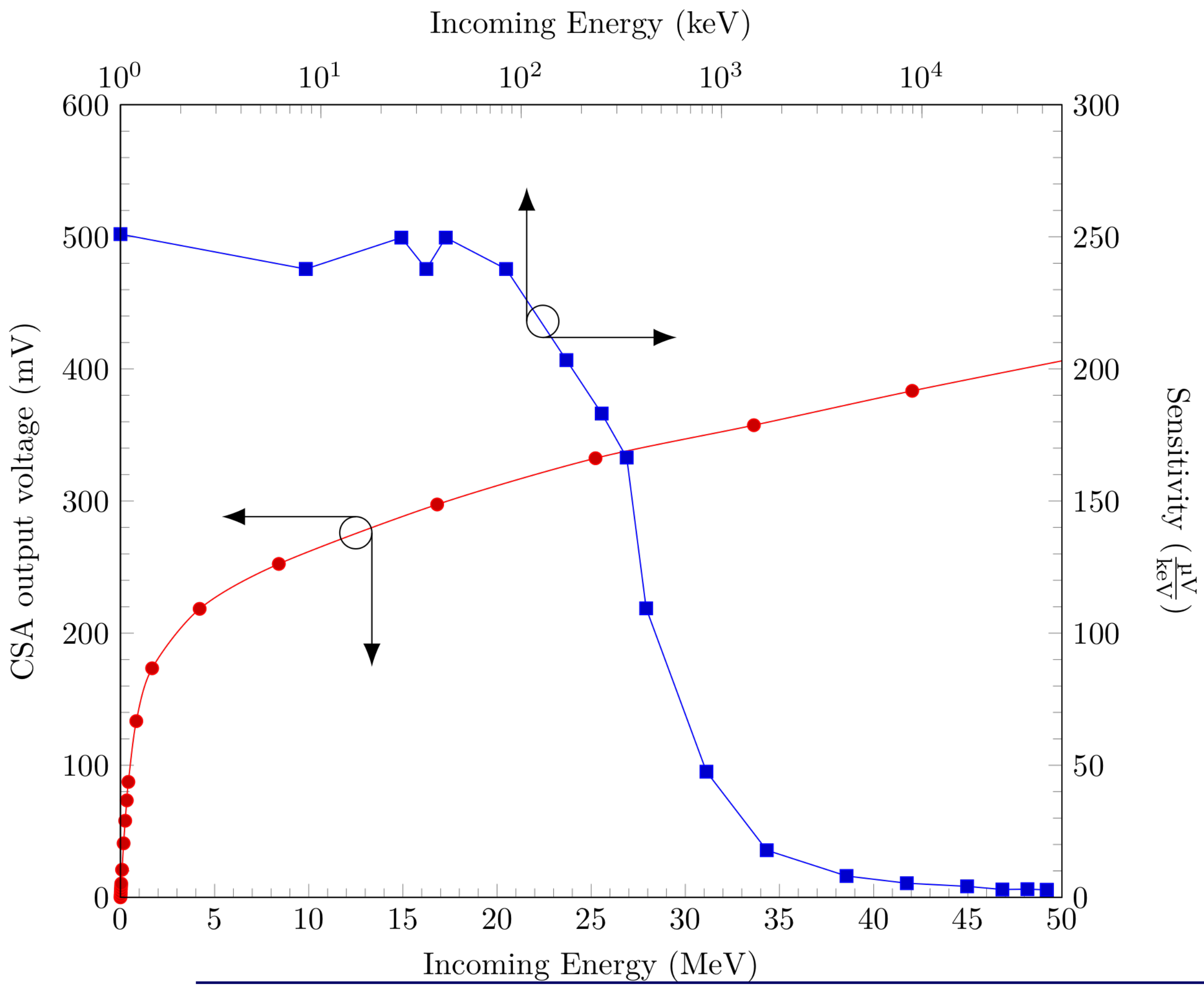
$C_{max} = WLC_{OX}$



A voltage shift (in the Krummenacher feedback) to the gate-to-source/drain terminals of the feedback MOS enables a precise variation of the voltage at which the kink in the compression occurs

Dynamic signal compression

The analog channel features a dynamic compression to fit the wide dynamic range (10 keV - 100 MeV) into the input range of the 11-bit ADC, while measure X-ray energies with 1 keV resolution in high-gain region



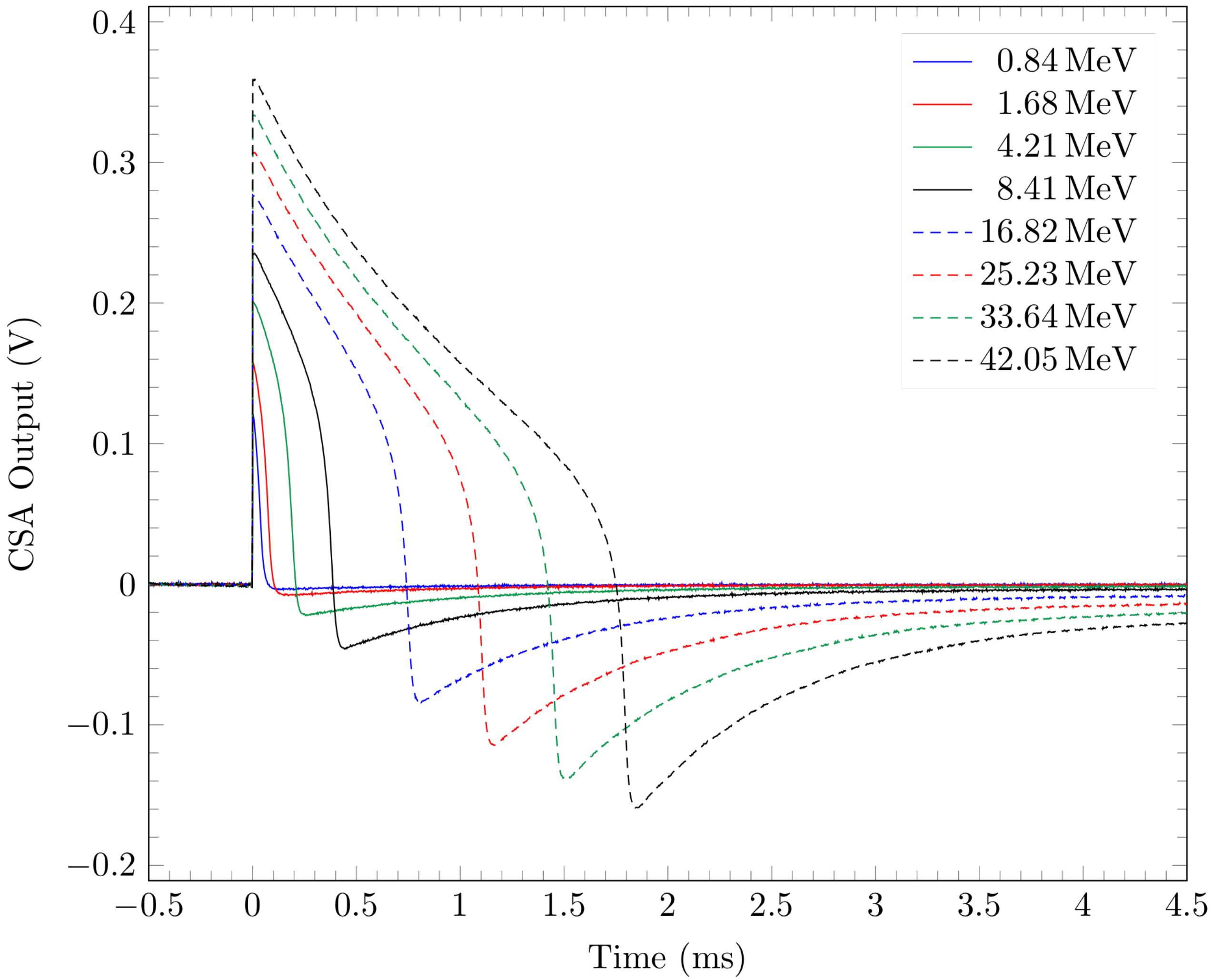
At the preamplifier output: kink at output voltage 200 mV, corresponding to an input particle energy of about 1 MeV (44 fC).

Preamplifier charge sensitivity:

High gain region: 250 μV/keV (5.7 mV/fC), equivalent feedback capacitance 175 fF

Low gain region: 3.0 μV/keV (68 μV/fC), equivalent feedback capacitance 14.7 pF (compression factor of about 80)

Dynamic signal compression and return to baseline at the preamplifier output



nonlinear discharge of the nonlinear integrating MOS capacitance

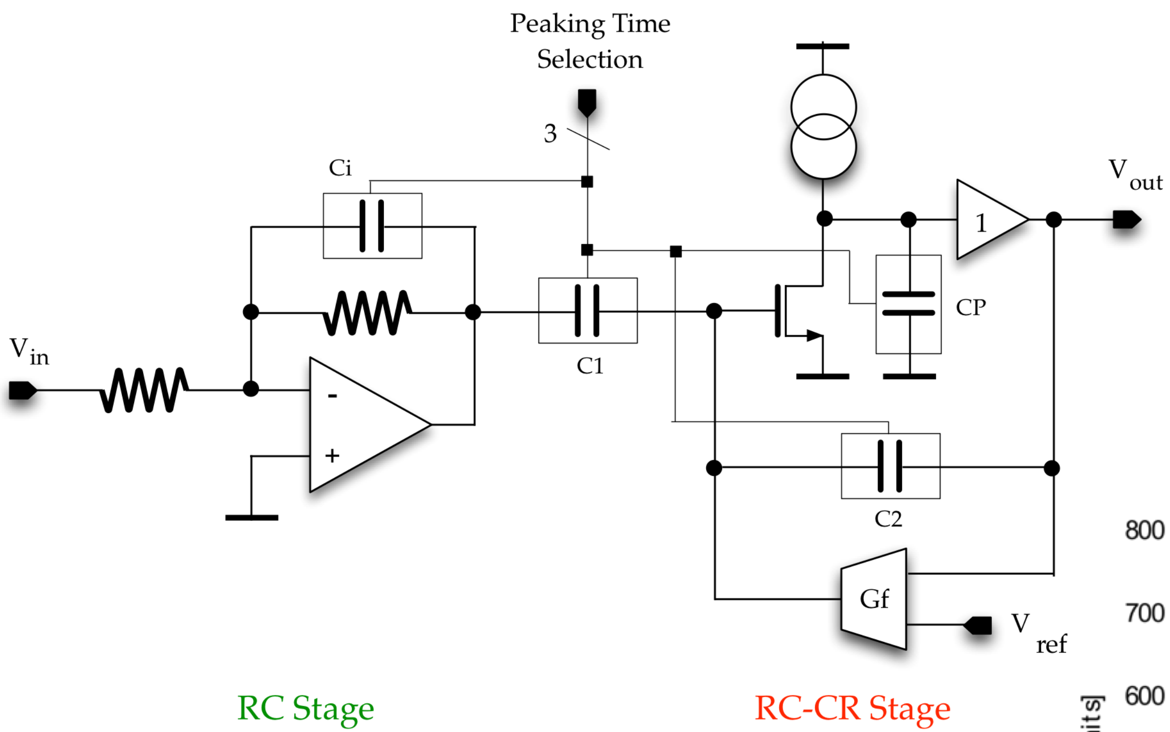
Slow discharge region:
large output levels,
feedback capacitance is large

Fast discharge region:
small output levels,
feedback capacitance is small

Undershoot at the end of the restoration phase:
complete unbalance of the Krummenacher stage for large voltage steps

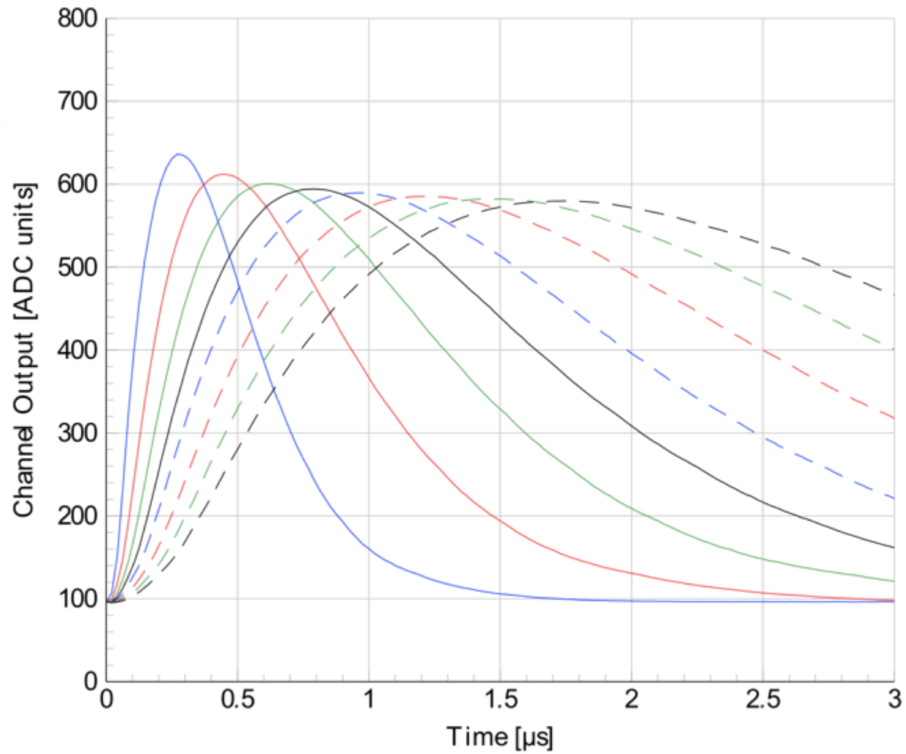
complete recovery in < 10 ms (compatible with the low event rate per strip, < 1 count per second including background)

Shaper



unipolar second order semi-Gaussian time-invariant filter

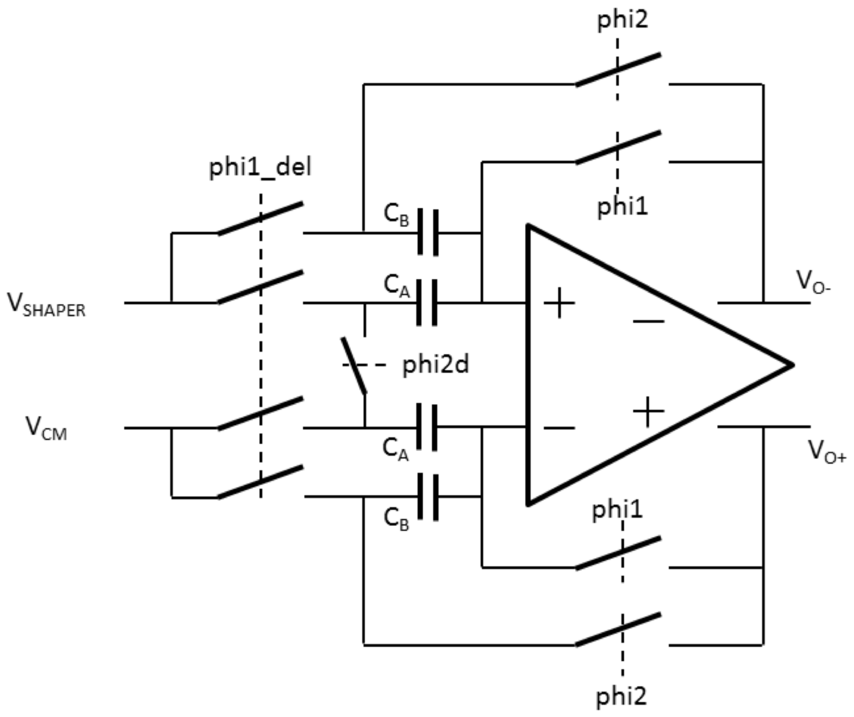
8 selectable peaking times (0.3 μs - 1.8 μs)

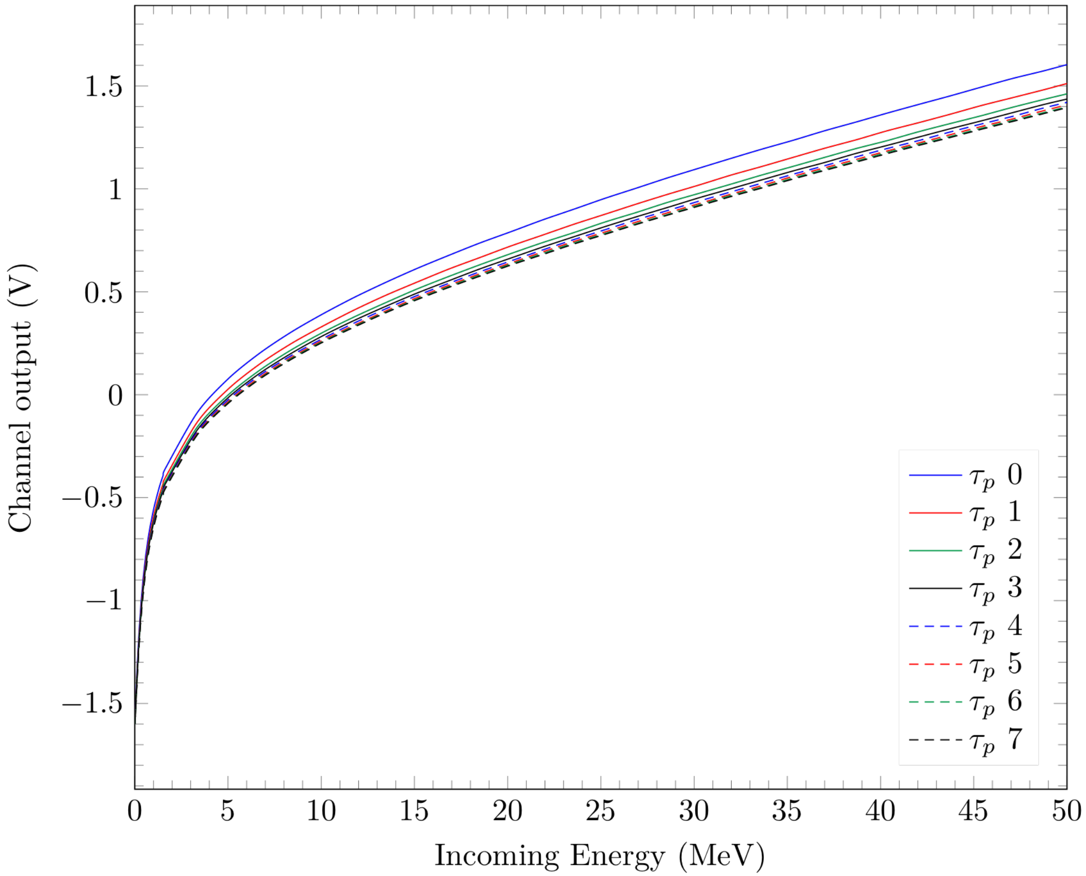


Choice of the peaking time determined by the minimization of noise contributed by the front-end and by the detector

Differential Sample&Hold

Provides a differential output signal suitable for the subsequent ADC, ranging from -1.8 V to +1.8 V with an almost rail-to-rail output dynamic range.



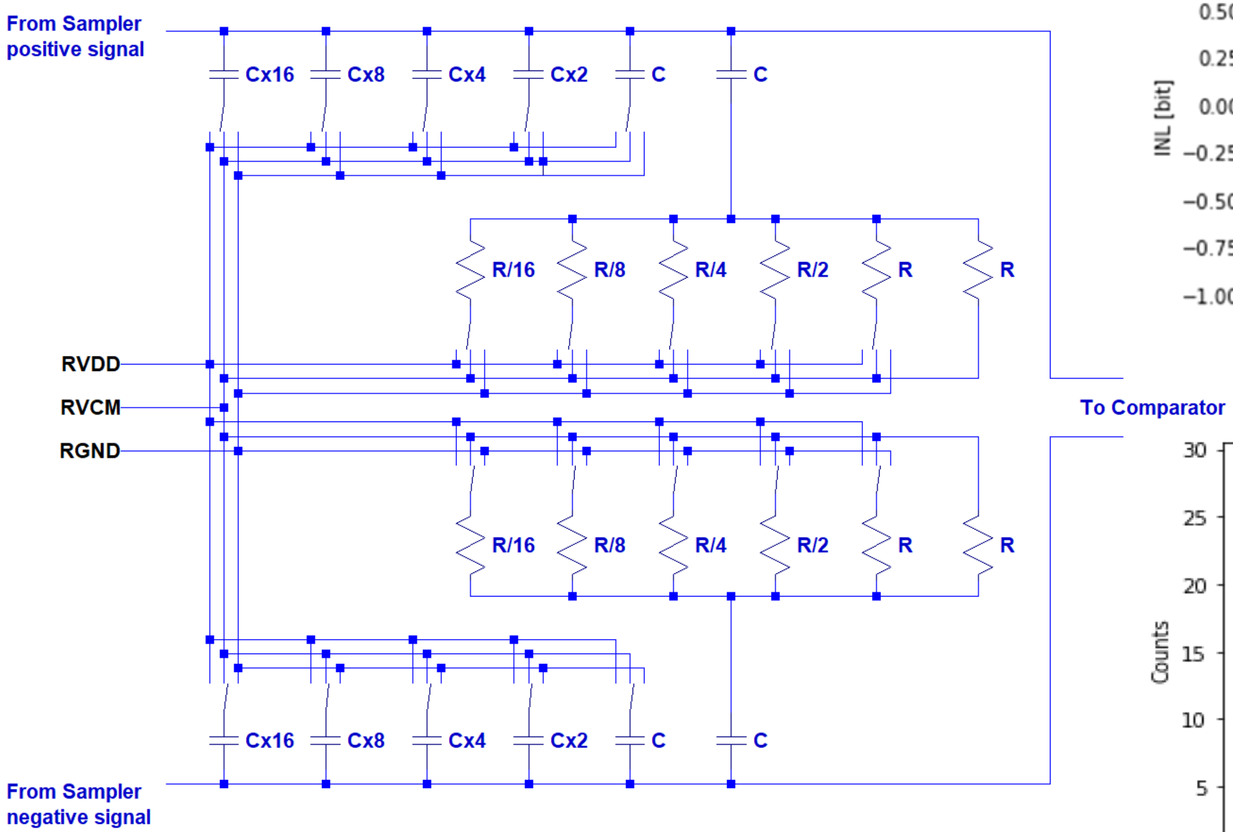


Gain of 7.7 from shaper and S&H

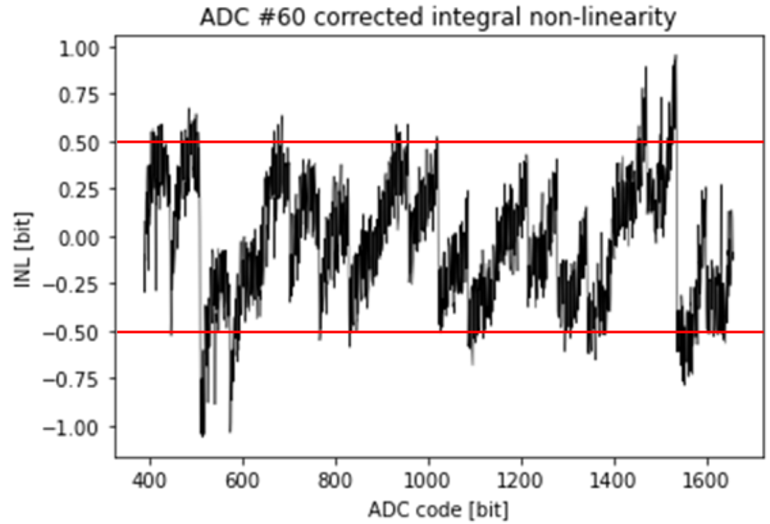
Total High-gain sensitivity: 1.9 mV/keV
Total Low-gain sensitivity: 23 μV/keV

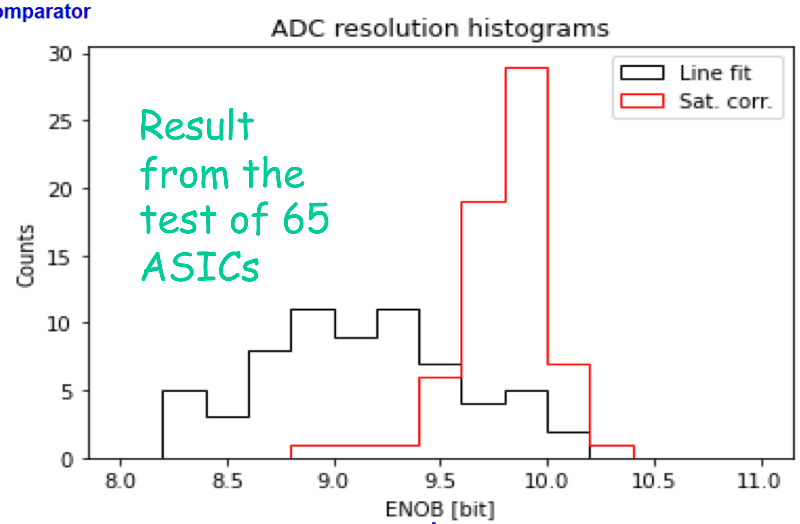
ADC

Hybrid DAC for the SAR ADC (differential architecture)



Tests using the temperature sensor input

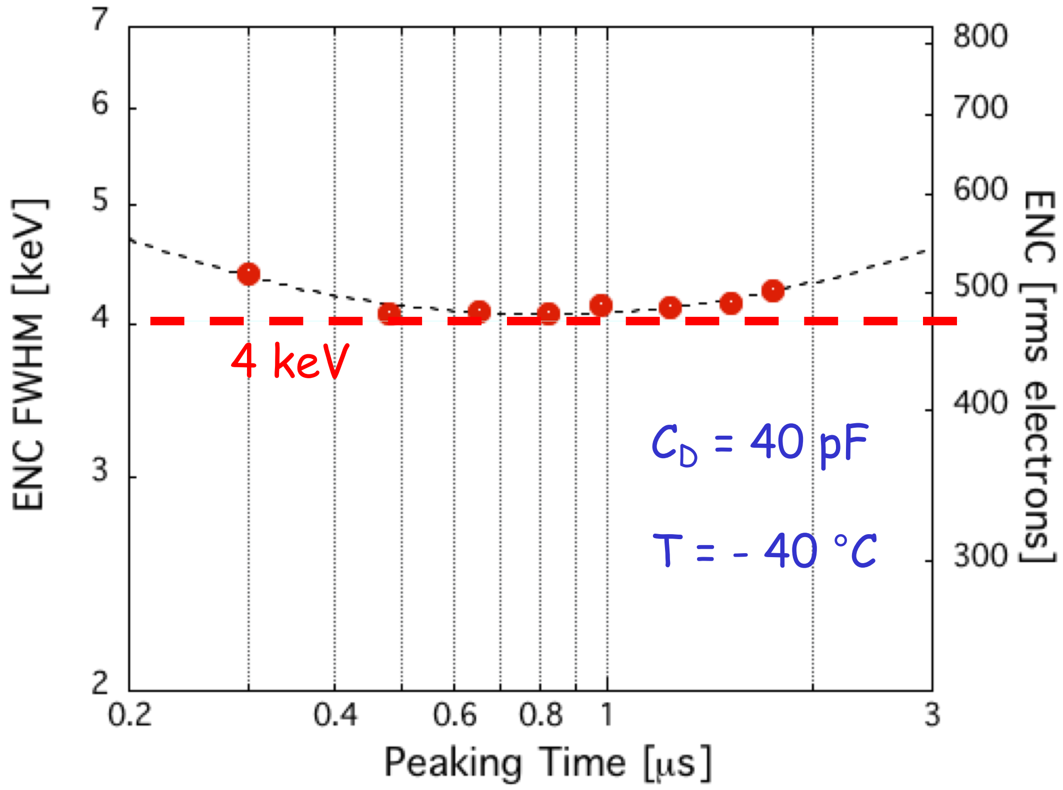


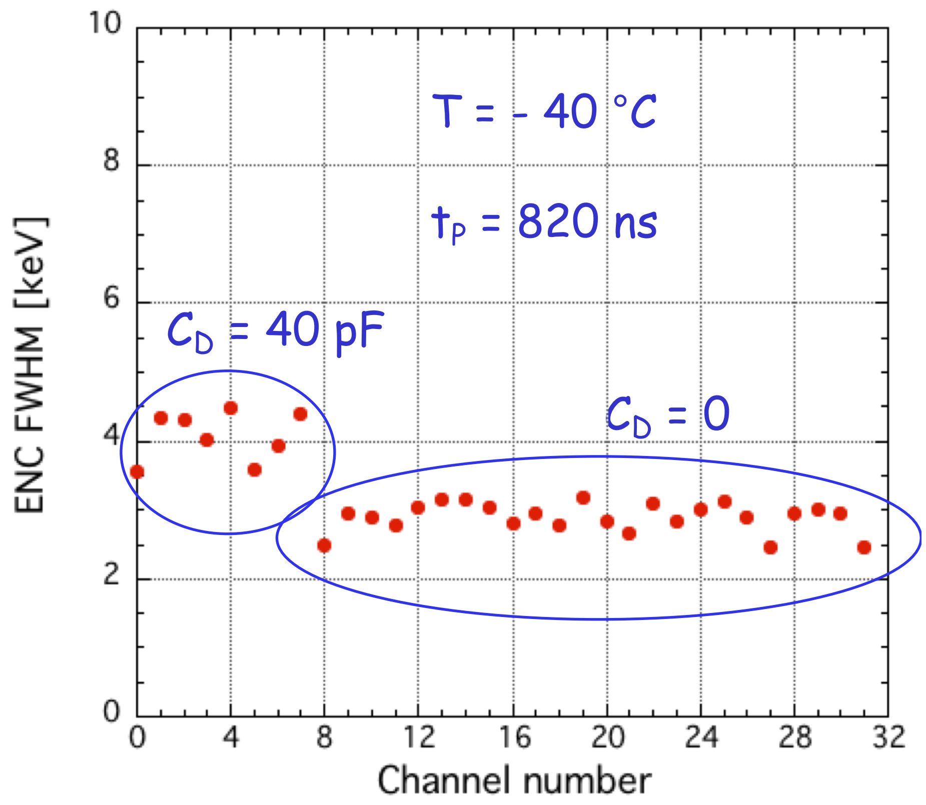


- Minimized effect of parasitics on the ADC references → no missing codes
- Capacitor mismatch higher than the models is limiting resolution to 10 bits (average ENOB 9.8 bits)

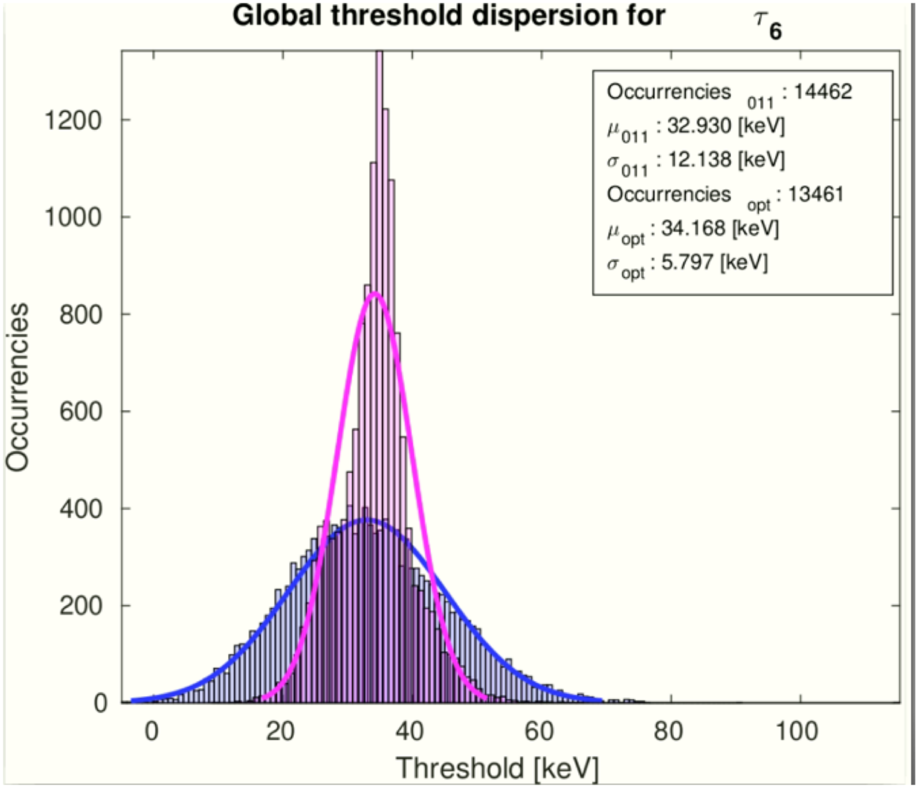
Noise

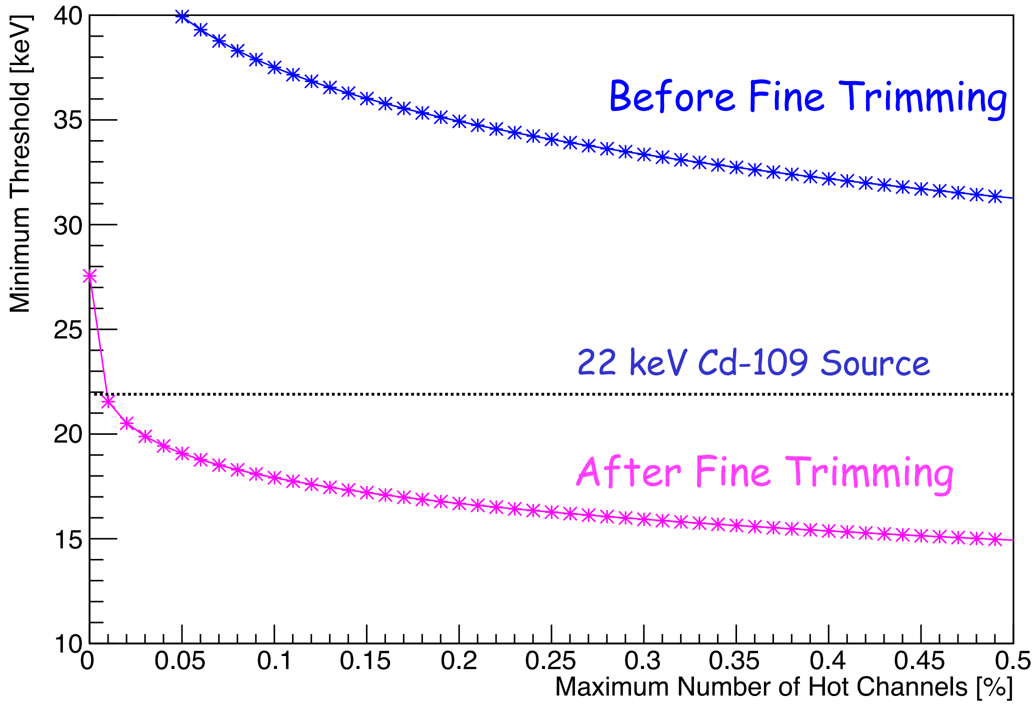
Noise is measured at the output of the ADC (ENC extracted from the variance of the distribution of output values)





Threshold setting





- 3-bit DAC in each channel for threshold fine trimming
- Threshold dispersion reduced by a factor of 2

After fine trimming :

- 0.4% Hot Channels for 15 keV Threshold
- 0.1% Hot Channels for 18 keV Threshold

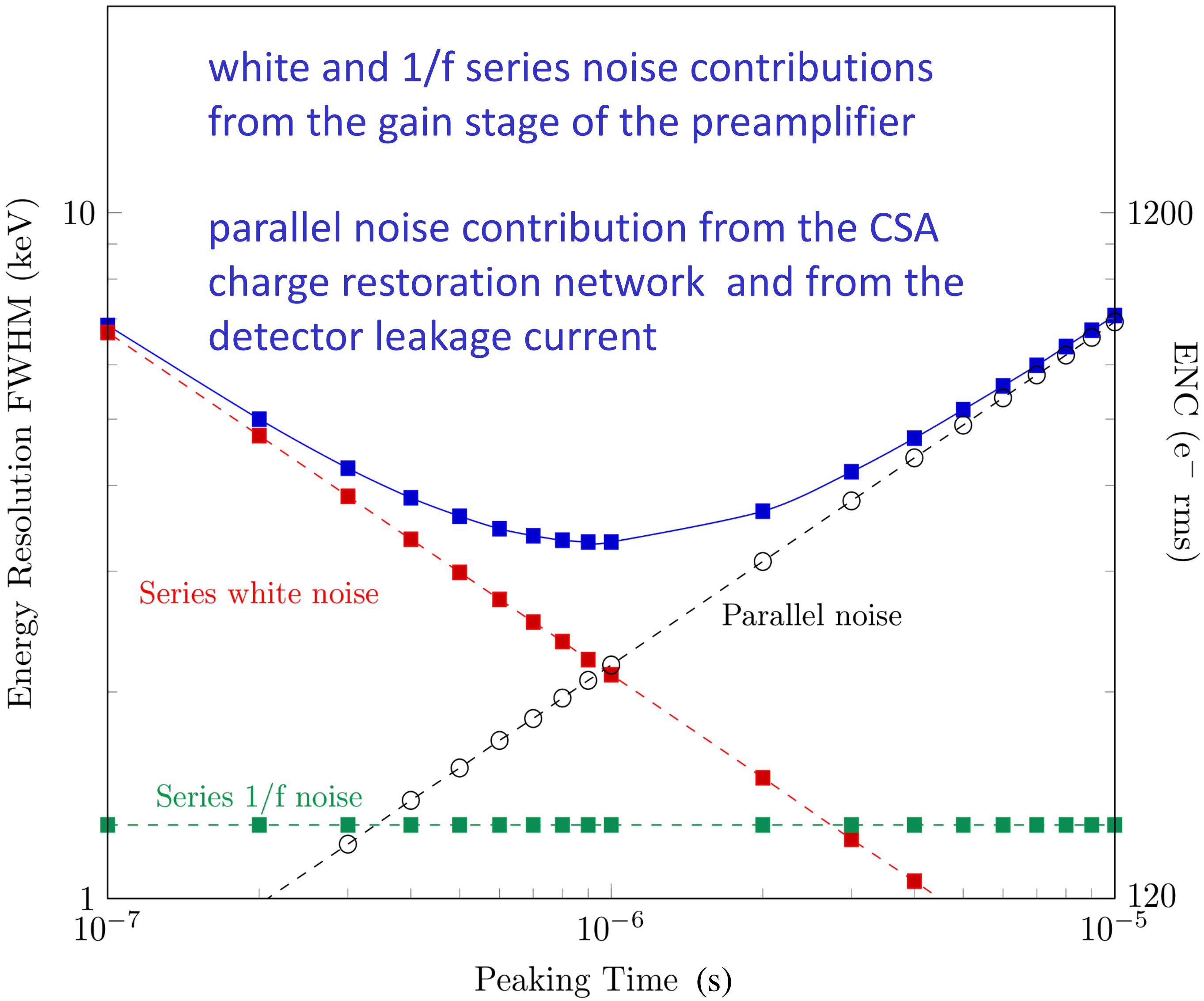
Conclusions

- The final version of the readout chip for the GAPS Si(Li) tracker is fully functional according to the detector specifications
- The analog front-end implements a dynamic signal compression technique to handle a wide dynamic range while keeping a high resolution at low signal charges
- The chip production in 2021 was successful, and front-end boards with ASICs are currently being tested and selected for the flight instrument
- The integration of the GAPS instrument is beginning now, preparing for the first flight of a series of long-duration balloon flights at high altitude in Antarctica

The GAPS collaboration

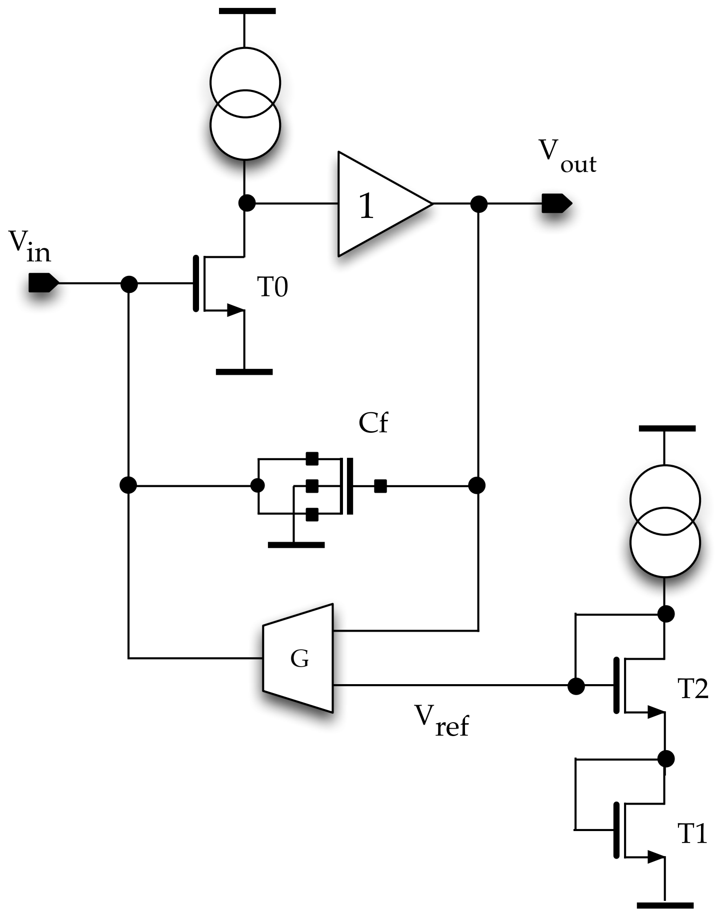
Backup slides

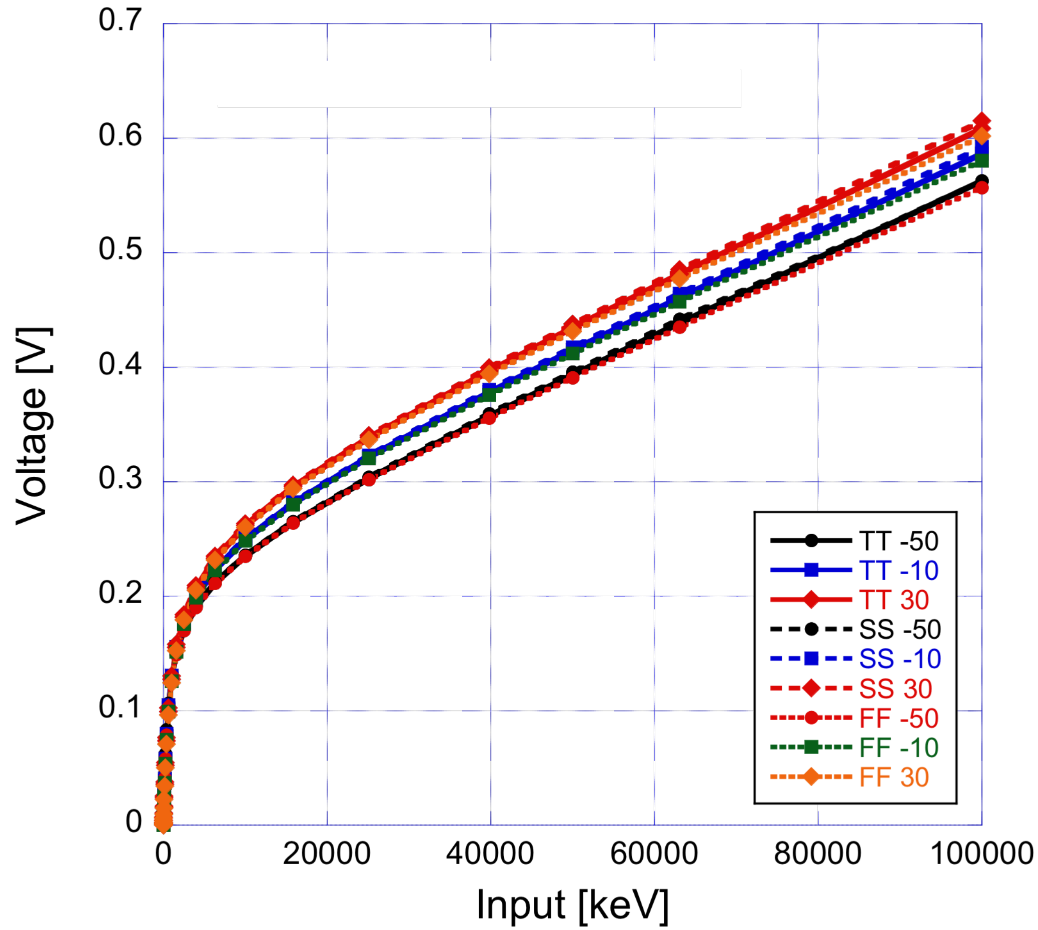
Peaking time and noise optimization (from simulations)



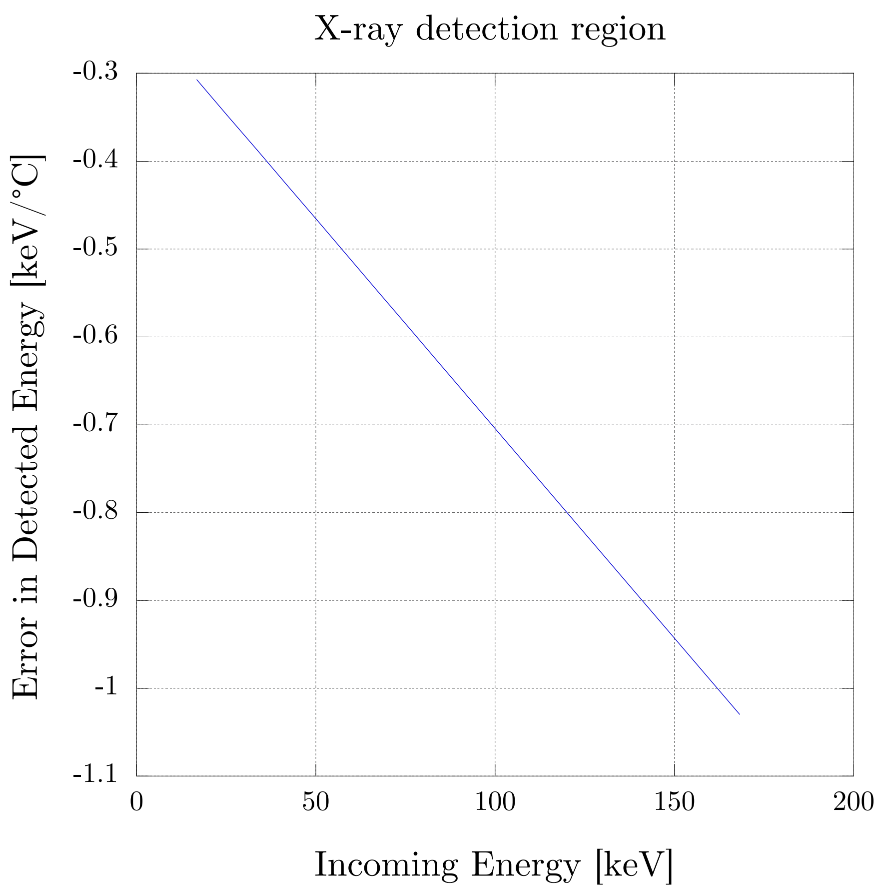
Mitigation of temperature effects on input-output characteristics

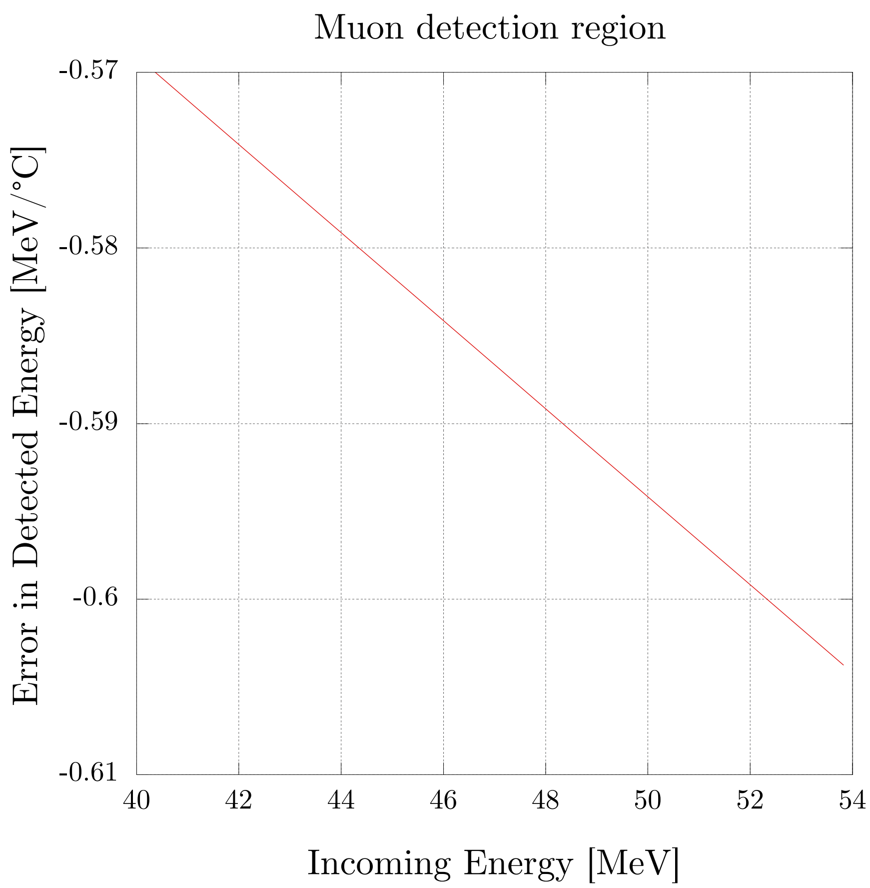
The input-output characteristic is affected by temperature variations (effect on transistor threshold voltages). The effect has been strongly mitigated by generating V_{ref} in a way which follows the temperature variations





Error due to temperature variations around - 40 °C





ADC nominal resolution: 1 keV

ADC nominal resolution: 80 keV

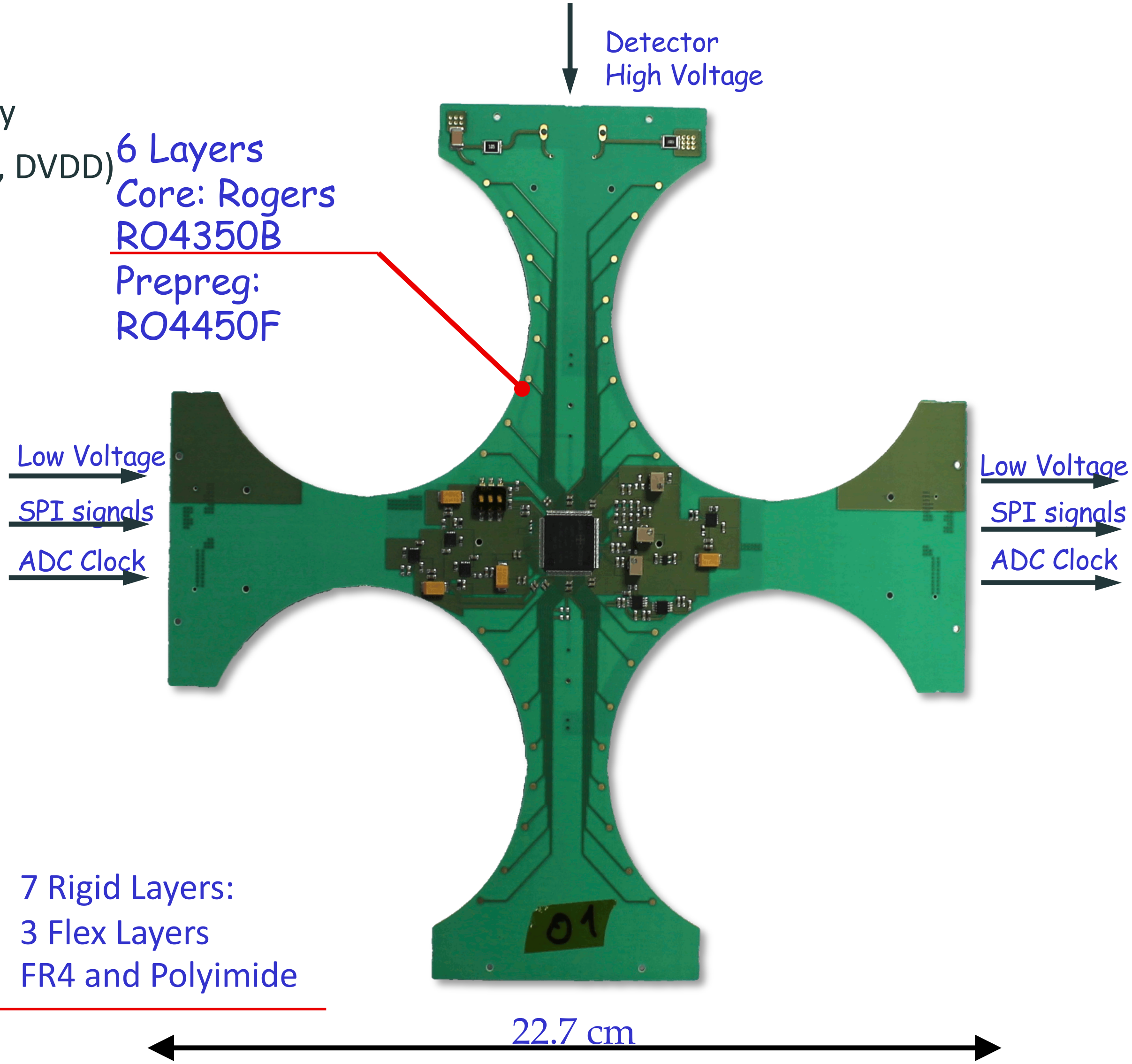
Front-end board

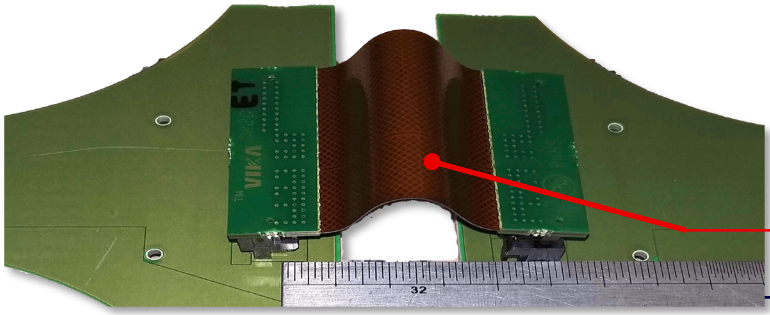
Front-end Board

- One ASIC connected to 4 Si-Li detectors
- voltage regulators and filtering for
  - Si(Li) detector High Voltage Power Supply
  - ASIC Low Voltage Power Supplies (AVDD, DVDD)
- ASIC SPI control signals
- ADC clock
- Temperature sensor
- ASIC calibration system (16 bit DAC)

Flex-rigid Board

- Connects Front-end boards in series
- Propagates
  - ASIC Low Voltage Power Supplies
  - SPI control signals and ADC clock





7 Rigid Layers:
3 Flex Layers
FR4 and Polyimide