The analog front-end for the Si-Li tracker of the GAPS experiment to search for Dark Matter

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General AntiParticle Spectrometer

- One of the great unanswered questions in physics and astronomy concerns the properties and composition of dark matter
- A very promising indirect signature of dark matter are cosmic ray antideuterons

General AntiParticle Spectrometer (GAPS):

- is a balloon-borne experiment designed to search for Cold Dark Matter
- searches for the low energy antideuterons (<3GeV/n) produced in the annihilation of CDM particles in the galactic halo
- Prototype flight (pGAPS) in 2012 @ Taiki, JAXA balloon facility in Japan

Final balloon flight from McMurdo Station Antarctica in 2020 (launch approved by NASA)

pGAPS balloon filling

The GAPS collaboration

The project is funded by NASA, JAXA, INFN

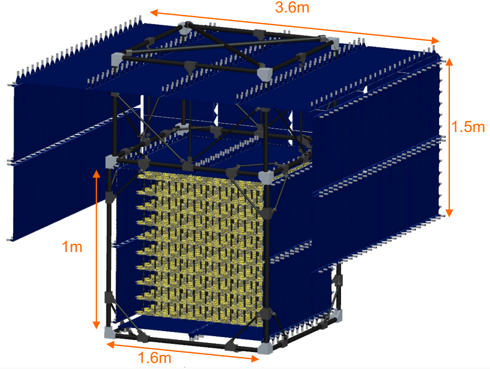
The instrument

TOF plastic scintillators

- outer TOF: $3.6 \times 3.6\text{m}^2$, 1.5m height
- inner TOF: $1.6 \times 1.6\text{m}^2$, 1m height
- **1m** b/w outer and inner TOFs
- **500 ps** timing resolution
- 16.5 cm wide plastic paddles
- PMT on each end

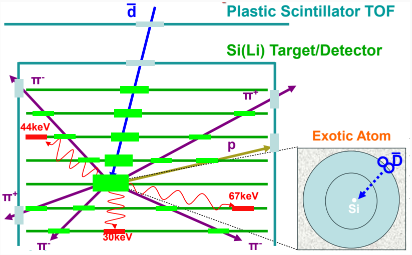
Si(Li) detectors

- 12×12 **Si(Li)** wafers
  - **4 inch** diameter
  - **2.5mm** thickness
  - segmented into **8 (or 4) strips**
- **10 layers** with 10 cm spacing
  $\rightarrow$ 3D particle tracking
- **4 keV** energy resolution
- dual channel electronics
  - X-ray: 20 - 80 keV
  - charged particles: 0.1-50 MeV



Not to scale

Antiparticle identification with GAPS



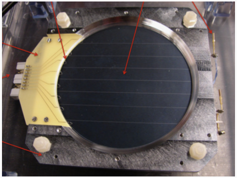
An antiparticle slowed by the atmosphere

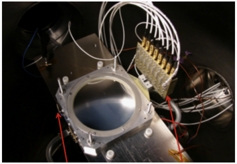
- passes through the TOF system (which measures particle velocity)
- Loses energy in layers of Si(Li) targets/detectors
- Stops, forming exotic excited atom
- Atom de-excites, emitting X-rays
- Remaining nucleus annihilates, emitting pions and protons

3 techniques to uniquely identify antideuterons

- time of flight, depth sensing and dE/dx loss
- simultaneous detection of X-rays
- multiplicity of pions, protons and other particles emitted from the nuclear annihilation

The lithium-drifted silicon Si(Li) detector





Si(Li) detectors provides

- active regions that can be made both large in area and deep in thickness
- 4 keV energy resolution necessary to distinguish X-rays from anti-*p* or anti-*D* exotic atoms

The baseline GAPS design requires

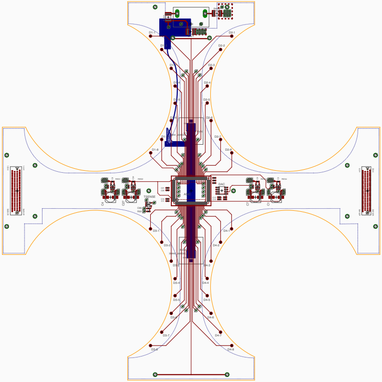
- 12×12 wafers
- 10 layers
- 1440 detectors
- 11520 channels
- 4inch diameter
- 2.5 mm thick
- 8 strips

pGAPS used a discrete amplifier for detector readout

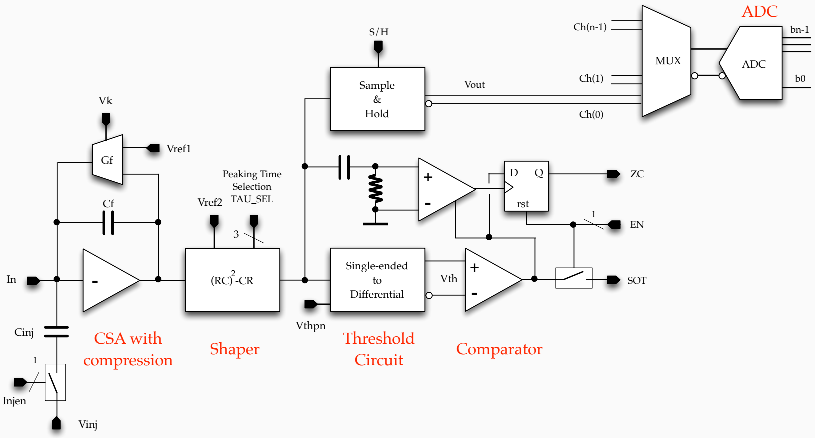
Goal: ASIC design for the final 2020 flight

Main requirements for the front-end electronics

- Modular structure:
  4 sensors per module
  1 ASIC per module
- Channels per ASIC: 32
- Operating temperature: -40 °C
- Power dissipation: <10 mW/channel
- Signal polarity: electrons
- Dynamic range: 10 keV-50 MeV
- Analog Resolution: 4 keV (FWHM)
- Threshold: 10 keV
- Detector leakage current: 5-10 nA
  (50 nA for tests at higher
  temperature)

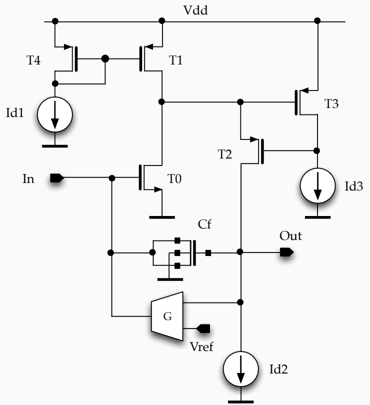


Readout channel block diagram



- Design performed in 180 nm CMOS technology
- One 11-bit hybrid SAR ADC per ASIC
- The channel can be operated either in triggered or self-triggered mode

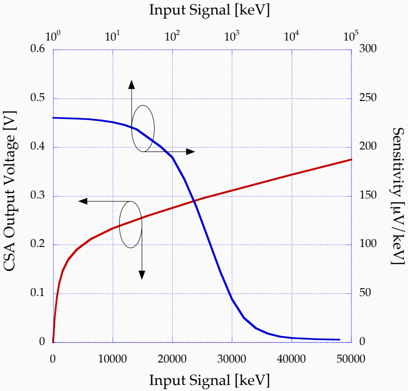
Charge Sensitive Amplifier

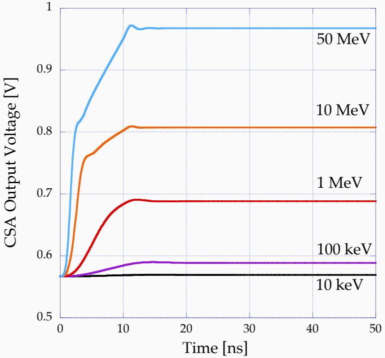


Main design features	
Bias V_{DD}	1.8 V
Input device W/L	2000/0.5
Input bias I_D	2.0 mA
Power consumption	4.0 mW
Feedback device W/L	240/6

- Architecture: active folded cascode (with local feedback) loaded by an active cascoded load
- Sensitivity: dynamic compression with MOS capacitor
- Reset: performed by a time continuous feedback implemented with a Krummenacher network

CSA response and dynamic range



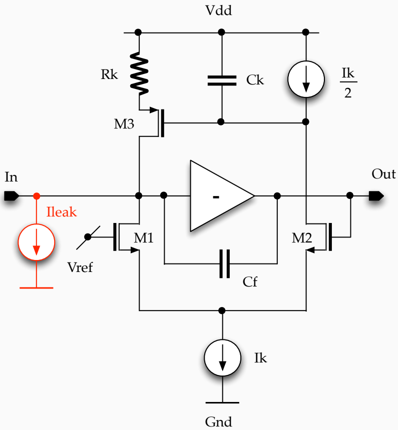


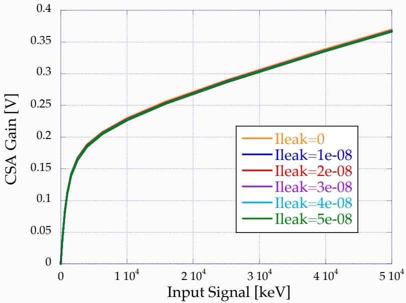
- Charge sensitivity:
  - High gain region: 230 μV/keV (C_f=190 fF)
  - Low gain region: 3.0 μV/keV (C_f=14.5 pF)
- Dynamic range: the CSA covers the full dynamic range of 50 MeV
- Rise time: t_r<15 ns

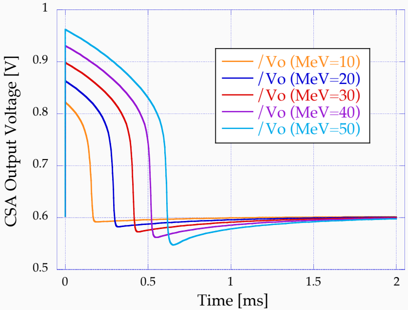
Improved charge restoration network

Krummenacher network to comply with the high detector leakage current

- I_{leak}=5-10 nA (detection at T=-40 °C)
- I_{leak}=50 nA (test at higher T)





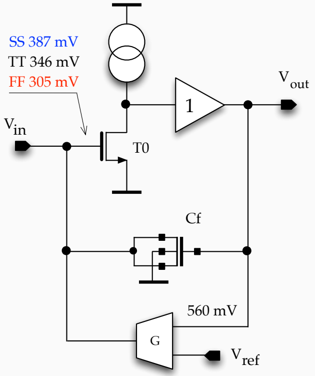


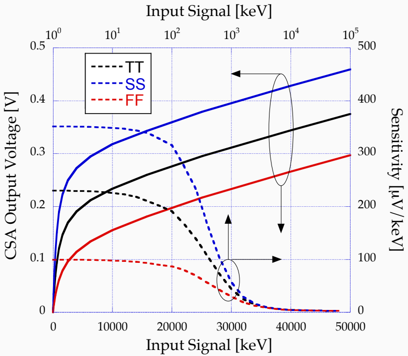
Additional degeneration resistance R_K

Effect of process variations

CSA sensitivity is affected by process parameters variation throughout

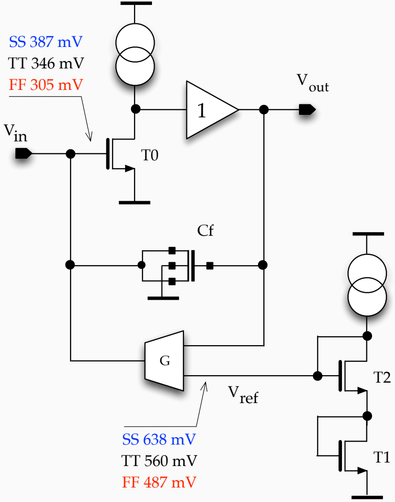
- the feedback device itself
- the CSA input device (which sets the input voltage)

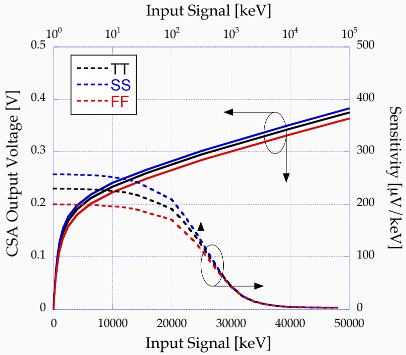




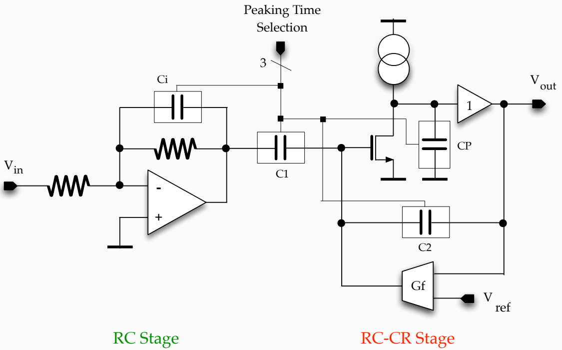
Mitigation of process variations effects

The effect of process parameters variation has been strongly mitigated by generating V_{ref} in a way which follows the variations of the amplifier input node





Time invariant filter



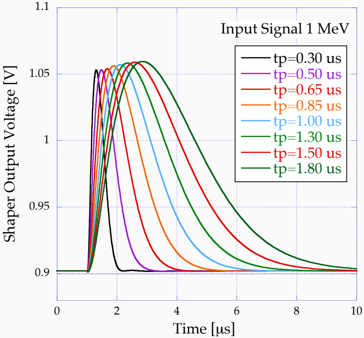
#	Peaking Time [μs]
1	0.30
2	0.50
3	0.65
4	0.85
5	1.00
6	1.30
7	1.50
8	1.80

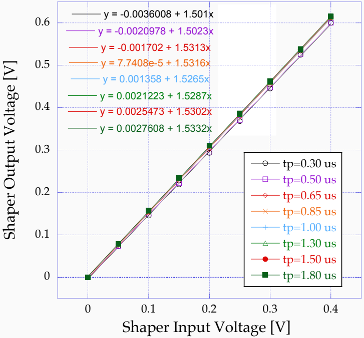
$$H(s) = \frac{R_2}{R_1}\frac{1}{1+s\tau}\frac{C_2}{C_1}\frac{s\tau}{(1+s\tau)^2}$$

- Unipolar semi-Gaussian ($RC^2 - CR$) shaping function $\rightarrow t_p$=2τ
- Peking time selection (3 bit): obtained by switching capacitances C_1, C_2, C_p and C_i in order to keep constant the ratios:

$$\frac{C_2}{C_1} \quad and \quad G_f = \frac{C_2}{t_p}$$

Filter performance

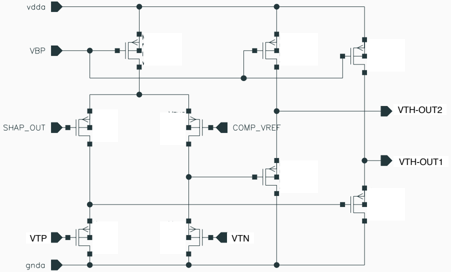


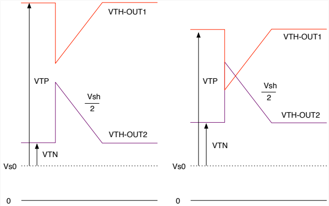


- The filter introduces a gain of 1.5 almost independent of the peaking time

Threshold generator

- A threshold circuit converts the single-ended signal at the output of the shaping section to a differential signal
- A differential threshold voltage is used to avoid possible crosstalk





$$V_{Th-Out1} = V_{Tp} - \frac{V_{Sh}}{2} + V_{S0}$$

$$V_{Th-Out2} = V_{Tn} + \frac{V_{Sh}}{2} + V_{S0}$$

The differential voltage applied at the discriminator input is

$$V_{Th-Out1} - V_{Th-Out2} = V_{TH} - V_{Sh}$$

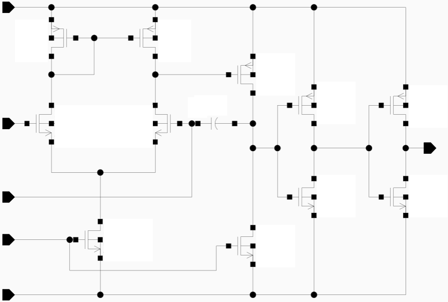
where $V_{TH} = V_{TP} - V_{TN}$ and V_{S0} is a constant DC voltage

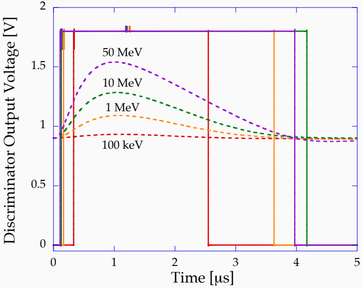
Discriminator

A comparator is used to discriminate the amplified pulse

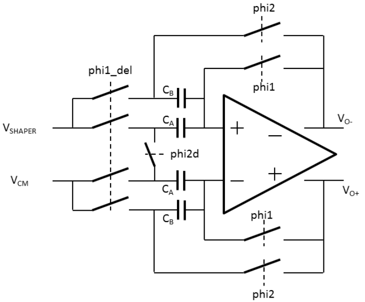
- Two stage operational amplifier
- small positive feedback is applied to produce a regenerative action
- small hysteresis → avoids re-switching induced by noise

The same scheme is used for the HIT and ZC comparator

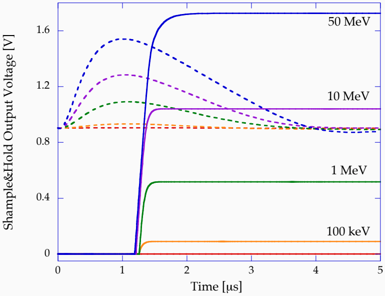


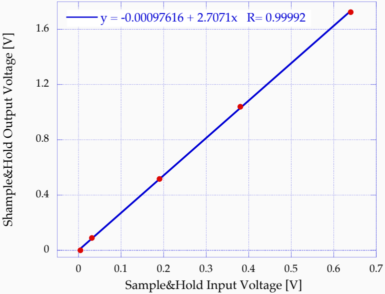


Single-ended to differential Sample & Hold



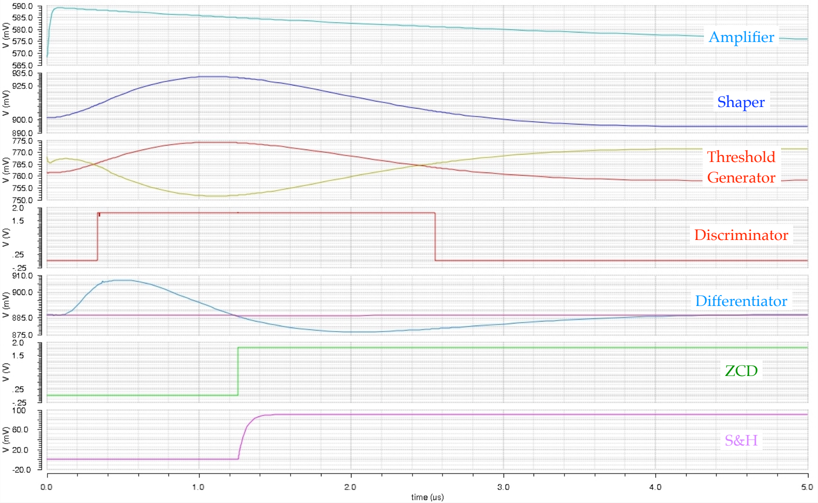
$$V_{O+} - V_{O-} = \left(1 + \frac{C_A}{C_B}\right) \cdot (V_{SHAPER} - V_{CM})$$





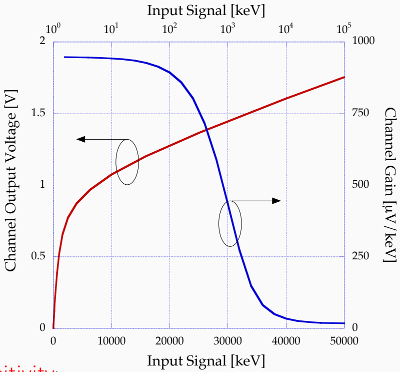
- Provides the differential signal to the 11-bits ADC
- Class AB output stage → rail-to-rail output range
- Introduces an additional 2.7 gain

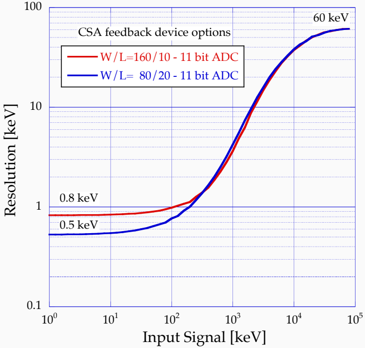
Overall channel time response



100 keV input signal

Overall channel performance



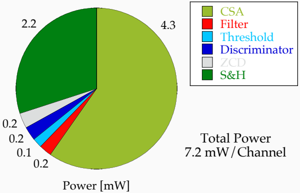


Sensitivity:

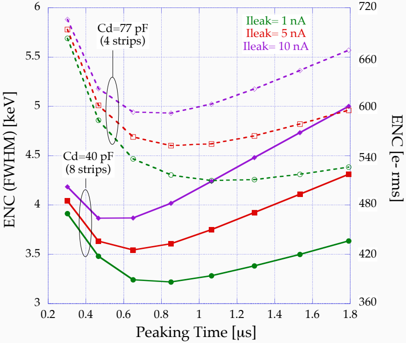
- High gain region: 950 μV/keV
- Low gain region: 15 μV/keV

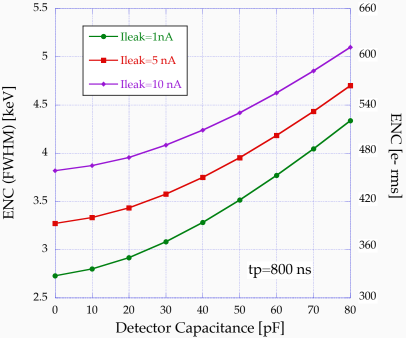
Power consumption:

- Analog channel: 7.2 mW $\times$11520$\approx$83 W
- System: $\approx$150 W



Noise Performance





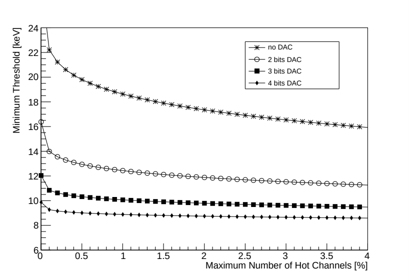
- ENC increases with t_p due to the detector leakage current shot noise
- The required resolution of 4 keV can be obtained only with the 8 strips option
- The minimum is obtained with t_p in the range 0.5-0.8 μs

Minimum threshold setting

The comparator threshold has to satisfy the following condition

$$Q_{th,min} \geq Q_{th,nhr} + Q_{th,disp} = ENC\sqrt{2 \cdot ln\left(\frac{f_0}{f_{n,max}}\right)} + \lambda\left(n_{ch,max}\right) \cdot \frac{\sigma_{V_{Th}}}{G_Q}$$

- f_0 is the noise hit rate at zero threshold
- *ENC* is the equivalent noise charge
- $\sigma_{V_{Th}}$ is the standard deviation of the threshold dispersion
- G_Q is the charge sensitivity
- $n_{ch,max}$ is the maximum acceptable fraction of hot channels



To set the minimum threshold at 10 keV a fine trimming of the threshold with a local 3 or 4-bit DAC will be implemented[1]

[1] L. Ratti, A. Manazza, "Optimum Design of DACs for Threshold Correction in Multichannel

Conclusions

A FE channel for the readout of the Si(Li) detectors of the GAPS experiment has been designed in a 180 nm CMOS technology

A first prototype of the full readout ASIC with 32 channels will be submitted for fabrication by July 2018

The submission of the final ASIC is foreseen by the end of 2018