Technological Challenges and Solutions for the Front-End Electronics of Solid-State Radiation Detectors

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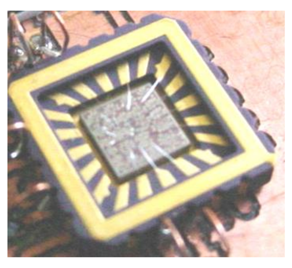
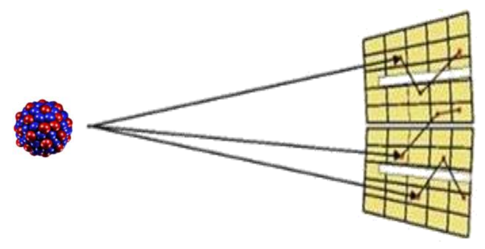
Introduction

Our research group is focused on the development of **low-noise**, **low-power** Front-End Electronics (FEE) solutions for **high resolution nuclear spectroscopy** with solid-state detectors.

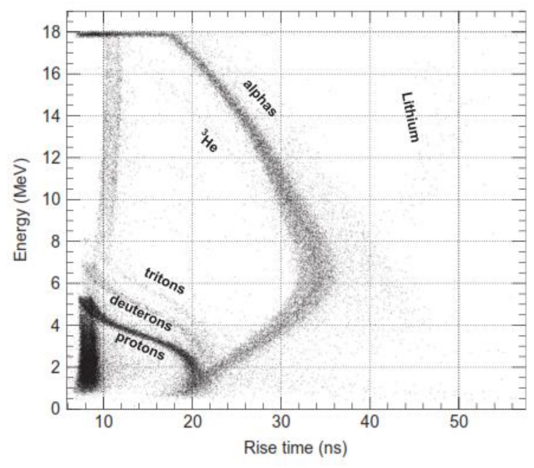


In the readout chain of modern highly-segmented detector arrays integrated solutions are mandatory:

- **Small Dimensions**
- **High radio-purity**
- **Low noise**
- **Low power dissipation**
- **Wide bandwidth**
- **High channel multiplicity**



Gamma –ray tracking



Particle discrimination

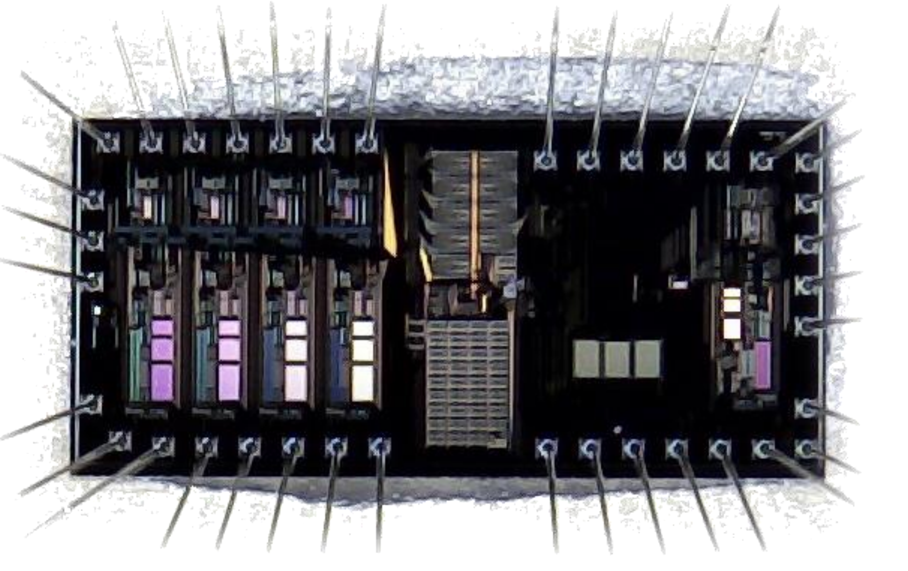
Pulse-shape analysis requires preamplifiers with high bandwidth because the information of interest is carried by the shape of the leading edge of the CSP signals.

Trade-off between power and speed

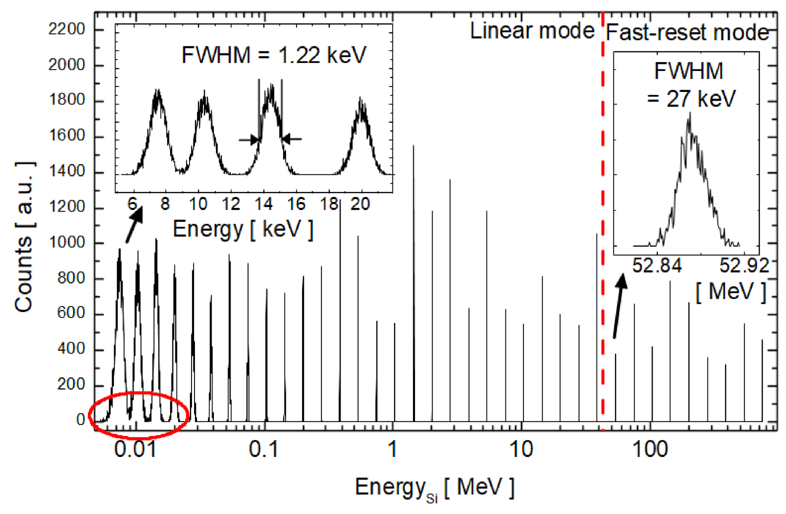
Fast-Reset ASIC preamplifier

ASIC multichannel charge-sensitive preamplifier realized in AMS 350nm technology

- 4 channels for holes and 1 for electron signals.
- Power consumption: 12 mW for each channel.
- Risetime: <10ns with 1 pF feedback capacitance and 4 pF detector capacitance
- Energy resolution evaluated with a dedicated test-bench and a pulser:
  - front channels: 0.75 keV
  - back channel: 1.22 keV
- Dynamic range with feedback capacitance equal to 1 pF:
  - linear mode: 40 MeV in silicon
  - fast-reset mode: ~800 MeV in silicon
- Requires an external feedback resistor for each channel



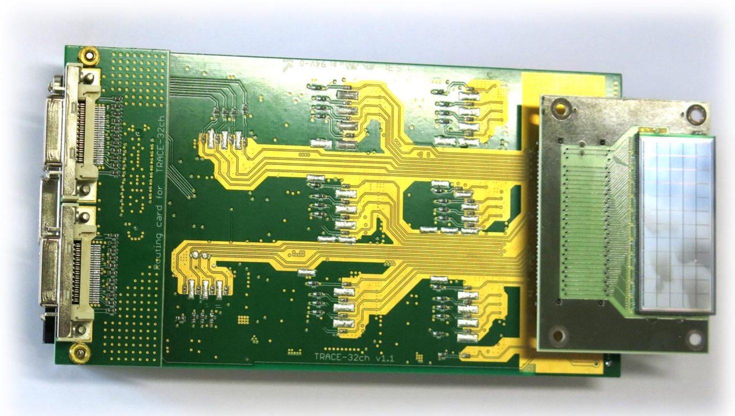
Photograph of the 3.3 mm X 1.5 mm chip wire-bonded in the cavity of a PLCC44 carrier. This image was taken with a magnifying camera connected to a PC through USB communication. The four blocks on the left are the hole channels, the block on the right is the electron one and the structure in the middle is the I2C engine.



The Fast-Reset device extends the dynamic range more one order of magnitude above the natural saturation limit of the preamplifier. On the left a spectrum obtained with a pulser (back channel).

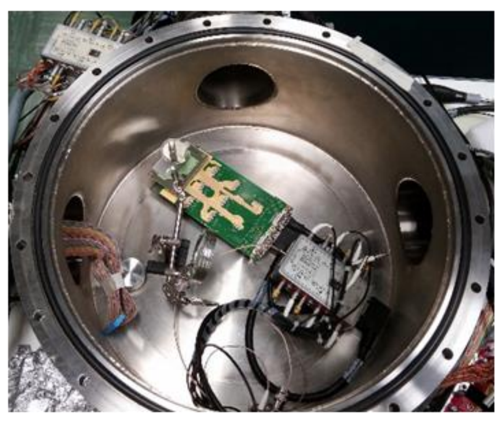
HIGH RESOLUTION SPECTROSCOPY EVEN IF THE PREAMPLIFIER IS IN DEEP SATURATION CONDITION

FEE of the TRACE silicon detector array



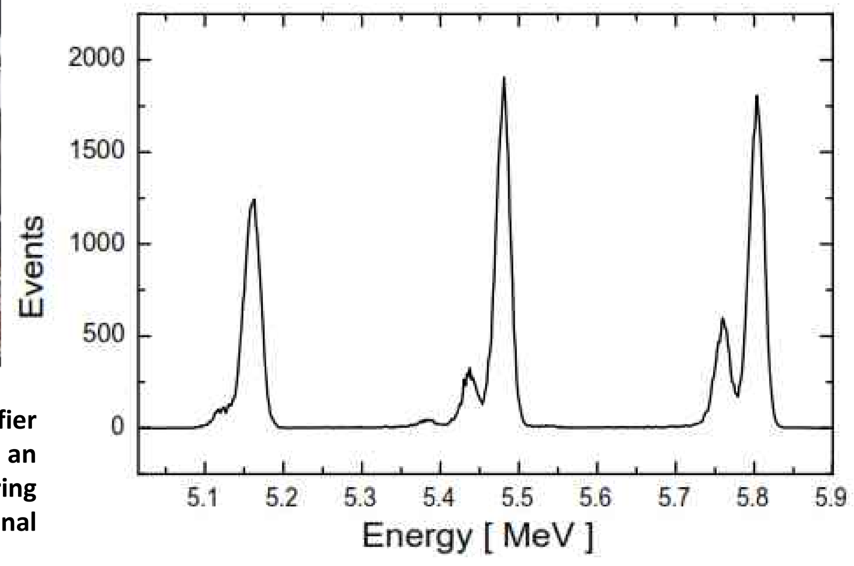
The TRACE32ch v1.1 preamplifier board connected to a TRACE silicon detector prototype.

The TRACE32ch-v1.1 preamplifier board was designed specifically to be compatible with the TRACE detector prototype standards. It is equipped with eight ASIC multi-channel charge-sensitive fast-reset preamplifiers for a total of 32 readout channels. It is realized with a **ROGERS 4003c** laminate, which is characterized by a very low dispersion coefficient and is fully compatible with FR4 process.
The board is powered with a dual ±3.3V power supply and has dedicate active power supply filters for each ASIC preamplifier.
Its main design goals are the minimization of the cross-talk between channels, the minimization of the parasitic capacitances referred to the input of the preamplifiers and a good degree of compactness.

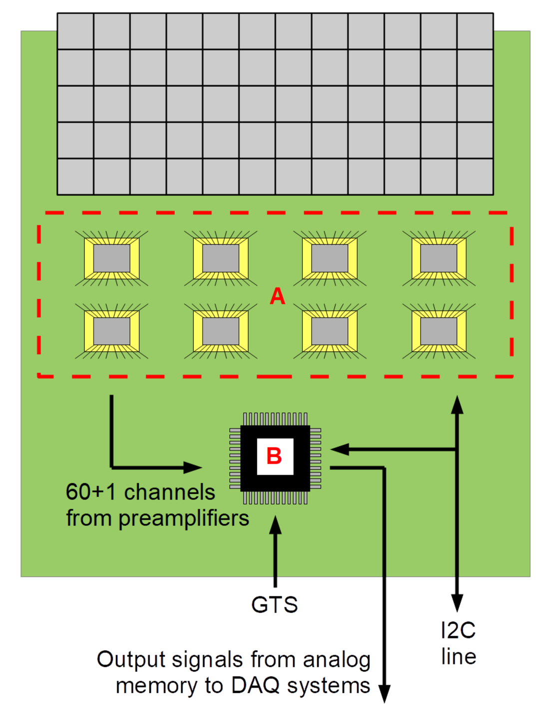


Picture of the TRACE32ch v1.1 preamplifier board inside a vacuum chamber with an ^{241}Am^{244}Cm^{239}Pu triple alpha source during an acquisition at the Legnaro National Laboratories.

21 keV FWHM @ 5.5 MeV



Spectrum of the ^{241}Am^{244}Cm^{239}Pu triple alpha source acquired with a TRACE silicon detector prototype connected to the TRACE32ch v1.1 preamplifier board. The resolution is around 21 keV @ 5.5 MeV.

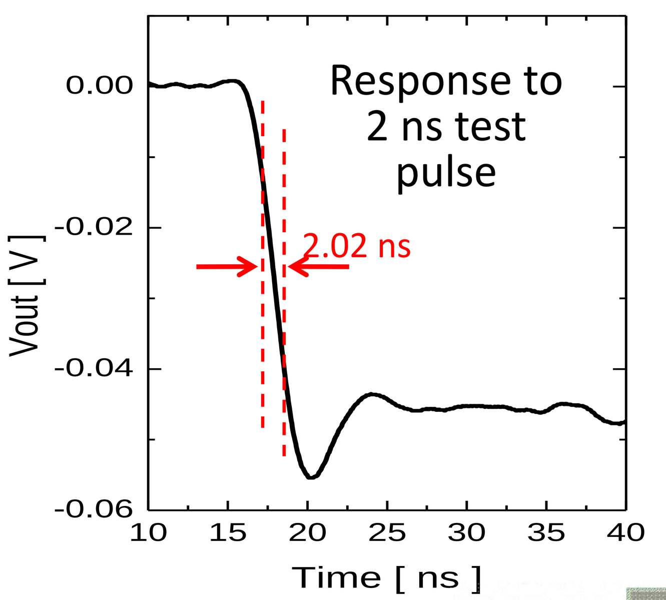


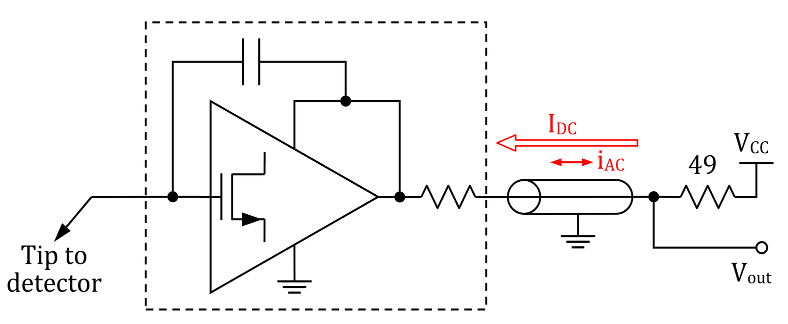
Conceptual diagram of the final version of preamplifier PCB for the TRACE detector array. On the PCB there are eight ASIC preamplifiers for a total of 60 channels (plus 4 spare). The output signals are routed to an analog memory ASIC, that sends them to the DAQ after proper multiplexing.
The ASIC preamplifiers are wire-bonded to the PCB and protected by metal covers soldered on the PCB.

Micro-Probe Preamplifier

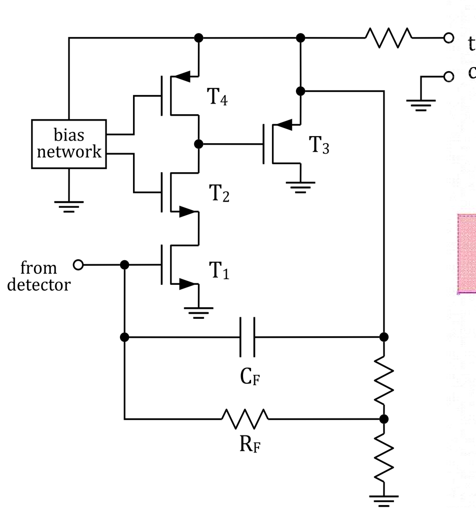
A low-noise wide-bandwidth charge-sensitive microprobe is being developed, able to capture the charge signals of semiconductor detectors. The microprobe works on a single terminated coaxial cable of whatever length, whose quality is key to achieving a good dynamic performance. The cable carries both the power supply (DC signal component) and the event pulses (AC signal component). The microprobe is particularly compact, consisting of a few physical devices, including a GΩ surface-mount resistor. It even requires no power-supply filtering capacitors. We realized an ASIC version of the circuit designed in a 0.35um 5V CMOS technology. Thanks to such a large degree of integration the microprobe can be placed very close to the detector electrode and is particularly light, compact and hence suited for hostile environments and for applications where a high radio-purity of the front-end is required, like in rare-decay research in underground laboratories. The rise time is in the ns range. The energy range is beyond ±20 MeV, and the power consumption is ~35 mW.

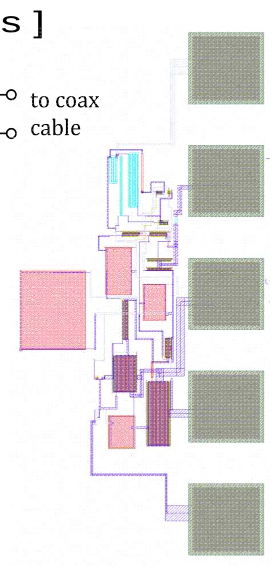
Capturing voltage signals with a probe is a common and simple action that any experimenter executes when using an oscilloscope. We propose here the concept of probing a charge signal. This requires a proper miniaturized circuit to be placed in close proximity to the probe tip, in such a way to minimize the length of the detector/front-end connection wiring. It is in fact well known that the parasitic parameters of such physical connection can substantially spoil the quality of charge measurements. We designed a very peculiar charge-sensitive preamplifier, ultra compact and requiring one shielded cable only for power supply and signal transmission, which is particularly suited for this application. The circuit consists of a few active and passive components and can be realized in the form of an hybrid circuit or an ASIC.





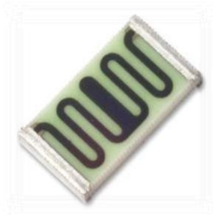
(a) DC coupled to detector



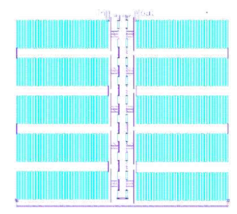


Integrated feedback resistors

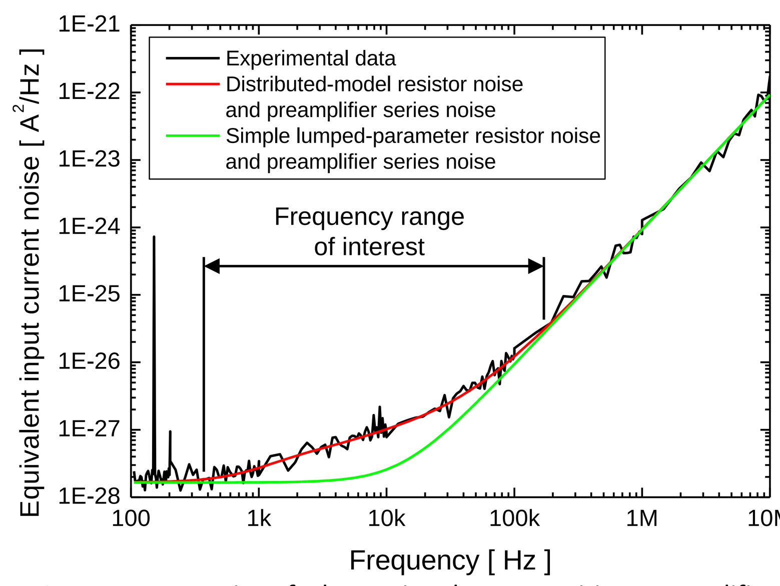
Charge-sensitive preamplifiers (CSP) require high-valued feedback resistors as continuous-time reset devices: higher resistance values correspond to lower current noise and better spectroscopic performances. Designing integrated multi-channel CSP such resistors are generally left as external components or substituted with active transconductors. The former are bulky and not adequate for situations where a high degree of integration is required, the latter generally suffer from linearity and noise problems. A possible solution could be the use of large integrated polysilicon resistors. These ones, however, suffer from a very high distributed capacitive coupling to bulk, which tends to turn such devices into transmission lines. Simple resistor models are no longer adequate to describe both the impedance and the noise generators of such integrated resistors. A closed-form model was developed which describes the current noise produced by a resistance with distributed capacitance. A 100 MΩ integrated polysilicon resistor was realized and the power spectral density of noise produced by this device has been measured connecting it as a feedback resistor to a low-noise charge-sensitive preamplifier.



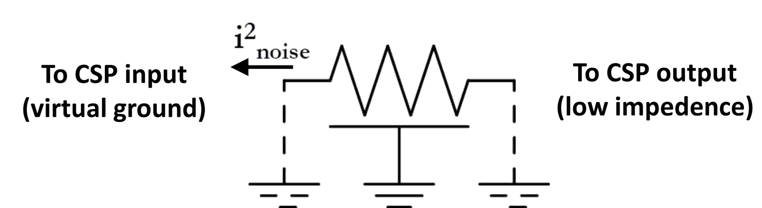
Discrete, thin-film 0603 resistence



Integrated, polysilicon resistor (AMS C35)



Input current noise of a low-noise charge-sensitive preamplifier with an integrated 100M Ω polysilicon resistor connected in parallel to the feedback capacitance.



$$i^2_{noise}=4KT\sqrt{\frac{\pi Cf}{R}}\left[\frac{\sin\left(2\sqrt{\pi RCf}\right)+\sinh\left(2\sqrt{\pi RCf}\right)}{\cosh\left(2\sqrt{\pi RCf}\right)-\cos\left(2\sqrt{\pi RCf}\right)}\right]$$

References

Digital pulse-shape analysis with a TRACE early silicon prototype
Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 764, 11 November 2014, Pages 241-246

Design of an integrated low-noise, low-power charge sensitive preamplifier for γ and particle spectroscopy with solid state detectors
2014 IEEE Nuclear Science Symposium and Medical Imaging Conference, NSS/MIC 2014, 7431043

Study of the effects of parasitic capacitance on large integrated feedback resistors for charge-sensitive preamplifiers
2014 IEEE Nuclear Science Symposium and Medical Imaging Conference, NSS/MIC 2014 7431042