Electronics for cryogenic detectors for particle physics

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Summary

- Preamble;
- The base for the choice of the front-end configuration;
- Frontend for Low impedance Cryogenic Detectors;
- Frontend for Medium and High impedance Cryogenic Detectors.
Preamble: Electronics for cryogenic particle detectors

Take care:
This text colour is for general discussion…

This text colour is related to circuit design, mainly…
Index: The base for the choice of the front-end configuration;

- Preamble;
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- Frontend for Low impedance Cryogenic Detectors;
- Frontend for Medium and High impedance Cryogenic Detectors;
Noise sources vs configuration

Regardless the feedback configuration, the intrinsic noise sources of the amplifier contribute always the same way and the system can be modelled as:

The actors: preamplifier input, detector impedance, parasitic and load impedances as well as noise sources.

Z_B (or R_B): detector impedance;
\( \overline{i_B^2} \): detector noise;
\( i_{\text{sig}} \): detector signal;
C_P: parasitic capacitance;
R_L: biasing resistor;
\( \overline{i_L^2} \): R_L’s parallel noise;
C_A: amplifier input capacitance;
\( \overline{i_A^2} \): amplifier parallel input noise;
\( e_A^2 \): amplifier series input noise.

\[ V_O = \text{Amp accessible inputs} \]
Once the devices technology has been chosen, there is a bit of flexibility in connecting in parallel several preamplifiers or, better, to adjust the area of the transistor at the input of the preamplifier. The configuration is equivalent to this:

\[ \frac{e^2}{N} \approx \frac{e^2_{\text{white}}}{N} + \frac{1}{N} \frac{A_f}{f} \]

The product \( C_A A_f \) is technological and has the size of an energy. With cryogenic detector it is required very small, i.e. corner freq. of a few Hz.
Filtering for S/N optimization:

- It is now a common practice to acquire in continuous mode and then apply a sw trigger followed by a sw matched (optimum) filter.
- hw filtering is only for antialiasing and filters such as Thomson-Bessel or Butterworth are often used.
Front-end optimization

\[
V_O^2(\omega) = \frac{e_A^2}{N} + \frac{(Z_B \| R_L)^2}{1 + \omega^2 (C_P + NC_A)^2 (Z_B \| R_L)^2} \left[ i_B^2 + i_L^2 + Ni_A^2 \right]
\]

\[
V_O(\omega) = \frac{Z_B \| R_L}{1 + j\omega (C_P + NC_A)(Z_B \| R_L)} i_{\text{sig}}(\omega)
\]

\[\rightarrow\] The matched filter weighs are:

\[F_M(\omega) = \frac{V_O^*(\omega)}{V_O^2(\omega)}\]
And the final Signal /Noise, S/N, results in:

$$\frac{S^2}{N^2} = \int \frac{|V_0(\omega)|^2}{V_0^2(\omega)} \, \mathrm{df} = \int \frac{|i_{\text{sig}}(\omega)|^2}{1 + \omega^2 (C_P + N C_A)^2 (Z_B \| R_L)^2} \frac{\bar{e}_A^2}{N} + \bar{i}_B^2 + \bar{i}_L^2 + N \bar{i}_A^2 \, \mathrm{df}$$

\( N \) is proportional to the area of the input transistor.
For large or small values of $N$ the S/N reduces. It exists an optimum for $N$ that depends upon 2 main parameters:

- The impedance given by the parallel of $Z_B \parallel R_L \parallel C_P \parallel C_A$;
- The signal bandwidth.

\[
\frac{S^2}{N^2} = \int \frac{|i_{\text{sig}}(\omega)|^2}{1 + \omega^2 (C_P + NC_A)^2 (Z_B \parallel R_L)^2 \frac{e_A^2}{N} + i_B^2 + i_L^2 + Ni_A^2} \, df
\]
Feedback Topology and Front-end location

The topology of the very front-end can be based on:

- Sensor impedance;
- Signal bandwidth;
- Number of channels;
- Rate of events;
- Front-end Location: room or cold;
- Budget background contribution from the material close to the detector;
- …
Index: Frontend for Low Impedance Cryogenic Detectors. LID

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• Frontend for Medium and High impedance Cryogenic Detectors.
When the sensor is TES, MMC, MKID, the resistance is extremely small and we can approximate to \((Z_L \text{ could come into play in some cases with squid})\): 

\[
V_O = \frac{S^2}{N^2} \approx \frac{\alpha^2 U_{\text{energy}}^2}{\frac{e_A^2}{NZ_B^2} + Ni_B^2}
\]

The series preamplifier noise dominates and an advantage is obtained with large area transistors.
In this case, the limit in the use of a cold stage is the power necessary to operate an amplifier with a large input transistor. Power handling is less critical when the amplifier is room temperature operated ...
\[
\left( i_{\text{sig}}(\omega) = \alpha F(\omega) U_{\text{energy}} \right)
\]

\[
\frac{S^2}{N^2} = \int \frac{\alpha^2 |F(\omega)|^2 U_{\text{energy}}^2}{\frac{e_A^2}{NZ_B^2} + N_i B^2} \, df
\]

…anyway… there is a quite practical lower limit in the obtainable noise that is around 0.1 - 0.5 nV/√Hz at low frequency at room temperature: the setups work practically always unmatched.
Signals can be amplified by the SQUID, “the superconductor transformer”:

from Kent Irwin (NIST)
There are 2 classes of squids:

- The dc squids are readout by room temperature preamplifiers (and assisted by transformers in some cases);
- The rf squids are readout by cryogenic amplifiers.
dc squid (characterized by 2 Josephson junctions) are DC biased and are operated in closed loop with the so called FLL, Flux Locked Loop, a signal modulated sinusoid, $f_{\text{ref}}$. 
Preamplifier noise is not modulated (shifted) and its contribution is that around \( f_{\text{ref}} \); therefore, the effect of its low-frequency noise, if present, is mitigated:
The frequency at which the FLL operates is relatively small, from hundreds of KHz to few MHz and the front-end noise must be white: a room temperature operated front-end is almost always adopted.

Front-end series noise is sub-nV/√Hz, from 0.1 nV/√Hz to 1 nV/√Hz. Parallel noise ranges from negligible values, for JFET input stage, to a few pA/√Hz, bipolar input stage, but has marginal effects.
CRESST studies the Dark matter with an array of large mass CaWO₄ (Calcium Tungsten Oxide) scintillating crystals sensed by TES.

CRESST runs are very long with a stringent request on stability. To maintain steady the energy conversion gain, each detector of the array is equipped with a heater to which a compensating power and periodic pulses are sent.
The readout is with dc squid + transformer at cold (8:1) + transformer at room T (3:1) + room T amplifier (JFET input, 2SK147, with a noise floor of 0.7 nV/√Hz).

They claim a current noise close to that of the junction, 1.2 pA/√Hz, thanks to the great mitigation of the amplifier noise which comes from the support of the 2 transformers.
An rf squid (characterized by 1 Josephson junction) needs: the so-called tank or tuned circuit, L and C (*large inductance and small capacitance are necessary for obtaining large signal*), the transmission line to the front-end and the radio frequency generator.

At 30 MHz, for example, the wavelength is a few meters, no problem with front-ends at room temperature, at 1 GHz the wavelength is a few centimeters: a cryogenic stage is needed to keep the line shorter than half the wavelength.
For resonating frequencies > GHz, squid and tank circuit are in a single chip.
The tank circuit and the squid are side by side on the same chip. Changing the tuned frequency from chip to chip a single line can be exploited by sending a superimposition of tones to an array. The same single line can be used for readout, too, and de-multiplexing is made by sw. Each signal modulates the own tone.
A sensor that can be multiplexed without the need of a squid is the Microwave Kinetic Inductance Detector, MKID, a superconducting stub (its signals are larger than those of TES): a Temperature change induces a change in both the amplitude and phase of the applied tone. MKID can be multiplexed, too, with multi-tone biasing.
Both rf squid and MKID arrays are multiplexed through the use of a microwave cryogenic Low Noise Amplifier, LNA:

Most of the times the LNA limits the achievable resolution. Nevertheless it does a great job working at and below 4.2 K.
Active devices able to work around 4 K and below are those manufactured in III – V compound such as HEMT (InP, InGaAs, …), MESFET in GaAs and AlGaAs and HBT in SiGe and Si-MOS.
The HEMT is a "sandwich" between 2 semiconductors with a bandgap larger than that of the un-doped 2D sheet placed in between.

Electrons driven in the sheet from the applied gate voltage are quantized and move within it at very high speed at any temperature as there is no scattering.
The SiGe HBT has the p-base of smaller bandgap with respect to the emitter as a small percentage of Ge atoms are introduced to modify its nature.

This metallurgical modification of the base allows the diffusion of a high level of dopant concentration, which improves the speed, the gain and also the gain at low temperature (not verified for all...): 

\[
h_{FE} \approx \frac{I_C}{I_B} \approx \frac{N_e}{P_b} \frac{n_{ib}^2}{n_{ie}^2} = \frac{N_e}{P_b} \exp \left( \frac{\Delta E_C}{K_B T} \right)
\]
Design and implementation of microwave amplifiers must follow well-defined rules about both the geometry of all the connections for obtaining proper terminations and the stability of the transistors that are otherwise prone to oscillate at high frequency.

The amplifier are multistage common-source / common-emitter, open loop operated.

IEEE Tran. on Micr. Th. and Tech, 2013, 61 3285
A question would be: why do not use microwave amplifiers for the readout of dc squids, or, in general, not modulated detectors?

The III-V compounds are heterostructures obtained by joining dissimilar materials together. At their interfaces defects sites can form which act as capture centres for charge carriers. $1/f$ noise adds if the duration of the signal is comparable to that of the trapping time constant.

\[ I = e(N_{TOT} - 1) \mu \frac{V_{BIAS}}{L^2} \]

\[ \Delta t = \tau_0 e^{-t/\tau} \]
Generation-recombination of carriers at trapping centres gives low-frequency noise that worsens the S/N for dc squids, for instance, since it could extend to large frequencies.
Index: Frontend for Medium and High impedance Cryogenic Detectors, the medium impedance case

- Preamble;
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- Frontend for Low impedance Cryogenic Detectors;
- Frontend for Medium and High impedance Cryogenic Detectors:
  - Medium impedance detectors
Front-end optimization with medium to large impedance detectors

The medium to large impedance detectors include thermistors as thermal sensors, ionization detectors, photo-detectors,…
For the case of thermistors, their impedance values extend from a few hundred $\text{K}\Omega$ to hundreds $\text{M}\Omega$, while the signals rise times extend from a few $\mu$s to tens of ms, or the signal bandwidth from about one hundred KHz down to tens of Hz. Also in these cases the front-end works most of cases unmatched and the S/N must be optimized on a case-by-case basis.
Front-end optimization with medium impedance detectors

Small crystals are relatively fast and thermistor impedance must be maintained small to minimize signal integration from the parasitic and amplifier input capacitances. The range being between hundreds $\text{K}\Omega$ to few tens of $\text{M}\Omega$.

Total capacitance should be less than 10 to 20 $\text{pF}$ to avoid signal integration or amplifier series noise early contribution.
Front-end optimization with medium impedance detectors 2

Small capacitances values are first of all obtained with small area transistors:

\[ i_{\text{sig}}(\omega) = \alpha F(\omega) U_{\text{energy}} \]

\[
\frac{S^2}{N^2} = \int \frac{\alpha^2 |F(\omega)|^2 U_{\text{energy}}^2 Z_B^2}{e_A^2 + i_B^2 Z_B^2 + i_L^2 Z_B^2} \, df
\]

\[(N=1)\]

... and the constraints are satisfied if the first amplifying stage is cooled....
Front-end optimization with medium impedance detectors

According to Dan McCammon the first use of a cryogenic setup was with the IRAS (NASA) infrared satellite. The readout was for photodetectors.

A pair of source follower Si-JFET were put at cold and a second warm stage implemented a trans-impedance feedback with a feedback resistor of 20 GΩ (Eltec model 102 metal film) held at 2 K.

One of the first subsequent applications on cold readout is this. A few details are interesting.
Front-end optimization with medium impedance detectors 5

The setup minimizes the stray capacitance by locating the load resistor at the same detector temperature and closed to it. To work at low temperature the load resistor must be made metal film for stability and its value cannot be very large.
Front-end optimization with medium impedance detectors

This setup was used for readout detector arrays with average resolution better than 5 eV\textsubscript{FWHM} (see ref below).


Front-end optimization with medium impedance detectors

The detector signal is slow and III – V compound devices and Si-MOS have low-frequency noise which can be a limit, Si-JFET transistors are more often used operated at their optimum temperature between 120 K – 150 K. They are normally configured in common-source, unity gain, (to avoid long feedback path from room temperature to inside the fridge) with their source resistor at room temperature to minimize power dissipation at cold.

HINT: the value of the biasing resistor connected to the source terminal must be large enough otherwise its thermal noise is not negligible.
Front-end optimization with medium impedance detectors

The connection between the JFET and the detector must be short and the link must assure a negligible heat injection coming from the big thermal gradient. The JFETs are in a box, suspended with Kevlar cables for example, to minimize thermal conductance toward the bath and create their working environment. Often a heater is put close to them to give an initial increase of temperature, then their dissipation is able to maintain the operating temperature. The connection to the detector must also minimize microphonic effects.
The EDELWEISS experiment attempted to mitigate the low-frequency noise in series to the JFET gate with an AC bias: the detector signal modulates the AC bias while the noise in series does not, so that its contribution is that at the modulation frequency, where the contribution of the low-frequency noise is mitigated.

To maintain symmetry the bias is differential given through 2 small capacitances: the AC bias is triangular and integrated across the capacitances in order to become a square signal.
Front-end optimization with medium impedance detectors

Noise result is quite good. The frequency of the bias is between 500 Hz and 1 KHz (I do not know the actual value for this plot).

The mitigation of the low frequency noise seems efficient with the spectrum of the signal superimposed for comparison.

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Residual low frequency noise could be from detector friction and wire vibration, namely, parallel noise, the residual effect limiting the final resolution in several applications.
Index: Frontend for Medium and High impedance Cryogenic Detectors, the high impedance case

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Front-end optimization with high impedance detectors 1

\( S^2 = \frac{\alpha^2 |F(\omega)|^2 U_{\text{energy}}^2}{\int \omega^2 (C_P + N C_A)^2 \frac{e_A^2}{N} + i_B^2 + i_L^2 + Ni_A^2} \) \( \, df \)

We speak about thermistor impedances from tens of MΩ above hundred MΩ.
Front-end optimization with high impedance detectors 2

\[ (i_{\text{sig}}(\omega) = \alpha F(\omega) U_{\text{energy}} ) \]

\[ \frac{S^2}{N^2} = \int \frac{\alpha^2 |F(\omega)|^2 U_{\text{energy}}^2}{\omega^2 (C_P + N C_A)^2 \frac{e_A^2}{N} + i_B^2 + i_L^2 + N i_A^2} \, df \]

In these cases it is almost impossible to try to match the front-end to the detector. Parallel noise could dominate. Signal bandwidth and parasitic capacitance are very important for defining which parameters to optimize for the front-end.
Front-end optimization with high impedance detectors 3

The reasons for large impedances and large capacitances are several:

- A very large dynamic range of signals, typical in neutrino physics studies, which extends from a few KeV up to a few tens of MeV asks for thermistors that can handle large signals;
- Low background, if required, finds benefit if the front-end is operated far from the detector;
- The detector is composed of a large-mass crystal to which the thermistor is glued: to reduce its thermal capacity to a minimum, the temperature must be as small as possible, less than 10 mK;
- Crystals are large and several: heat injection must be minimized;
- ...
Front-end optimization with high impedance detectors

Actual choice for front-end location: room temperature, very safe for background.

Possible front-end location, mixing chamber and above the lead shield.

CUORE is an example of a rigorous low background requirement. It is composed of 1000 TeO$_2$ crystals having each a mass of 750 g. Thermal Sensors are NTD thermistors having large resistance values.

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Front-end optimization with high impedance detectors

To satisfy background everything in CUORE is macroscopic:

- Signal BW is less than 5 Hz;
- Thermistor impedances are a few hundreds MΩ on average;
- Load resistors at room Temperature are 60 GΩ to mitigate their parallel noise;
- The parasitic input capacitance is about 500 pF;
- Very tight stability of the front-end baseline.
Front-end optimization with high impedance detectors

Parallel noise from load resistors is the dominant effect:

\[
\frac{S^2}{N^2} \approx \int \frac{\alpha^2 U_{\text{energy}}^2}{i_B^2 + i_L^2 + N_i^2} \, df
\]

\[
\sqrt{i_L^2} = 0.5 \text{ fA/\sqrt{Hz}}
\]

Fridge

T=10 mK

T=300 K
Front-end optimization with high impedance detectors 7

An example of preamplifier operated at room temperature is this: the configuration is differential with only 2 JFETs, J1 and J2, at the input.

Circuit is designed for having a large open loop gain (extensive use of OpAmp), to obtain a very precise large closed loop gain, and to constrain the JFETs to work at constant current and constant voltage.

The circuit is thermally compensated with a drift smaller than 1 μV/°C.
Front-end optimization with ionization detectors 8

Veljko Radeka mail: “In 1968 (paper you requested) I described in some detail a charge amplifier for germanium detectors, with a JFET at low temperature, slide 3;;;”

Here is the first charge sensitive preamplifier based on the use of transistors. It was 1968.

This preamplifier is, at the same time, the first example of cryogenic front end. It was intended for the readout of Ge(Li) detectors, forced to stay at cold during their whole operating life.
Front-end optimization with ionization detectors 9

GERDA is a detector composed, in its first phase, of about 60 enriched Ge detectors readout with a cold charge sensitive preamplifier having background constraints.

https://www.mpi-hd.mpg.de/gerda/

Front-end optimization with ionization detectors 10

The preamplifier has a Si JFET input transistor and the operating temperature is LAr, 87 K. A few tens of cm is its distance from the detector to minimize its background.

Front-end detector background safe distance.

Ionization detectors (CDMS exp.) working at deep cryogenic temperatures are readout with a charge sensitive preamplifier, too. The only concern is that the distance of the first stage of the front-end cannot be too close to the detector for avoiding heat injection: the input capacitance is large.

The detector has a very large impedance and microphonism is a concern. In this solution the JFET is biased such a way its gate is close to zero voltage in order to minimize charge injection from parasitic capacitance.

Feedback and bias resistors are 40 MΩ, but located at 10 mK.
EDELWEISS uses a different approach. Bias and feedback resistors are replaced with relays which are closed from time to time, tens of seconds rate, to regulate both the detector bias and the gate of the JFET.

The preamplifier is operated in voltage sensitive configuration, namely, the JFET is a follower, and the charge signal is integrated across the detector, stray and JFET capacitance, about 250 pF.
The residual frequency dependent noise is mainly (I suppose…) microphonism and the resolution they claim is better than $700\text{ eV}_{\text{FWHM}}$. 

$$i_{\text{sig}}(t) = \alpha Q \delta(t)$$
Silicon Photomultipliers, SiPM, have become familiar at LAr temperature in neutrino experiments such as DarkSide and DUNE.

In these experiments they are exploited to measure the single photon emitted by interaction of the neutrino with the Lar.
In DUNE an hybrid cold preamplifier is used that has a commercial SiGe at its input and a standard bipolar OA in the second stage. Series obtained noise is a compromised with the requirement in power dissipation. 1/f noise is adequate for these detectors.

\[ C_A f = 4 \times 10^{-27} \text{ J} \]
CONCLUSIONS

Thank you and sorry for any possible lack ...
SPARE SLIDES
SuperCDMS studies the Dark matter, too, again TES for the phonon channel. The readout is with dc squid (a series of 100 squids to mitigate preamplifier noise contribution) + room temperature amplifier.

They claim a current noise close to about 10 pA/√Hz, with 1.2 nV /√Hz being the series noise of the preamplifier.
Frontend for LID: dc squid 2

Here other examples of room temperature operated amplifiers: one with bipolar input (0.35 nV/√Hz)…

…and an other with JFET input transistors (1 nV/√Hz @300 K, 0.6 nV/√Hz @ -100 °C).

Proc. SPIE 9904, doi: 10.1117/12.2232859

IFN3600 has about 600 pF input capacitance
Here a preamplifier operating at both room temperature and 125 K with a performance of about 5 \( \mu \Phi_0 / \sqrt{\text{Hz}} \).
Frontend for LID: ac squid 4

Here arrays of TES sensors are coupled to arrays of rf squids …
Flux ramp modulation is a way to multiplex TES /rf-squid arrays in open loop condition by coupling each channel to a different stub.
A monolithic SiGe amplifier composed with the cascade of 2 common-emitter stages. The DC bias is made with 2 current mirrors which are AC-decoupled with inductances.
Cryogenic microwave amplifiers are able to show less than 100 pV/\sqrt{Hz} at the centre bandwidth, around a few GHz. This correspond to about 2 K noise temperature, which for an rf squid transfer coefficient of 100 µV/Φ₀ gives about 1 µΦ₀/\sqrt{Hz}, with the noise floor of the rf squid that could be 5 – 10 times better.
A cryogenic family of low 1/f HEMTs was developed at CNRS/C2N, France.

Best performance is obtained at 4.2 K, with a 250 pF input capacitance HEMT.

Noise is around 5 nV/\sqrt{Hz} @ 1 Hz and about 0.2 nV/\sqrt{Hz} is the floor @ 4.2 K. The factor of merit $C_A A_f$ for this HEMT family is $6.3 \times 10^{-27}$ J, a rather good feature.

The HEMT is capable of operating up to 1.5 GHz, although optimized for low-frequency operation.
Nevertheless... low frequency noise is not an intrinsic noise source and technological processes could be optimized for low noise.

With this cryogenic amplifier in SiGe the noise was very low. Authors claimed a level below $8 \times 10^{-8} \Phi_{0}/\sqrt{\text{Hz}}$! The SiGe adopted was the NESG3031.

A differential input cascoded pair, buffered at the output and operated in open loop.

Cryogenics 57 (2013) 129–133