Electronics for double beta decay high-impedance bolometers

Paolo Carniti

Claudio Gotti

Gianluigi Pessina

INFN e Università di Milano Bicocca, IT

INFN Milano-Bicocca

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Preamble about the energy resolution of our large mass detectors 1

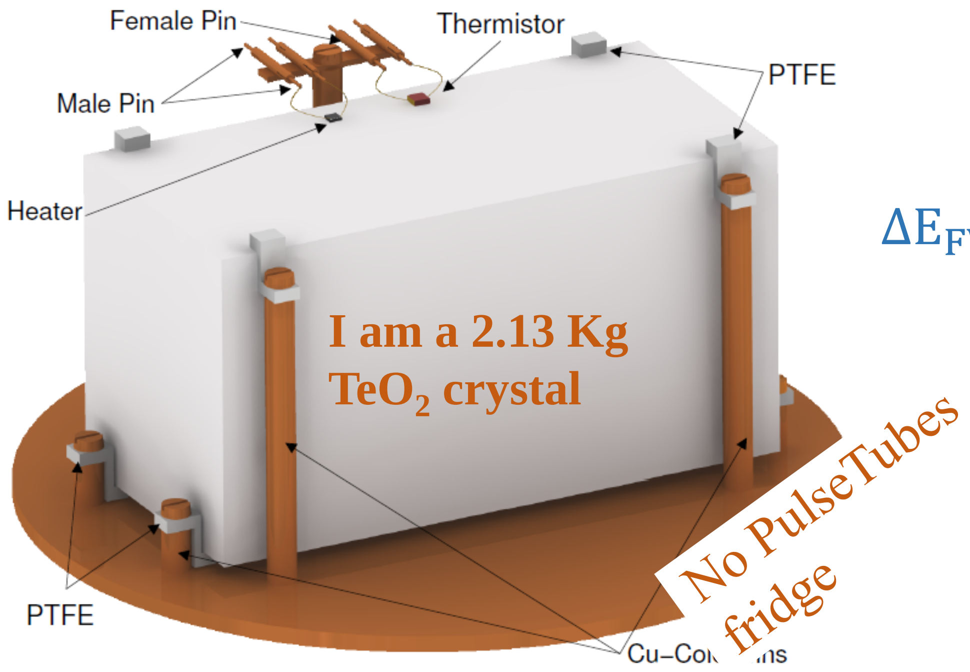


Figure 1. The detector setup. The crystal is held by means of eight S-shaped PTFE supports mounted on Cu columns. The thermistors and the heater contacts are realized through crimped Cu pipes glued on a Cu plate. The entire setup is enclosed inside a Cu shield kept at base temperature.

Table 2. FWHM energy resolutions (in keV) evaluated from the calibration spectrum o resolution is evaluated on the right (Gaussian) tail of the peak (see figure 4).

145 keV	570 keV	1461 keV	2615 keV	5407 keV
3.9±.3	4.7±.4	6.6±.3	7.8±.7	7.8±.2 †

Debye T:
Si 640 K
Ge 370 K
TeO_2 232 K

2012 JINST 7 P01020

Large mass detectors are not conventional and it is useful to consider a normalization of their performance in term of more conventional detectors

$$\Delta E_{FWHM\_TeO_2} \div \alpha_{NTD} C_H \sqrt{Noise} \div \alpha_{NTD} \frac{3M_{TeO_2}}{160}\left(\frac{T}{T_{D\_TeO_2}}\right)^3 \sqrt{Noise}$$

(Supposing the Noise limited by the environment and α the thermistor response)

$$160\frac{T^3_{D\_TeO_2}}{3M_{TeO_2}}\Delta E_{FWHM\_TeO_2} \div \alpha_{NTD} T^3 \sqrt{Noise}$$

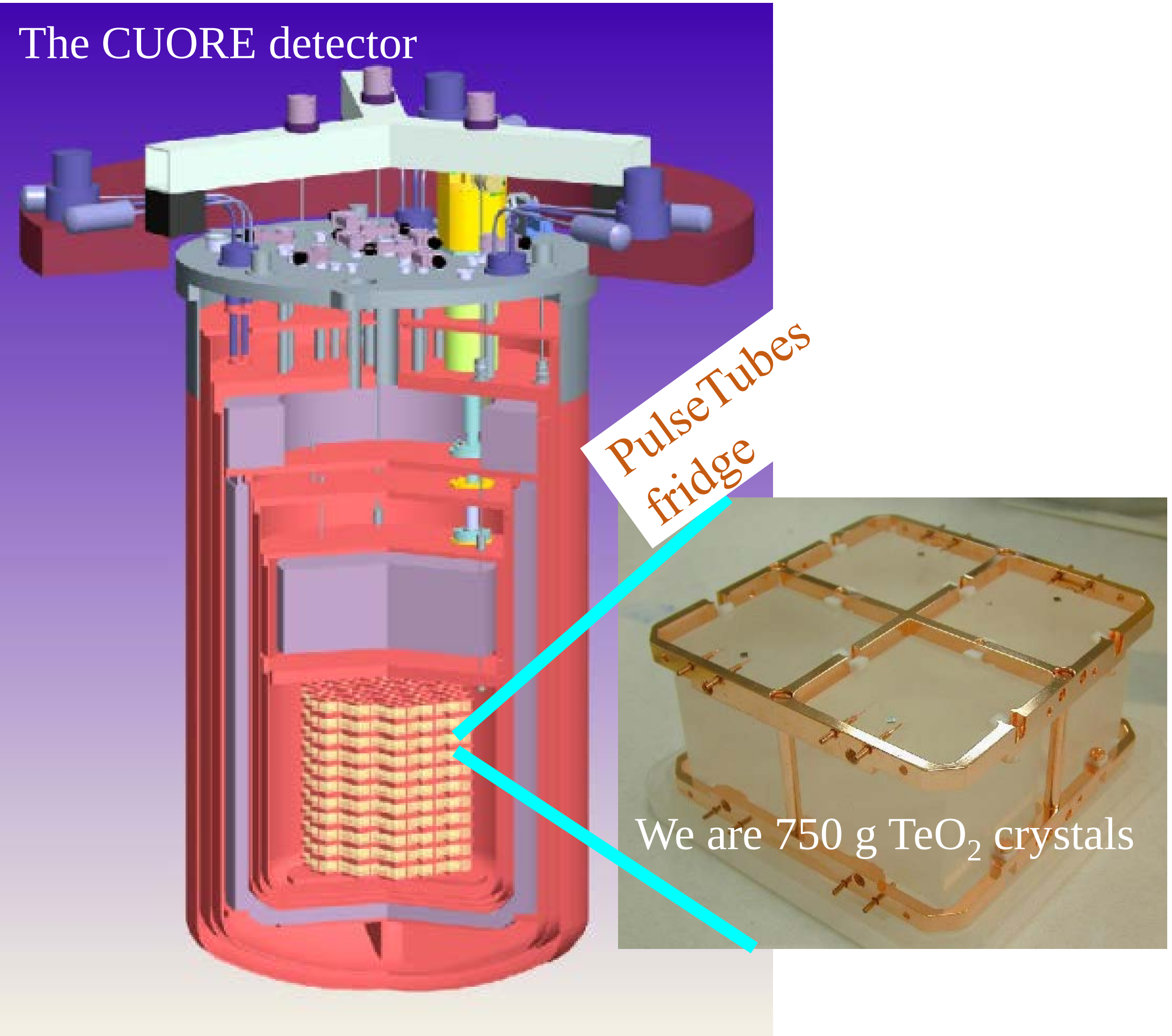
So that a Ge held at the same temperature and noise level will get a resolution:

$$\Delta E_{FWHM\_Ge} = \frac{M_{Ge}}{73}\frac{160}{3M_{TeO_2}}\frac{T^3_{D\_TeO_2}}{T^3_{D\_Ge}}\Delta E_{FWHM\_TeO_2}$$

$\Delta E_{FWHM\_TeO_2}$ =3.9 keV_{FWHM} ⇒ M_{Ge}=25 g → 8.3 eV_{FWHM}; M_{Ge}=50 g → 17 eV_{FWHM}

PhysRevD.99.082003: 33g Ge 41 eV_{FWHM}

Preamble about the energy resolution of our large mass detectors 2



In CUORE the average resolution of the baseline is about 2.5 keV_{FWHM} (while at about 3 MeV it worsens to about 8 keV_{FWHM}).
Than, again in term of a Ge crystal equivalent:

$\Delta E_{FWHM\_TeO_2} = 2.5\ keV_{FWHM}$ ⇒

- $M_{Ge} = 25$ g → 15 eV_{FWHM}
- $M_{Ge} = 50$ g → 30 eV_{FWHM}

Again the performances in term of a Ge equivalent are comparable.

PhysRevD.99.082003: 33g Ge 41 eV_{FWHM}

http://inspirehep.net/record/1763941/

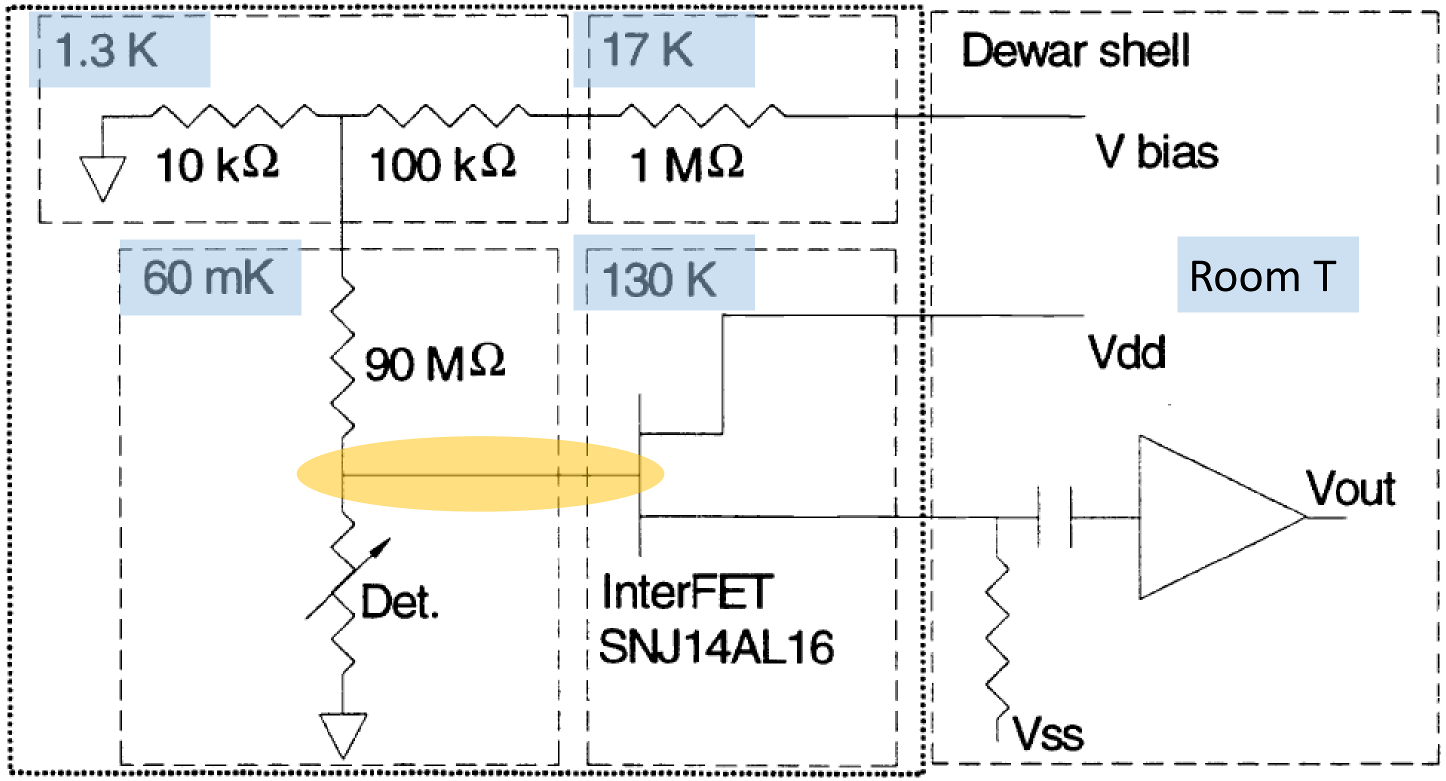
PHYSICAL REVIEW LETTERS 120, 132501 (2018)

Reading approaches: general

Limiting the sensor to thermistors, that allow to cover an extensive range of energies, the possible readout solution can be several:

- ✓ Cold front-end with DC bias;
- ✓ Cold front-end with AC bias;
- ✓ Room temperature operated front-end with DC bias;
- ✓ Room temperature operated front-end with AC bias.

Cold front-end, FE, DC bias

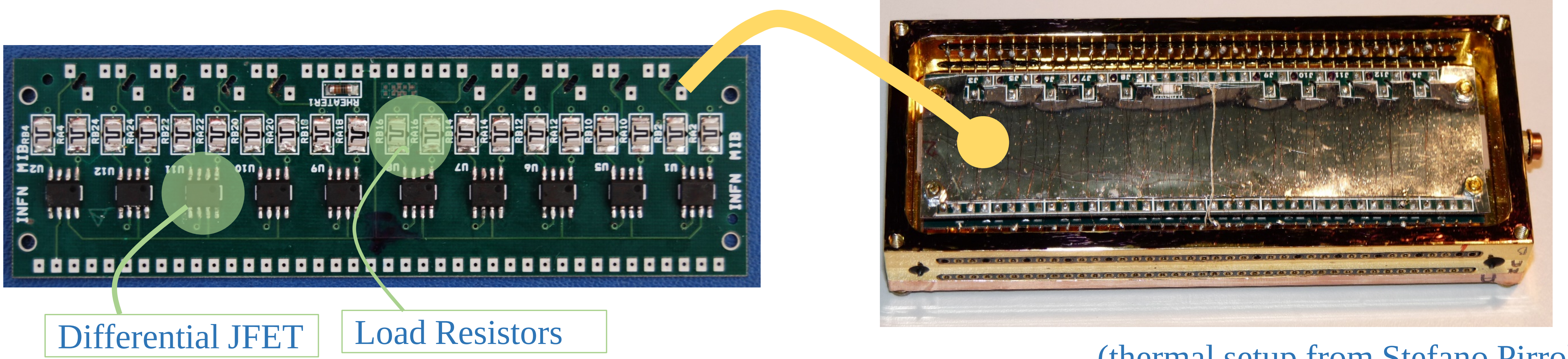


Classical cold FE is done with a source follower Si JFET, a JFET working in unity gain configuration (now also with special HEMT developed at CNRS/C2N).

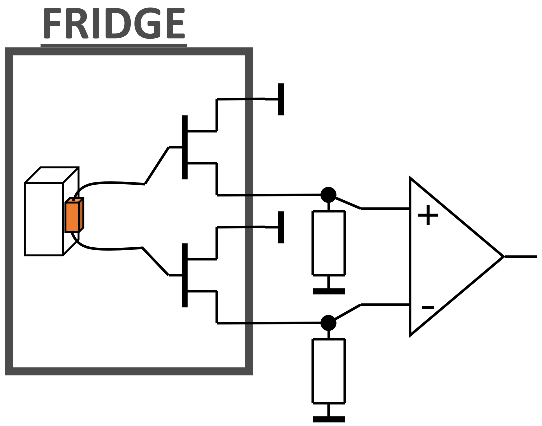
This first application was with micro-bolometers.

Proc. SPIE 3765, EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy X, (22 October 1999); doi: 10.1117/12.366556

Prototype cold FE for CUORE 1



(thermal setup from Stefano Pirro)

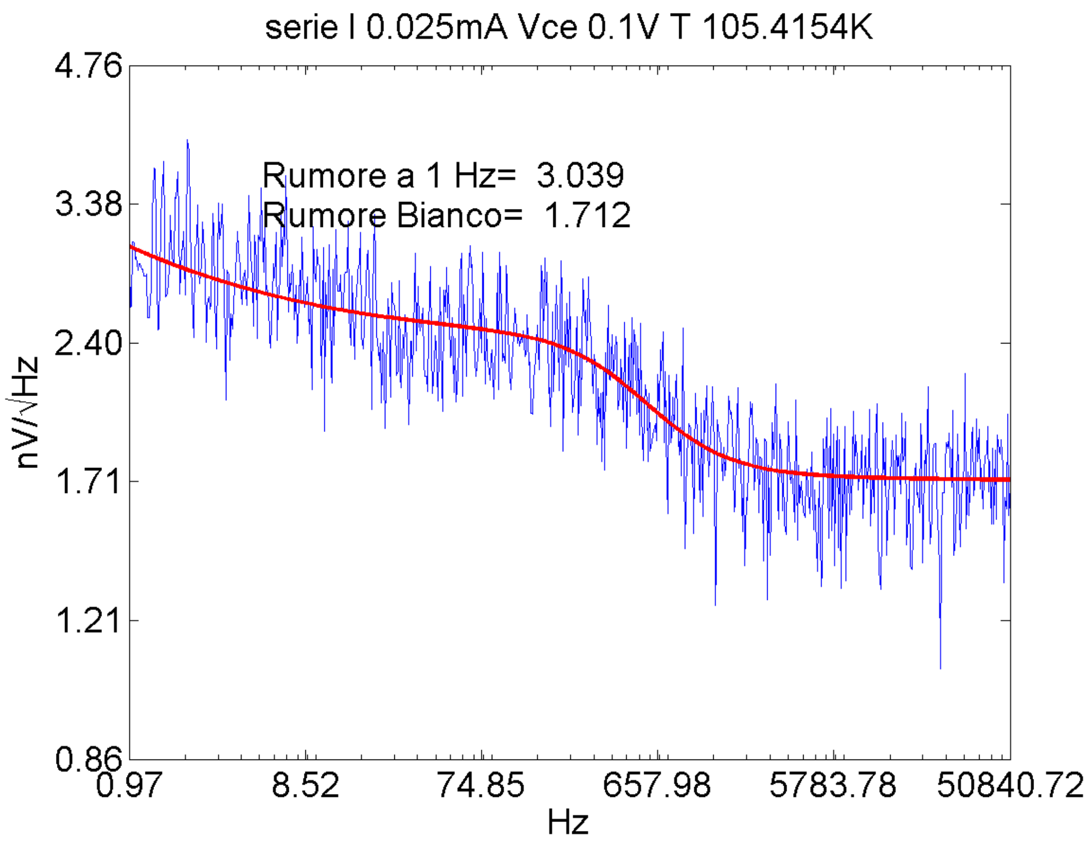


This is a ten channels board, each channel in differential configuration. This layout is still operating in hall C.

Based on our experience we studied a solution for CUORE able to work at the 4.2 K stage (where the power dissipation limited to less than 100 mW)...

NIMA, 559, 828, 2006

Prototype cold FE for CUORE 2



A study of a solution for a 1000 channels was done, aimed at working at a negligible dissipation.

Optimizing power dissipation we found a compromise with noise at about 5 μW/ch, or 15 mW for the readout of 3000 chs.

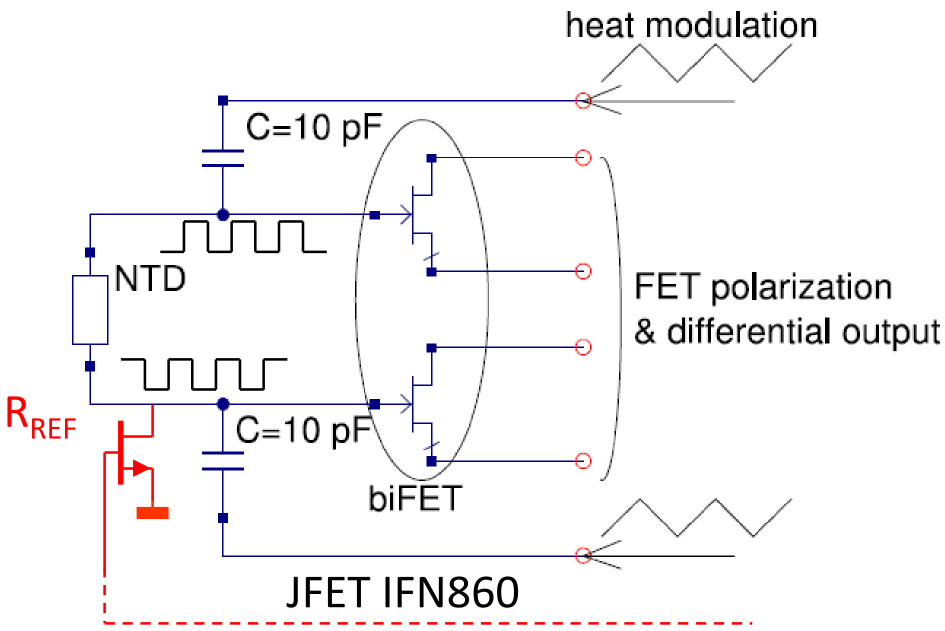
Considering the power budget of about 0.1 W at 4.2 K there is margin to increases a bit the power and lowering the noise for the LD channels.

Anyway, comparing the performances with the warm FE the adoption was for the latter…

IEEE TNS, 51, 2975, 2004

NIMA, 517, 313, 2004

Cold FE + AC bias 1



2017 JINST 12 P08010

EDELWEISS uses cold electronics with AC bias with very good results.

Advantages:

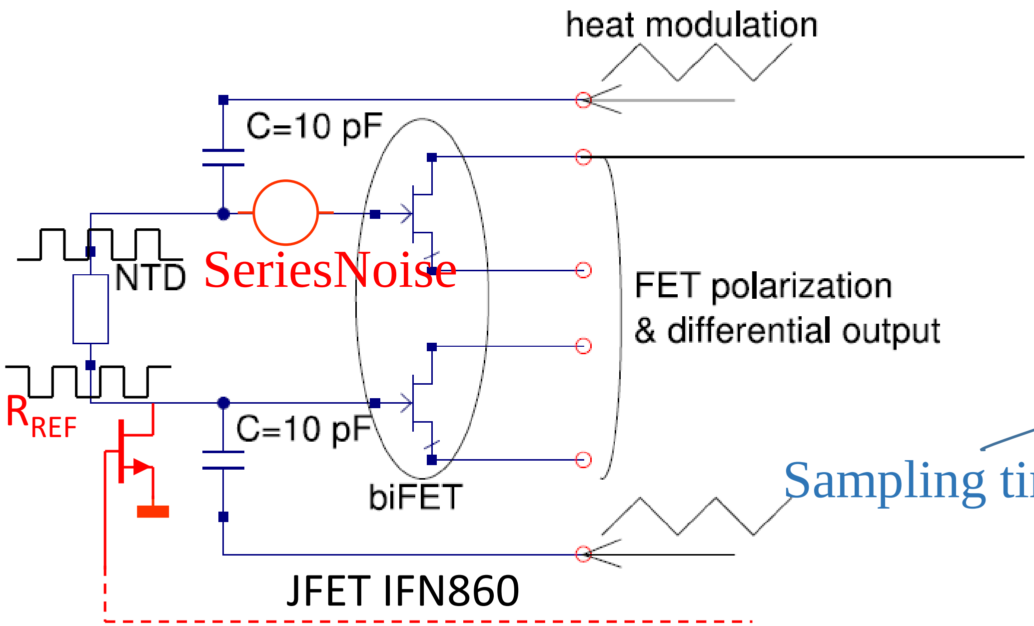
- 1/f noise of the input JFET is attenuated (the output is read syncrously with the square wave, while the series noise at the reading freqeuncy does not modulate the squae wave):
- Parallel noise of the load resistors is not present as the bias is given with capacitors and the referne resistor is very large.

(my) warnings:

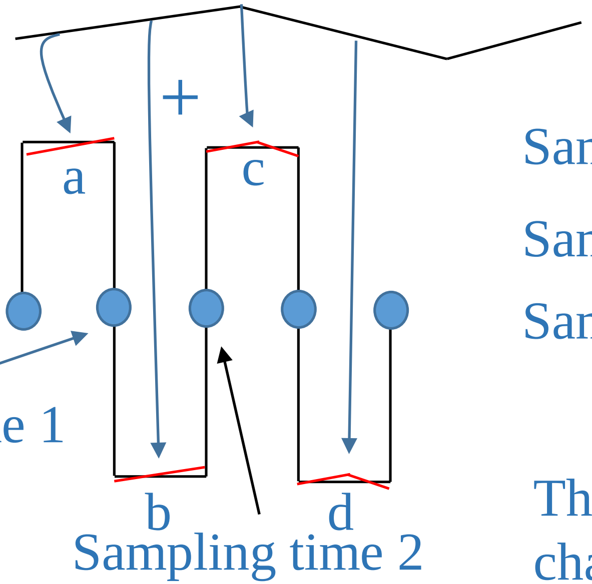
- Possible noise injection from the bias source if the time constant given by the capacitors is not small enough;
- Long term stability from the sawtooth.

Cold FE + AC bias 2

Series Noise adds to the square wave. Case 1: low frequency noise



2017 JINST 12 P08010



Sampling time 1= a-b

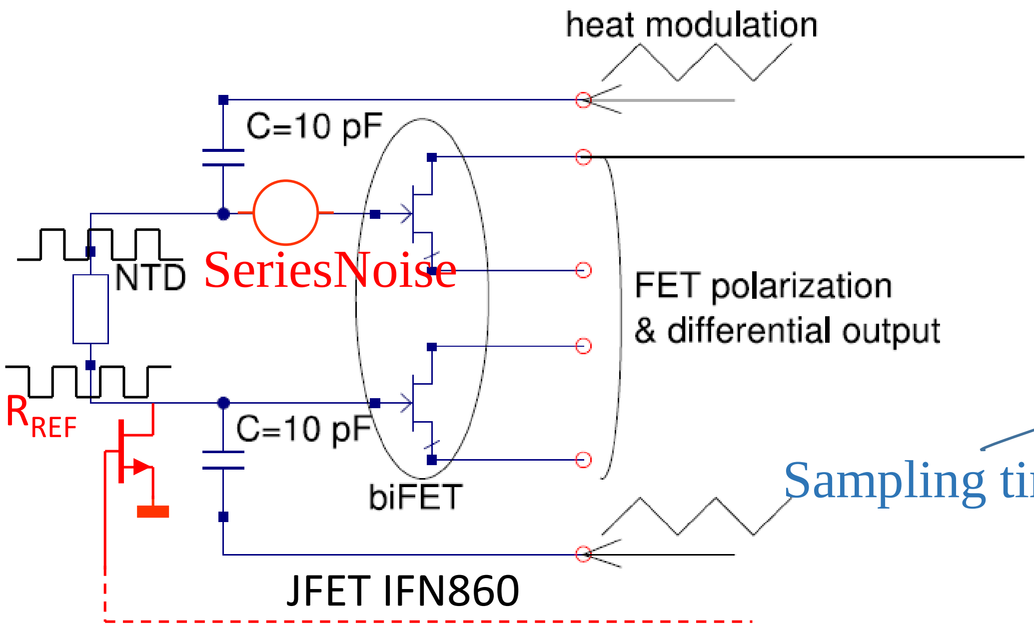
Sampling time 2= b-c

Sampling time 3= c-d

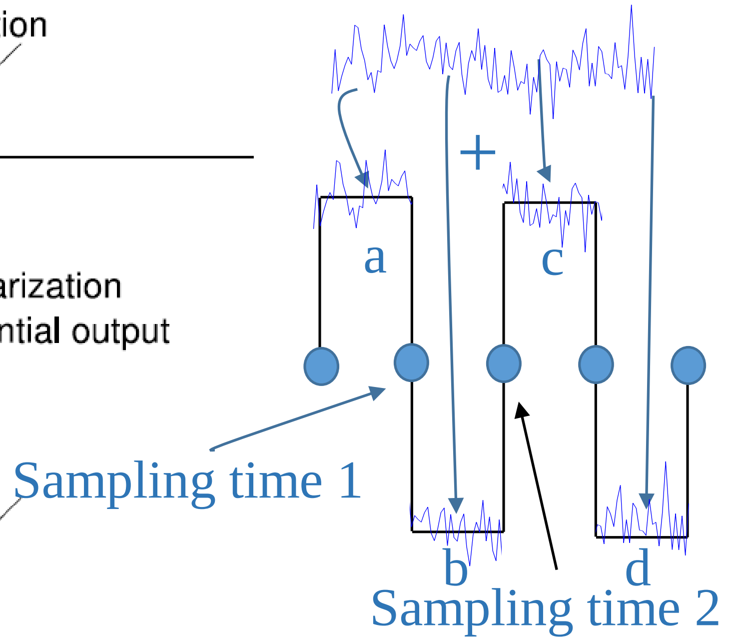
The noise is slow in this case and change a little from slot to slot: doing the difference to generate the signal the noise cancels out

Cold FE + AC bias 3

Series Noise adds to the square wave. Case 2: white noise, fast noise



2017 JINST 12 P08010



Sampling time 1= a-b

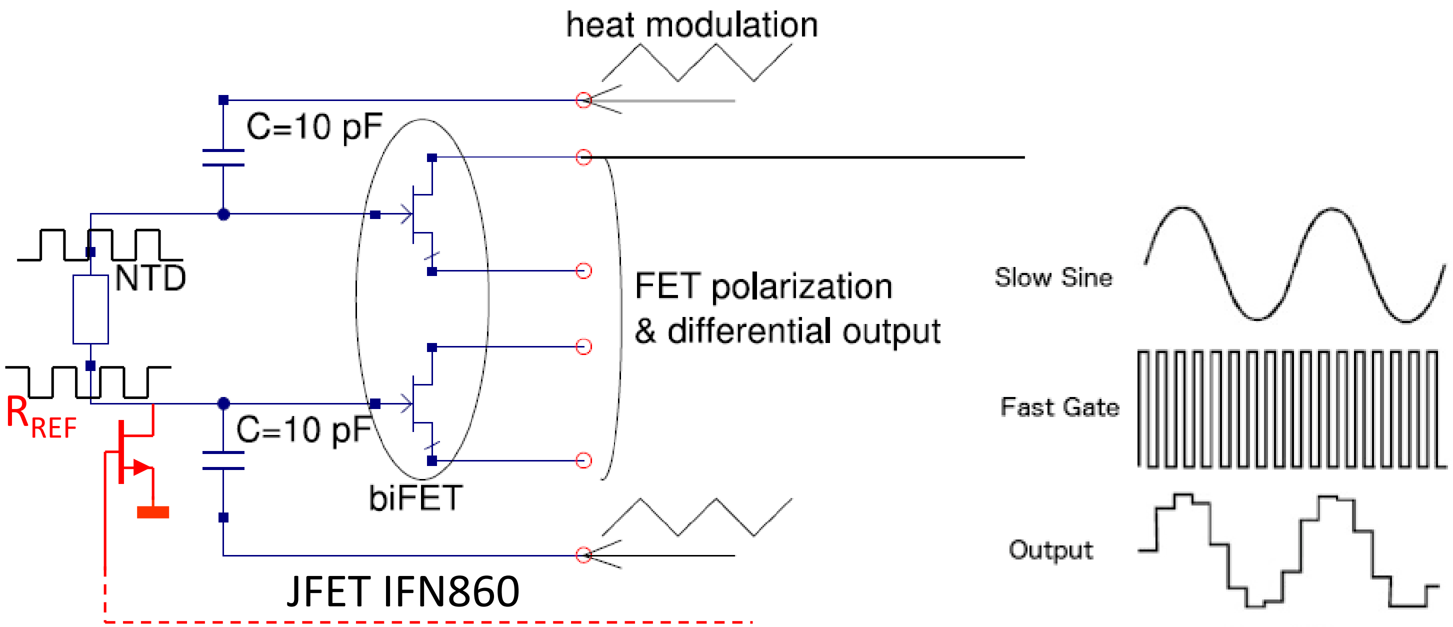
Sampling time 2= b-c

Sampling time 3= c-d

Now the noise is fast and, from sample to sample, it appears not-correlated: the white noise close to the sampling frequency is effective.

Cold FE + AC bias 4

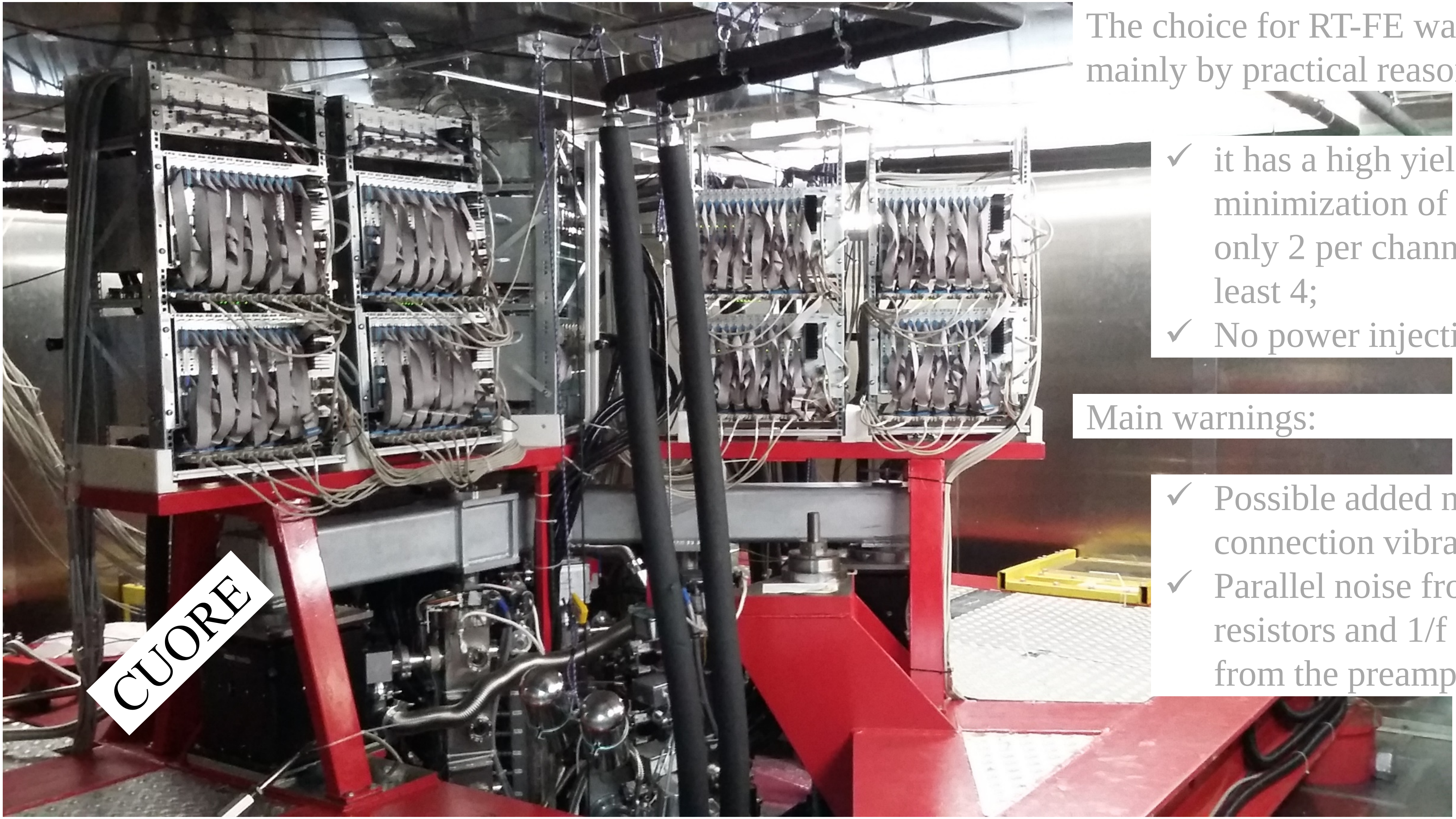
Now the signal: the signal change the resistor value, that modifies the square wave amplitude: the signal modulate the square wave



2017 JINST 12 P08010

Let's suppose the detector signal a sine. If the sine frequency is much smaller than that of the square, than the input signal emerges at the sampling times from the process described before.

Room T operated, RT-FE 1



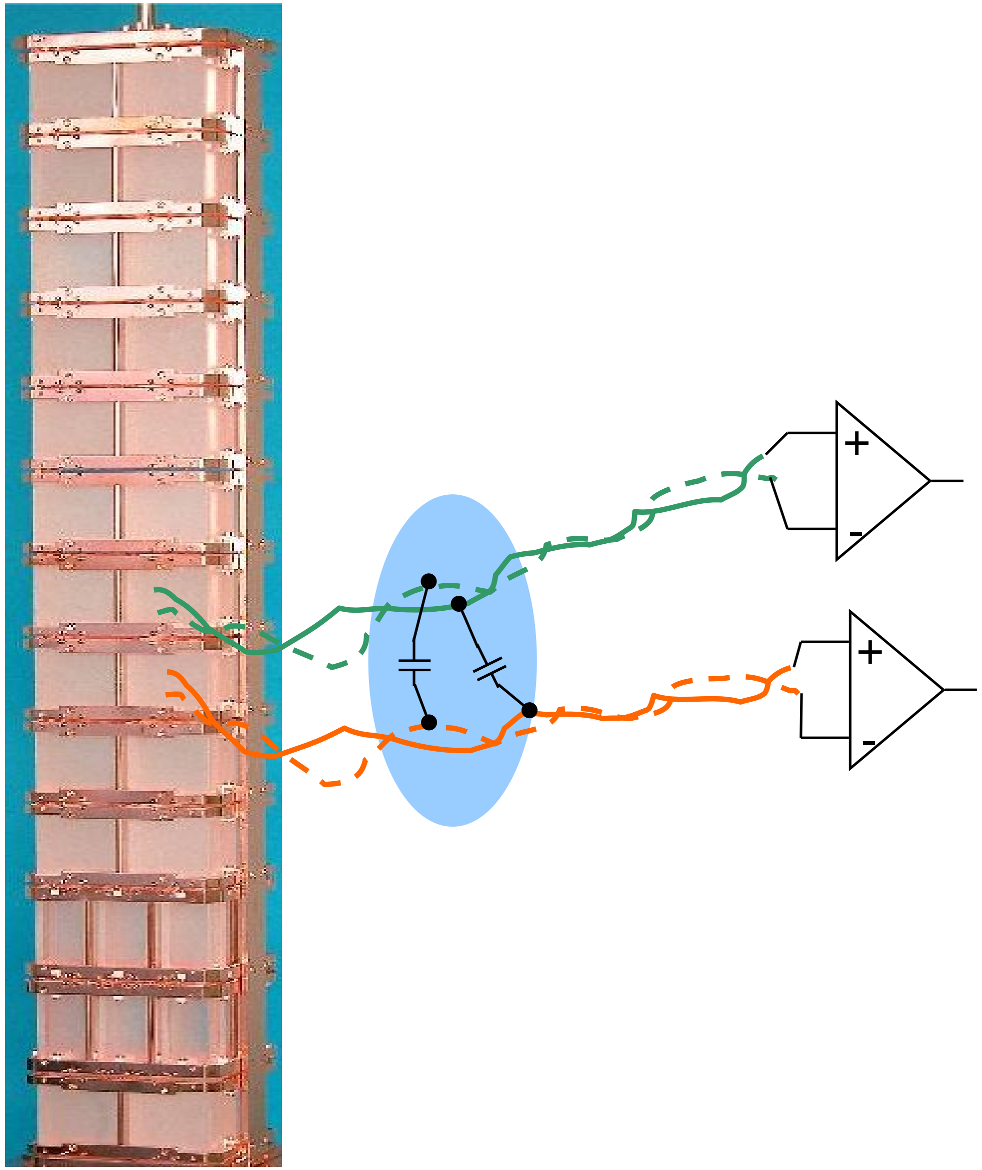
The choice for RT-FE was motivated mainly by practical reasons:

- ✓ it has a high yield as there is the minimization of connections, only 2 per channel against at least 4;
- ✓ No power injection, at all.

Main warnings:

- ✓ Possible added noise from connection vibrations;
- ✓ Parallel noise from the load resistors and 1/f series noise from the preamplifier.

Room T operated, RT-FE 2



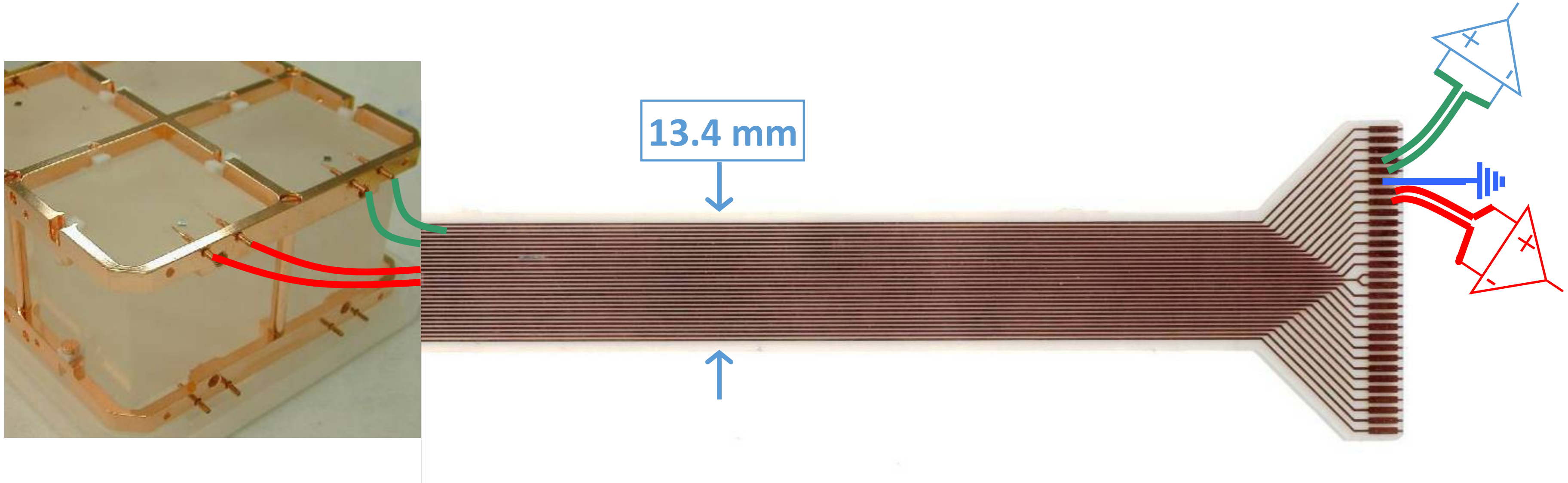
- The differential configuration is very useful when array of detectors are packaged to minimize cross-talk;
- Depending on the layout, this could be an help also when a cold stage is used (see Edelweiss);
- Depending on the link length, common mode disturbances are attenuated.

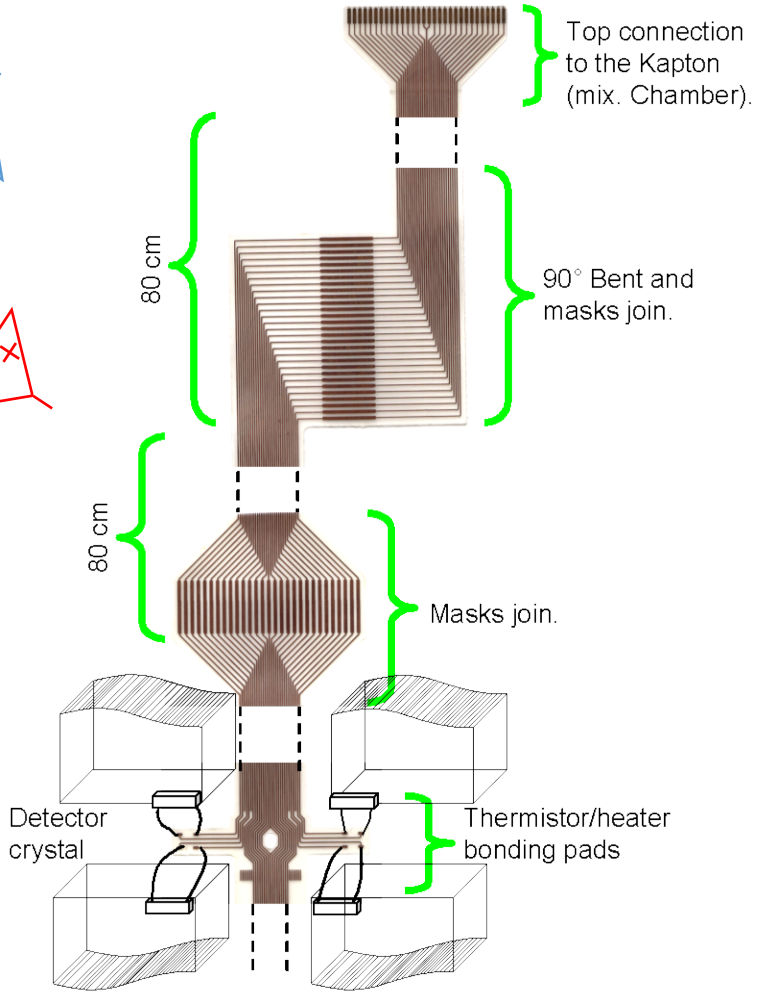
Detector impedance:

- The expected range is a few MΩ, up to tens of MΩ, for TH channels and slightly less for LD channels;
- Signal bandwidth is a few tens of Hz for TH and up to hundred of Hz for LD (LD bandwidth could be larger, we will see).

Link

Another important benefit is the minimization of the exposition of the detector to material with possible presence of background. As an instance the link of for CUORE is made with a custom designed strip made by PEN.



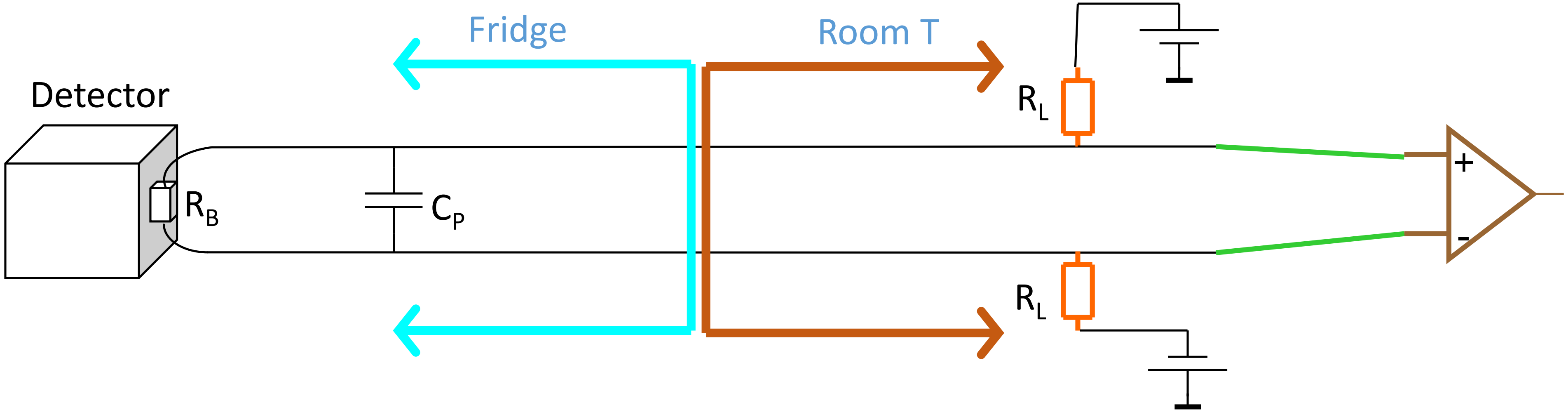


The layout is for a ribbon having 10 pairs each separated by a gnd.

The width of every connection is 0.2 mm and the distance between the center-to-center of any connection is 0.4 mm (0.2 mm is the gap), the thickness 70 μm.

The length of the link is about 2 m, custom.

Preamplifier 1

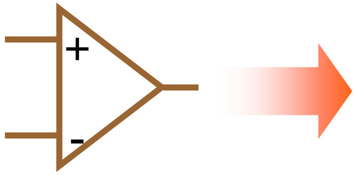


Essential characteristics:

- ✓ The load resistors, R_L, are at room temperature;
- ✓ The preamplifier is at room temperature, too;
- ✓ The preamplifier is voltage sensitive, large impedance, differential input.

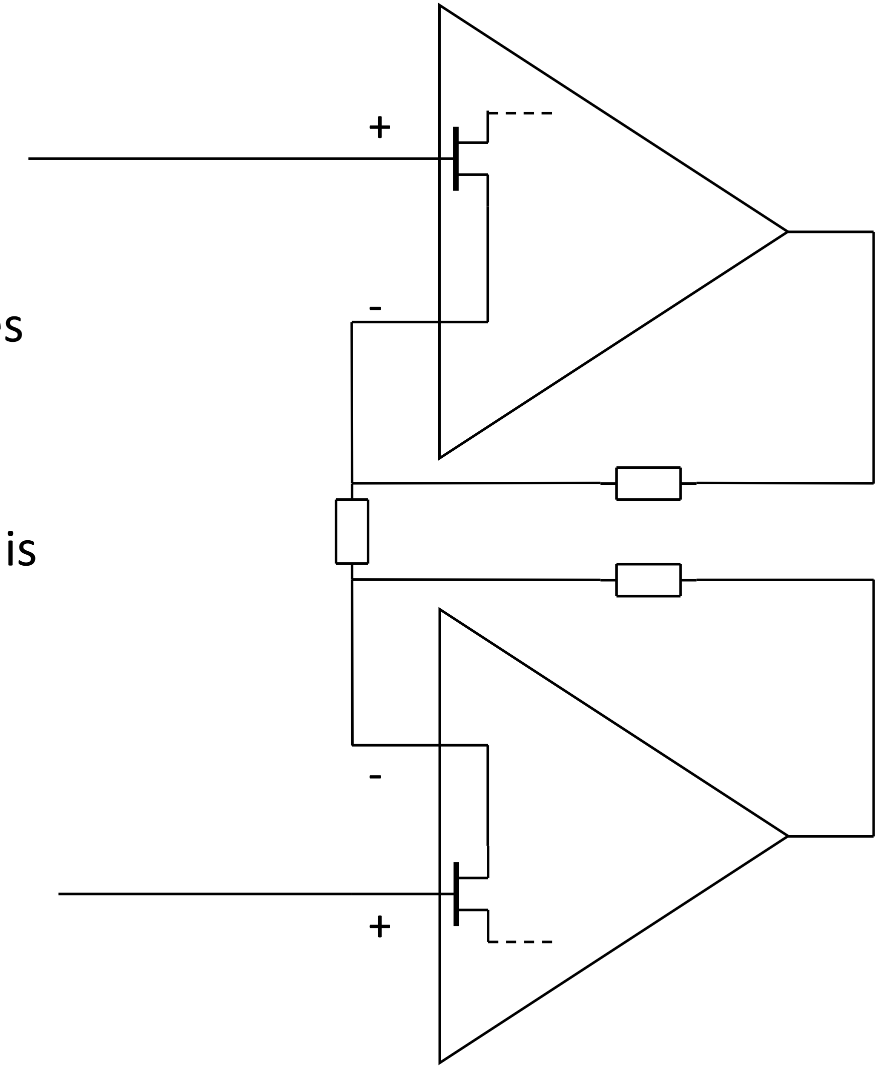
Preamplifier 2

Alta Frequenza, Vol. 56, N.8, p. 347-351, 1987;
NIMA, Vol. A370, p.220-222, 1996;
IEEE TNS, V.44, p.416-423, 1997;
NIMA, Vol. 444A, p. 111-114, 2000;
NIMA, Vol. 444A, p. 132-135, 2000;
2009 NSS Conference Record.



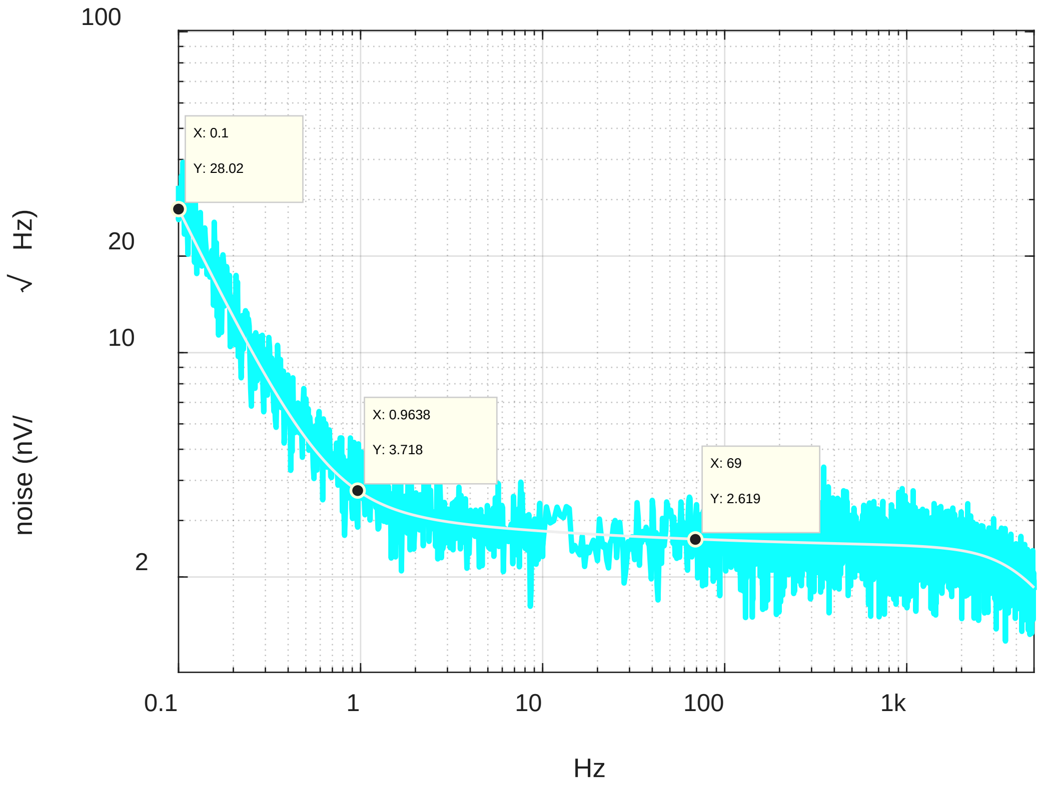
In our configuration the Sources of the 2 JFETs are used as inverting inputs.

This way the input series noise is due to only 2 transistors, while the input impedance remains very large.



Preamplifier 3

Series 1/f noise of preamplifiers has been minimized by selecting very low noise JFET. The preamplifiers can be operated in Low power Mode and High Power mode.
In low power mode white noise is a bit large, about 2.5 nV/√Hz, but power dissipation is small. This adoption is possible for the large impedance NTD, normally equipping the Thermal signals from the crystals.

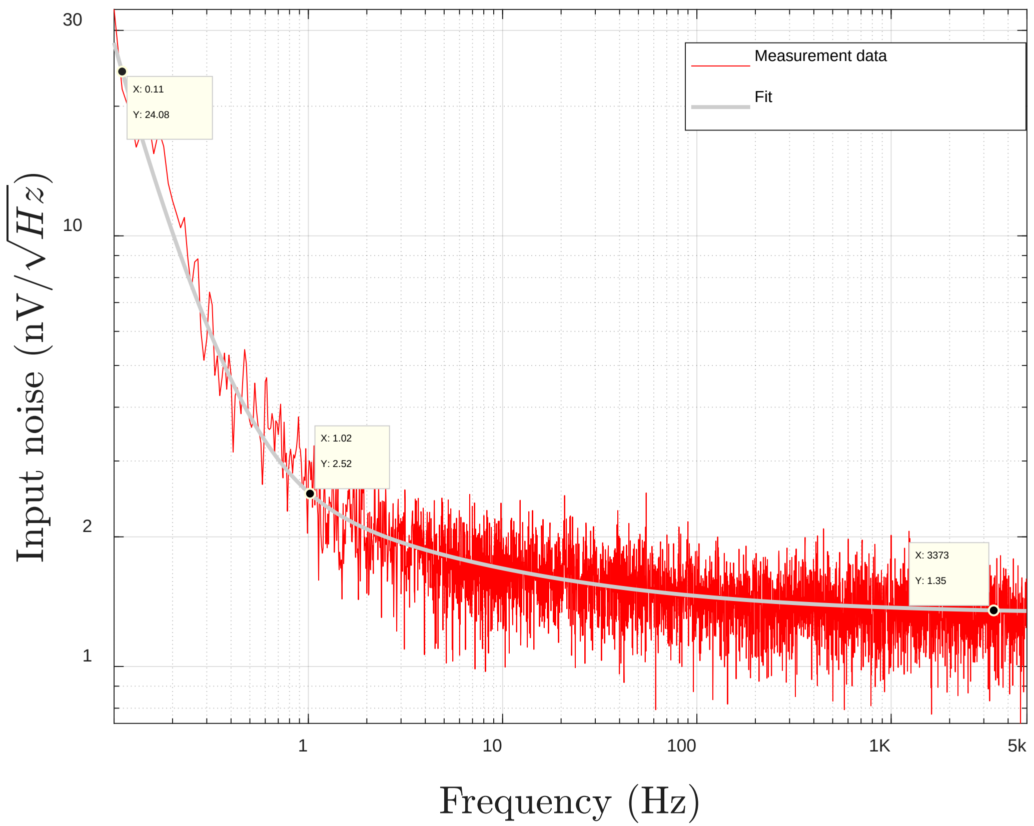


- A new generation of JFETs is being used. The new JFETs have characteristics slightly better than those of the CUORE-JFET, no longer available, and are cheaper;
- Here the preamplifier series noise in the TH readout configuration (each JFETs operated at 0.5 mA). Note that the white noise is contributed by the feedback resistors, too, and is similar to the CUORE preamplifiers;
- 1/f noise is slightly smaller, but an average of a large number of samples is necessary for confirmation;
- Noise is measured down to 0.1 Hz now to guarantee adequate performance (we would it to be smaller than 40 nV/√Hz @ 0.1 Hz).

Preamplifier 4

In High Power mode the noise is slightly larger than 1 nV/√Hz fitting the NTDs on the light detectors that are faster and have small value impedances.

Note that the noise is almost white down to 1 Hz, and increases below. We believe that the increase of noise below 1 Hz is mainly due to thermal tribulation and we are studying this.

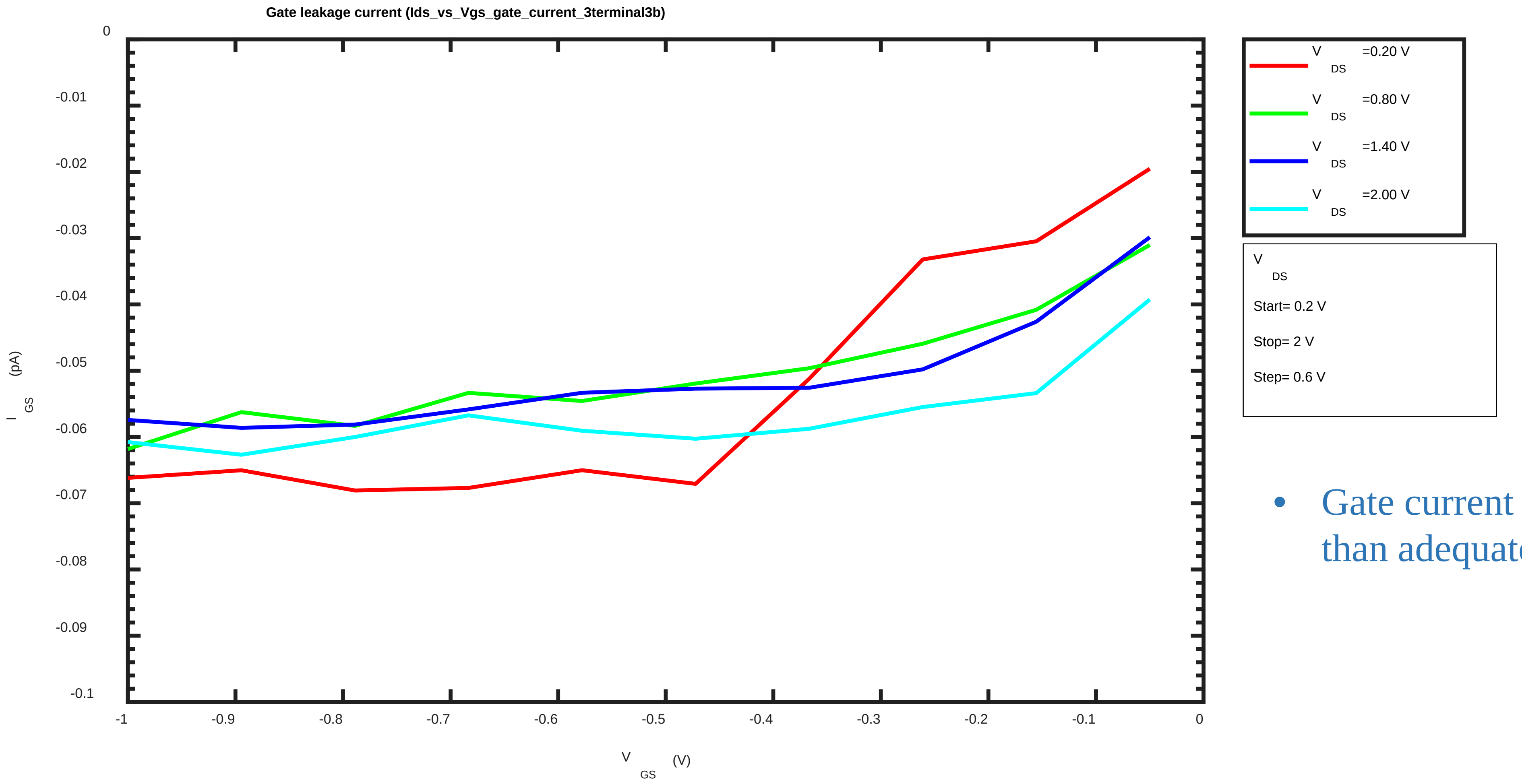


- This is the noise in LD mode (each JFET operated at 5 mA);
- White noise is as expected (still contributed slightly from the, unavoidable, feedback resistors).

Preamplifier 5

Parallel noise could be an important limiting factor. The selected JFET show a gate current of less than 100 fA. The parallel noise from this source is negligible up to a 50 MΩ thermistor held at 15 mK.

This noise is not a limit for our setup.

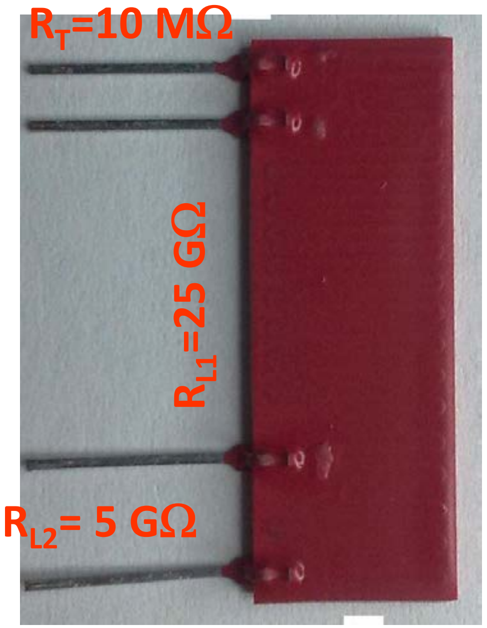


- Gate current of the new JFETs is more than adequate.

Preamplifier 6

Parallel noise from detector biasing resistors is the limiting factor for our noise.
As an instance, in CUORE we use now 60 GΩ at room T, that become a limit for thermistor with a resistor larger than 3 MΩ held at 15 mK.

We are planning to test new resistors with 200 GΩ (equal to the noise of 10 MΩ at 15 mK) value in CUORE as the NTD there have a larger value with respect to that expected.



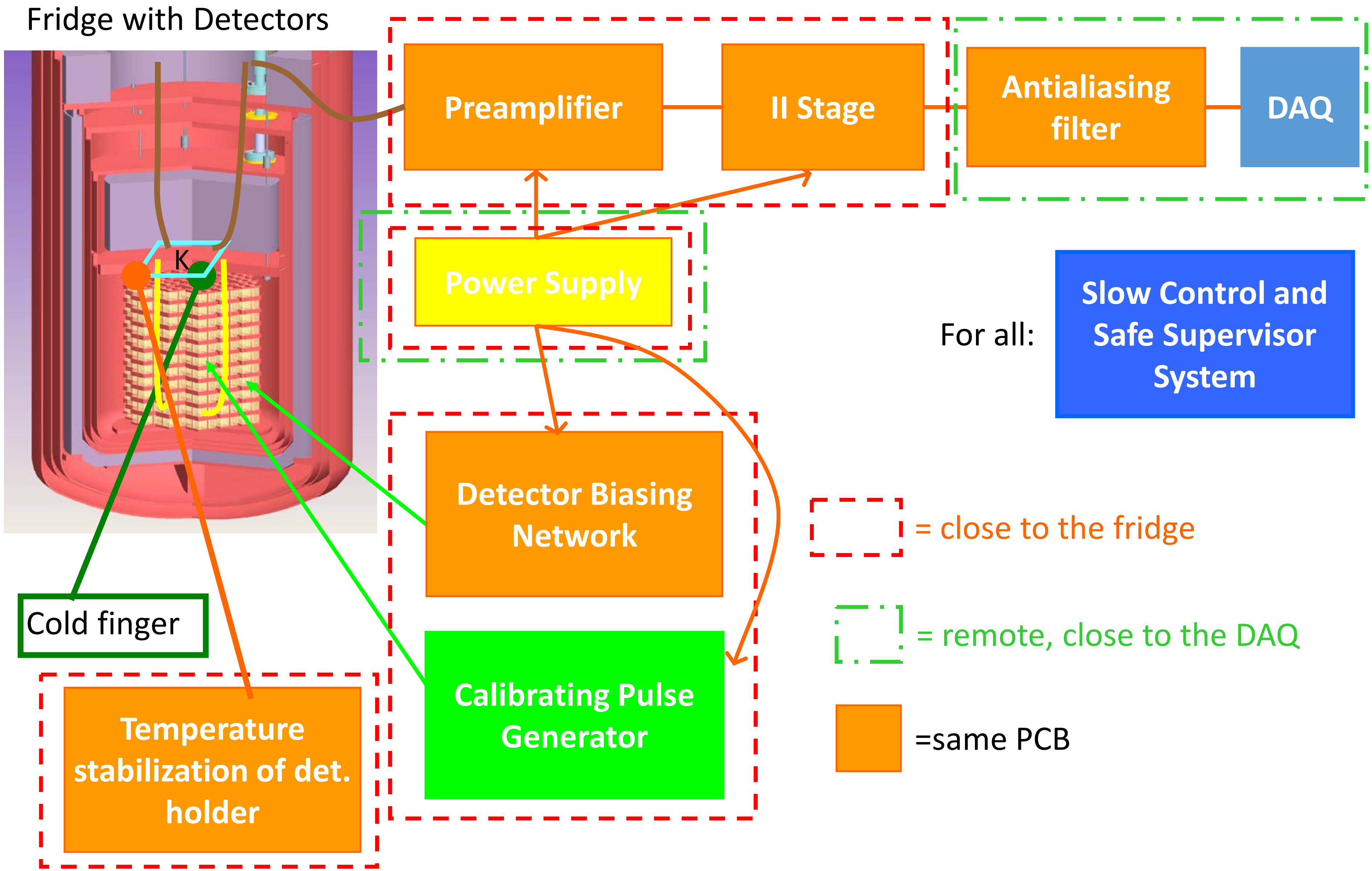
- Resistors are custom made for not showing 1/f noise at large bias;
- To operate large value resistors we need to be able to apply large biases: in CUORE the bias range was extended to 50 V.

IEEE TNS, V.49, p. 1808 (2002).

We have taken care of another very important constraint, with the same importance as noise, in our Electronics setup:

Thermal Stability and accuracy are at the level of the ppm/°C in every part of the system, to guarantee a steady behavior on long runs.

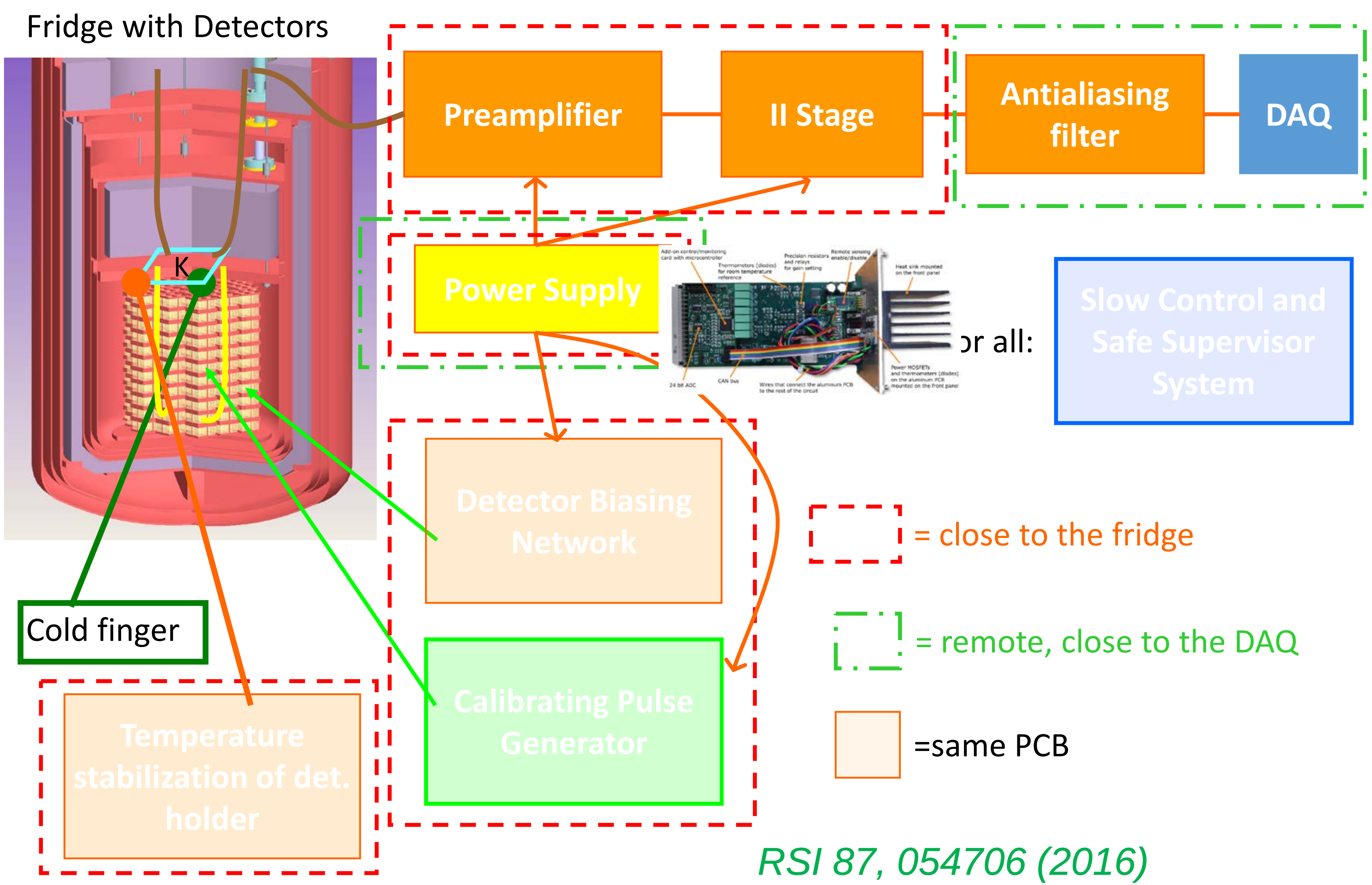
Electronics system 1



The Electronics for such a system is not consisting in the preamplifier only. There are several other parts that must assure the great stability over long runs.

2018 JINST 13 P02026

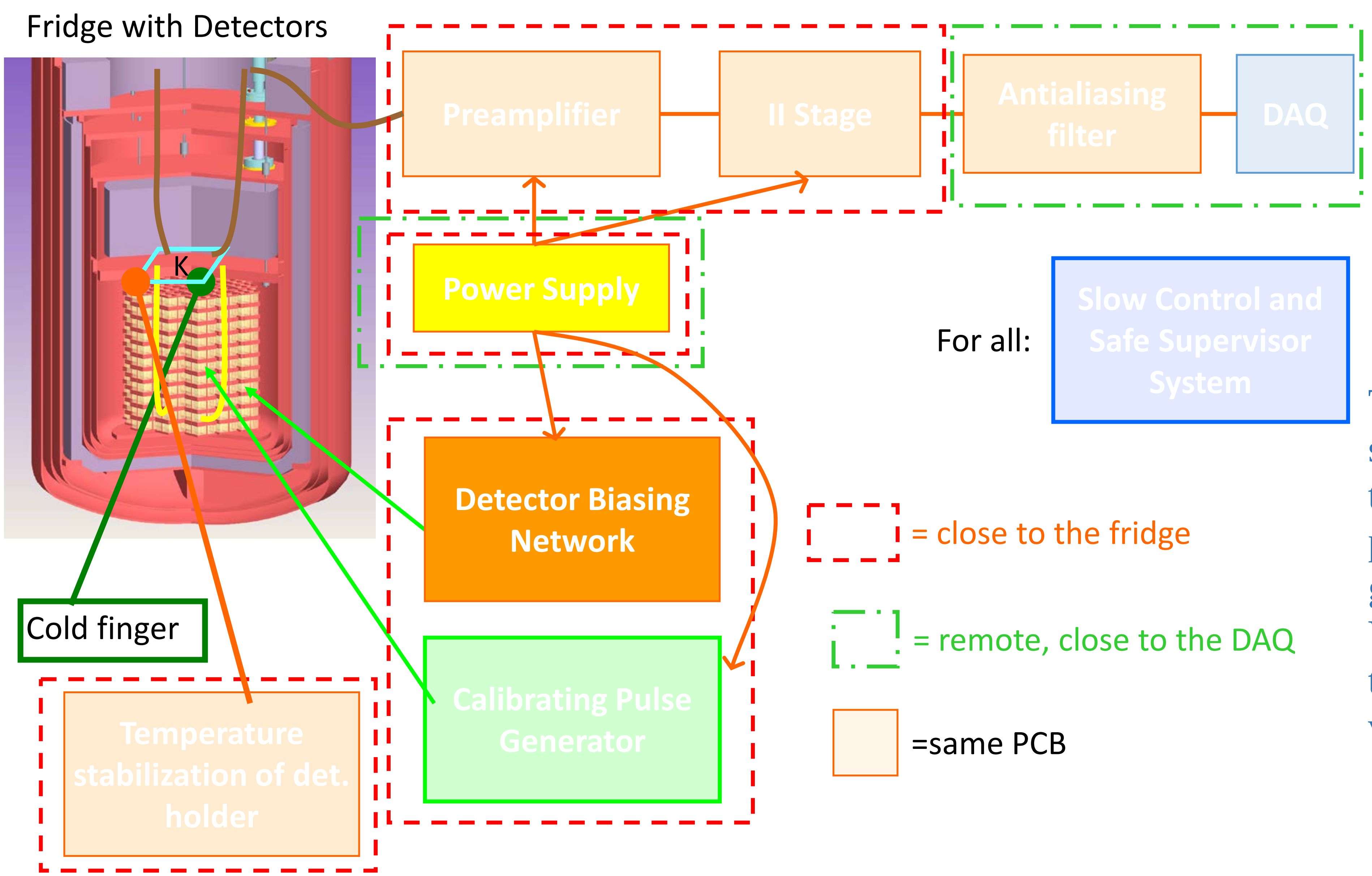
Electronics system 2



RSI 87, 054706 (2016)
RSI 86, 124703 (2015)

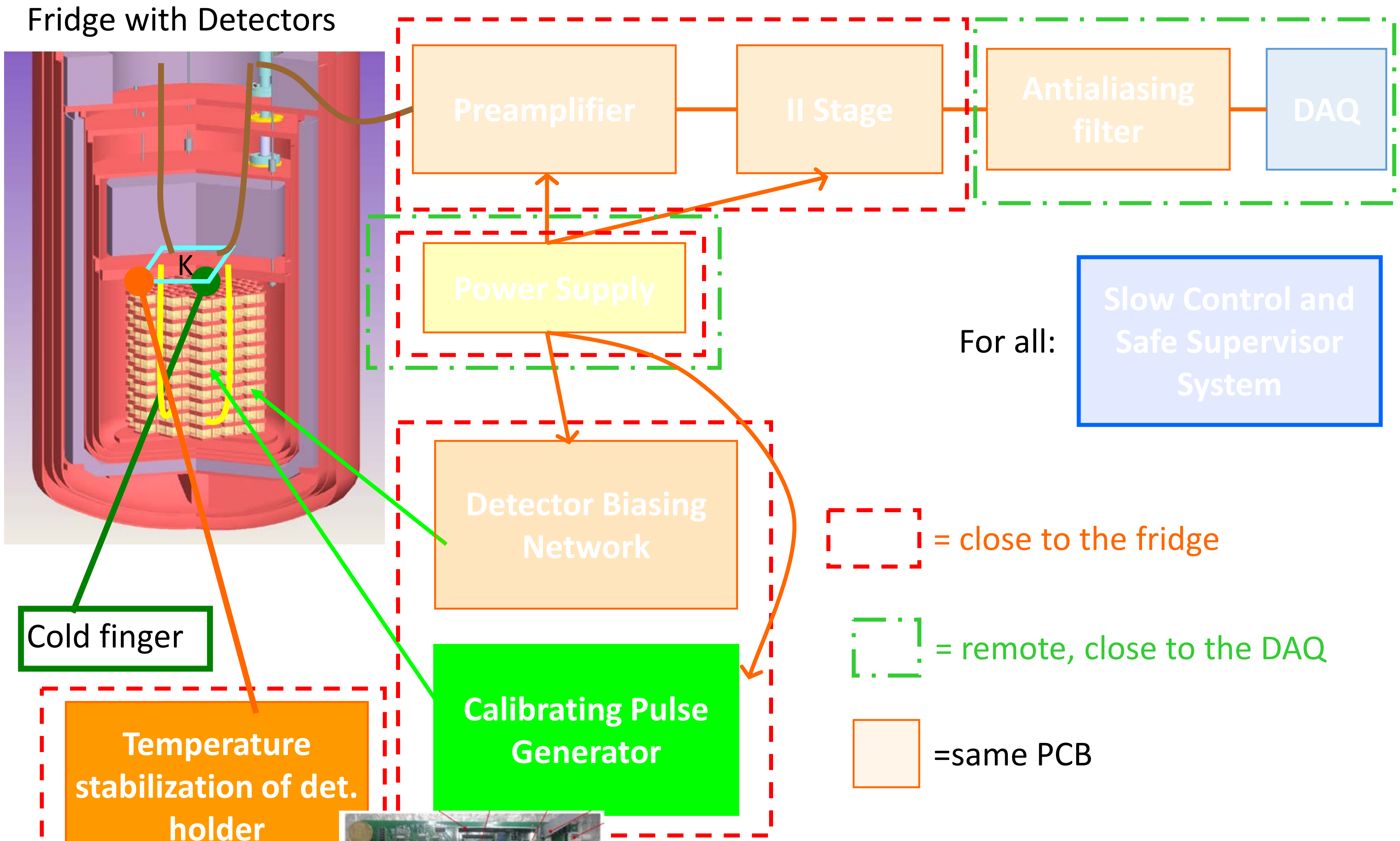
The amplification chain has the gain stable at a few ppm/°C, while the thermal drift of the preamplifiers is trimmed for being smaller than 1 μV/°C.
This has been possible thank to the power supply system that operate as a low noise source and as a 1 ppm/°C reference voltage.

Electronics system 3



The detector biasing system was also designed to be stable below 50 ppm/°C and is able to generate up to 50 V (±25 V) of voltage to allow for the adoption of very large value load resistors.

Electronics system 4

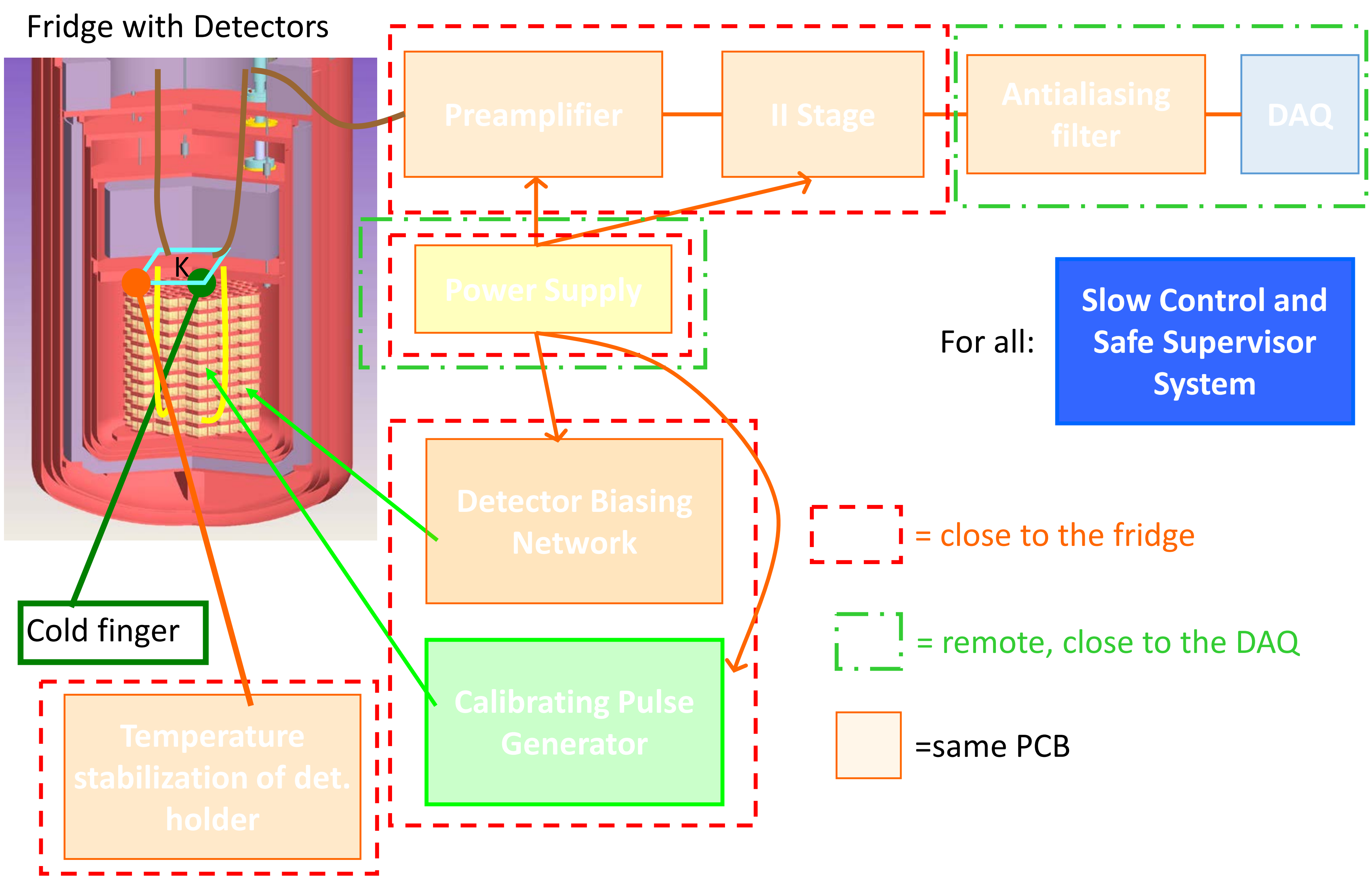


For detector stabilization a voltage pulse is sent to the crystal heaters. The pulse emulates a particle energy and is precise at better than 1 ppm/°C in both amplitude and width.
The pulser is also able to generate a DC signal and this is exploited to stabilize the baseline temperature of the detector holder.

2018 JINST 13 P02029

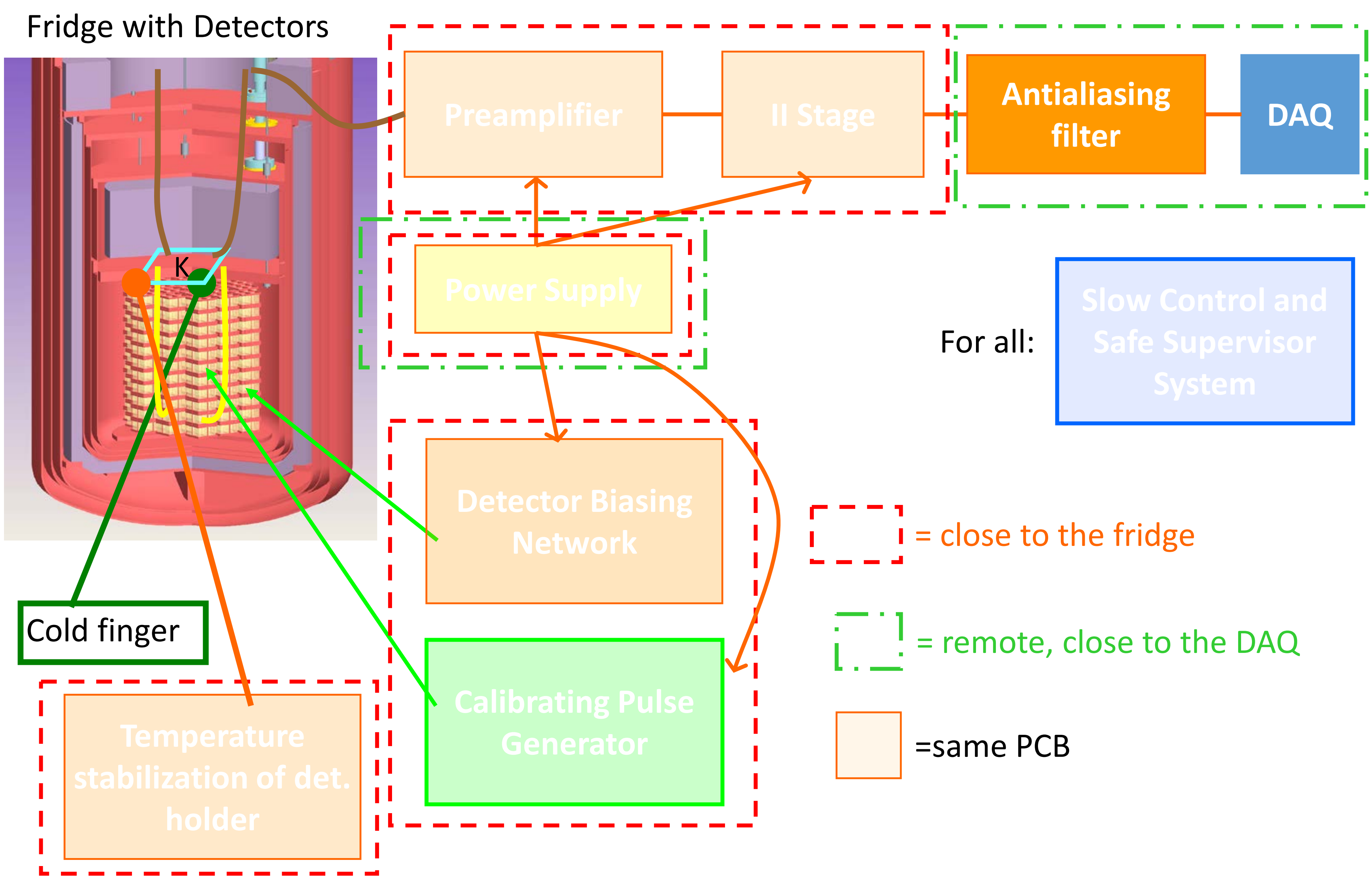
IEEE TNS, 52, 2005

Electronics system 5



The Electronics system is completely programmable in its parameters via fibre optic.

Electronics system 5



We have just done an upgrade in which the antialiasing filter merges with the DAQ…

The new DAQ 1

The new board, a digitally adjustable antialiasing filter and DAQ:

12 channels, 6-pole Bessel-Thompson low pass filter

Broad cut-off frequency choice (2 orders of magnitude, **24 – 2500 Hz**)

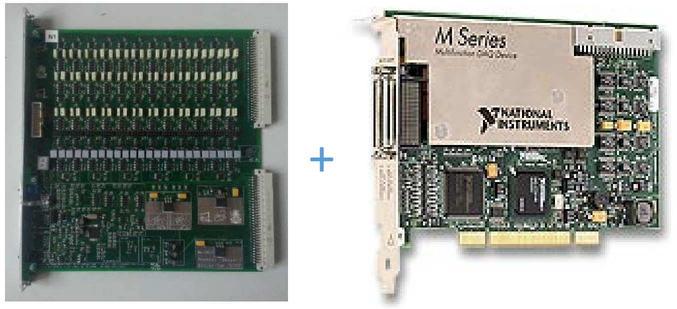
Cut-off frequency is digitally programmable (10 bits)

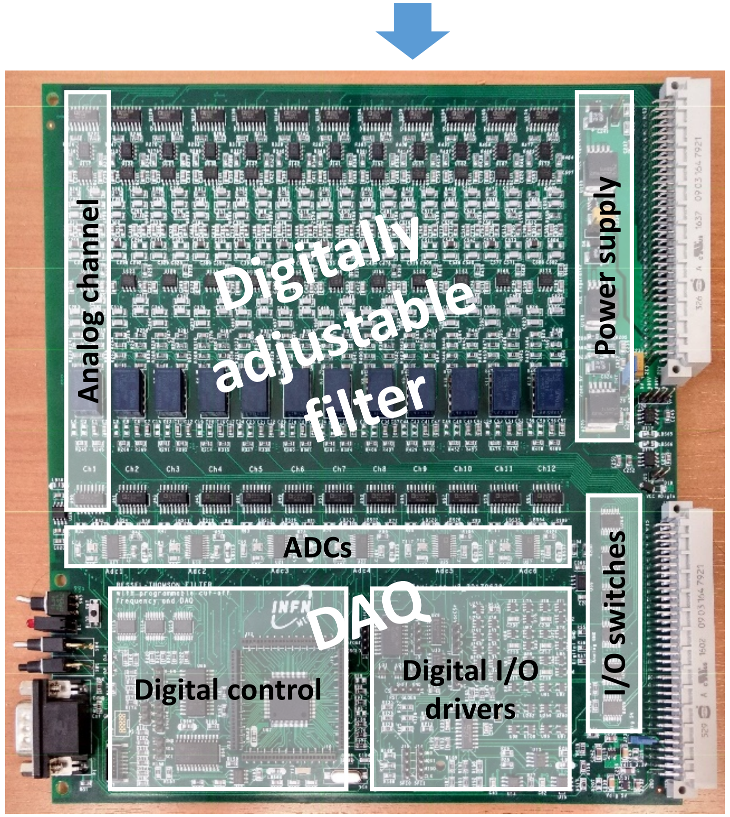
Lower power consumption (-66% wrt CUORE board)

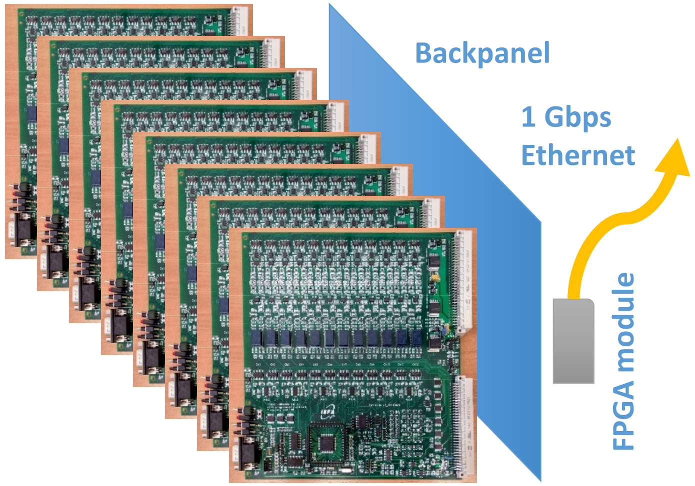
Integrated high resolution sigma-delta **24-bit ADCs**

Sampling rate up to **25 ksps** (250 ksps with half channels)

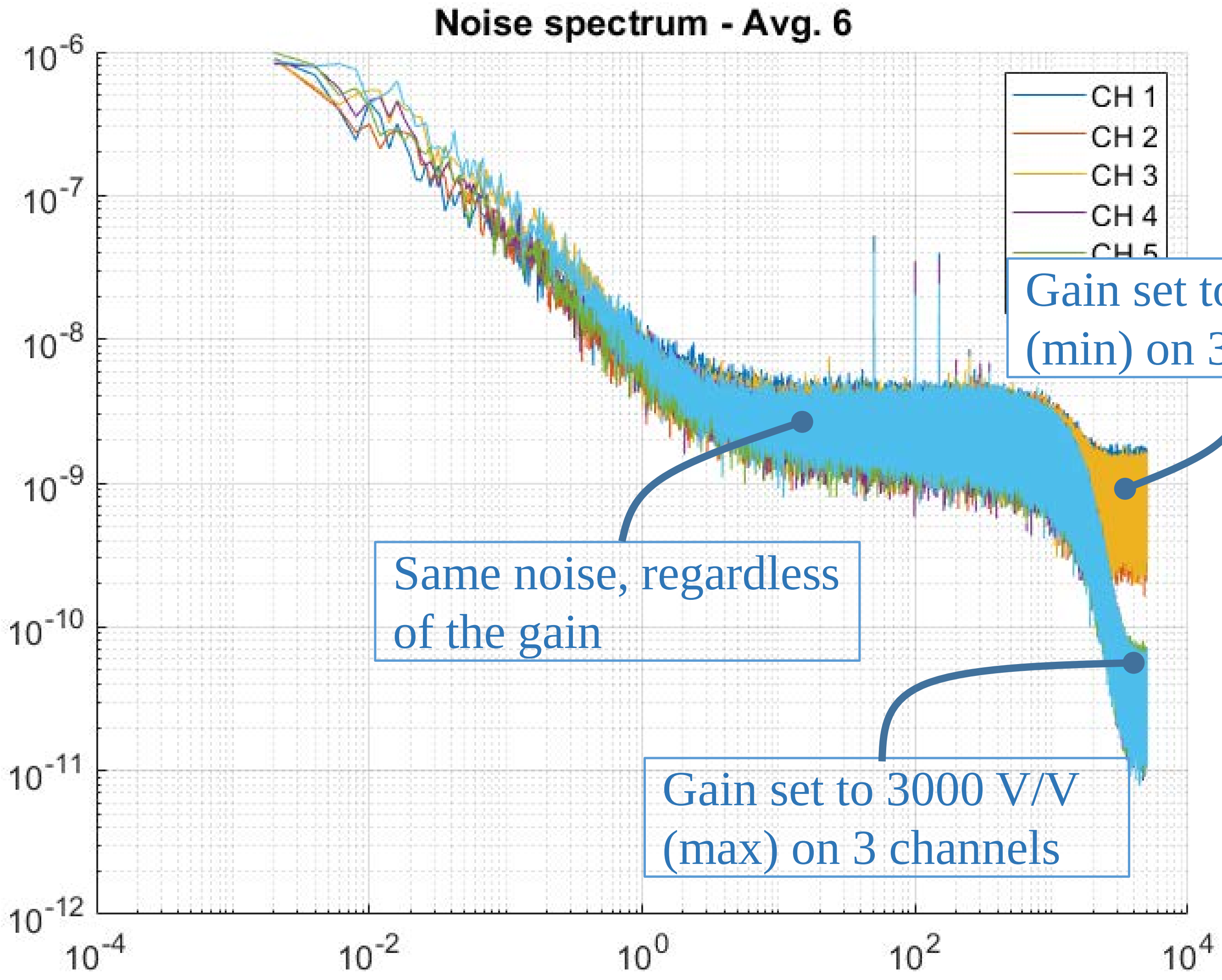
Twofold operation: AA filter + DAQ or AA filter with standard analog outputs (external DAQ)







The new DAQ 2



Noise referred to the inputs of 6 channels to be installed in CANFRANC the next week, when the detector has 0 Ω.

This proves the power of the 24-bits: the ADC does not limit the noise performance even if the gain is set to a low value: the second PGA stage starts to become useless.

Ni has just launched a new 24-bits DAQ board featuring 32 differential channels. This board is able to perform characteristics similar to ours.

Optional Buffered Mode IIR Filtering

Filter Cut-Off Frequency	Filter Type	Stopband Attenuation	Passband Ripple
2 kHz Filter	Fourth order, Elliptic Filter	-120 dB	0.2 dB
1 kHz Filter	Fourth order, Elliptic Filter	-120 dB	0.2 dB
200 Hz Filter	Fourth order, Elliptic Filter	-120 dB	0.2 dB
20 Hz Filter	Fourth order, Elliptic Filter	-120 dB	0.2 dB
2 Hz Filter	Fourth order, Elliptic Filter	-120 dB	0.2 dB

It provides also a sw active filter in 5 frequencies steps. The filter is a fourth order, but has a strong drawback in our application: it is an elliptic filter optimized for a steep roll-off. As such, it could distort the signals in the pass-band since it is not flat, having 0.2 dB of ripple, or 2 %, (we had such experiences with the Butterworth filters in our early detectors).

The cost of this board is larger than our and it needs dedicated crate and interface boards.

Summary

SPARE 1

Searching for low-mass dark matter particles with a massive Ge bolometer operated above ground

E. Armengaud,[1] C. Augier,[2] A. Benoît,[3] A. Benoit,[2] L. Bergé,[4] J. Billard,[2,*] A. Broniatowski,[4] P. Camus,[3] A. Cazes,[2] M. Chapellier,[4] F. Charlieux,[2] D. Ducimetière,[2] L. Dumoulin,[4] K. Eitel,[5] D. Filosofov,[6] J. Gascon,[2] A. Giuliani,[4] M. Gros,[1] M. De Jésus,[2] Y. Jin,[7] A. Juillard,[2] M. Kleifges,[8] R. Maisonobe,[2] S. Marnieros,[4] D. Misiak,[2] X.-F. Navick,[1] C. Nones,[1] E. Olivieri,[4] C. Oriol,[4] P. Pari,[9] B. Paul,[1] D. Poda,[4] E. Queguiner,[2] S. Rozov,[6] V. Sanglard,[2] B. Siebenborn,[5] L. Vagneron,[2] M. Weber,[8] E. Yakushev,[6] A. Zolotarova,[1,†]

(EDELWEISS Collaboration)

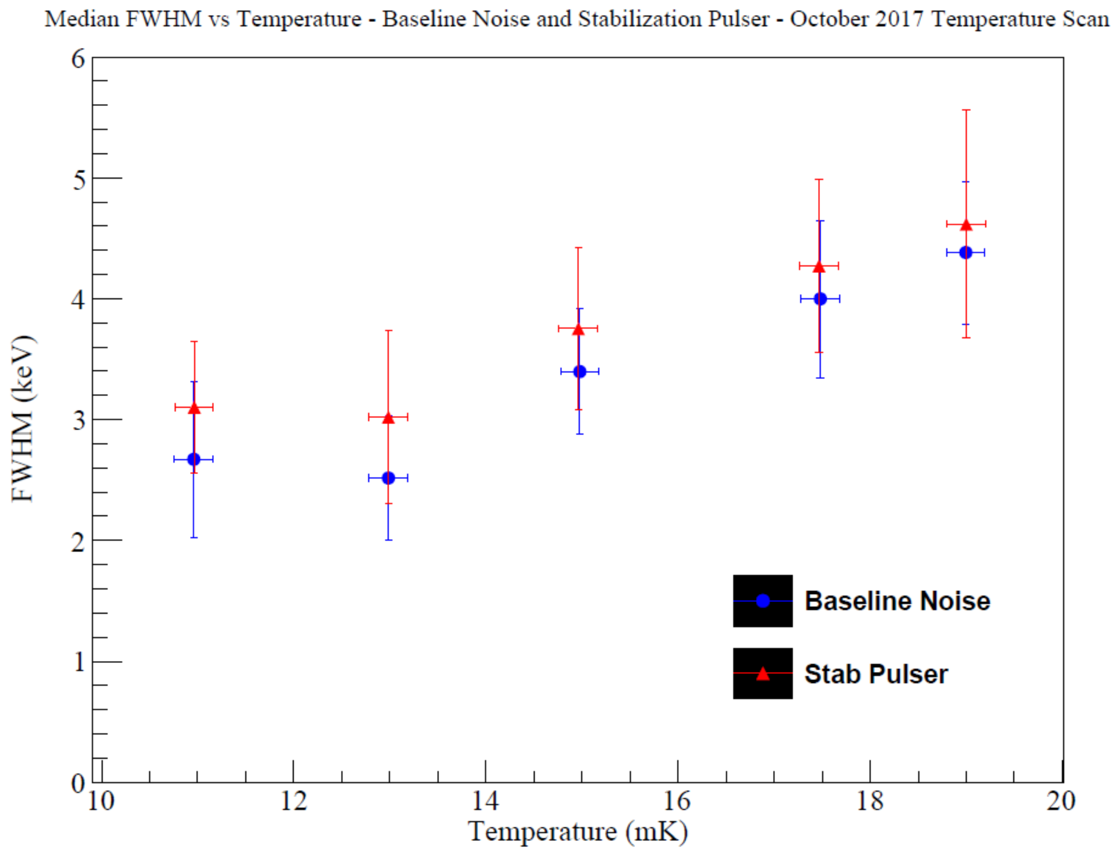
The EDELWEISS Collaboration has performed a search for dark matter particles with masses below the GeV scale with a 33.4-g germanium cryogenic detector operated in a surface lab. The energy deposits were measured using a neutron-transmutation-doped Ge thermal sensor with a 17.7 eV (rms) baseline heat energy resolution leading to a 60 eV analysis energy threshold. Despite a moderate lead shielding and the high-background environment, the first sub-GeV spin-independent dark matter limit based on a germanium target has been achieved. The experiment provides the most stringent, nuclear-recoil-based, above-ground limit on spin-independent interactions above 600 MeV/c^2. The experiment also provides the most stringent limits on spin-dependent interactions with protons and neutrons below 1.3 GeV/c^2. Furthermore, the dark matter search results were studied in the context of strongly interacting massive particles, taking into account Earth-shielding effects, for which new regions of the available parameter space have been excluded. Finally, the dark matter search has also been extended to interactions via the Migdal effect, resulting for the first time in the exclusion of particles with masses between 45 and 150 MeV/c^2 with spin-independent cross sections ranging from 10^{-29} to 10^{-26} cm^2.

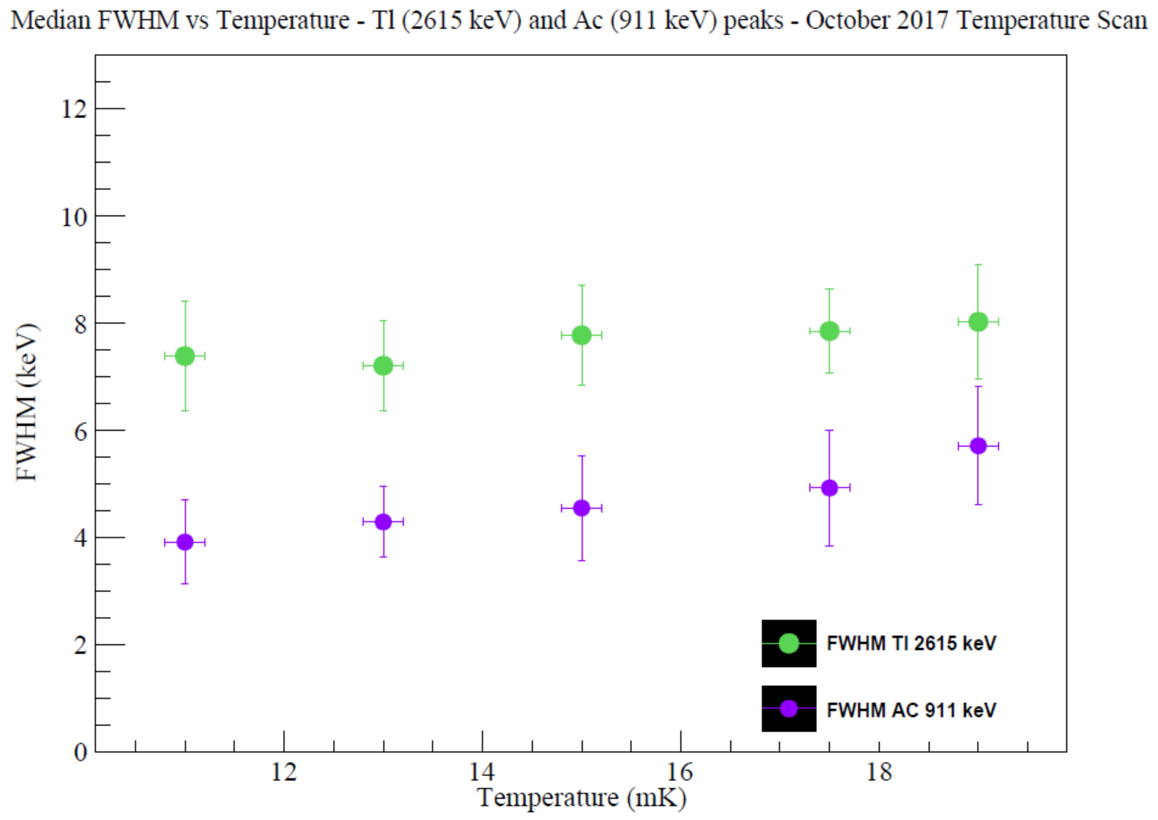
DOI: 10.1103/PhysRevD.99.082003

PhysRevD.99.082003:
33g Ge 41 eV$_{FWHM}$

SPARE 2

CUORE baseline resolution, left, and resolution at large energy, right





http://inspirehep.net/record/1763941/

Noise spectra from AC bias at EDELWEISS

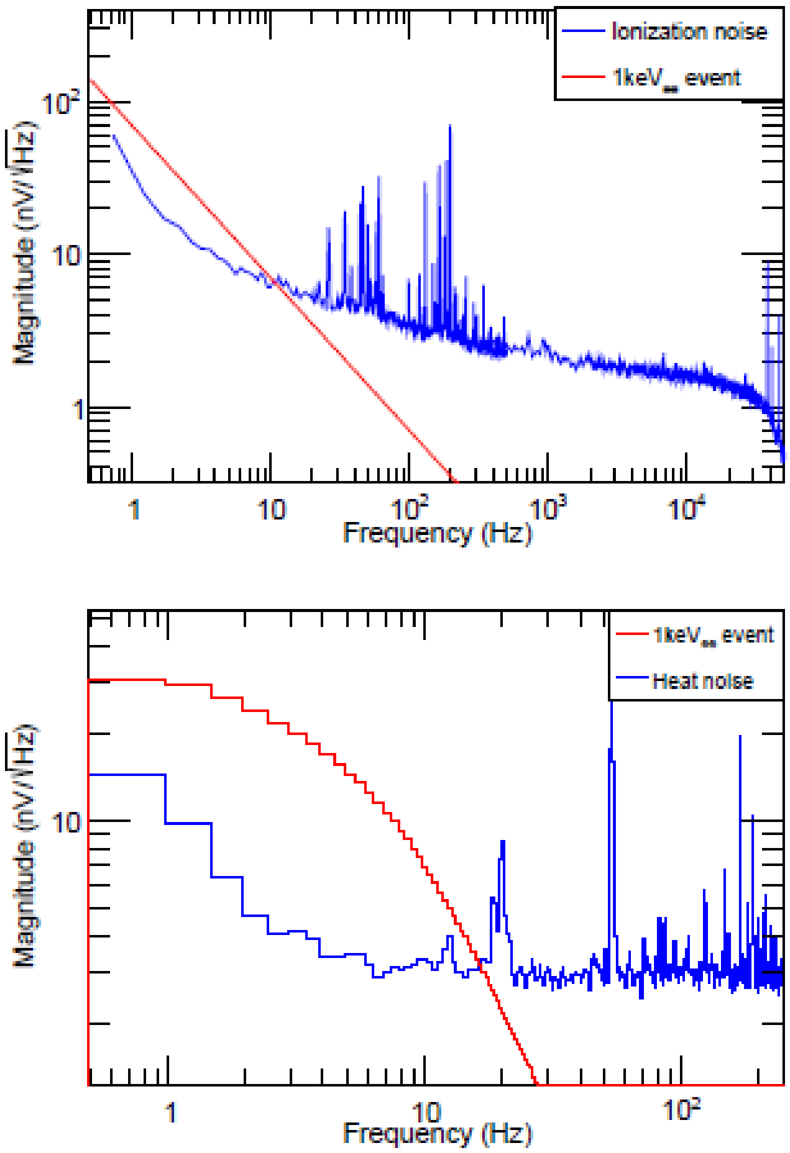


Figure 8. Typical average Fourier noise spectra of an ionization channel (top) and a heat channel (bottom) for an FID detector. In both figures, the red histogram corresponds to the spectrum of a 1 keV_{ee} (electron equivalent) signal.

2017 JINST 12 P08010

SPARE 4

A crate containing 78 channels to be trimmed in temperature