The CUORE bolometric detector for neutrinoless double beta decay searches

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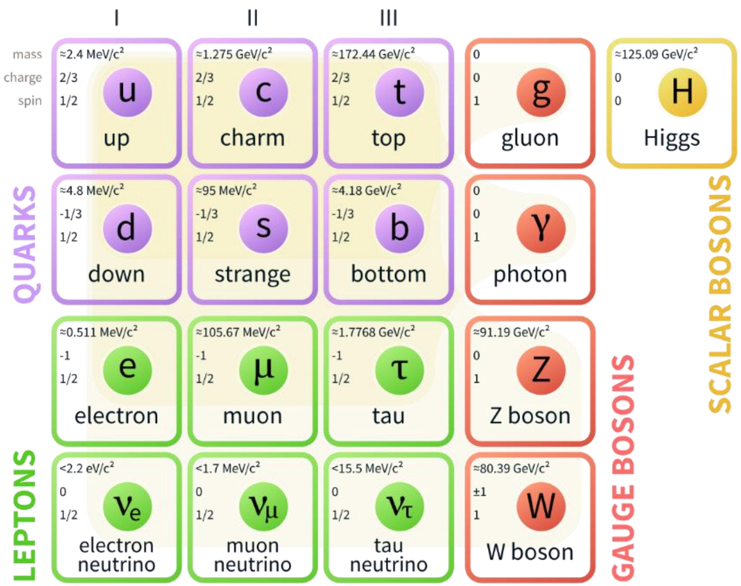
TIPP 2017 – 25/05/2017 - Beijing

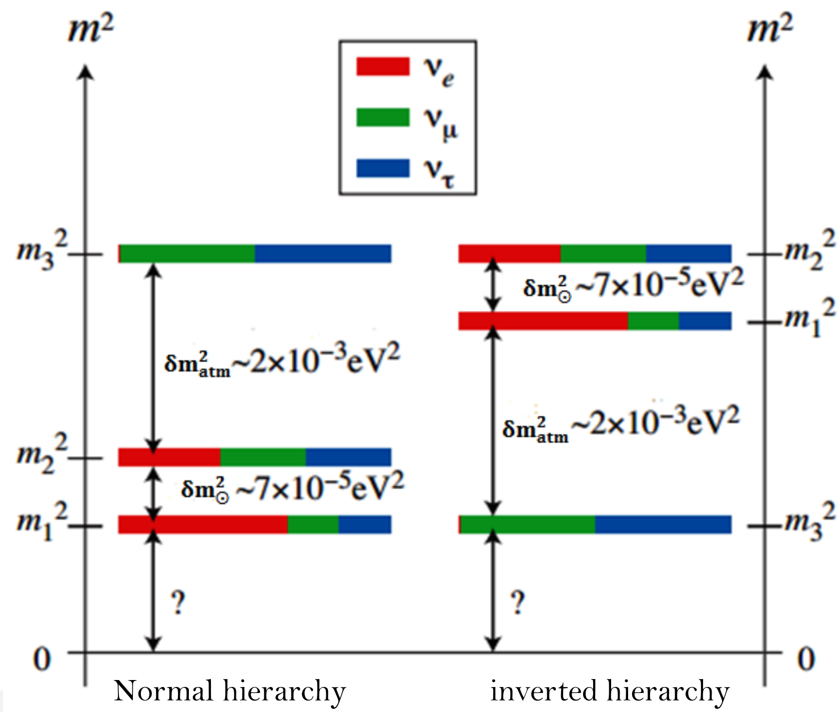
Neutrino



In the standard model each lepton family is associated to a neutrino.
Neutrinos are modeled as massless Dirac particles which interact weakly with ordinary matter.

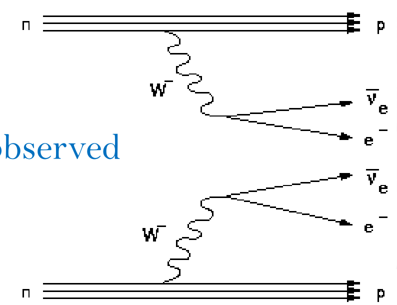
The neutrino flavor oscillations suggest that neutrino is a massive particle but does not give the possibility to measure it nor even define the neutrino hierarchy mass.

$P_{\alpha\to\beta} \propto \sin(\delta m^2_{i,j})$ where $\alpha = e, \mu, \tau$ and m_i $(i = 1,2,3)$ is the neutrino mass.



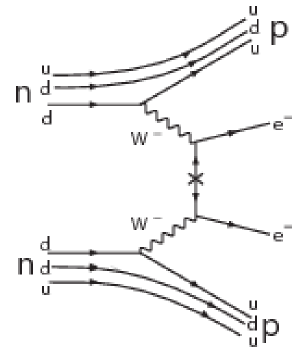
Neutrinoless double beta decay

observed



$2\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu_e}$

$$T_{1/2}^{2\nu} \sim 10^{18} \div 10^{22} \ \text{years}$$



Never observed

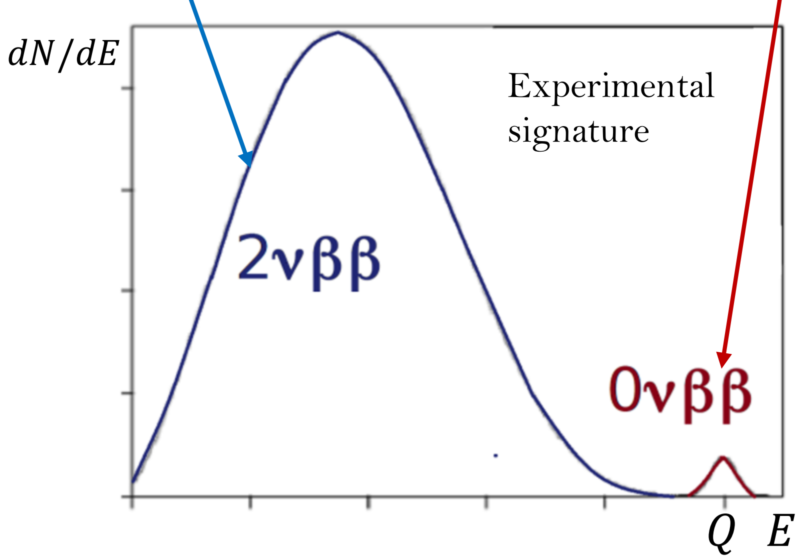
$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

$$T_{1/2}^{0\nu} > 10^{25} \ \text{years}$$

Physics implications

- Leptonic number violation
- $\nu \equiv \bar{\nu}$
- Neutrino mass estimation:

$$|\langle m_\nu \rangle|^2 \propto \left(T_{1/2}^{0\nu}\right)^{-1}$$



Experimental sensitivity:

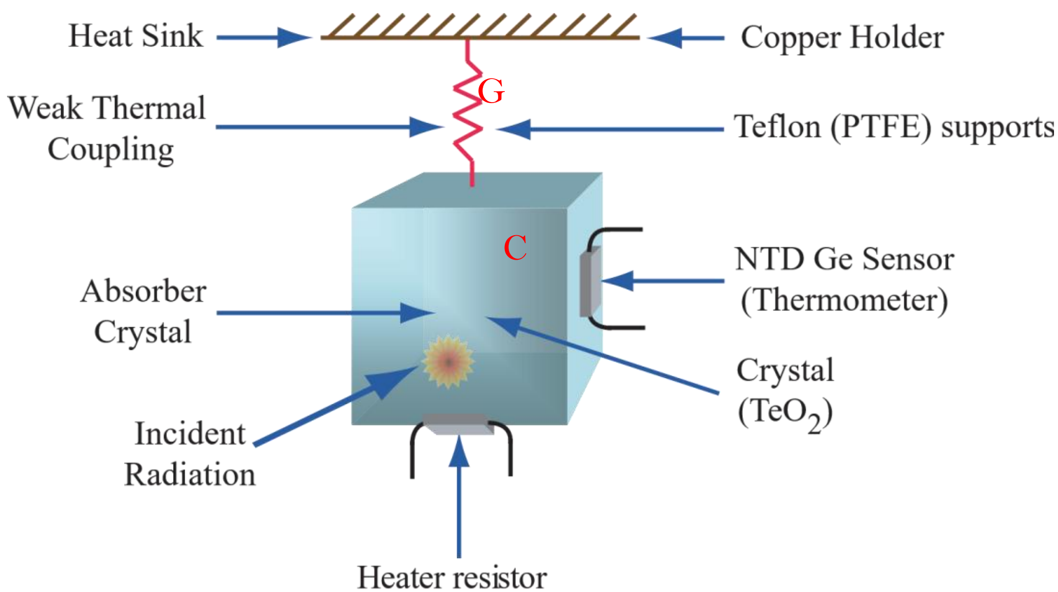
Lifetime corresponding to the minimum detectable number of events over a background at a given confidence level:

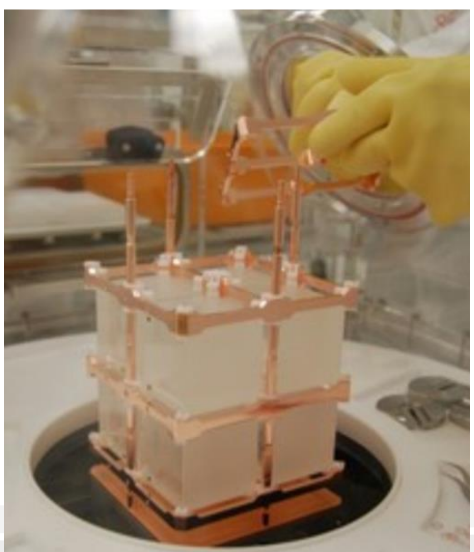
$$S^{0\nu} = ln2 \cdot \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

B: background index
M: mass
t: experiment lifetime
ΔE: energy resolution at $Q^{0\nu\beta\beta}$

Extremely low background, large masses, long observation periods and high energy resolutions are needed

Bolometric technique

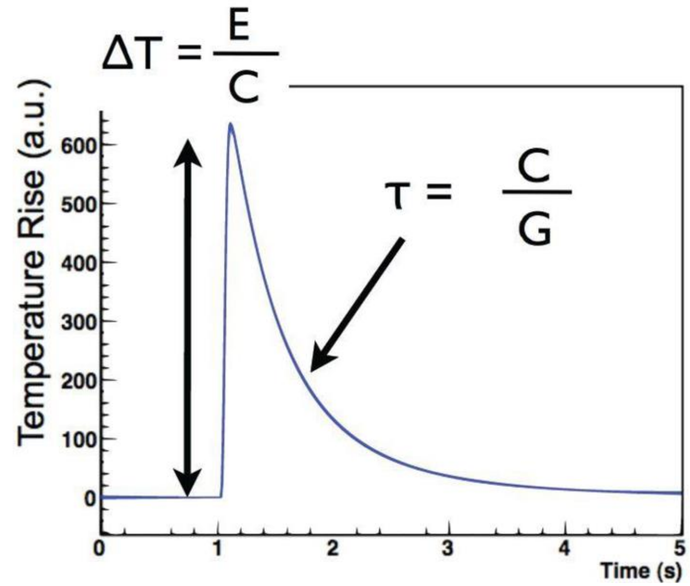




Operating principle

The energy released by the incident particle originates a temperature rise.

An NTD (Neutron Transmutation Doped) thermistor converts the rise temperature in an electrical signal.



Typical values for CUORE crystals

$$T \sim 10\ mK$$
$$M \sim 750\ g$$
$$C \sim 2\ nJ/K$$
$$\tau \sim 1\ s$$
$$\Delta T/\Delta E \sim 10\text{-}20\ \mu K/MeV$$
$$\Delta V/\Delta E \sim 300\ \mu V/MeV$$

Why bolometers?

- Excelent energy resolution
- Wide target choice
- Scalability to ton scale experiments

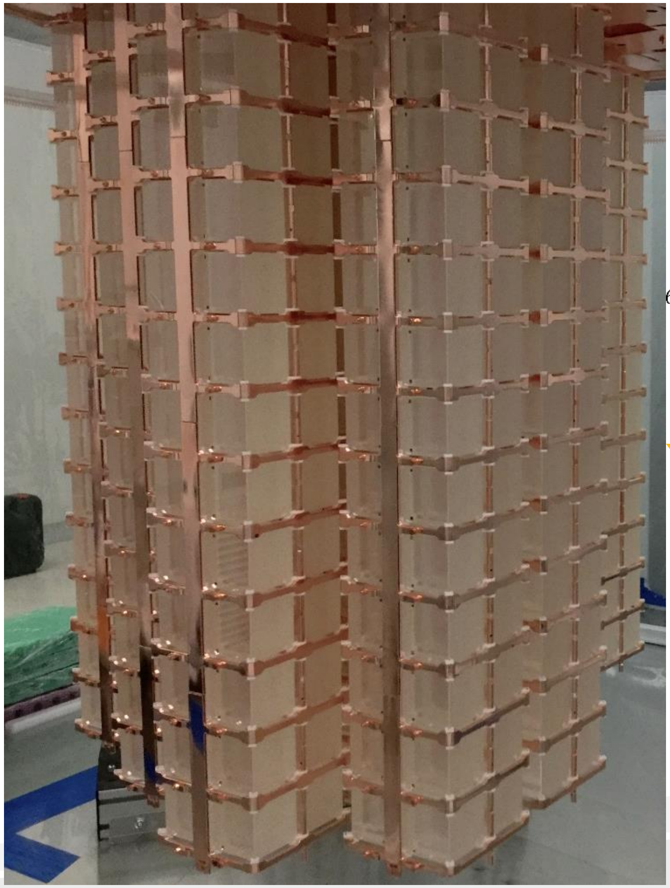
The CUORE experiment

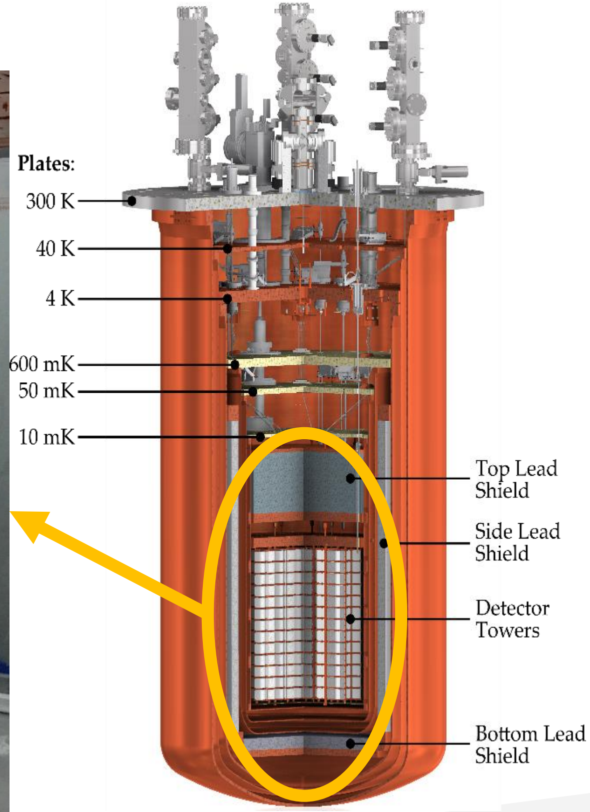
CUORE is the first ton scale experiment that researches the $0\nu\beta\beta$ decay in ^{130}Te using a bolometric technique. It is located at the underground laboratory of Gran Sasso.

- ✓ **Large mass**: 988 TeO_2 crystals($5x5x5\ cm^3$). Detector mass: 742 Kg
- ✓ **Background goal**: 0.01 counts/keV/Kg/yr
- ✓ **Energy resolution goal**: 5 keV
- ✓ Isotopic abundance: 34.167%
- ✓ Q_{Te}-value: 2528 keV
- ✓ Operating temperature: ~ 10 mK

Target sensitivity:

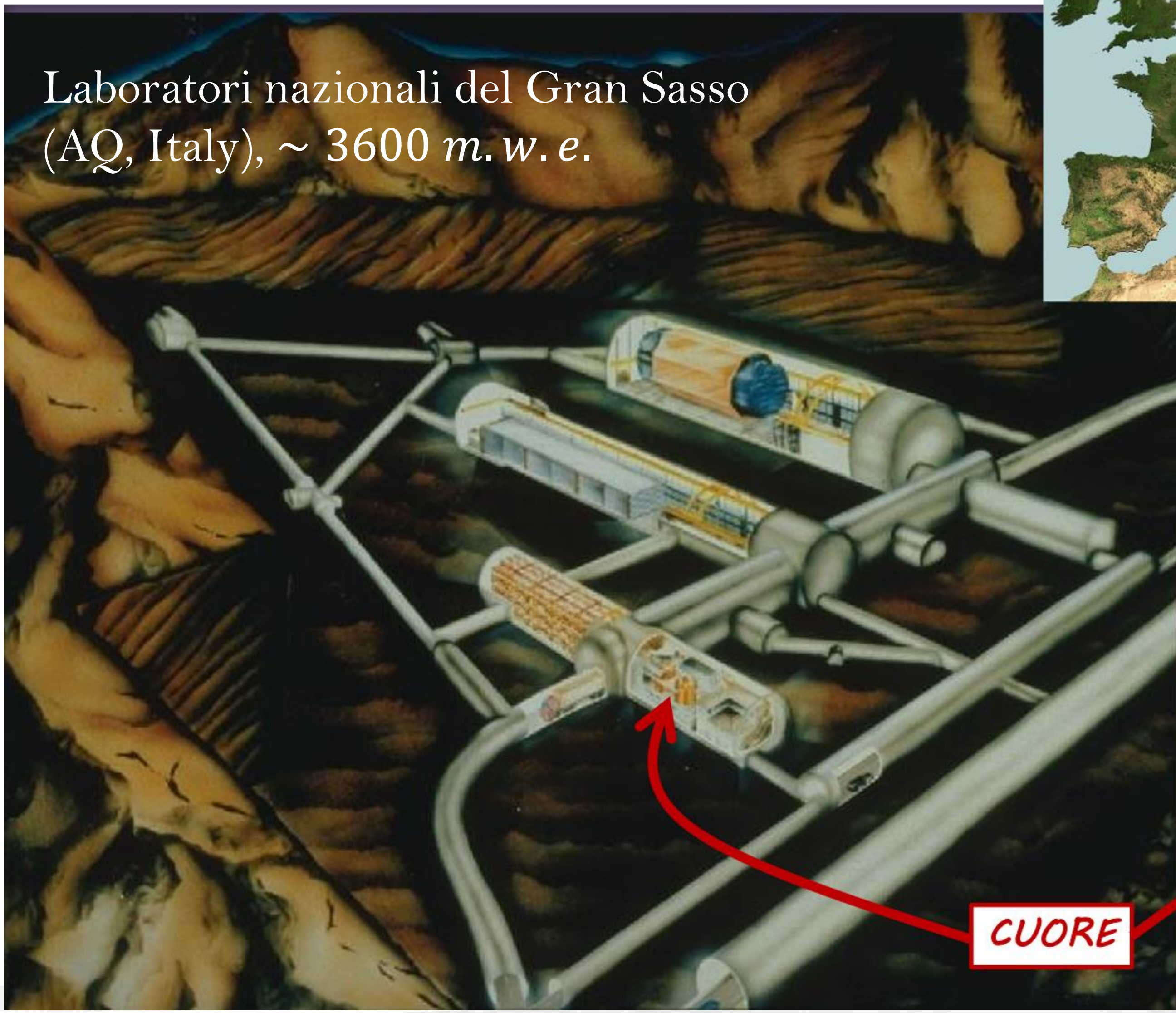
$S^{0\nu} > 9 \cdot 10^{25}$ yr (CL 90%)



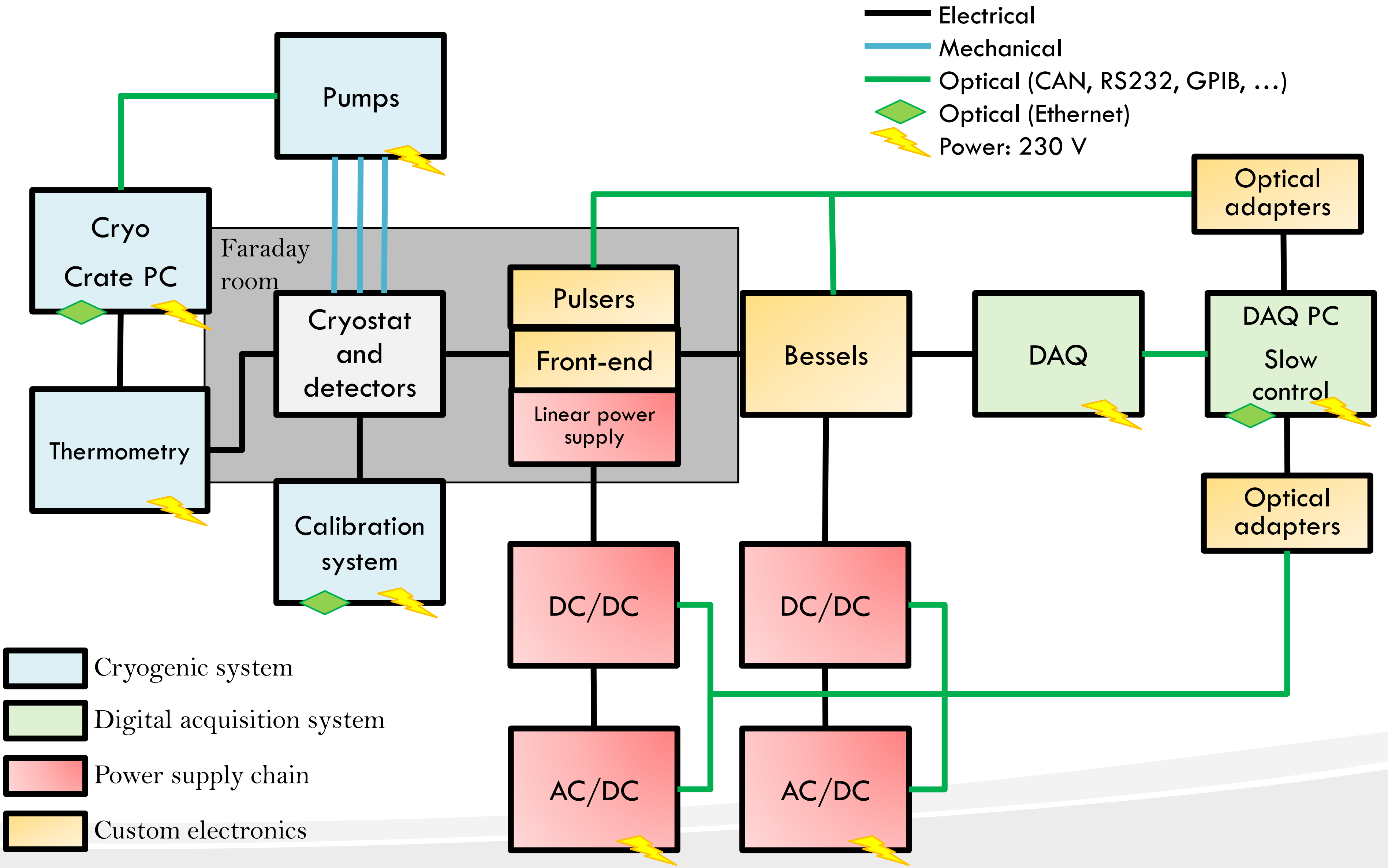


CUORE location

Laboratori nazionali del Gran Sasso
(AQ, Italy), ~ 3600 $m.w.e.$



CUORE setup

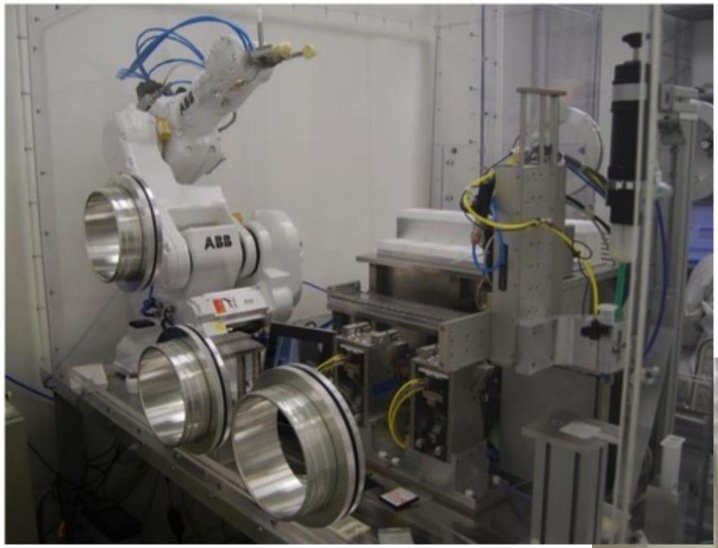

Electrical
Mechanical
Optical (CAN, RS232, GPIB, …)
Optical (Ethernet)
Power: 230 V
Pumps
Cryo
Crate PC
Faraday
room
Cryostat
and
detectors
Pulsers
Front-end
Linear power
supply
Bessels
DAQ
DAQ PC
Slow
control
Optical
adapters
Optical
adapters
Thermometry
Calibration
system
DC/DC
DC/DC
AC/DC
AC/DC
Cryogenic system
Digital acquisition system
Power supply chain
Custom electronics

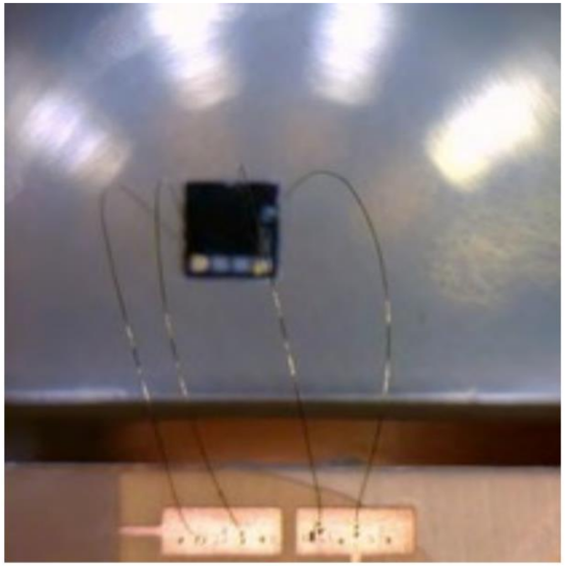
CUORE tower construction

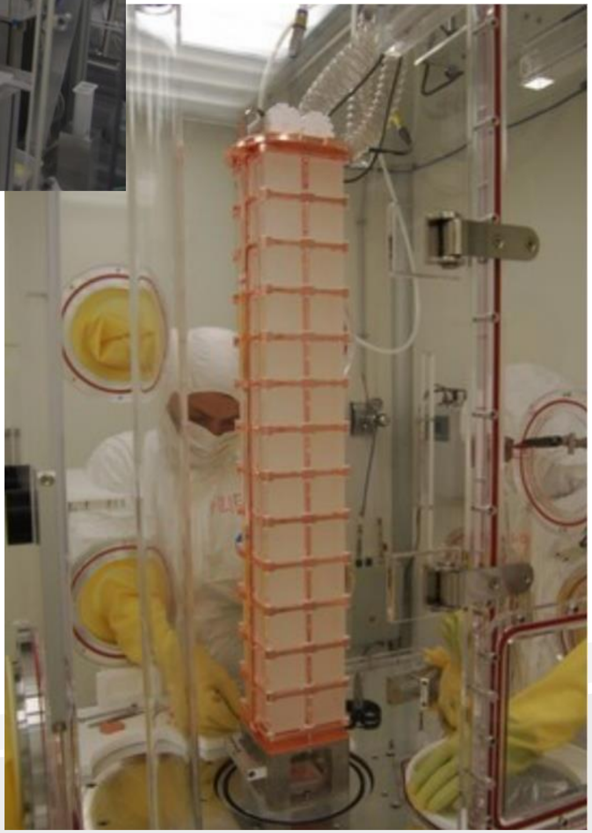
Main construction stages:

1. Thermistor and heater gluing
2. Tower assembly (in glove boxes)
   - Copper support structure
   - Teflon supports
   - Crystals
   - Lines for signal redout
3. Sensor and heater bonding

All these steps refined thanks to the pilot experiments CUORICINO and CUORE-0.

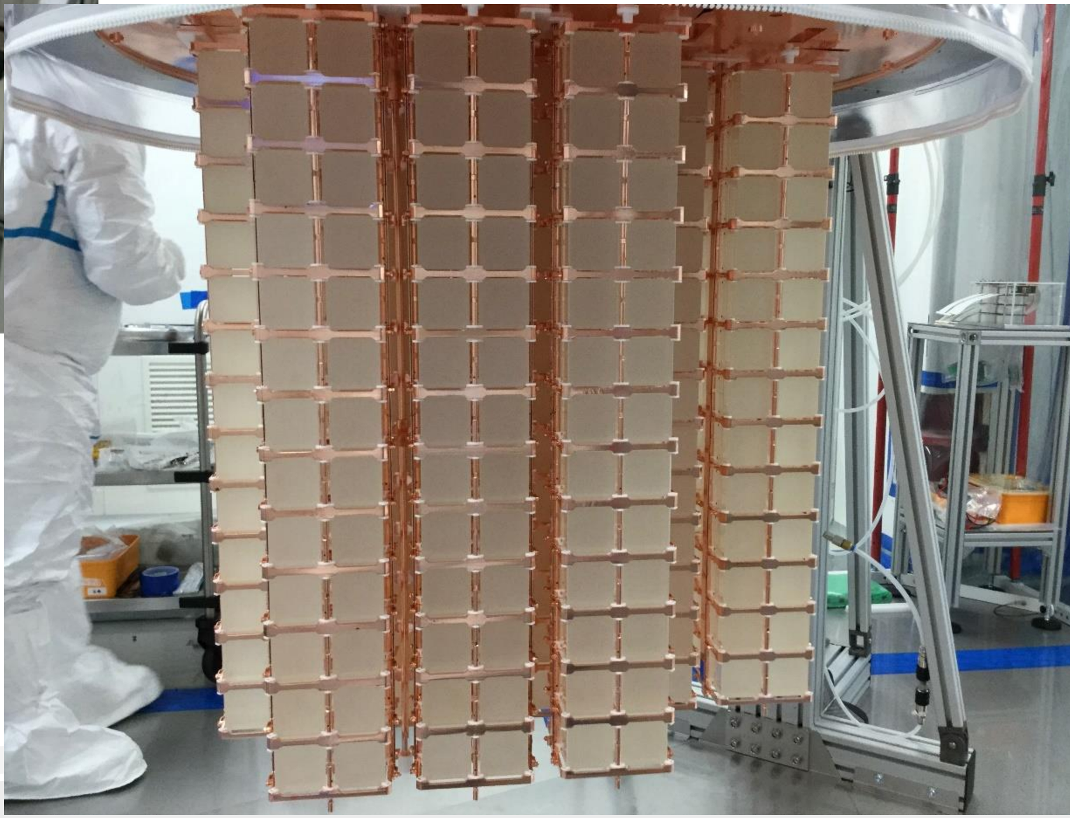






CUORE detector construction

The towers were finally installed inside the cryostat.
This represents the first and only time when the towers were exposed to radon-free air.



All the towers were installed in August 2016, 1 tower per day.

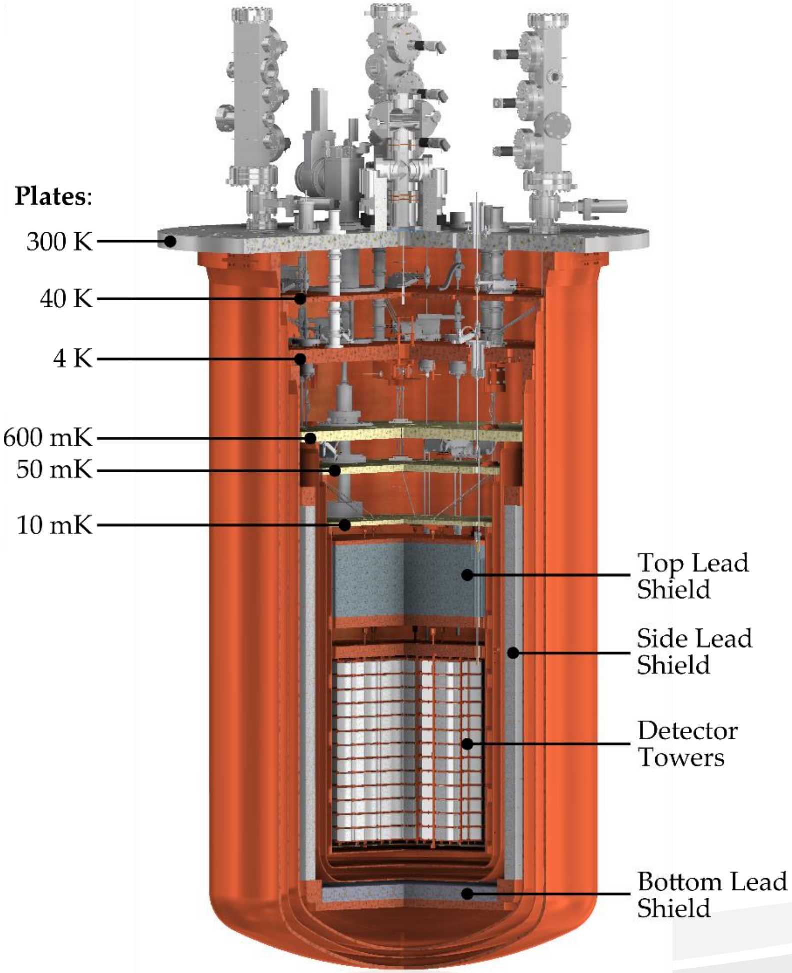
The CUORE cryostat

Custom diluition refrigerator

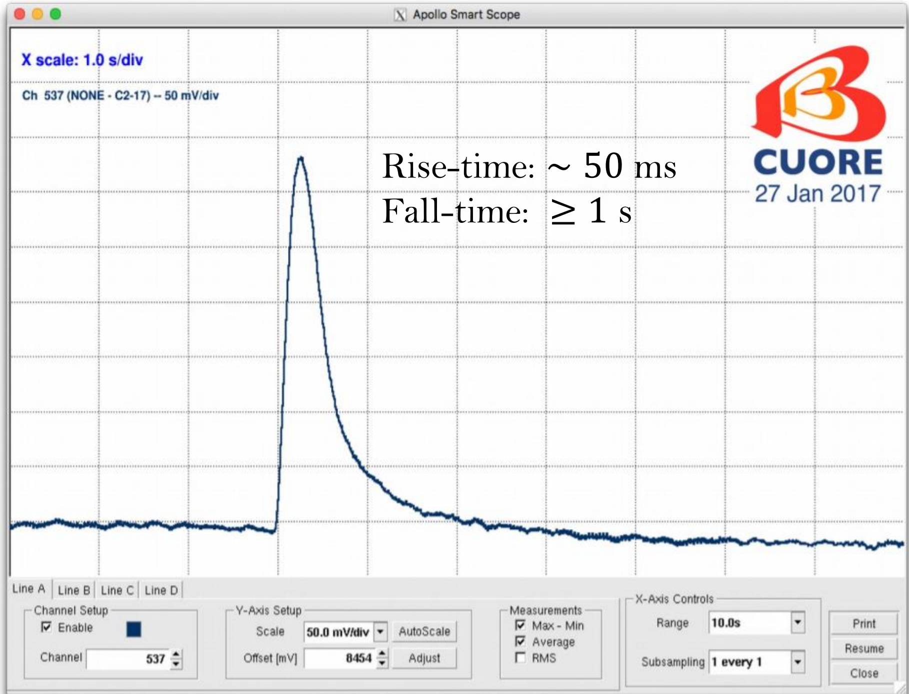
- ~ 1 ton of detectors cooled at ~ 10 mK
- ~ 20 tons cooled below room temperature
- Multi-stage suspension system to mechanically decoupled the detector from the cryostat

Cryostat comminissioning completed in March 2016

- Long term stability demonstrated
- Cool down started in late 2016.
- Base temperature: $\sim 8 - 10\ mK$ reached in January 2017



Signals of interest



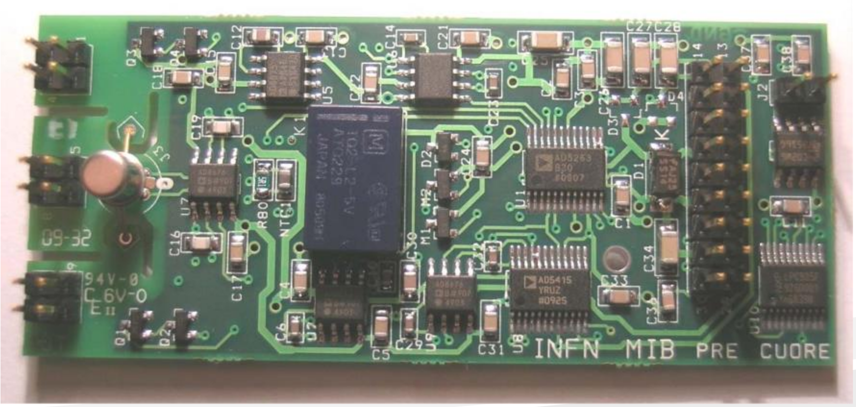
Features

The rate of the signals of interest is extremely low.

For macro-bolometers, the time evolution of the thermal signals is slowed by the large heat capacitance. The electrical signals are very slow.

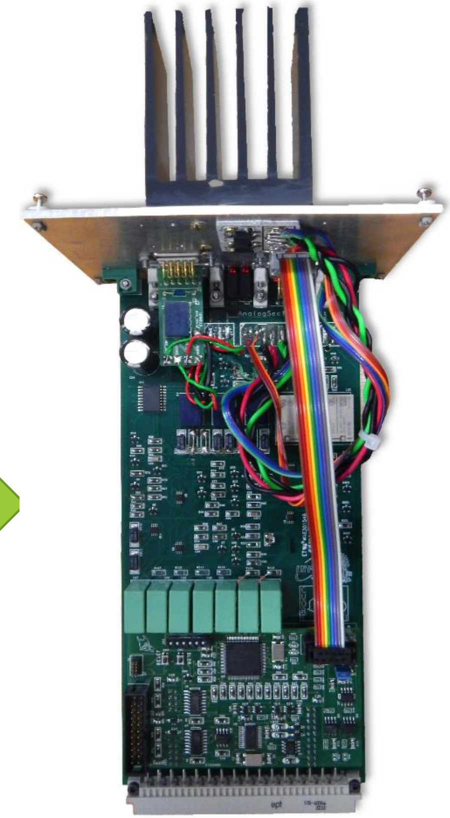
Low noise (i.e. high energy resolution), especially at low frequency, and outstanding stability are required to maximize the sensitivity.

- ✓ Microphonism and cross-talk minimized using a differential voltage sensitive preamplifier and twisted cables.
- ✓ 1/f noise minimized by using matched JFET at the input
- ✓ Thermal calibration to compensate for the drifts
- ✓ Bandwidth of interest: ≤ 15 Hz



CUORE preamplifier

Power supply chain



AC/DC:

- 48 V
- Up to 25 A
- Commercially available

DC/DC:

- Provides the bias to the linear power supply (two adjustable output voltages, $6.5\,V - 15$ V)
- Provides the bias to the digital system. (one adjustable output voltage, $4.5\,V - 8$ V)

Linear power supply (LPS):

- Provides the bias to the main board and to the analogic system (dual programmable output voltage, $\pm 2.5\,V - \pm 6.25$ V)

Stabilization system

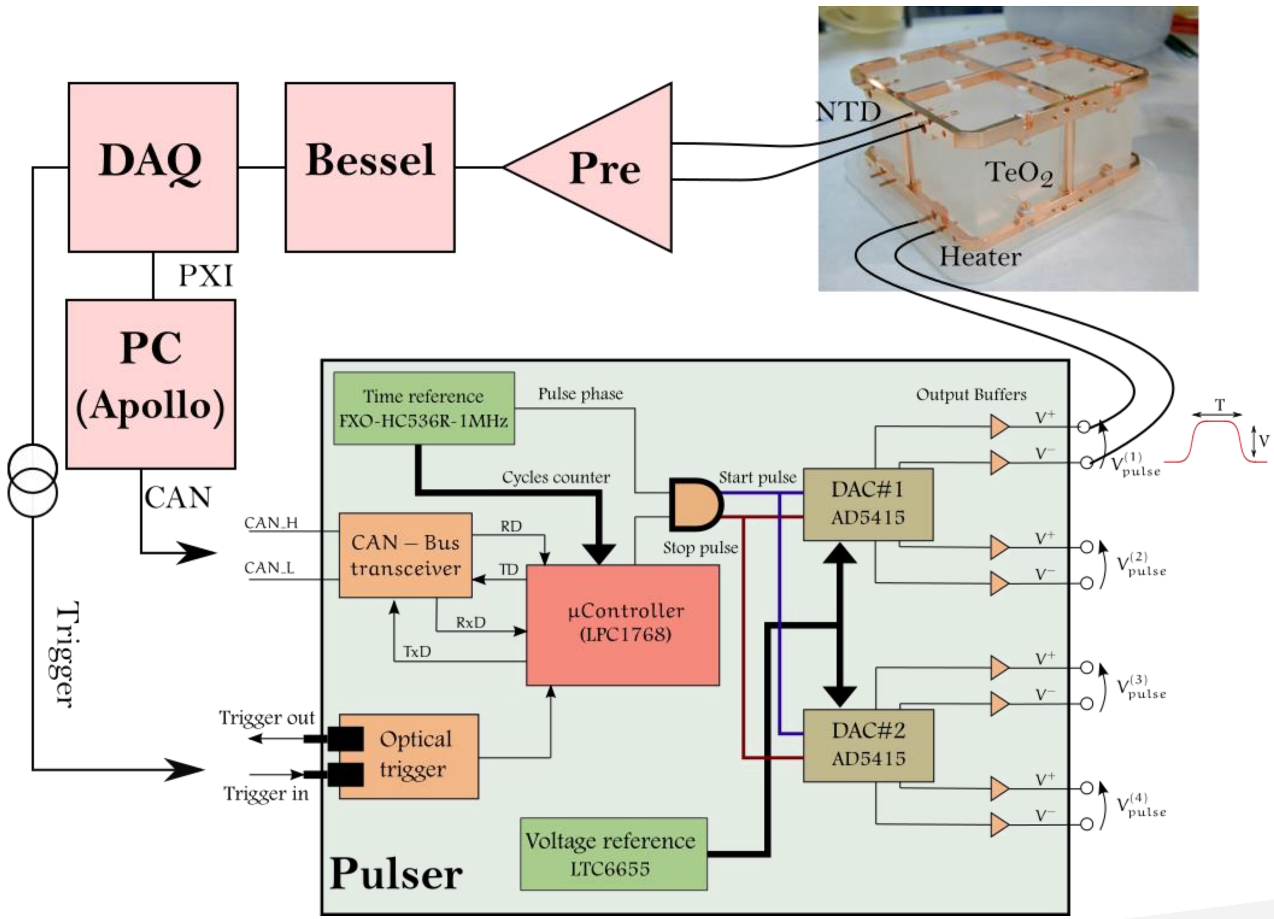
Goal

Periodically deliver a Joule pulse in order to compensate for the system drifts. Energy released per pulse:

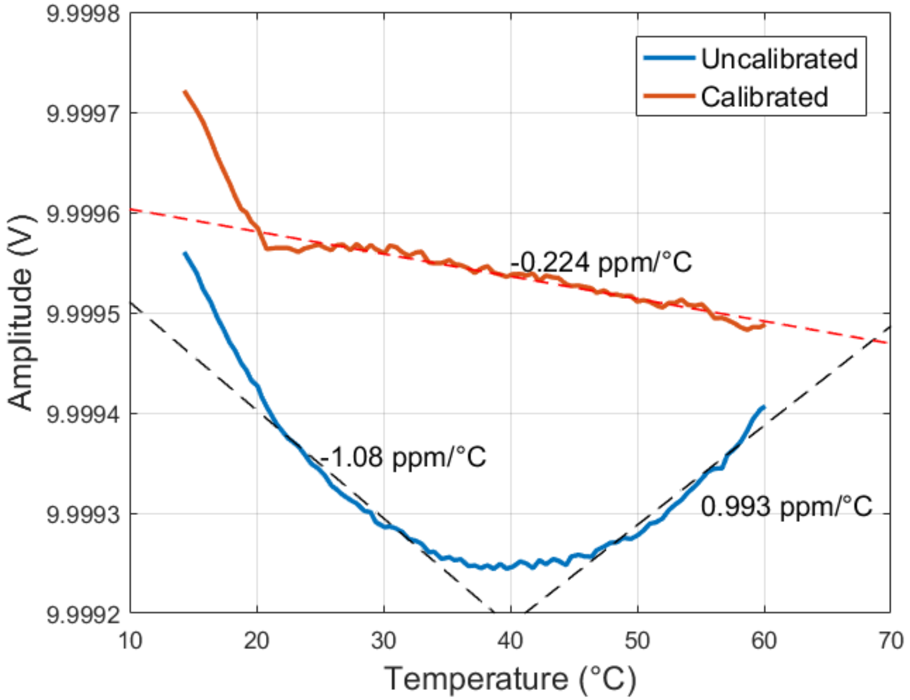
$$E \propto \frac{V^2 t_W}{R_H}$$

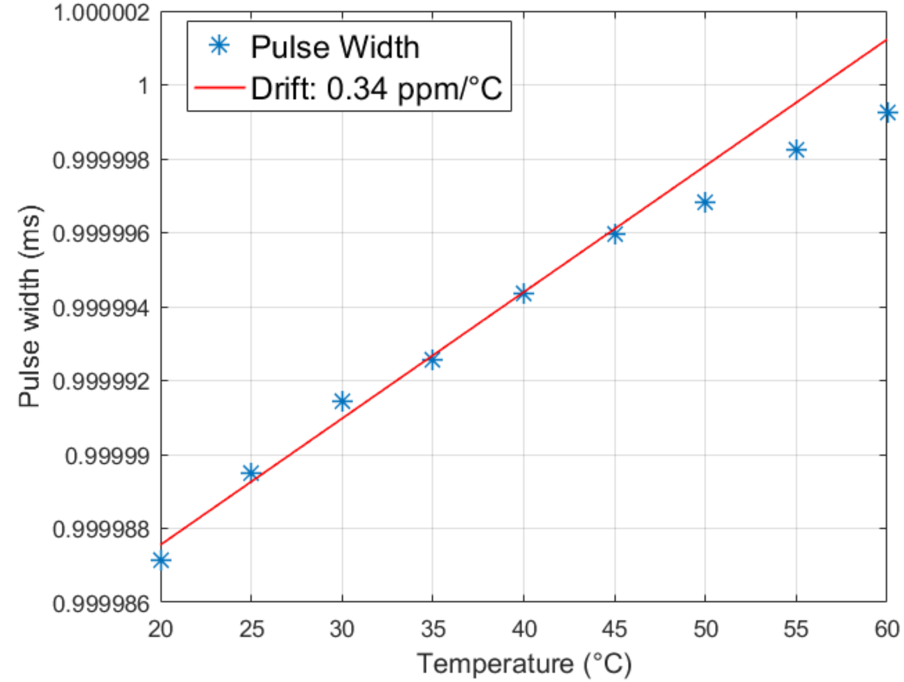
Main requirements

- Delivering ultra stable squared pulses (temperature fluctuation rejection between 20°C and 60°C).
- Low noise and jitter
- Providing DC voltage level for the temperature stabilization.



Pulse amplitude thermal stability





The thermal drifts of the voltage reference, the DAC and the reference clock can cause a variation of the energy provided by the pulses: $\boldsymbol{dE/dT = 2\,dV/dT + dt_W/dT}$

Each board has been calibrated in order to compensate such drifts by adjusting an on-board 8-bit trimmer.

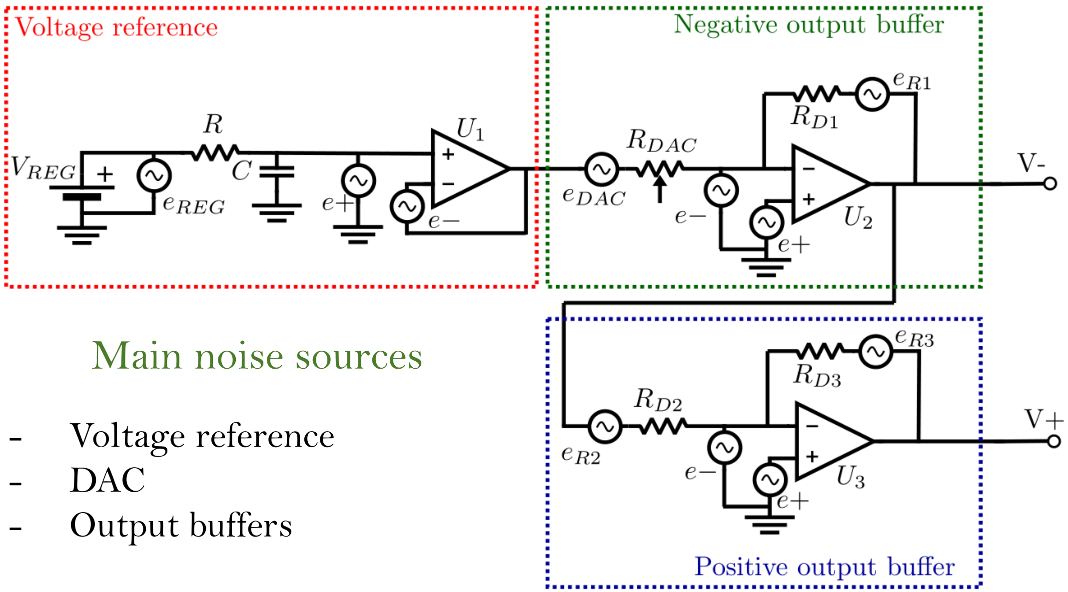
Results (20-60 °C)

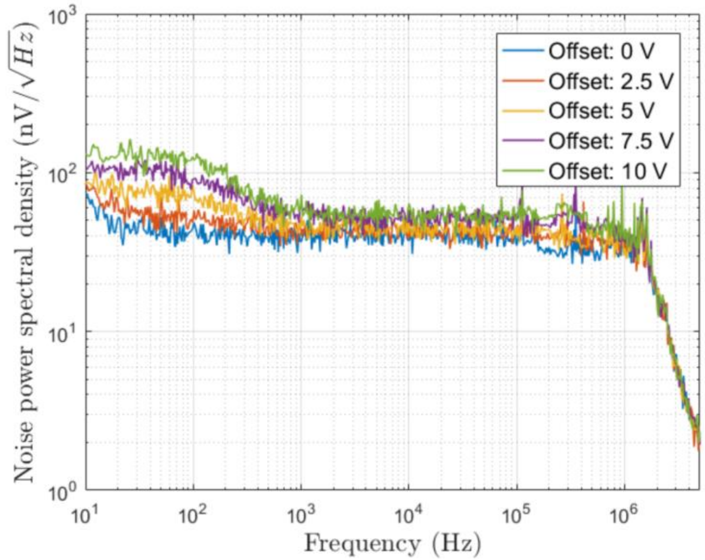
Intrinsic thermal stability: $dV/dT \sim \pm 1\,ppm/°C,$ $dt_W/dT \sim \pm 0.35\,ppm/°C$

After thermal calibration: $2\,dV/dT \simeq -dt_W/dT \quad \rightarrow \quad dE/dT \sim \pm 0.1\,ppm/°C$

Pulse resolution: voltage noise

Pulse amplitude or width fluctuations determine the intrinsic energy resolution of the pulser. It must be neglibile with respect to the bolometer resolution: 5 keV @ 2.5 MeV





Main noise sources

- Voltage reference
- DAC
- Output buffers

At noise of the voltage reference is modulted by the DAC: $\overline{e^2} \propto (V/V_{REG})^2$

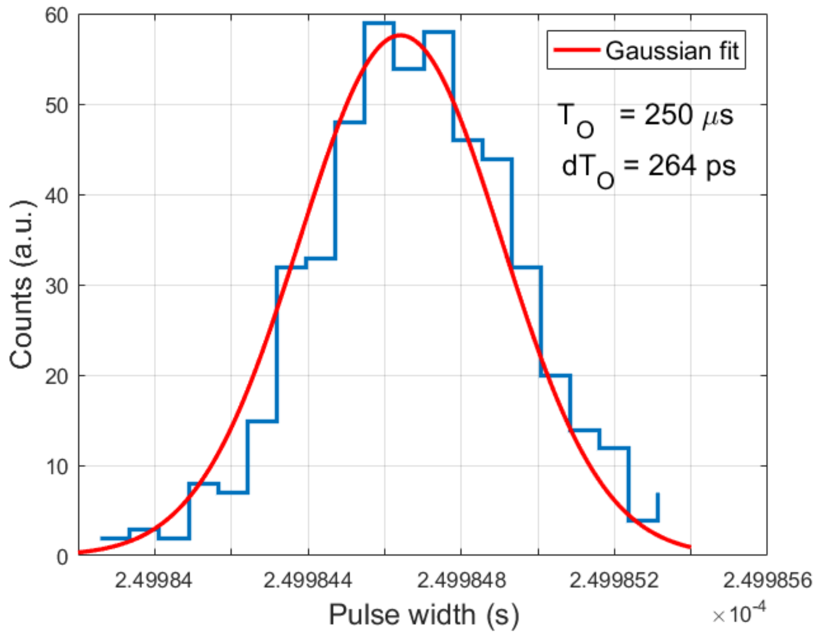
The high frequency noise averages to zero during the pulse delivery and do not effectively contribute: $BW_N \propto t_W^{-1}$

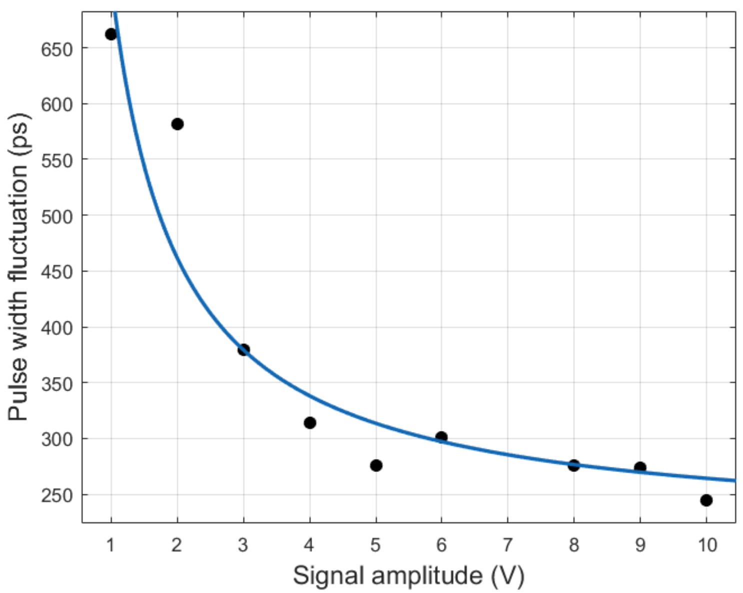
$$dV_{RMS} \propto \sqrt{\overline{e^2} BW_N} \propto \frac{V}{\sqrt{t_w}} \rightarrow dE_{RMS} \propto dV_{RMS} t_W \propto V\sqrt{t_W} \propto \sqrt{E}$$

$$\frac{dE_{RMS}}{E} = \frac{2 \cdot 10^{-3}}{\sqrt{E[eV]}} \rightarrow \frac{dE_{RMS}}{E} = 2\ ppm\ @\ E = 1\ MeV$$

Pulse resolution: width fluctuation

Pulse amplitude or width fluctuations determine the intrinsic energy resolution of the pulser. It must be neglibile with respect to the bolometer resolution: 5 keV @ 2.5 MeV



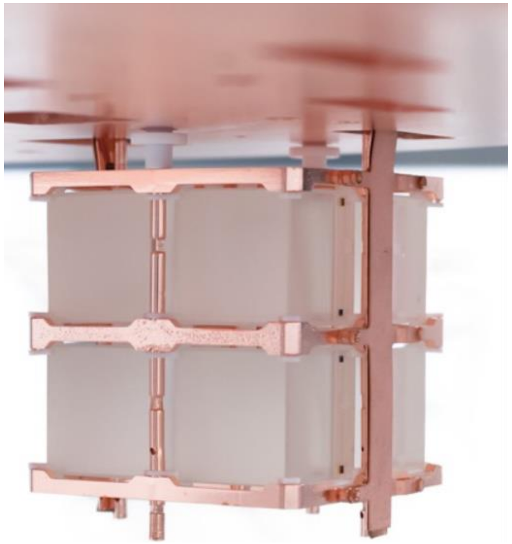


Results:

Pulse width fluctuation estimated as the standard deviation of the pulse width distribution of 1000 pulses acquired with a RTO1044

$$\frac{dE}{E} = \frac{dt_W}{t_W} \leq 0.5\ ppm$$

Preliminary measurement with mini-tower



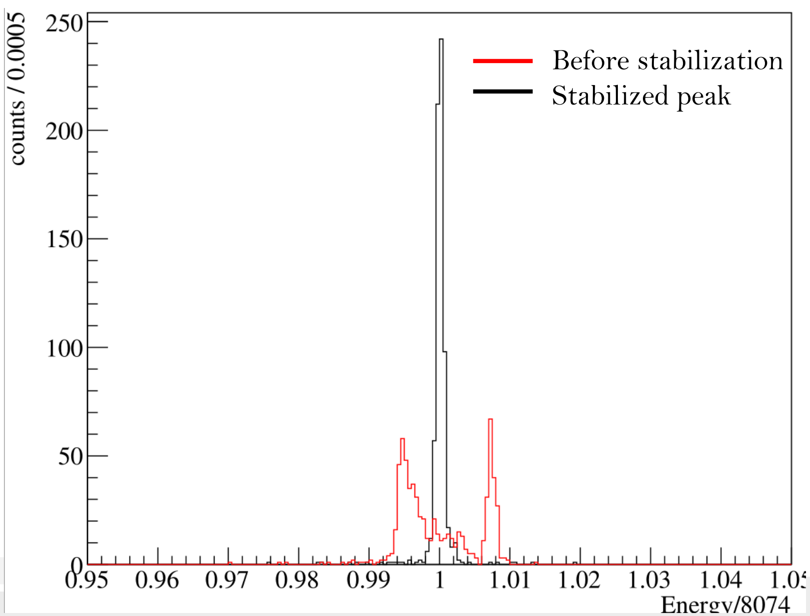
In the end of 2015, a run was performed using 8 CUORE crystals.

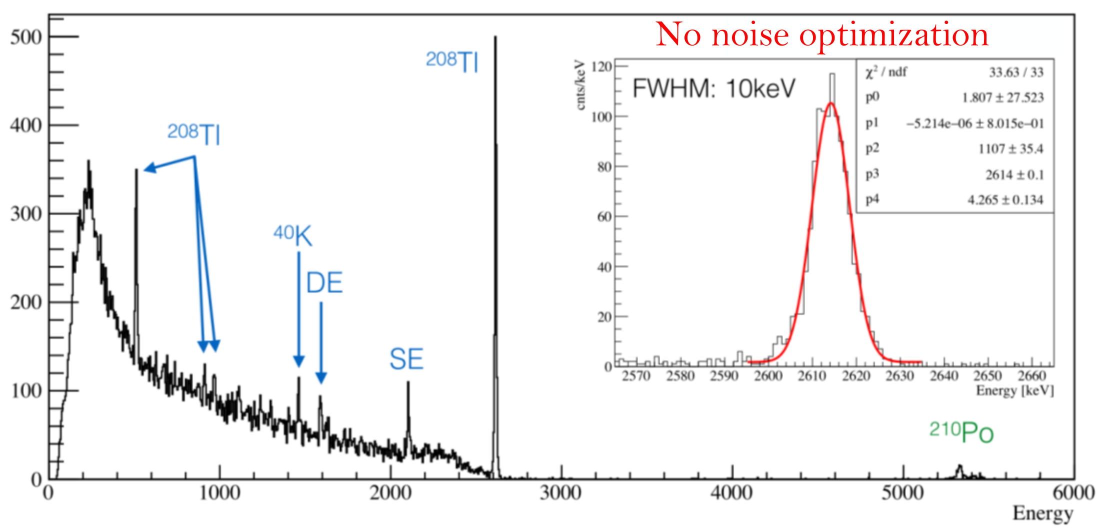
Goals

- Cryostat commissioning
- Small scale test of CUORE whole setup before the full detector assembly.
- Small scale electronic chain test in the final environment.

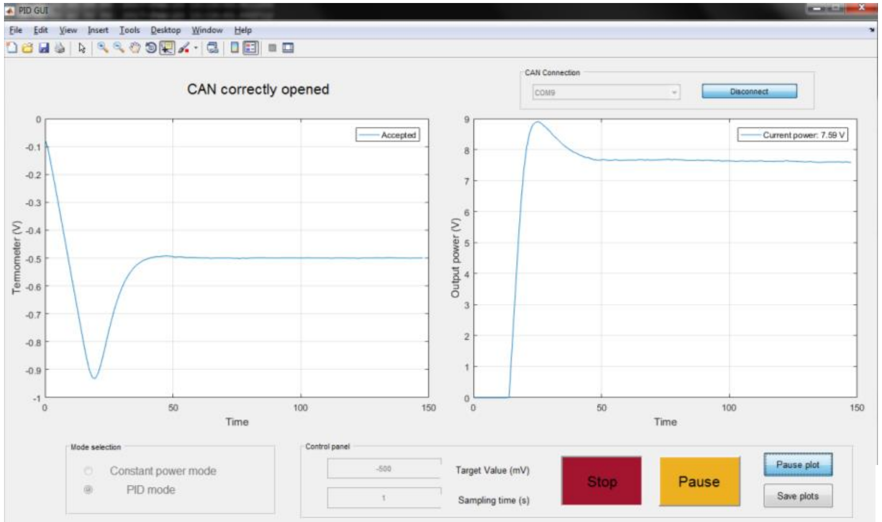
Important notes

No optimization for noise reduction: energy resolution worse than that of CUORE!





Temperature stabilization



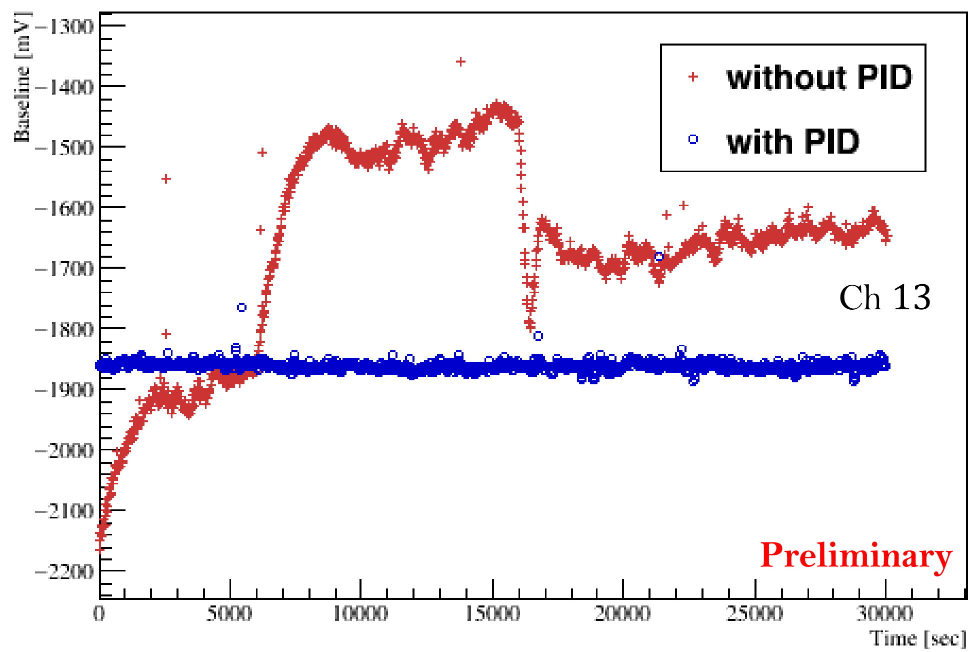
The pulser can provide a costant and adjustable power to warm up the detector.

Goal

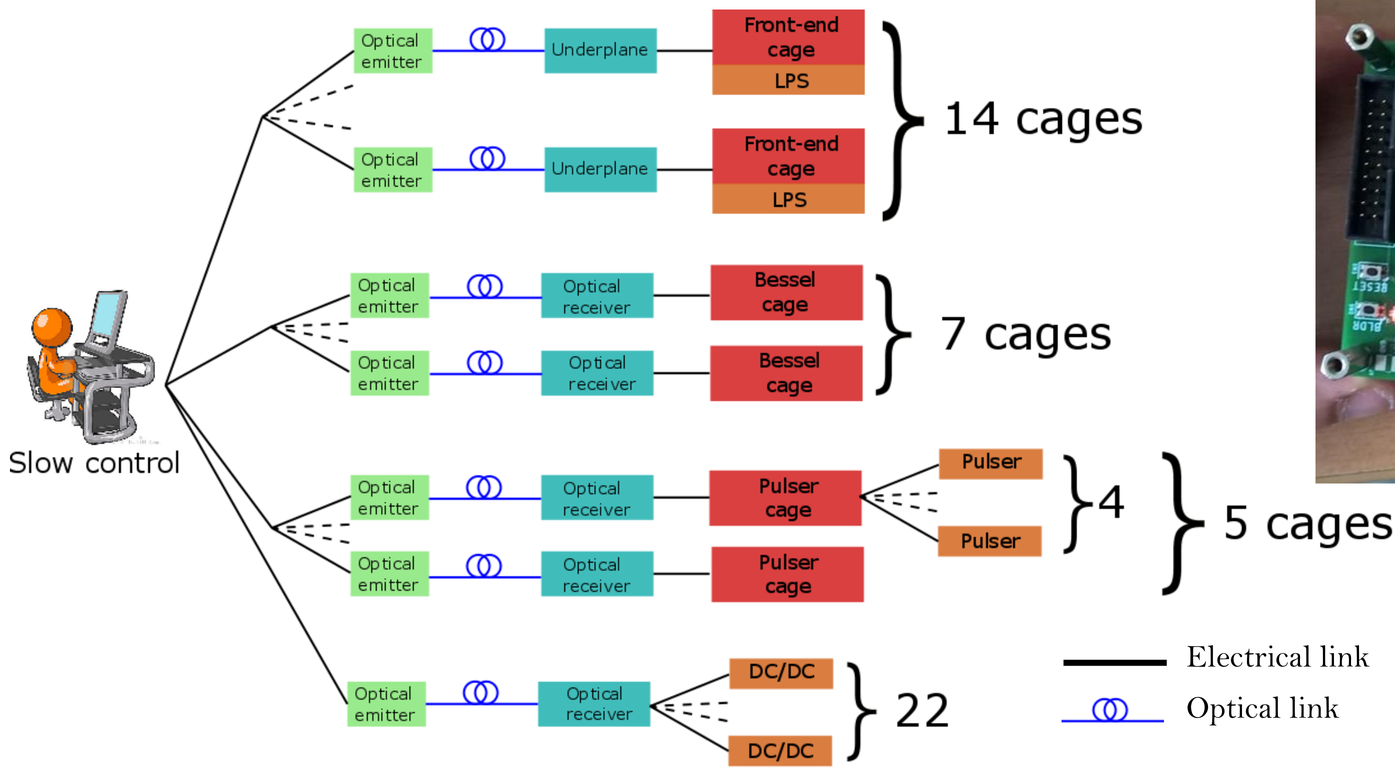
- Optimize the operating temperature of bolometer and NTDs.
- Reject the usual temperature fluctuations of the cryostat

The current stabilization system setup is based on a Proportional-Integral-Derivative (PID) algorithm written in MATLAB.

The calculating capability of the pulser board can be exploited to embed the PID controller into the microcontroller firmware.



CUORE remote control



~ 50 adapters used

The whole electronics can be set and monitored via CAN bus protocol from a unique remote controller.

A CAN-to-Optical decoupler was developed in order to optically disentangle the slow control with the electronic system (DC/DC, LPS, front-end board, bessel filter and pulsers).

Electronic assembly

The whole system setup was pre-installed, calibrated and characterized in the Milano Bicocca labs. Then the system was moved to the final experimental setup at LNGS.

The setup was installed, tested and optimized between the 2016 and early 2017.

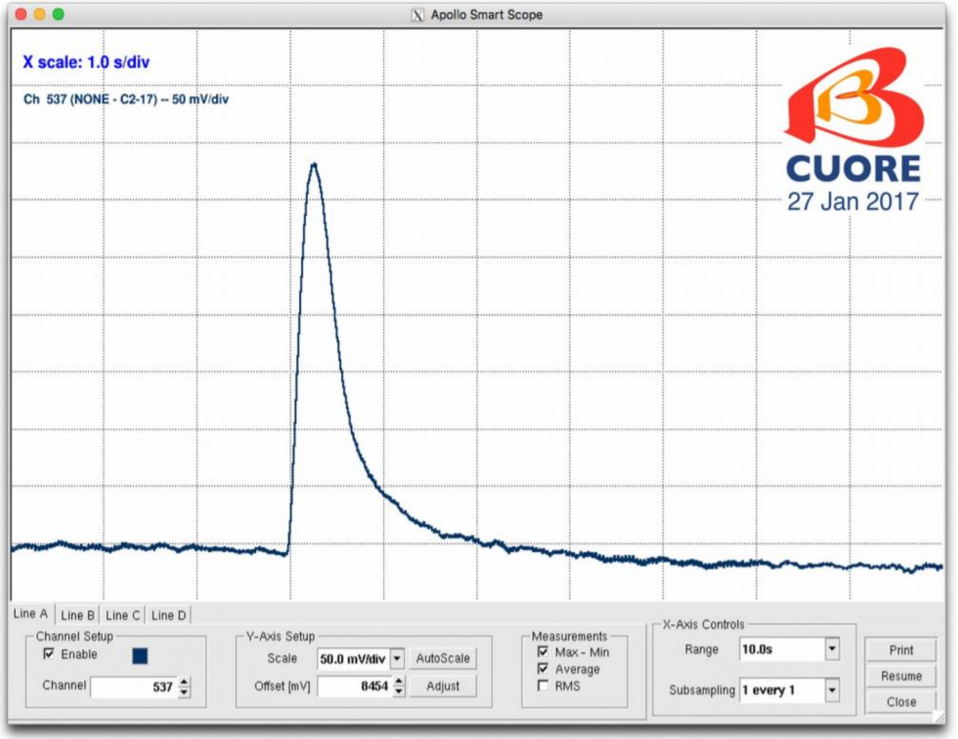
Frontend and stabilization system

Optical decouplers

Power supply chain

Conclusions

- CUORE is a ton scale experiment researching the neutrinoless double beta decay in ^{130}Te adopting a bolometric technique.
- The detector installation completed successfully in the second half of 2016
- The electronic system was installed in first half of 2016 and then optimized on-site.
- The experiment reached the base temperature of 10 mK in early 2017.



- The CUORE detector operation has started and the first pulses have been acquired.
- Electronic and DAQ debugging, noise, working point and trigger optimiztion almost completed.
- The first physics data will come soon

The end

Thank you for the attention!