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Leakage detection in water distribution networks using cosmic ray neutrons in the thermal region

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UNIVERSITÀ DEGLI STUDI DI BRESCIA & INFN PAVIA

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Introduction

- In 2023, I presented here (for the first time) an idea
  - **to use cosmic ray neutrons (in the thermal region) to identify leakages in water distribution networks**
- At the time the research was still in the early stages, I only presented a series of MC studies to support the original idea
- Later, we refined the technique: we investigated the effect of different soil compositions, the placement of the crack in the pipeline, the moisture gradient in the subsurface, etc.
- And we published this work...
- Today, for the first time, we also present **preliminary** experimental data (to be published later this year)

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Full Length Article

Investigating the possibility of leakage detection in water distribution networks using cosmic ray neutrons in the thermal region

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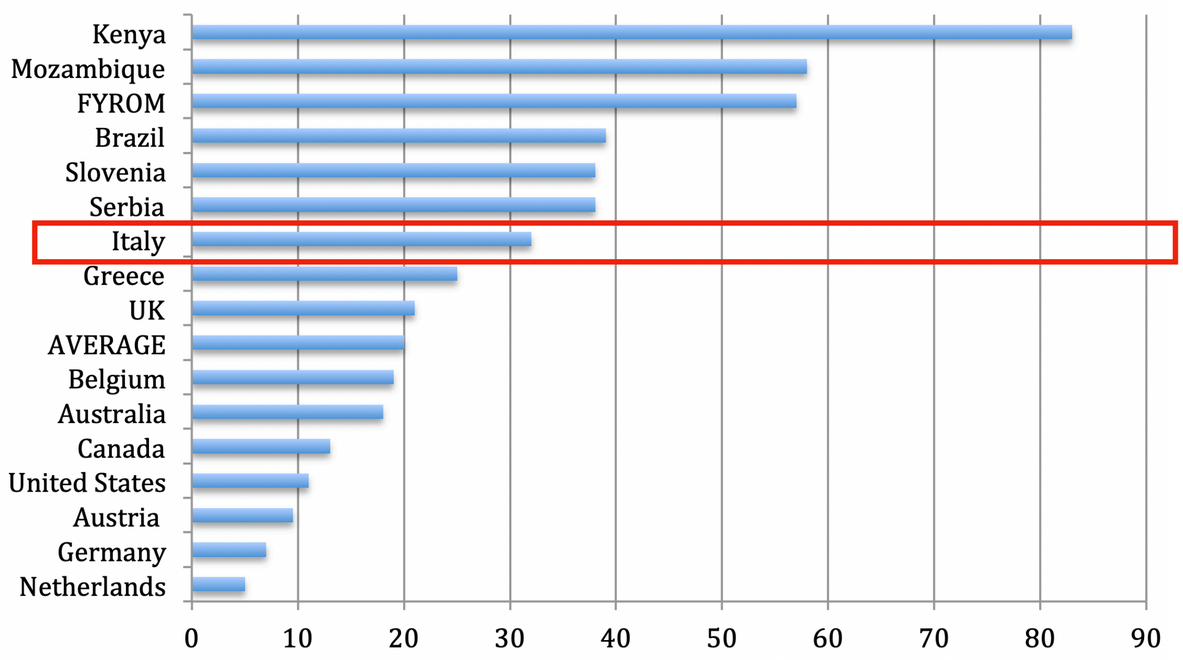
Leakages in water distribution networks

- Leakage rate in water distribution networks
  (data from Global Water Intelligence, 2008)

- Did things get better for Italy 15 years later?

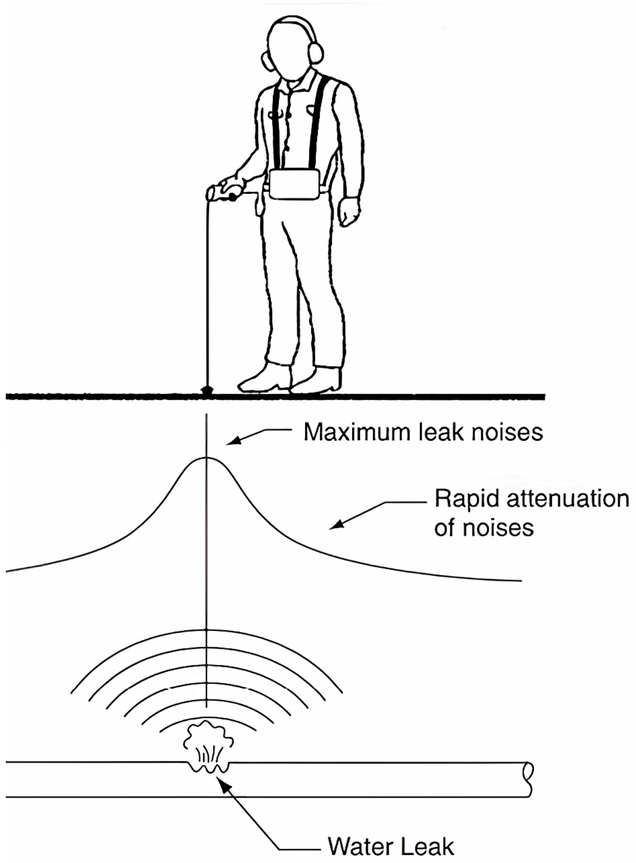
- ISTAT (Italian national institute of statistics): **36.2%** of the water in the distribution networks is loss every year

- What are the mostly used techniques to identify leakages in distribution networks?



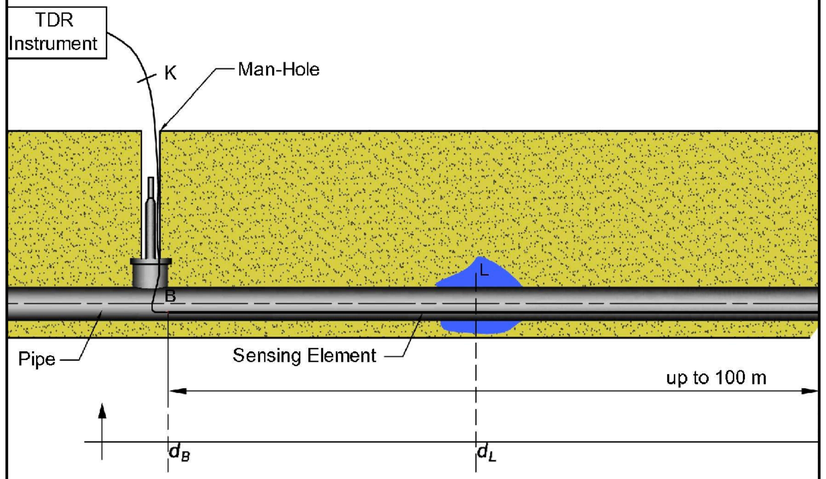
Common techniques for leakages detection

Sounding/acoustic devices



https://www.subsurfaceleak.com/

Noise correlator sensors



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Ground penetrating radars

Cosmic-ray neutrons and water content of soil

- The Cosmic Ray Neutron Sensing (CRNS) technique was originally proposed for hydrological and environmental applications and demonstrated by few research groups

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doi:10.1029/2009WR008726
doi:10.1002/2015GL063963
doi:10.2136/vzj2017.04.0086
doi:10.3390/agriculture9090202

- Fast neutrons penetrate a few tens of g/cm^2 of matter, that is some hundreds (tens) of meters (cm) of air (soil) before being thermalized

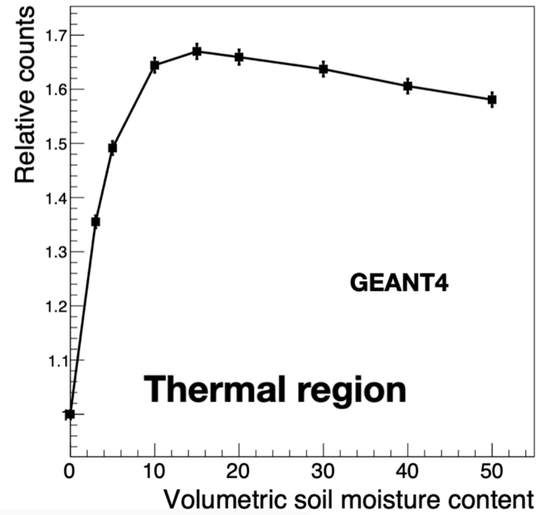
- An equilibrium concentration of neutrons is established in both air and soil, depending on:
  - the production rate of fast neutrons
  - the efficiency of moderating of fast neutrons, that is the content of hydrogen

- From the intensity of epithermal neutrons, the hydrogen content is inferred

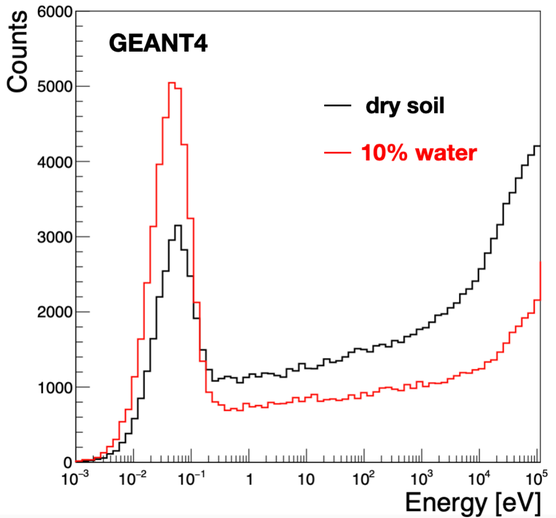
- Because of the dependence on air pressure, air humidity, vegetation, soil composition, etc., a reliable assessment of the soil water content requires the applications of complex corrections, filters and calibration functions

Cosmic-ray neutrons for leakage detection

- We investigated the possibility of using CR neutrons for subsoil leakages detection, with two important differences w.r.t. what currently used in this field:
- the use of two sensitive layers for neutrons
  - we are only interested in localizing underground regions with an anomalous large water content with respect to the surrounding soil
- the detection of neutrons in the thermal region

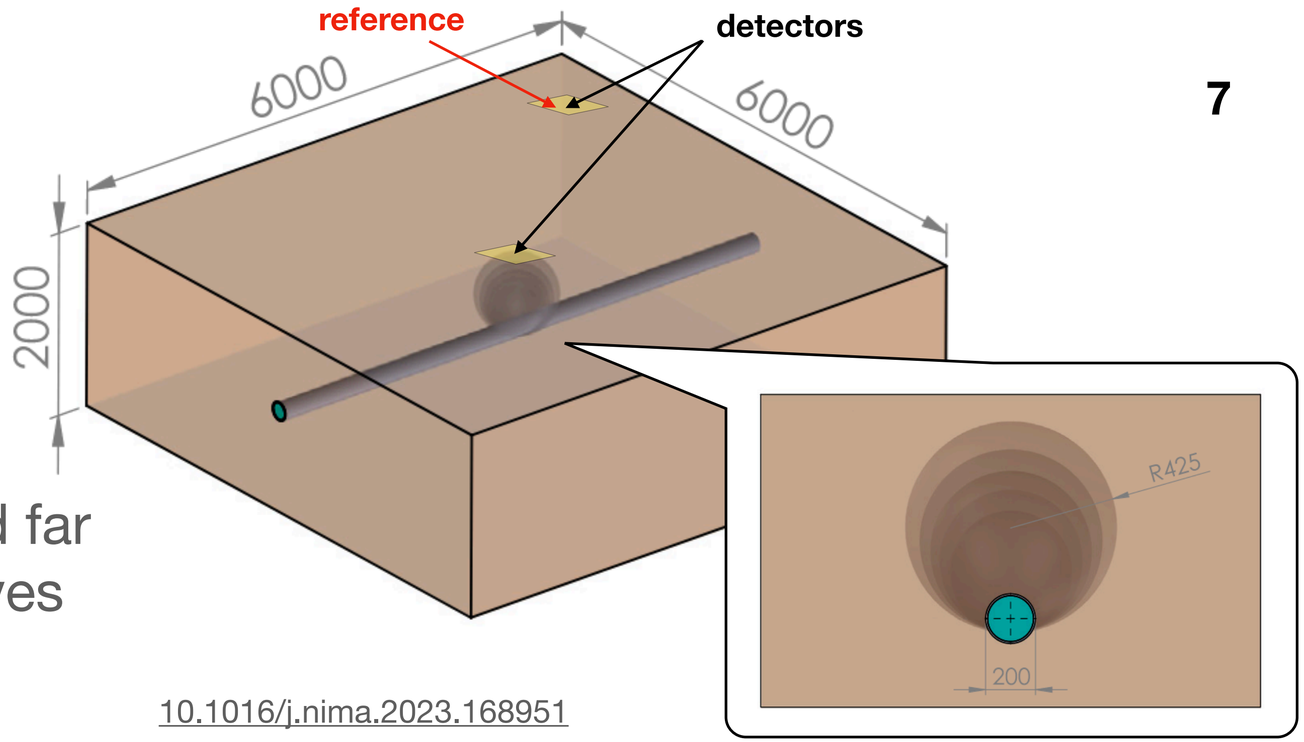


- Expected main advantages/drawbacks of this approach:
  - less sensitivity to calibration functions, thanks to a relative measurement between the two detectors
  - possible higher sensitivity to small signals
  - worse capability of an absolute measurement of the water content in soil

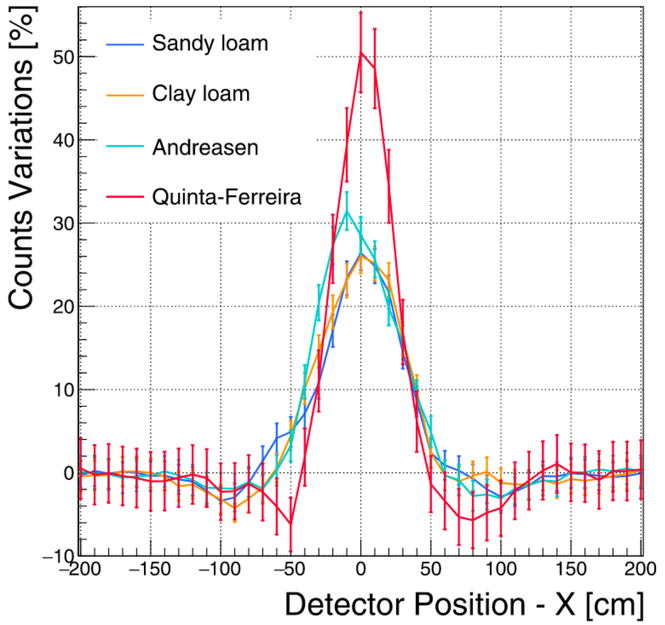


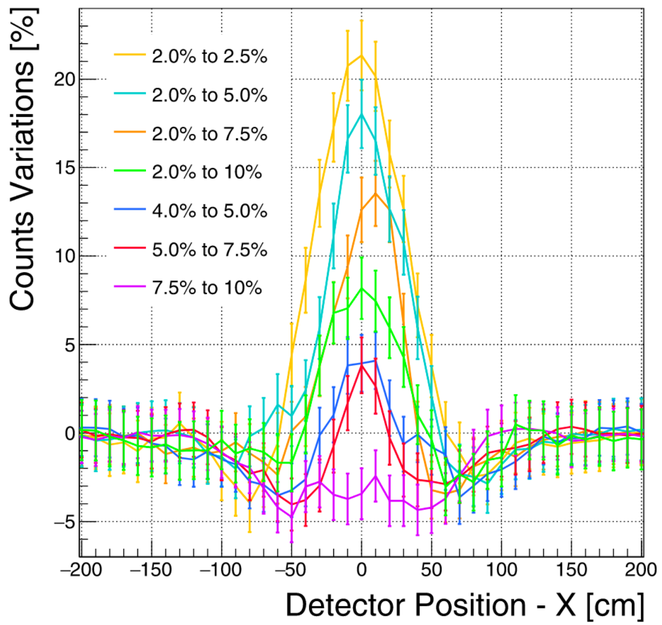
Some simulation results

- Several (realistic) scenarios of subsoil leakages from pipes were simulated
- One of the detectors (reference) is placed far from the pipe, whereas the other one moves along the pipe
- Performance of the technique mainly impacted by:
  - soil composition
  - environmental water content
- How much can we trust simulation results to claim the feasibility of the technique?



10.1016/j.nima.2023.168951

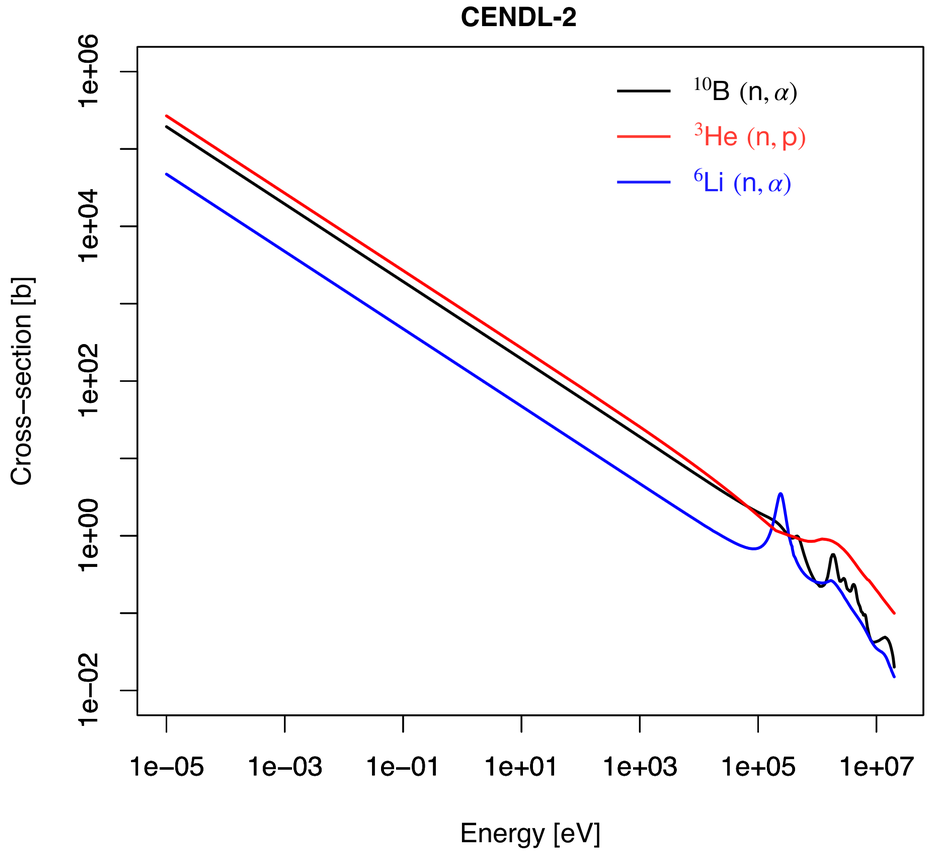


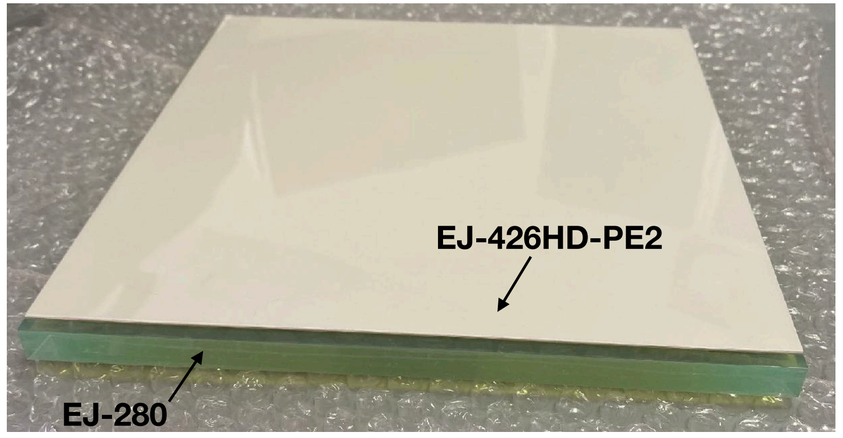


Detector

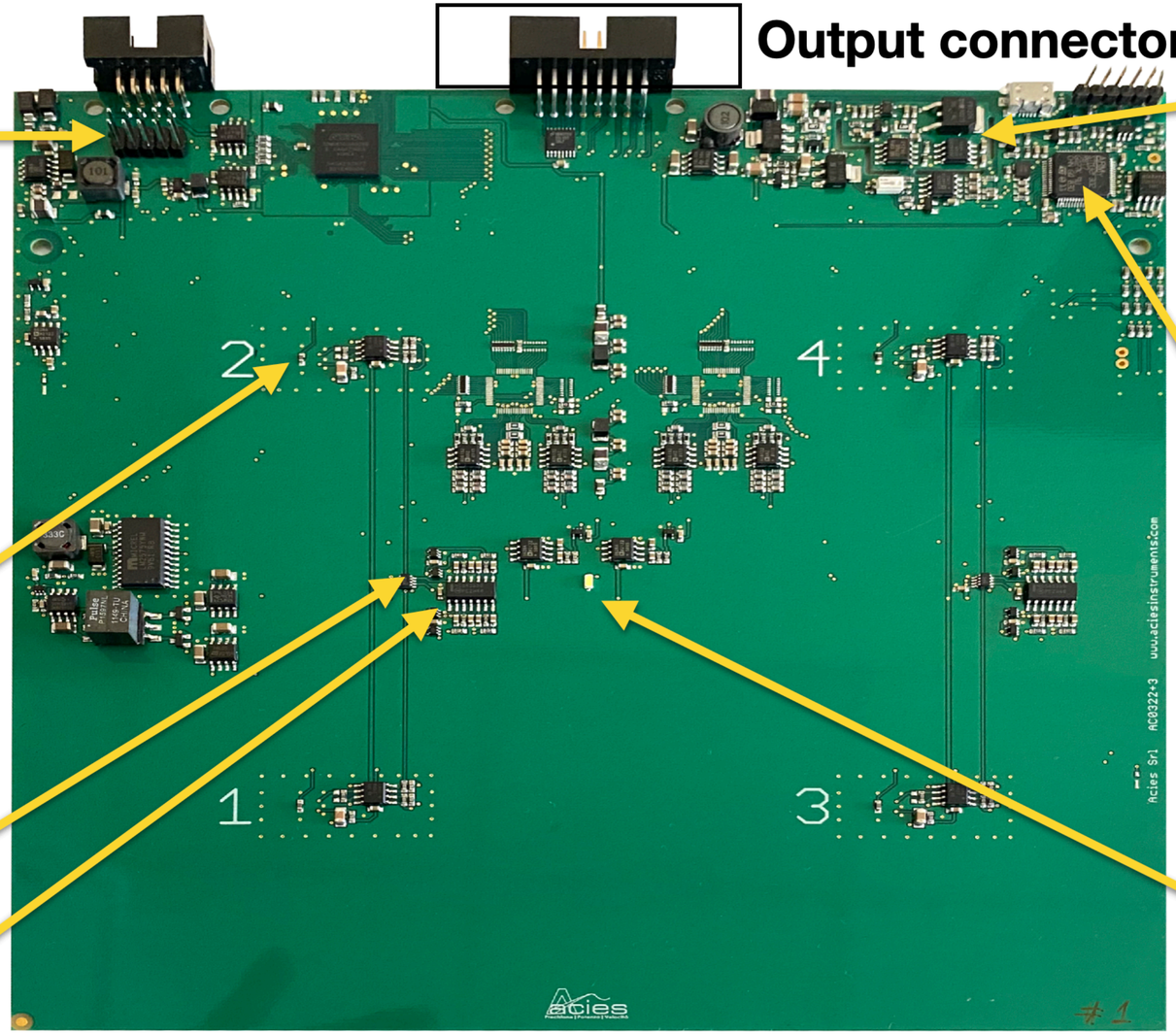
Detection of thermal neutrons

- Detection of slow neutrons generally based on the following processes
  - $^{10}\mathrm{B}\ (\mathrm{n},\alpha)$ reaction: $^{10}\mathrm{B} + {}^{1}\mathrm{n} \rightarrow {}^{7}\mathrm{Li}^{*} + {}^{4}\alpha + 2.31\ \mathrm{MeV}$
  - $^{3}\mathrm{He}\ (\mathrm{n},\mathrm{p})$ reaction: $^{3}\mathrm{He} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{1}\mathrm{p} + 0.764\ \mathrm{MeV}$
  - $^{6}\mathrm{Li}\ (\mathrm{n},\alpha)$ reaction: $^{6}\mathrm{Li} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{4}\alpha + 4.78\ \mathrm{MeV}$
- We chose the EJ-426HD-PE2 from Elijen Technology coupled to a WLS
- $^{3}\mathrm{He}$ and $^{4}\alpha$ detected by ZnS:Ag phosphor matrix with a broad blue fluorescent spectrum read by SiPMs





Front-end electronics: neutron modules



Supply and control connector

Output connector

Global V_b generator

Cortex-M
- SEPIC control
- UART
- USB 2

SiPM (opposite side)

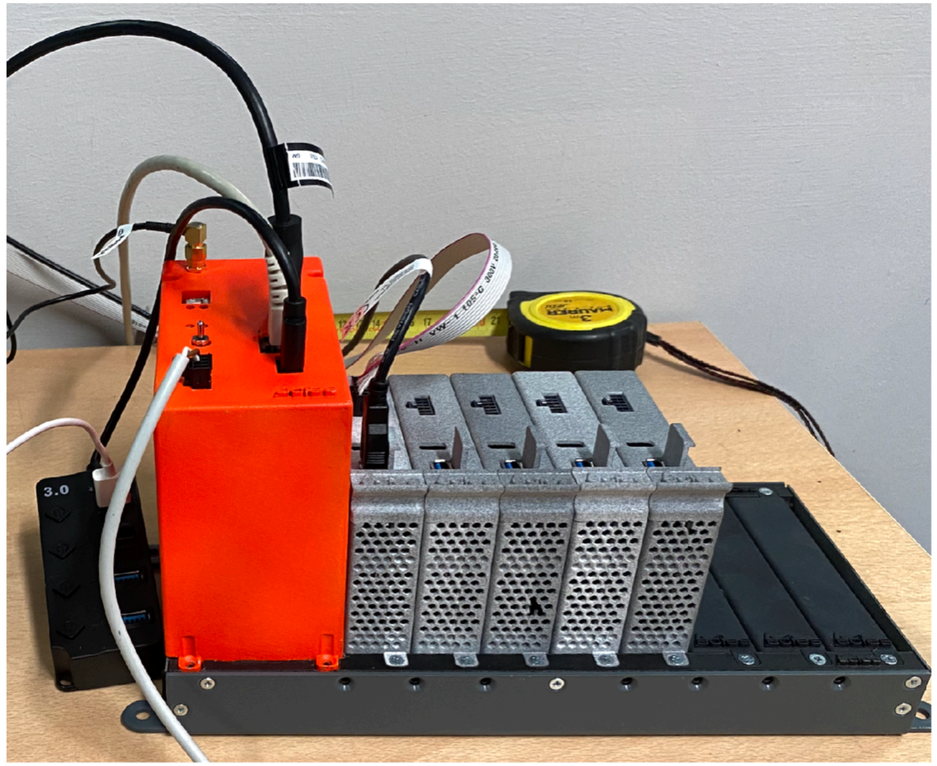
Discrimination

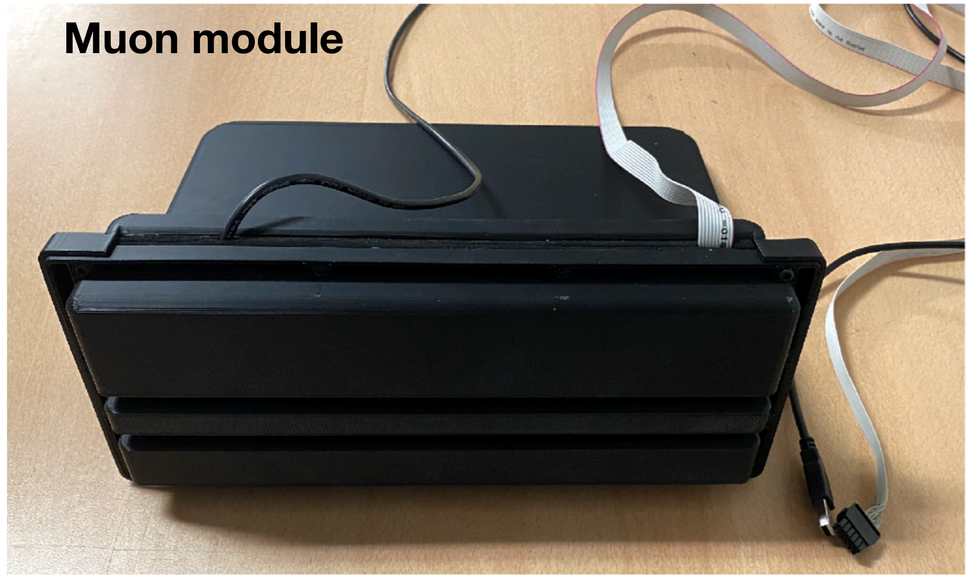
16-bit trim

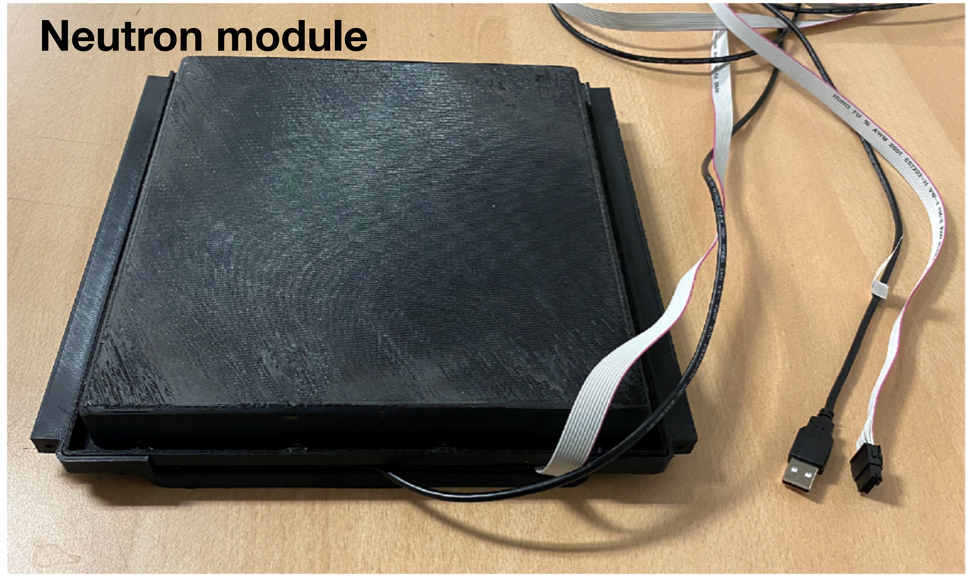
LED

Modular design

- Li-based scintillator + WLS + front-end electronics are housed in a light-proof case (3D printed)
- Two cables: one usb cable (for data) and one flat cable (for power supply)





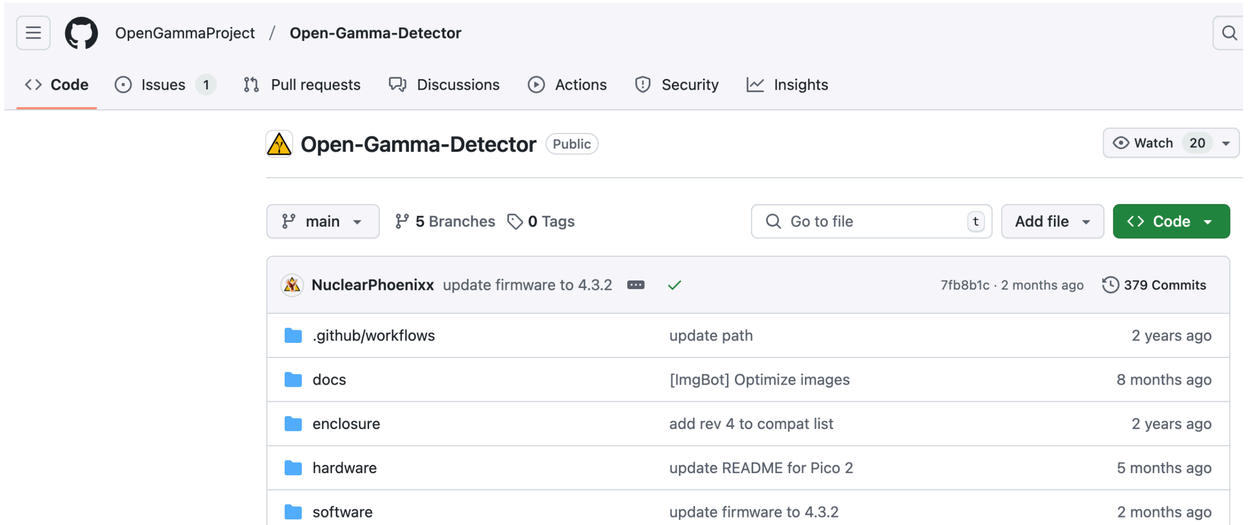


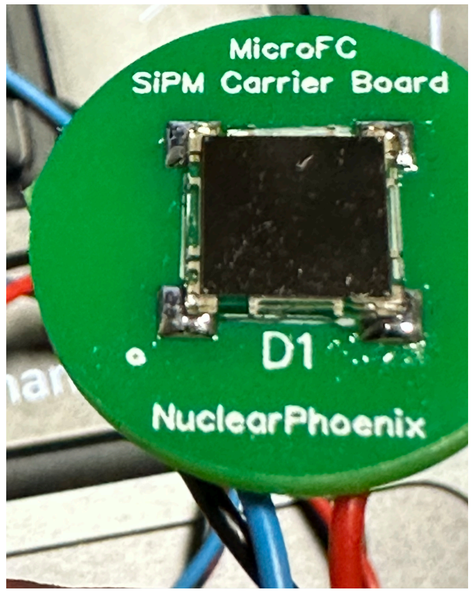
A (much) cheaper solution...

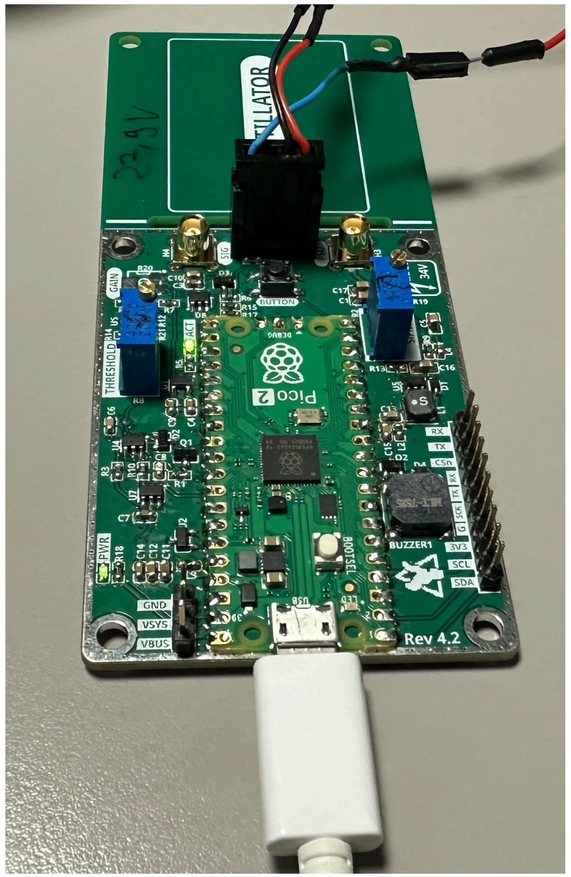
- We also investigated the use of an open-source project to read the SiPM

  https://github.com/OpenGammaProject/Open-Gamma-Detector

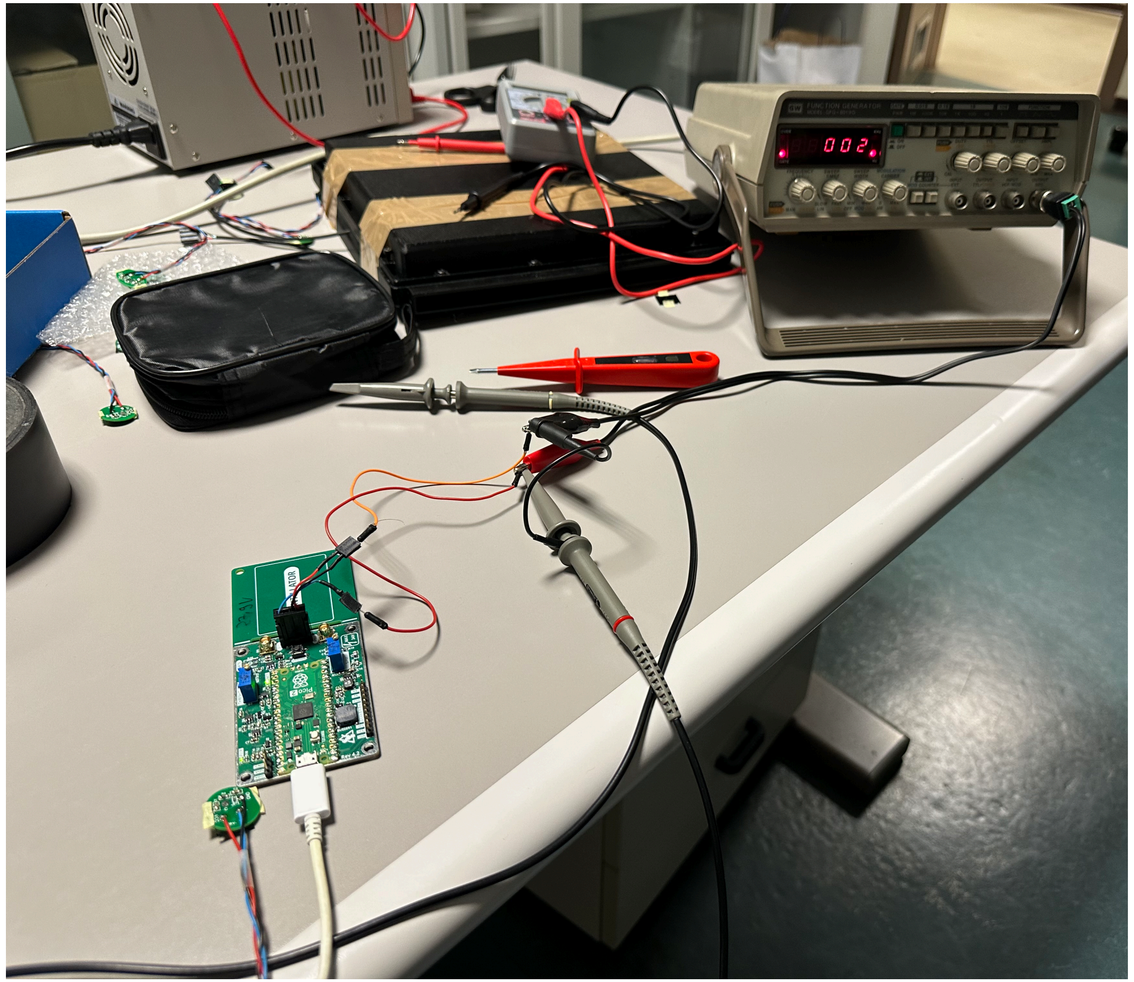
  - Both hardware (gerber) and software is made available
  - Our implementation based on a modified layout of the hardware
  - Cost: ~40 euro for both board and carrier
    - PCB + components from JLCPCB and Mouser
    - Assembly made @ Unibs and INFN PV

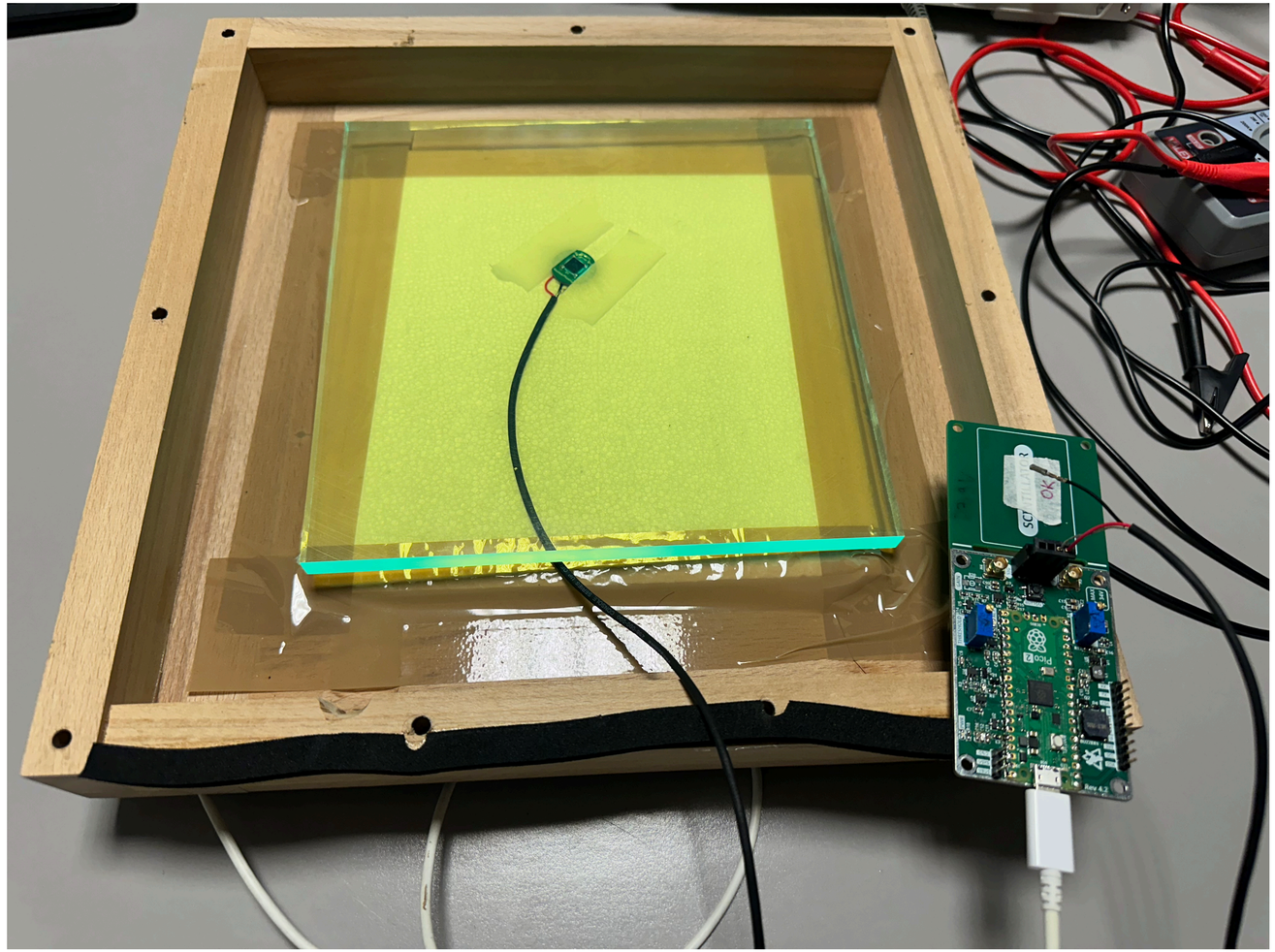






A (much) cheaper solution...





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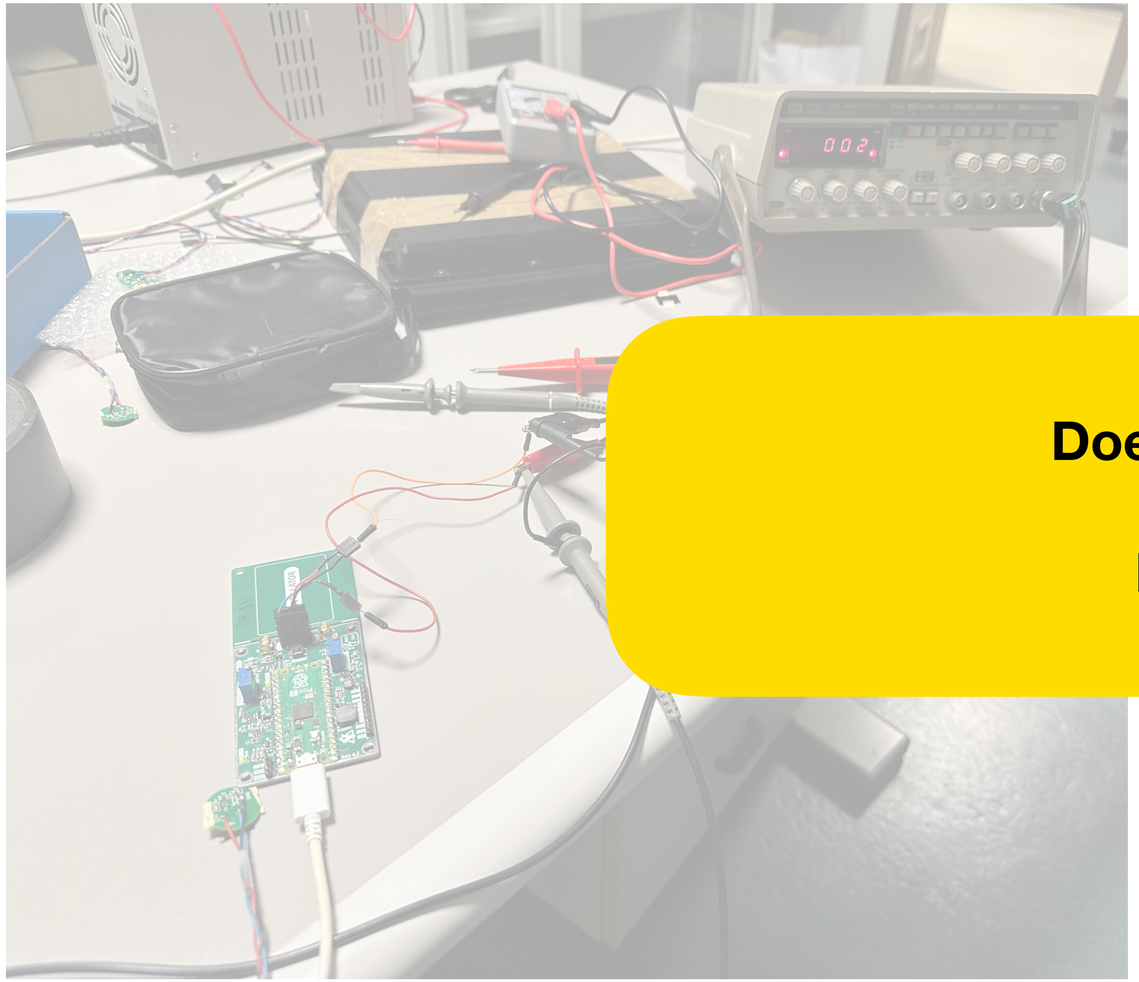
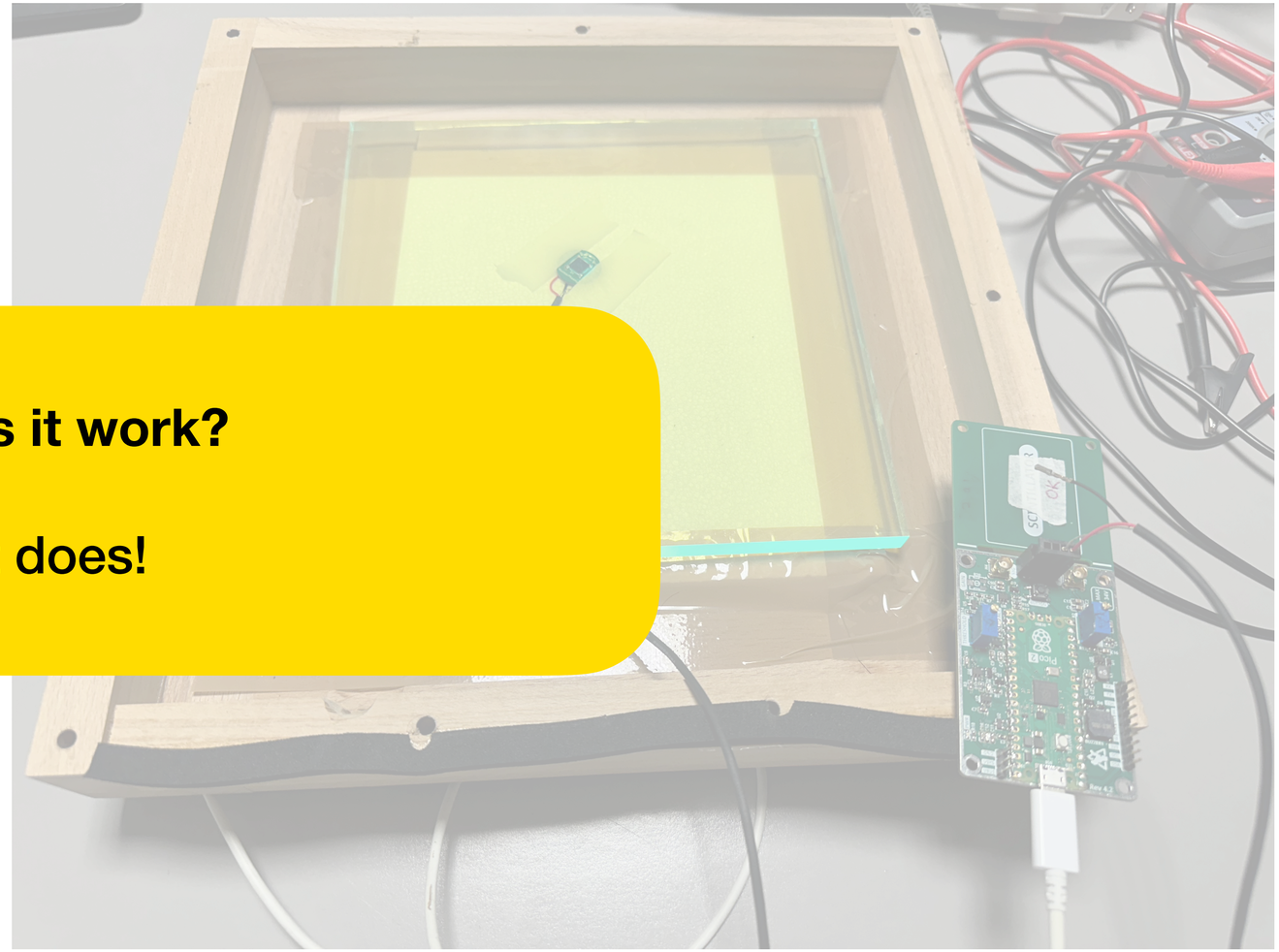




Does it work?

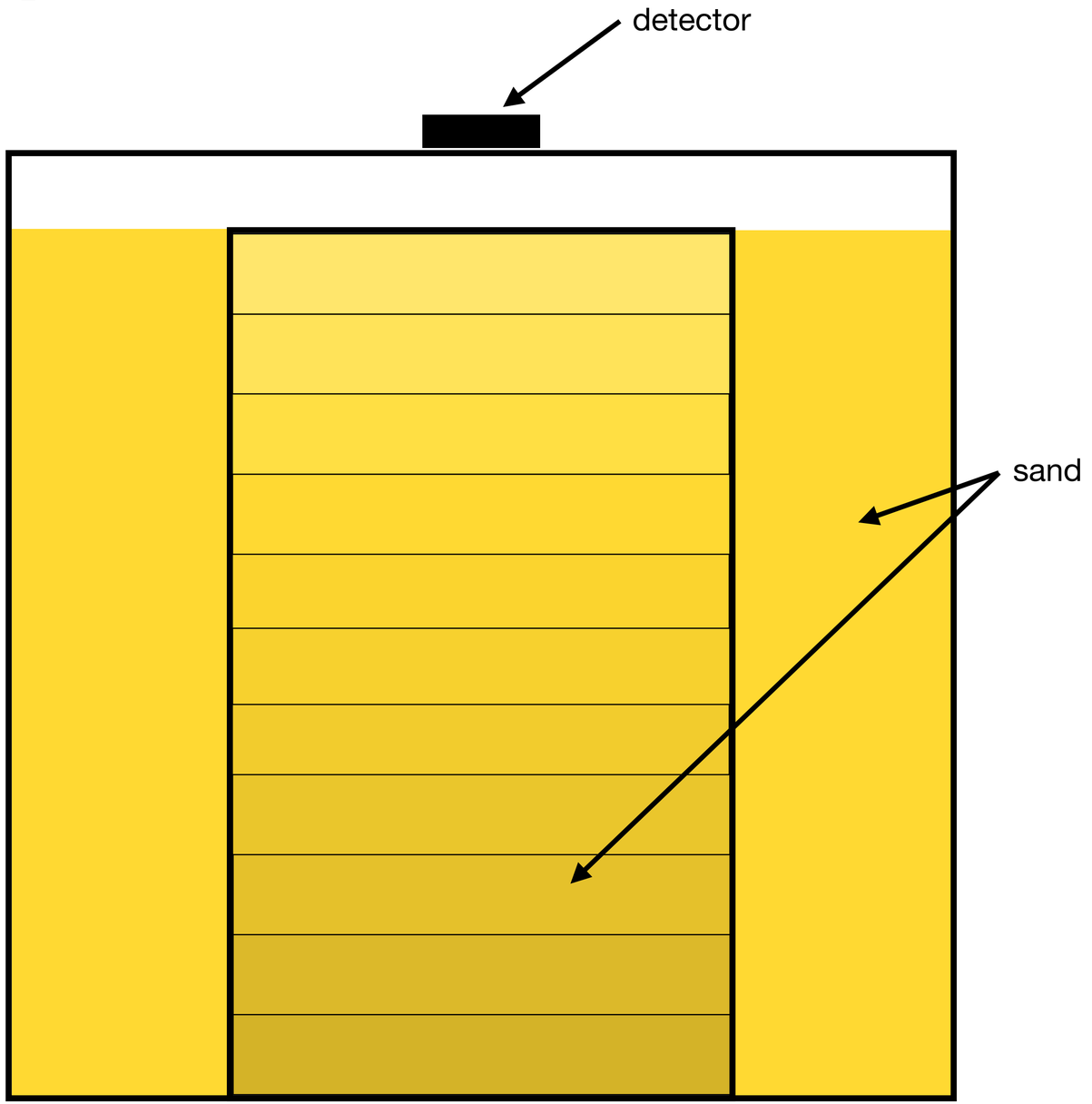
It does!

The detector

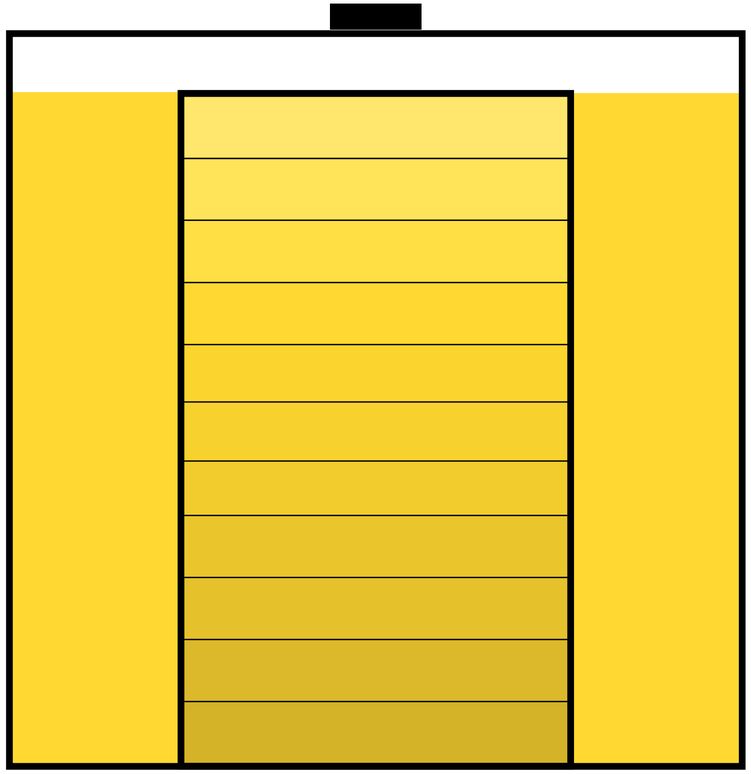
Experimental Setup

How to test experimentally?

- The goal is to test the technique in a controlled environment
  - Known soil composition
  - Known soil moisture with depth
  - Controlled environmental parameters
- A vessel containing homogeneous soil
- Within it, layers of small containers with same soil with known moisture
- Additional requirement: relatively cheap



Experimental setup



Experimental setup

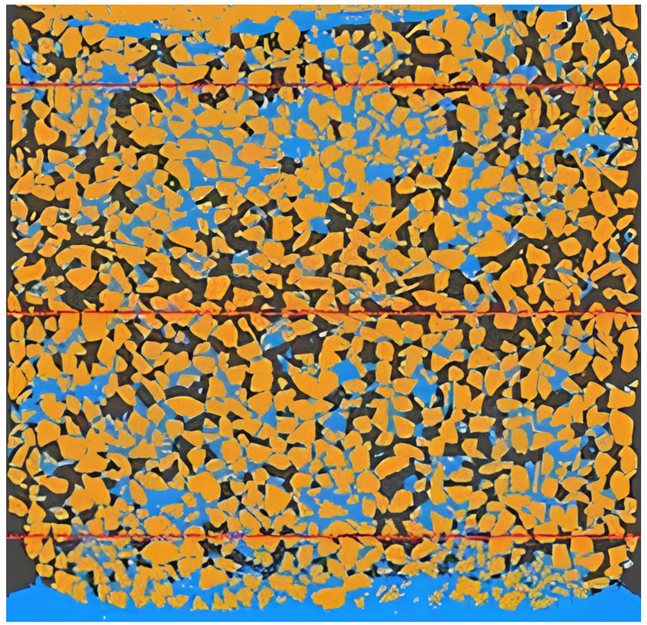
- Sand of know water content (moisture) is put in airtight bags

Problem

- how to assess the water content of sand?
- how to prepare bags of sand with the desired moisture?

Estimation of the moisture in sand

10.1007/s11440-018-0628-7

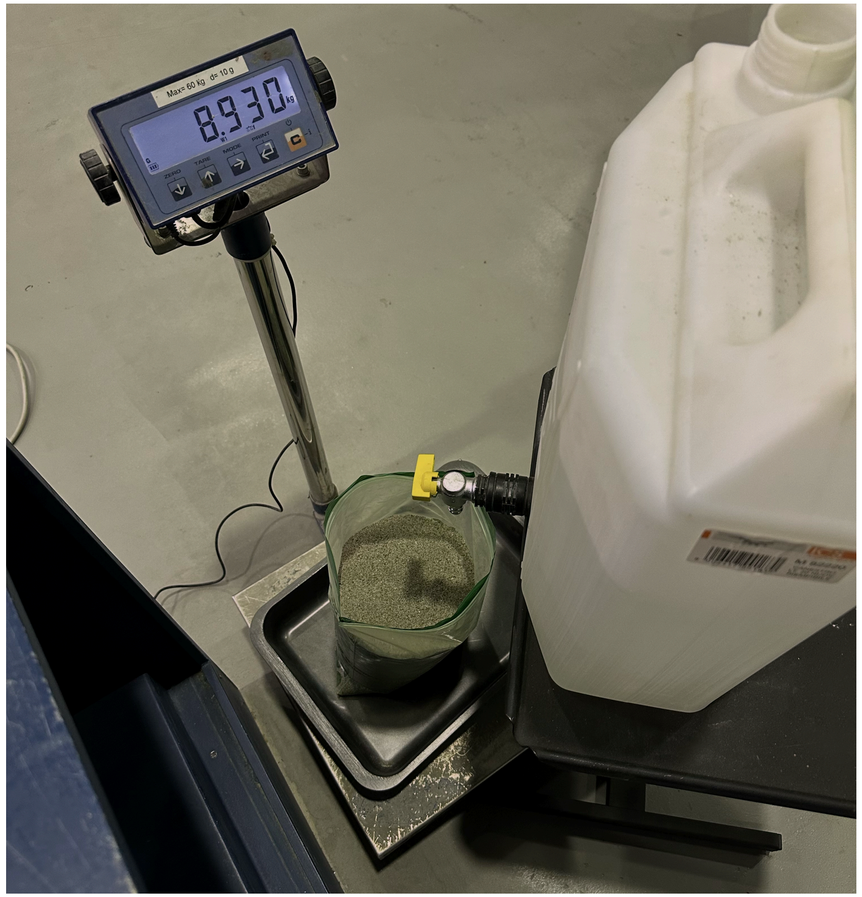


- When water is added to sand, it fills the spaces between grains with a negligible change in volume
  - The same happens when sand dries
- Thanks to this, the water content of sand can be derived from a relative measurement between dried and wet sand

- We dried several identical volumes of sand with different initial values of moisture
  - Industrial oven @ 120 °C up to 24 h
  - Reference volume: industrial baking pans
  - The weights of all pans were (statistically) identical at end: full dried sand (FDS)

Estimation of the moisture in sand

- Knowing the FDS mass (for the volume V_{PAN}), m_{FDS}, the **volumetric moisture content** θ of the sand can be determined by its mass m'
  - $\theta = \frac{1}{V_{PAN}} \frac{m' - m_{FDS}}{\rho_W}$



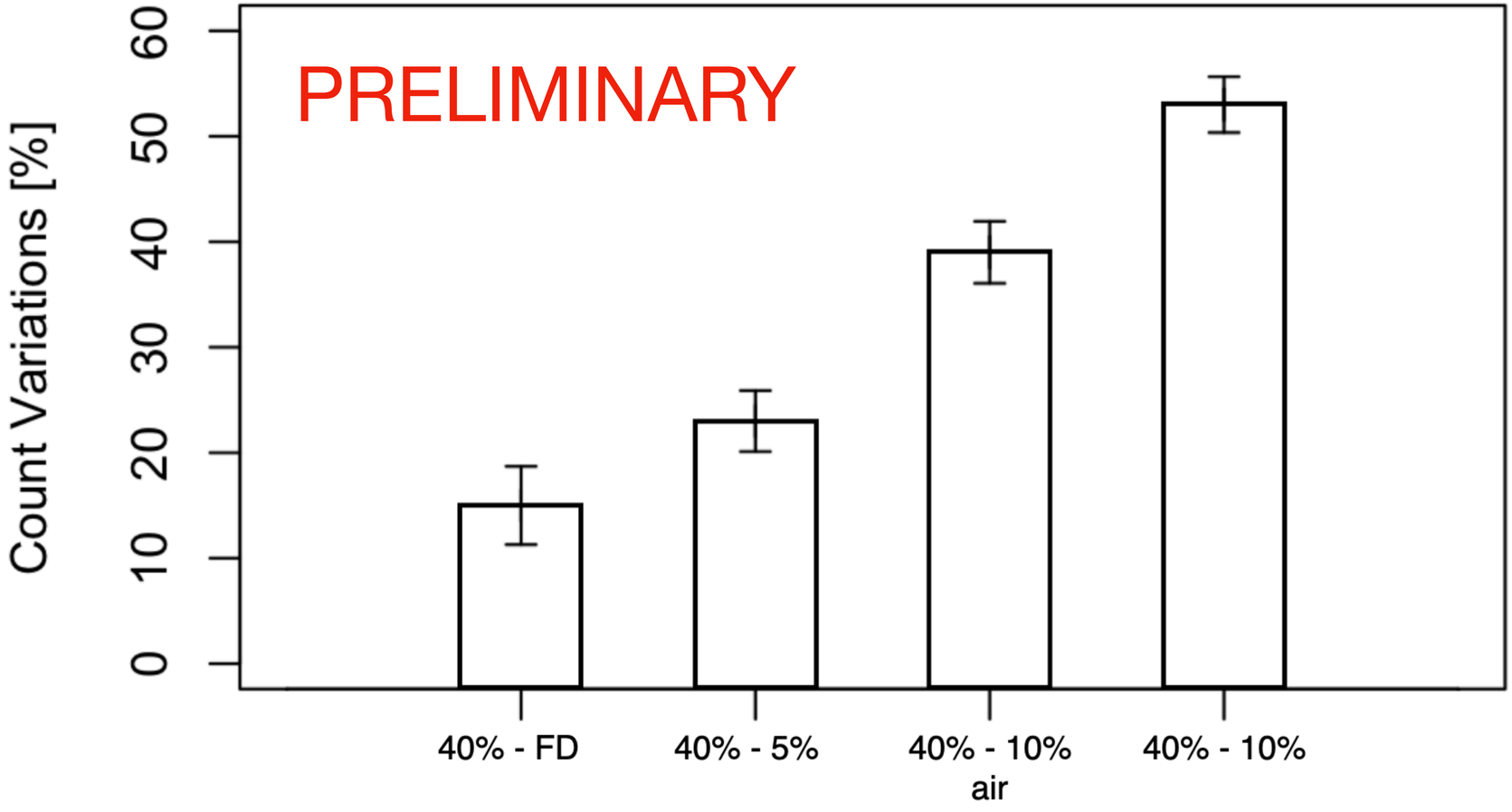
- Having a procedure to assess θ we prepared several airtight bags with different θ values
- We added the necessary quantity of water to achieve the desired θ in the bag
- In this way we can arrange them to recreate several humidity gradients

First experimental data

- The detector is initially placed on a $1\ m^3$ bag of naturally dried (2-3%) sand
  - At this stage we are using a single detector
- Next, the detector is placed on the barrel
  - Several configurations for the moisture gradient were considered
    - 40% - 20% - 10% - FD
    - 40% - 20% - 10% - 5%
    - 40% - 20% - 10% - air
    - 40% - 20% - 10%

First experimental data

- Percent counts variation, $(N_{barrel} - N_{bag})/N_{bag}$, for the different cases are shown below
  - Errors are statistical only



Conclusions

- We investigated the possibility of using cosmic-ray neutrons for the identification of subsoil leakages
- Simulations studies were encouraging, and convinced us to invest time and resources in the development of a suitable detector and experimental apparatus
- A detector has been designed and realised with some innovative solutions
- The proposed technique has been tested in a controlled conditions, by means of a specifically designed experimental apparatus
- First results show a dependence of the counts variations on the water content in the sand
    - Although these results were produced under special conditions, they represent an important achievement in view of future field tests