

# Industrial Challenges in Muography

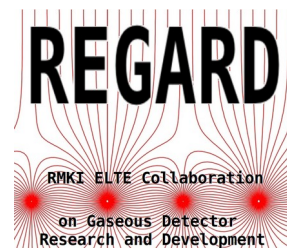
Selected Chapters from Muograph R&D  
and Field Measurements from WignerRCP

**Gergő Hamar**

Wigner RCP, Budapest, Hungary

for G.Hamar, G.Surányi, L.Balázs, D.Varga, B.Stefán,  
B.Rábóczy, L.Oláh, L.Tercsi, D.Moncz, S.Demők

**Collaborators:** BNC: Z.Kiss et al., Cuprum: K.Fuławka et al.  
MuonSolutions: M.Holma et al., Muotech: N.Zabari et al.



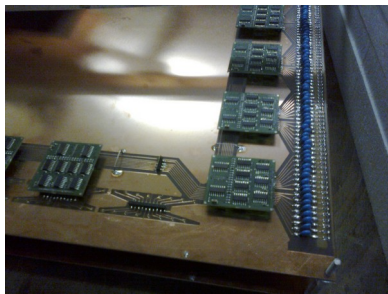
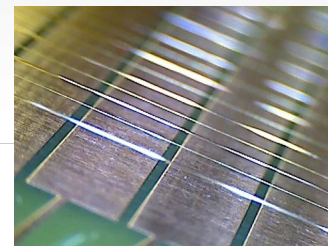
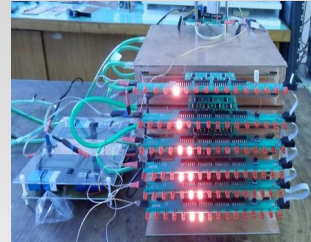
# Outline

- **Muograph Trackers of WignerRCP**  
Portfolio, Underground campaigns
- **Deep underground ch.**  
700m deep copper mine (Lubin mine, Poland)
- **Radioactive ch.**  
Inspection of an active reactor (BNC Reactor, Hungary)
- **Continous deformation ch.**  
Active mining site (Asarel mine, Bulgaria)  
Daily variations (Noor Solar PP, Morocco)
- **Subaquatic muography ch.**  
Detector R&D (WignerRcp, Hungary)  
Underwater verification (Dreher beer cellars, Hungary)  
Subaquatic pilot (Malaposta, Portugal)  
Shallow underwater survey (Hévíz thermal lake, Hungary)

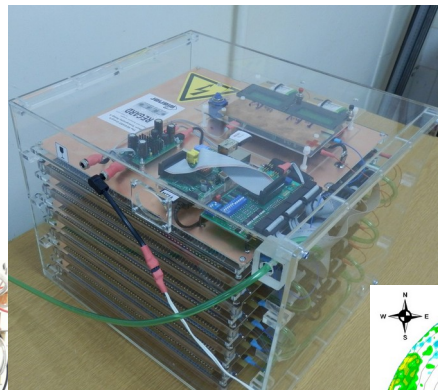
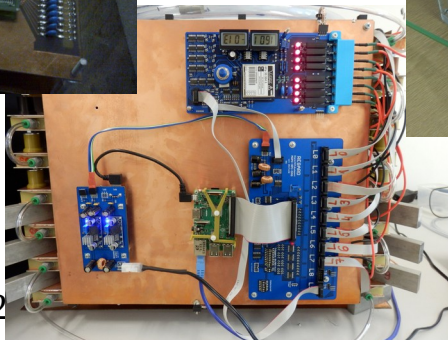


# Muograph R&D in WignerRCP

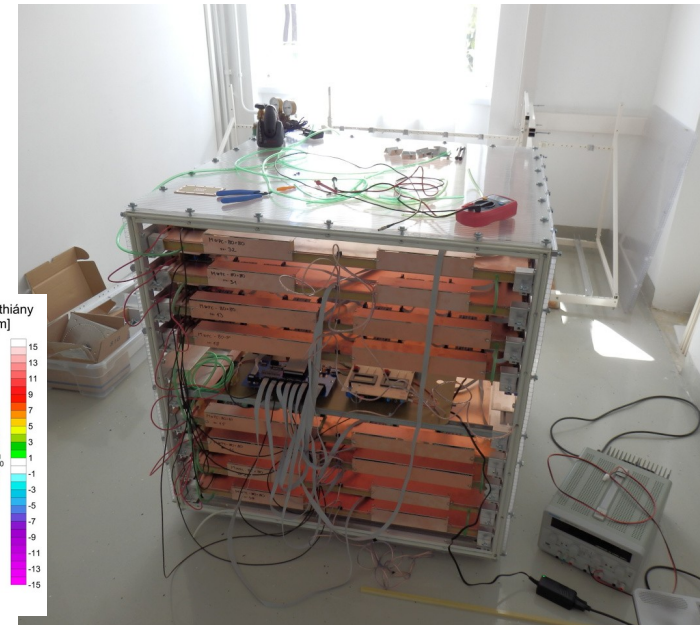
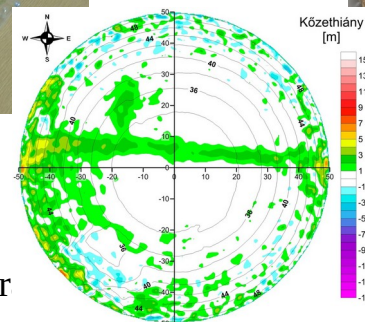
- **Muograph:** Muon tracker, Multiple layers of gaseous detectors  
High efficiency, Portable, low consumption, Field applicability  
Robust, User friendly, Autonom operation
- **Detector layer: MWPC,CCC :** Wire based gaseous chambers,  
Flat 2d chambers, Various geometric realizations
- **Data Acquisition system and electronics:** Custom design  
Rpi control: gpio, linux, wifi, ssh, android, remote c.  
Full muograph (LV,HV,Daq,UI) : 5-10 W
- **Field operation:** Good efficiency, Temperature and humidity tolerance,  
Inclinable support, Inox encasing, Mobile control
- **WignerRCP:** Design, Construction, Electronics, DataAcq.,  
Tracking and Analysis, Field operation, Geophysical interpretation.
- Muograph portfolio ..



Muographers202

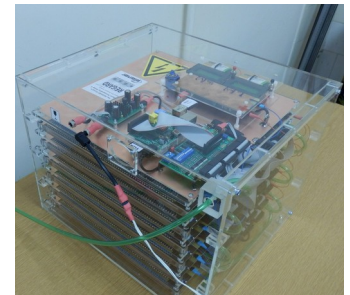


G.Hamar - Muogr



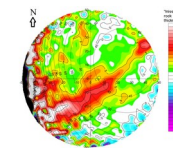
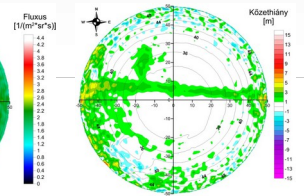
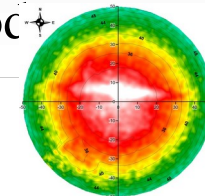
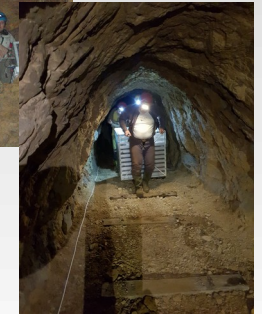
# Muograph Portfolio

- Application based designs, considering size, consumption, durability, target and focus, portability, and user access.
- **MTL-X** : Mwpc-80cm, 6-8 layers, 80kg, Inox encasing, support Mining appl., deep underground survey
- **MTS50** : Mwpc-50cm, 6-8 layers, 40kg, support Underground survey, tunnels, shallow structures
- **MTS40** : Ccc-40cm, 6-8 layers, 30kg, support High resolution version, underground, medium depth
- **MTS25** : Ccc-25cm, 5-6 layers, 20kg High resolution, small version, Natural caves
- **MTP-X** : Mwpc-13x40, 4 layers, 16kg, tube, subaquatic Subaquatic measurements, 600m underwater
- *BHD-X* : *Ccc-6x25cm, 4 layers, 10kg, 100mm tube Borehole version, lab setup, under R&D*
- **MMOS** : Mwpc-120cm, 7 layers, SakurajimaMO Surface muography, lead scatter layers, multi-muograph system
- **MTH-X** : Mwpc-80cm, 6-8 layers, 60+60kg, flat-pack and install Surface muography, two lead layers, cascading layout



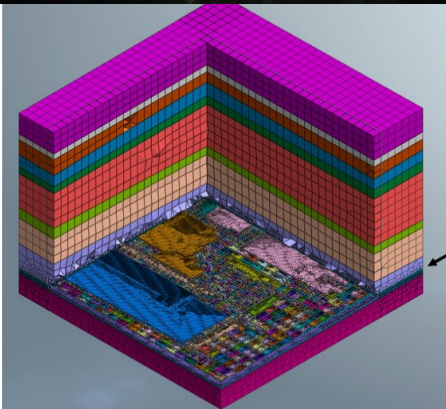
# Underground Muography Campaigns

- Jánossy tunnel system: reference
- Molnár János cave, Budapest: thermalwater sources
- Ariadne cave system, Ajándék cave: speleology
- Felsenkeller Lab., **Germany**: measure cosmic background
- Sátorkőpuszta cave: search for undiscovered caves
- **Esztramos**: search for unknown caves, examine old mine tunnels
- **Under the Buda Castle**: unknown voids, expected medieval tunnels
- **Királylaki cave and tunnel**: unknown caves, identify **fracture zones**
- **Kemi mine, Finland**: chromium mine, locate granite and oneboc
- St.Christophe Mine, **Germany**: reveal iron ore remnants
- **Jajce mine, BosniaH.**: bauxit mine, locate orebodies
- **Lubin mine KGHM, Poland**: copper mine, 650m depth
- **Asarel mine, Bulgaria**: active mining, underground and open pit
- Dreher beer cellar: building structure, underwater tests
- Lavrion, **Greece**: shallow depth underground survey
- Research Reactor Bud.: reactor muography, radioactive background
- Sopronbánfalvai Geodyn.Obs.: geological structures
- SosEnattos, **Italy**: site evaluation for gravitational telescope
- Hévíz thermal lake: underwater muography, reference meas.
- Malaposta mine, **Portugal**: flooded mine pilot



# Deep Underground ch.

- Agemera (HorizontEurope)  
Mining, Critical Raw Materials, Mine reevaluation, Novel technologies
- KGHM Cuprum
- **Copper mine in Lubin (Poland)**  
active mining site, ore production ~8 Mt/y  
ore layer at **650m depth**, large area coverage ~150km<sup>2</sup>  
deep shafts, room-and-pillar method
- Environment: **active mining**



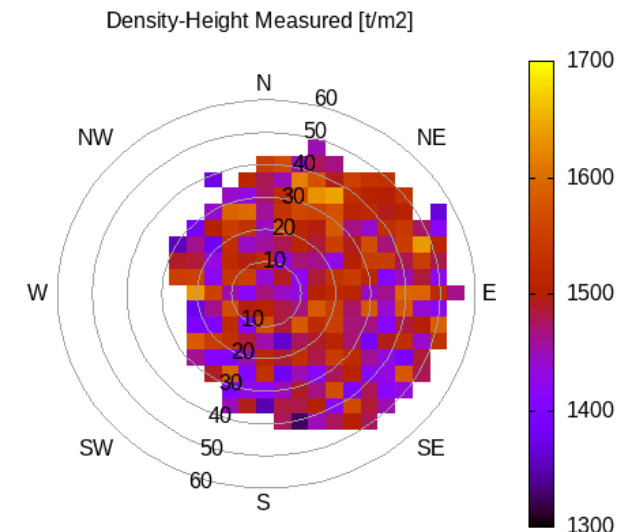
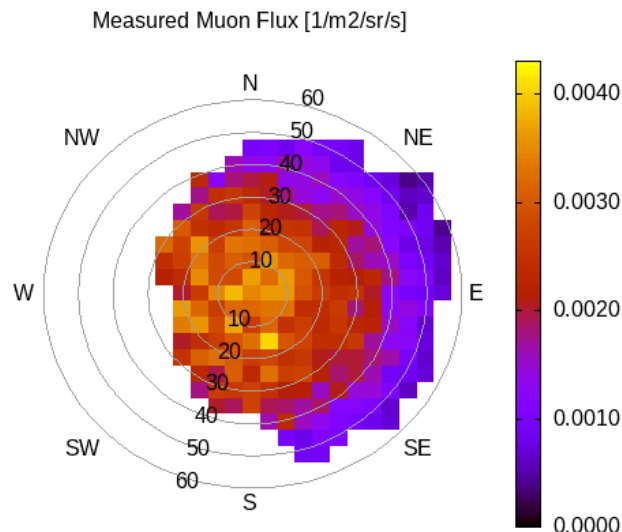
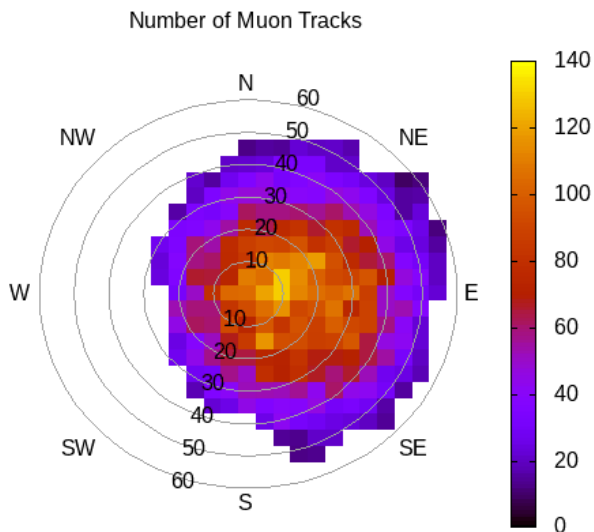
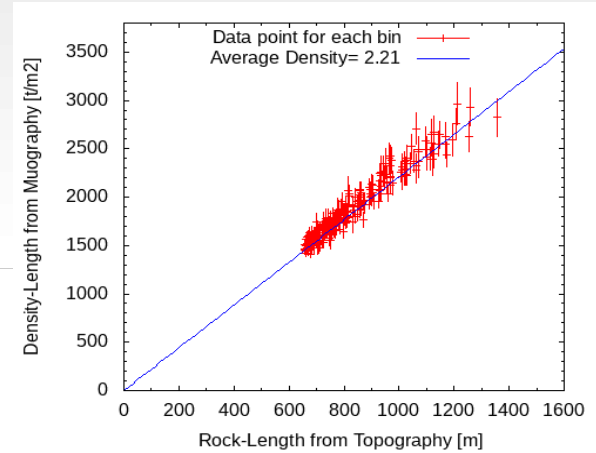
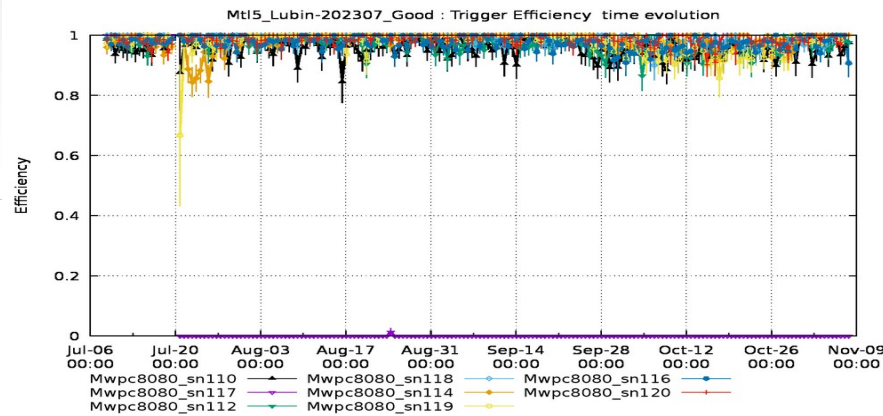
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deep shafts, room-and-pillar method
- Environment: **active mining, high temperature 36°C, high humidity >90%**



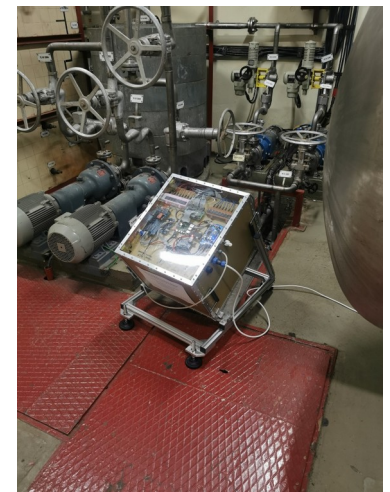
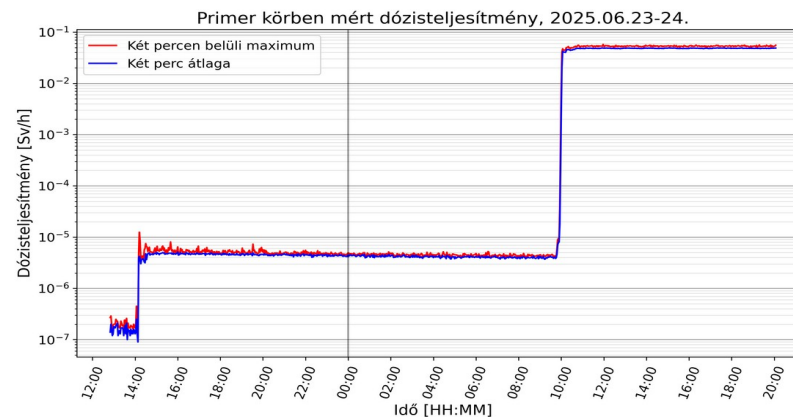
# Deep Underground ch.

- Deep underground : **650m rock** ~ 1600 mwe
- Low flux : ~**0.002** at Zenith (five orders of magnitude wrt open sky)
- Track rate: **5 muons / hour**  $\approx$  9k muons / month !
- Muon spectrum parametrization differs a lot  
-> various DensityLength conversion differs ~20%



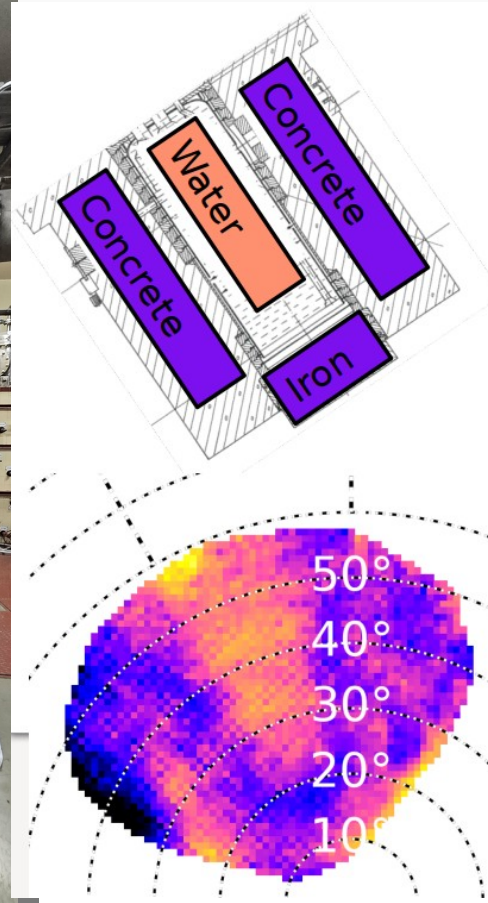
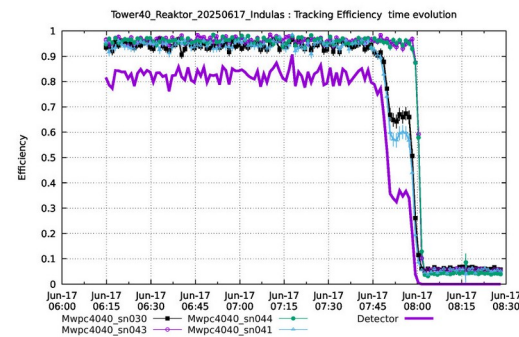
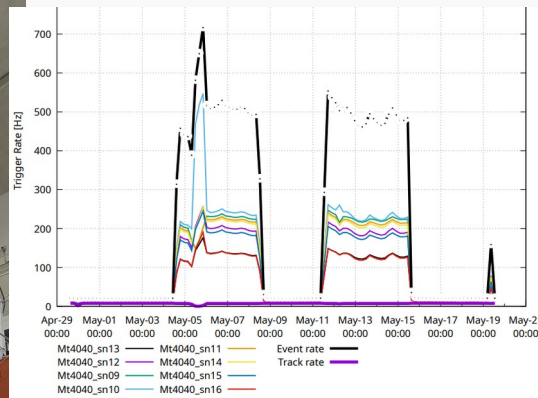
# Radioactive environment ch.

- Reactor muography  
structural inspection, monitoring, disaster awareness, ...
- Real measurement in active reactor ?
- Huge radioactive background  
expected dose ?  
muograph survival ?  
muon track identification ?  
imaging capability ?
- BNC Nuclear Research Reactor (Budapest, Hungary)  
High neutron flux for various research projects  
Operation few days a week
- Installments into:  
Experimental hole : several meters from core (low dose)  
Primer support : underneath core (extreme high dose)



# Radioactive environment ch.

- Experimental Hall: Dose rate : **9 uSv/h** → High trigger rate  
Track rate undisturbed, **Imaging** is nice
- Primer circuit: Dose rate : **50 mSv/h** (public lim. 1mSv/year, occ. 50mSv/year)  
Continuous triggering, Occupancy ~50% : single track not visible  
Muograph **survived** > 1 Sv dose without any damage  
after: **back to normal operation**



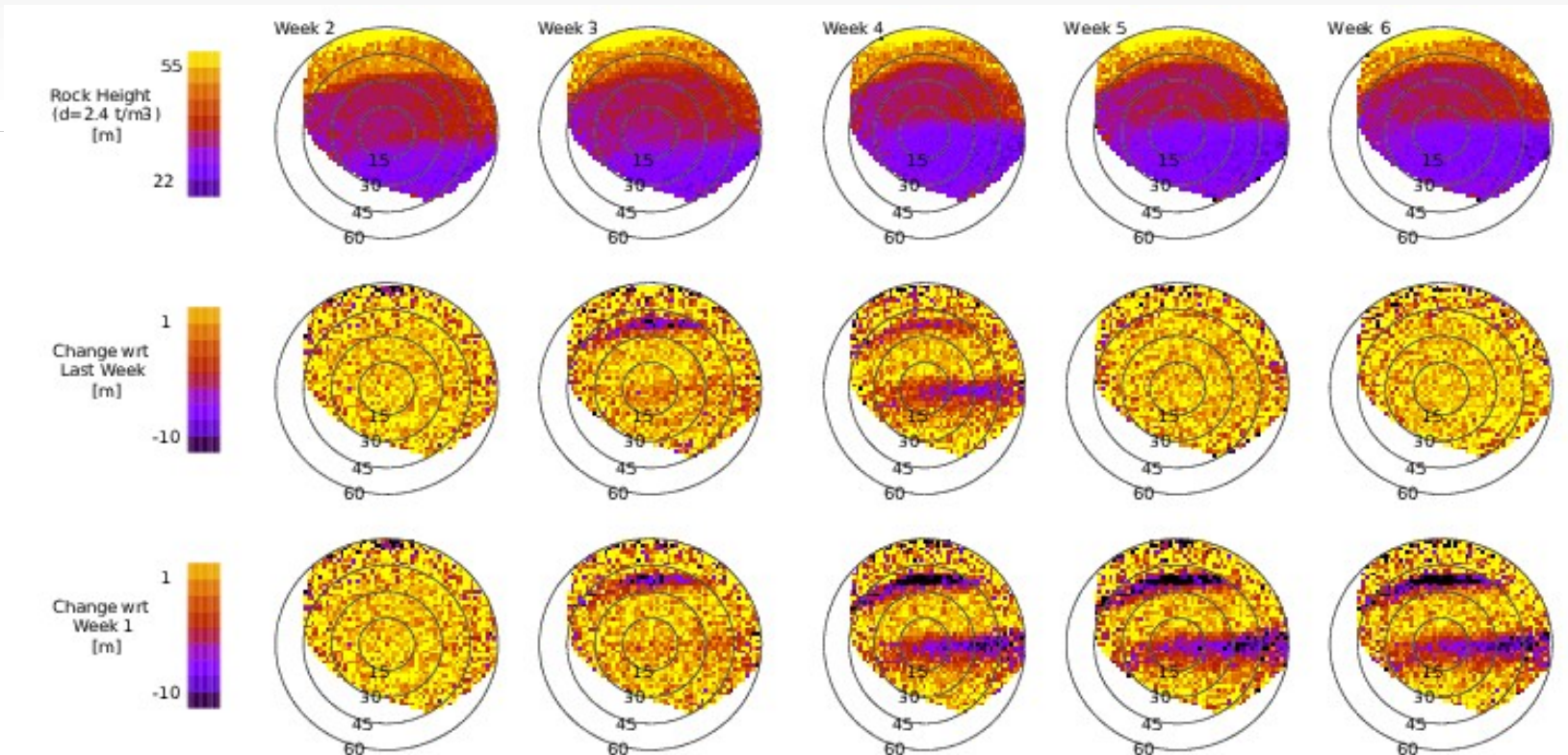
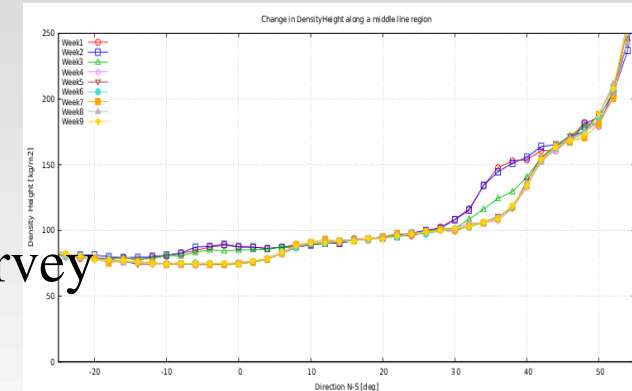
# Active Mining site ch.

- **Asarel copper mine** in Bulgaria  
copper ore 13Mt/y,
- Both Underground and Open pit operations
- Underground, and Surface Muograph installed to evaluate fault zone



# Active Mining site ch.

- Active mining → removing debris, landscaping
- During muograph operation the surface got changed (they forgot to tell us, that they operate in that part as well)  
Muogram evolution clearly reflects the movement  
Time-evolutional muography, Compatible with survey



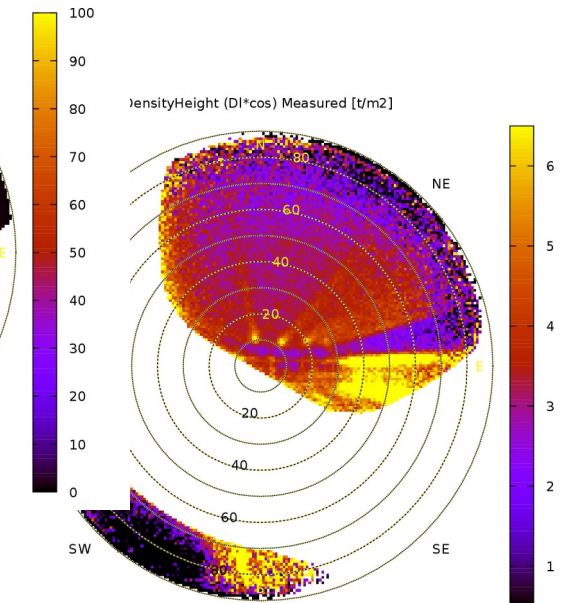
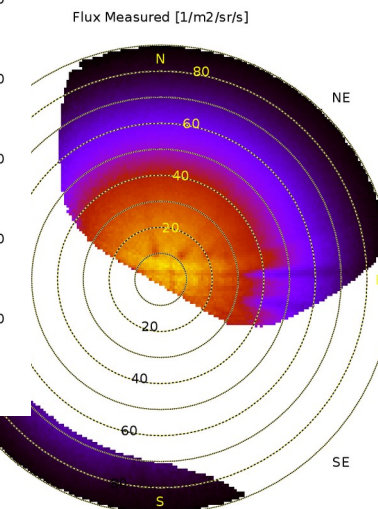
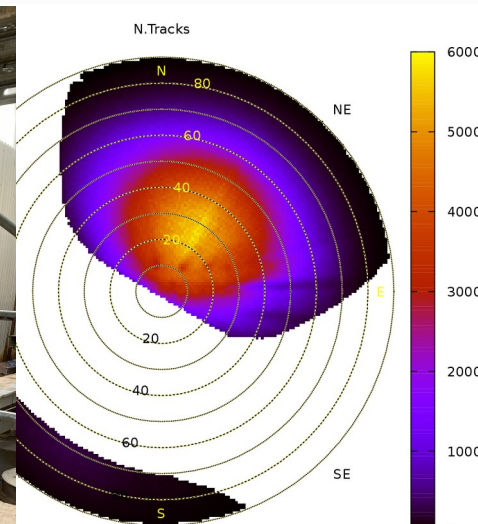
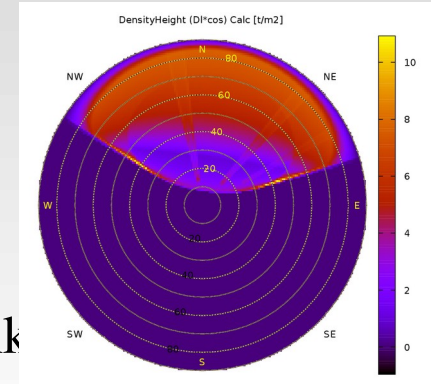
# Daily variations ch.

- **Noor Solar Power Plant** : Ouarzazate (Morocco) + Muotech Ltd.
- Various techniques for harvesting solar energy
- Heated molten salt storage as buffer
- Salt tank buffer : 44m diameter, 16m height  
Molten salt about 400°C  
buffer → **Continuous change** in SaltLevel
- Muography target: localization of **internal steel pipes** in the hot tank



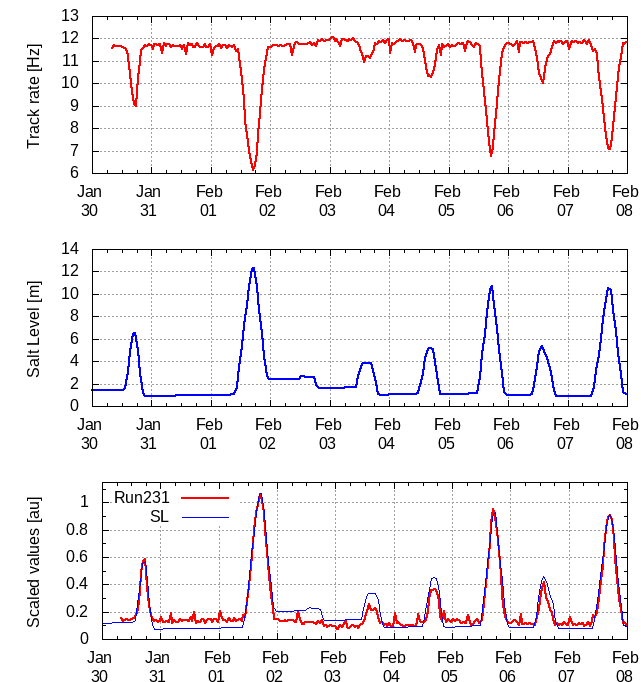
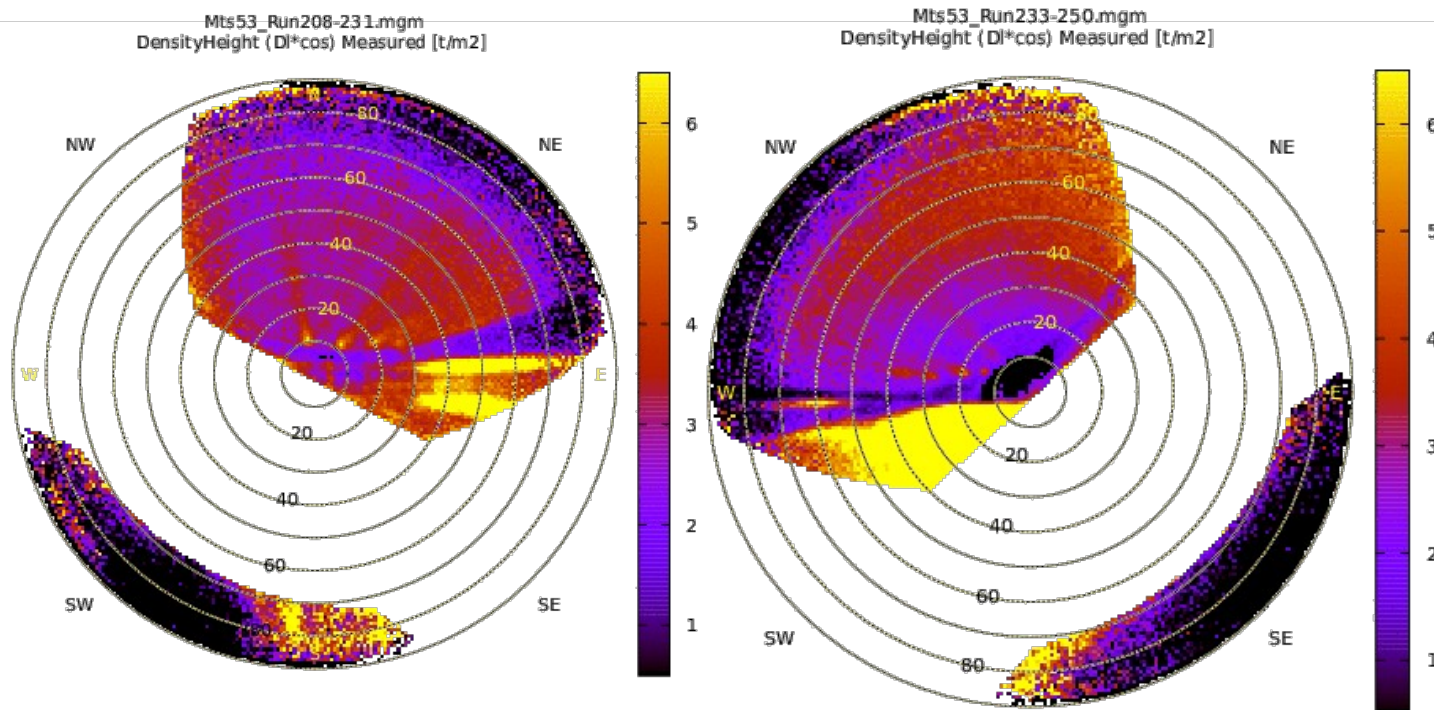
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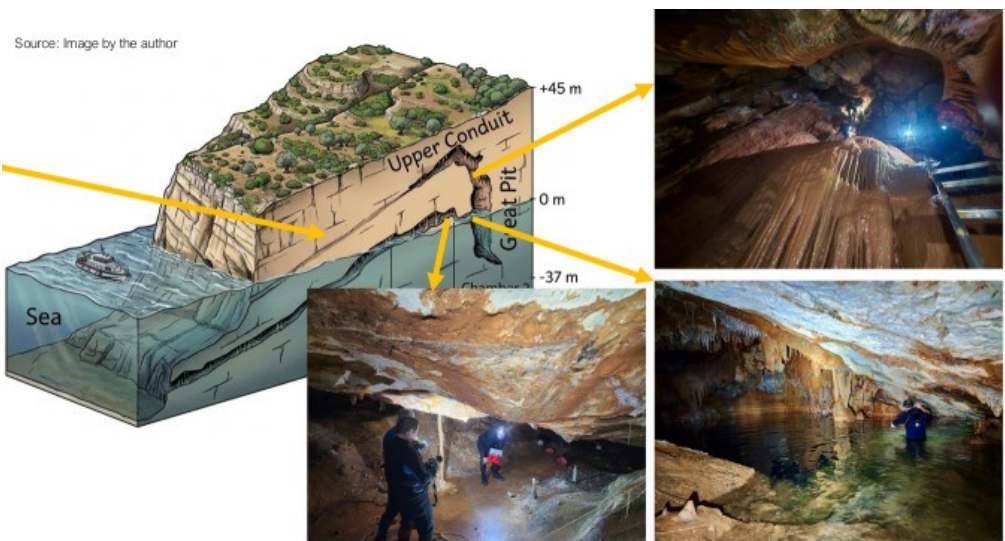
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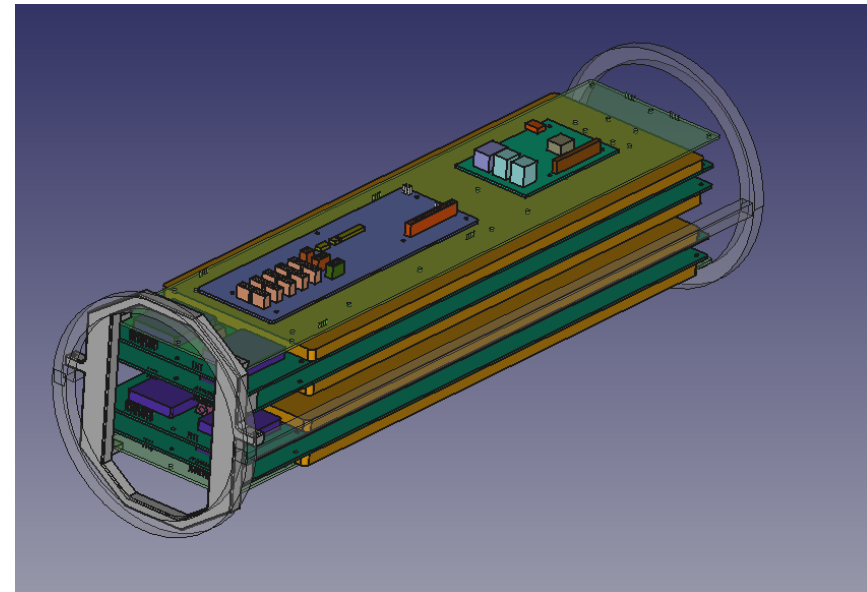
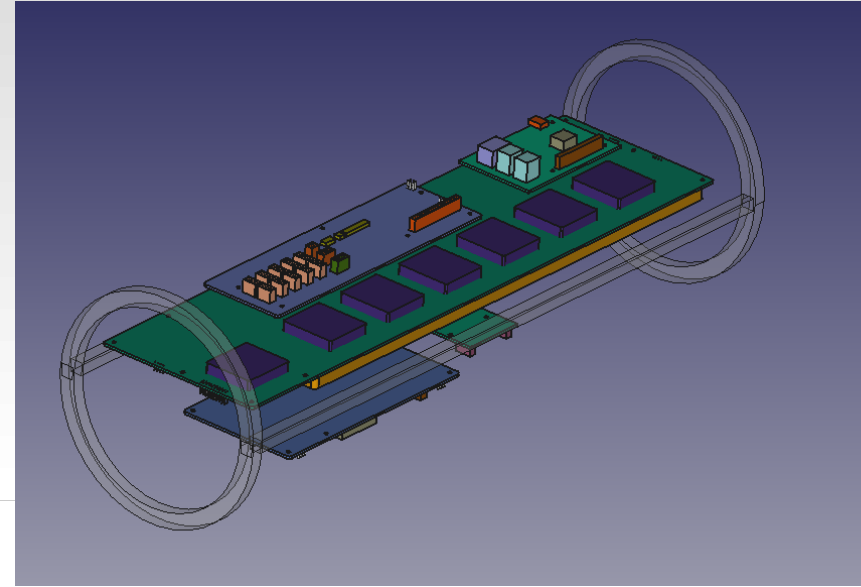
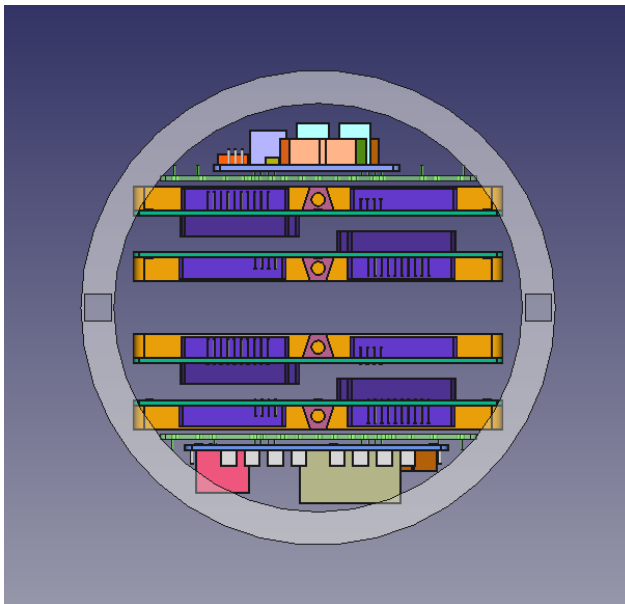
# Subaquatic Muography ch.

- Underwater muography flooded mines and tunnels recultivation inspection aquatic and subsea caves liquid-flow tube systems
- Sealed resistive container
- Installation and movement by divers or underwater-robot
- Power and communication long cables or exchangeable battery pack
- Gaseous trackers sealed operation: lifetime? slow degradation?



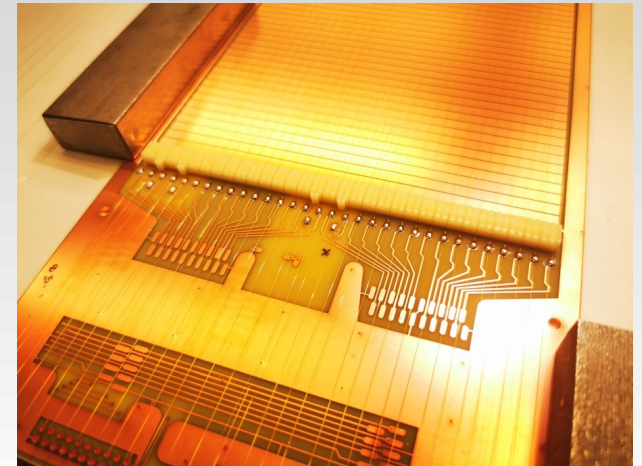
# Underwater muograph

- High pressure resistant Tube (d200x500)
- Deepwater nautilic connectors
- Wire Chamber based Gaseous Tracker  
four layers of 128x256mm<sup>2</sup> active a.
- DataAcq. + DcDc + HighVoltage + RPi  
+ Sensors : all still fit into the Tube
- Design + Construction at WignerRCP



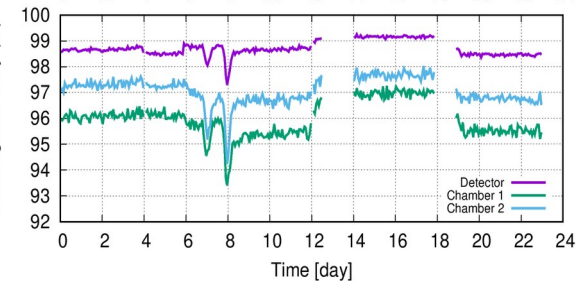
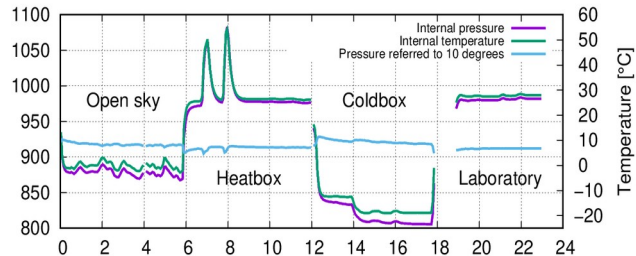
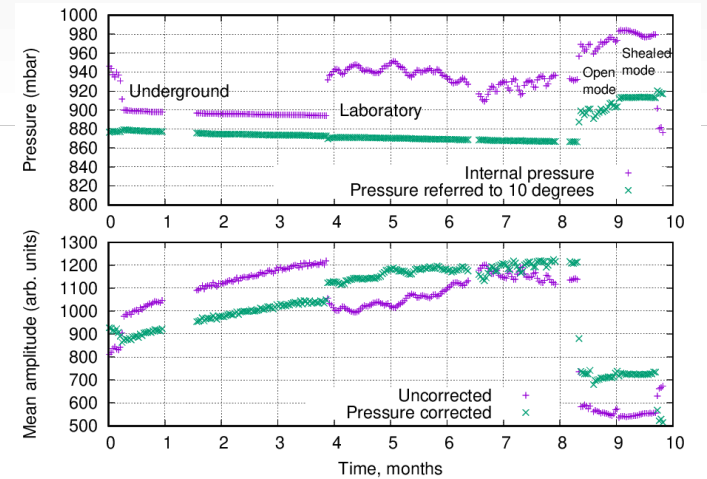
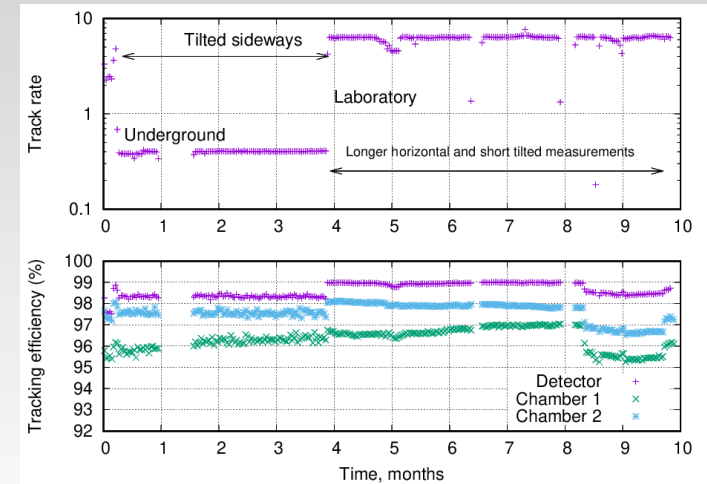
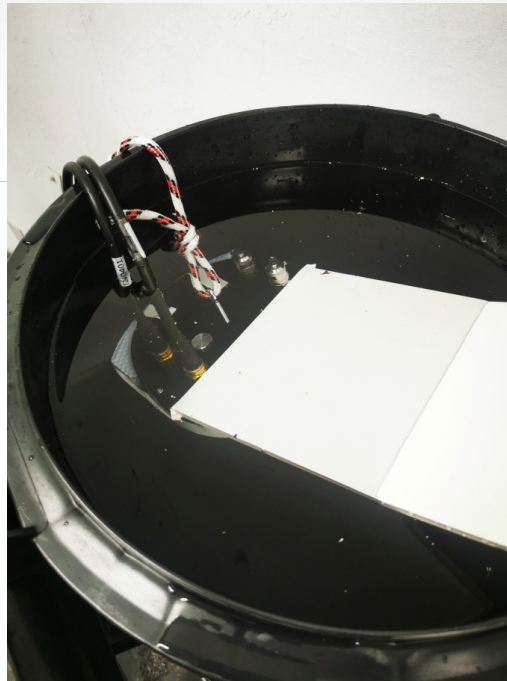
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- Design + Construction at WignerRCP



# MTP Performance

- Excellent gas tightness  
no performance degradation
- Temperature test: -20 °C to +50 °C
- Simple underwater test: ok
- Underground muography at JánossyT.



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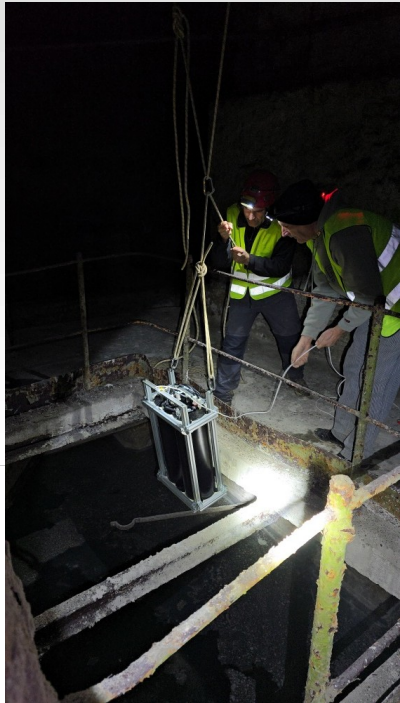
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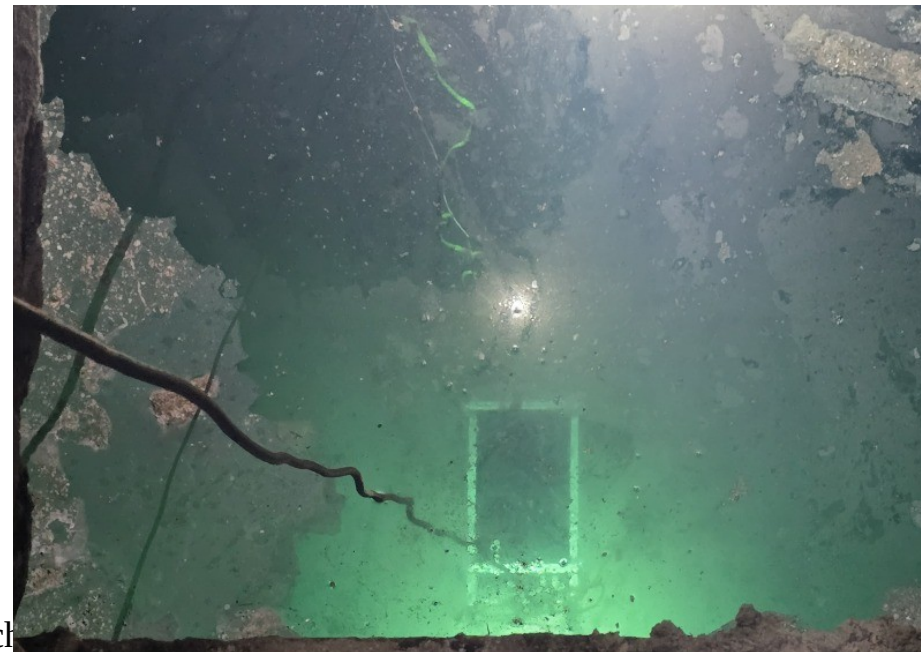
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# Subaquatic operation: Dreher

- Cellar of the Dreher Brewery in Budapest (Hungary)



- Water with pH ~ 12
- Building structure visible
- Confirmed with underground muograph



# Subaquatic operation: Malaposta

- **MineIO** project (A Holistic Digital Mine 4.0 Ecosystem, HorizonEurope)
- In-situ underwater technology validation for muography and robot operation in water-filled mines
- Malaposta open quarry, Portugal
- Carried, deployed, and retrieved via INESC TEC robot »EVA«

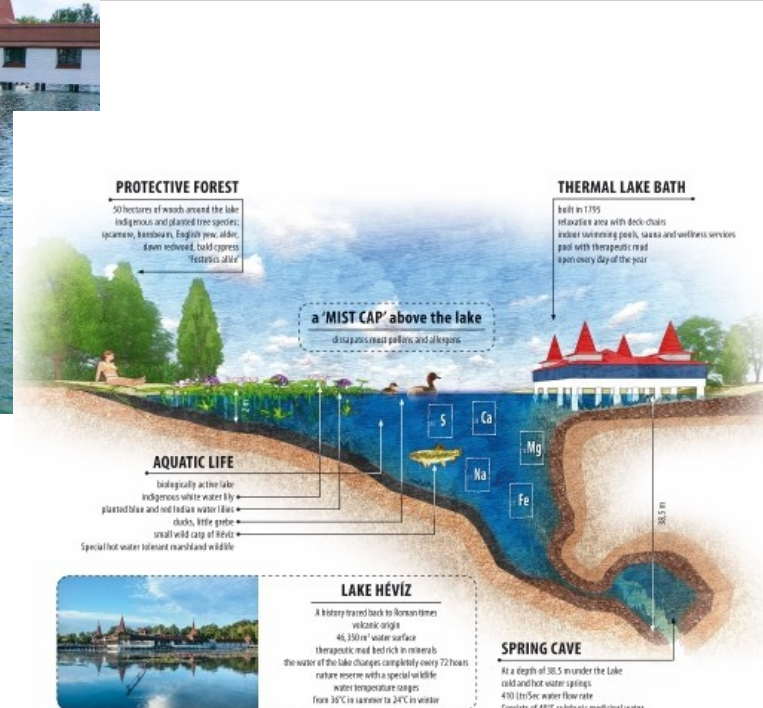


**MINE.IO**

A Holistic Digital Mine 4.0 Ecosystem

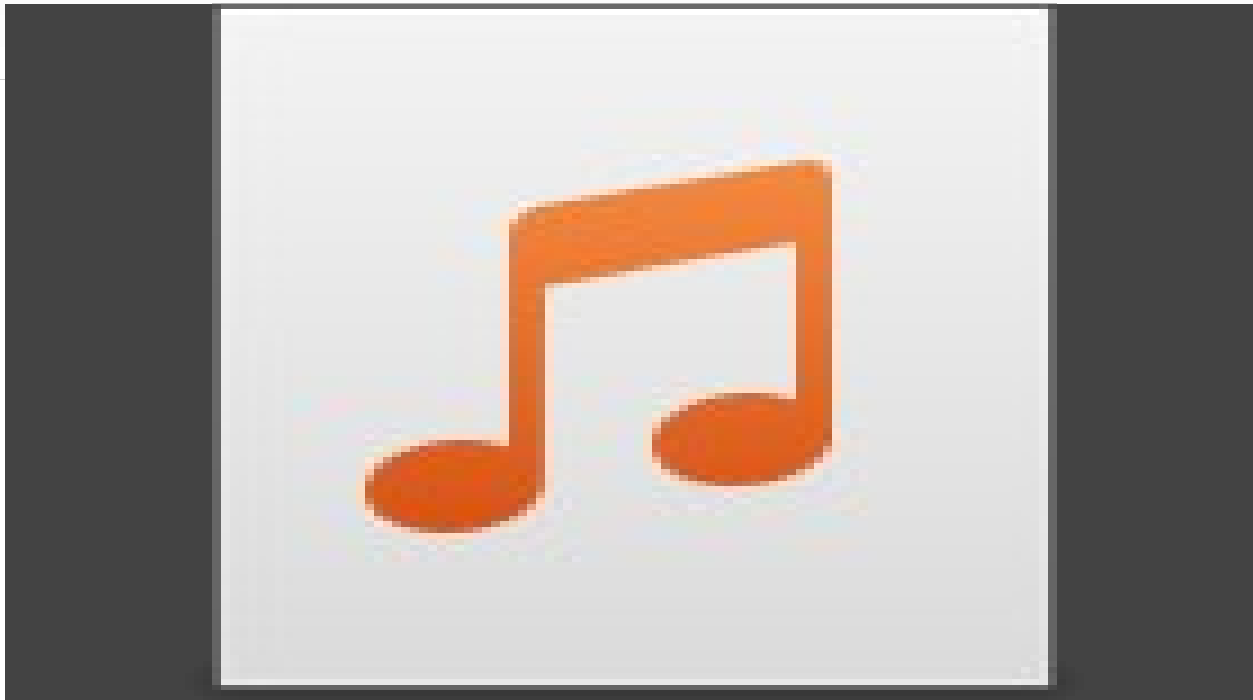
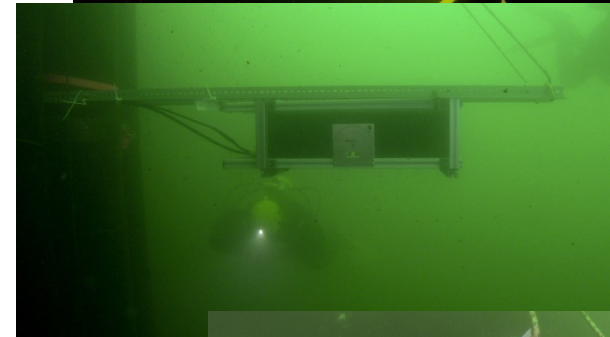
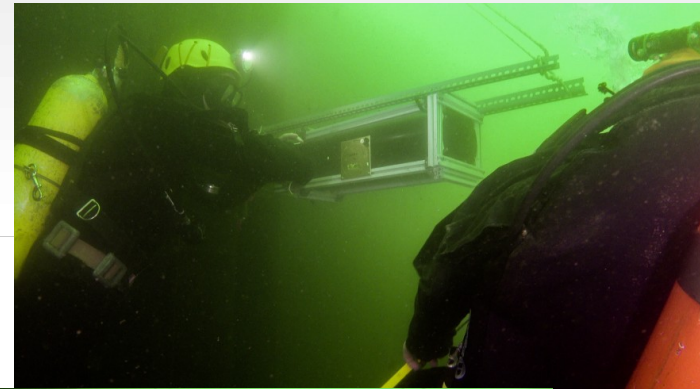
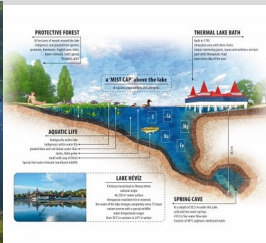
# Subaquatic operation: Hévíz

- Hévíz (Hungary) : famous 35m deep large thermal lake (the largest swimmable in the world)  
underground source is 38°C with 410 liter/sec flow



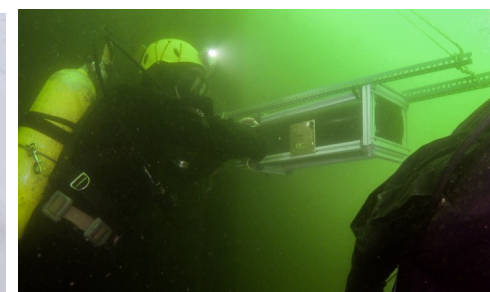
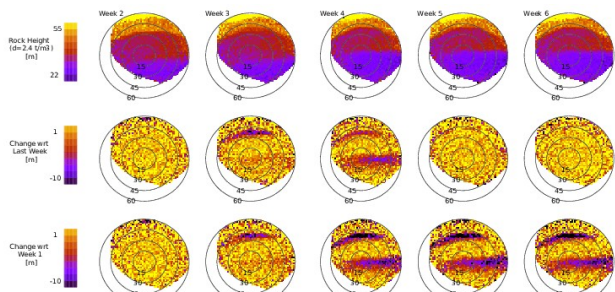
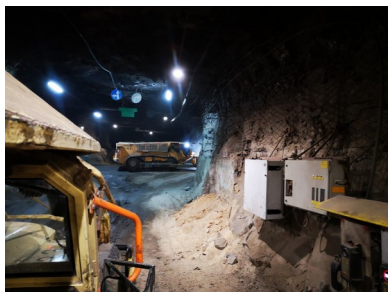
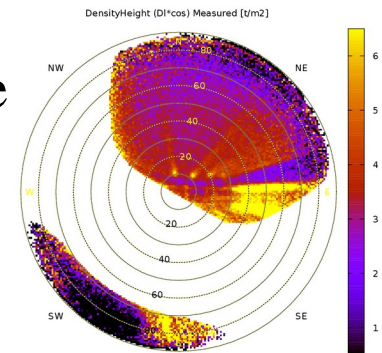
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- Hévíz (Hungary) : famous 35m deep large thermal lake (the largest swimmable in the world)  
underground source is 38°C with 410 liter/sec flow
- Recently started measurement series focus on precision measurement for shallow-depth muon-flux and density-length conversion and pilot for diver + muograph operation



# Summary

- **Muograph Trackers of WignerRCP**  
Multiple layer gaseous tracker, custom design, portable, low consumption, autonomous, wide portfolio, active r&d for novel challenges
- **Deep underground ch.**  
depth of 650m: low rate, harsh env., stable op, conversion issue
- **Radioactive ch.**  
several layers: excellent gamma rejection  
huge dose rate 50mSv/h : no track, survived ~Sv
- **Continuous deformation ch.**  
Active mining and landscaping: inspection works  
Daily variations can be handled, small scale target is possible
- **Subaquatic muography ch.**  
compact design, gaseous tracker in sealed tube  
desing+construction+verification done  
pilots: water res., flooded pit, thermal lake



# Acknowledgements

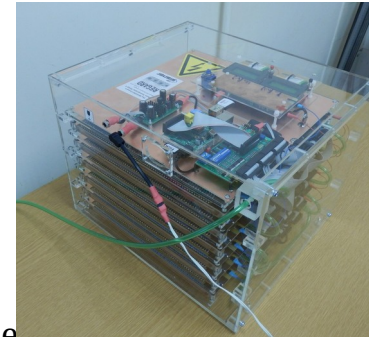
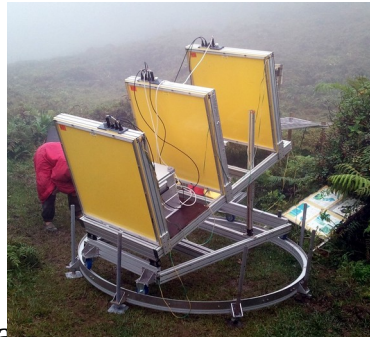
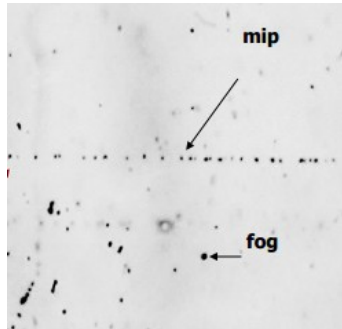
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  - Agemera, MineIO
  - Muotech, MuonSolutions
  - BNC, ISNTEC, NoorPP
  - VMI, CERN DRD1
- 
- Funded by  
Hungarian NDRI - TKP2021-NKTA-10  
HUN-REN KSZF-144/2023  
Agemera:  
MineIO : HEU GA n.101091885  
WignerRCP: WKTP 2026



# Backup Slides

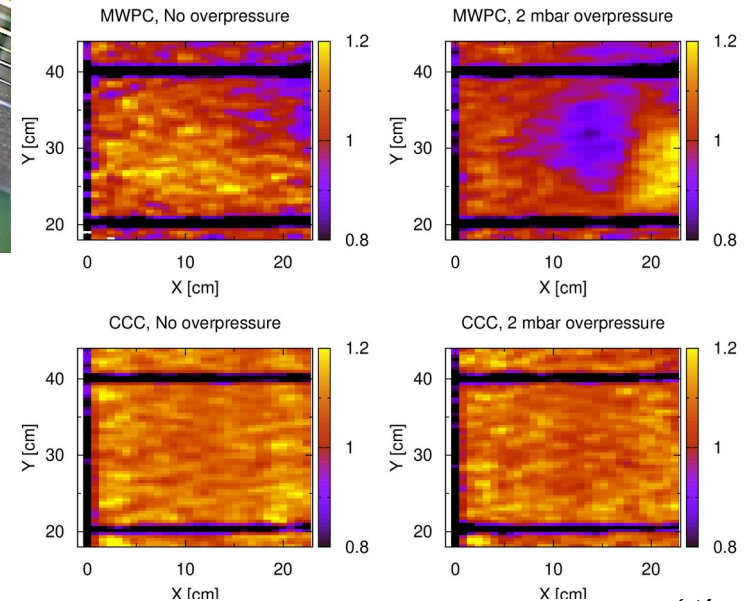
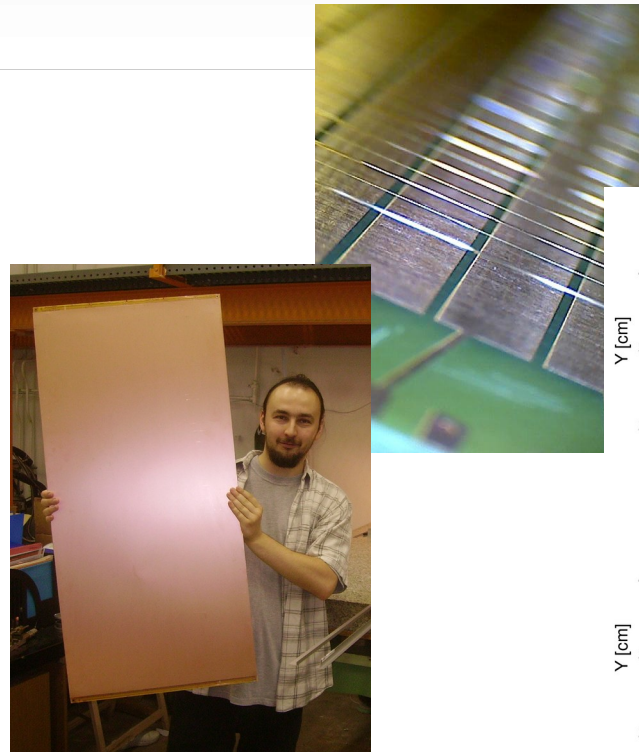
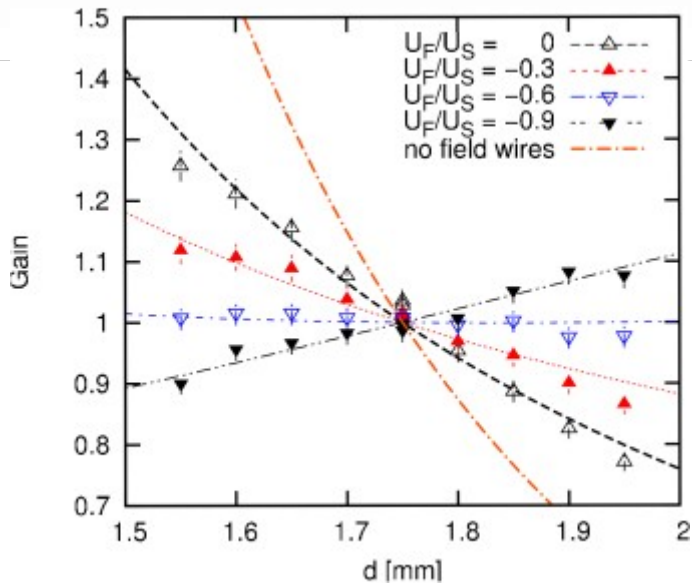
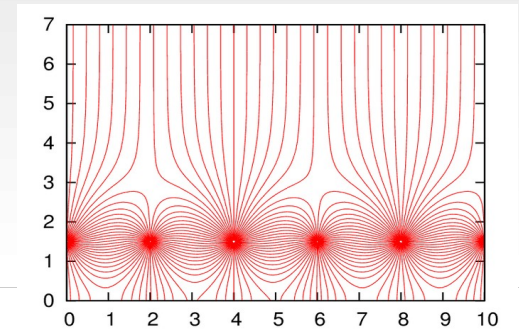
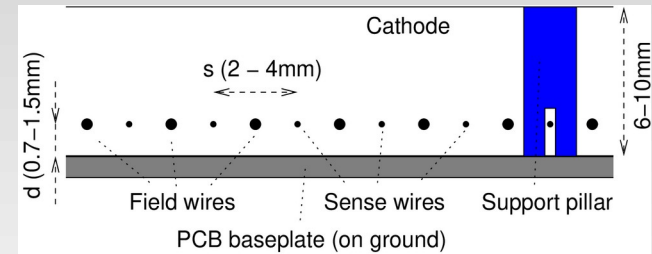
# Muography Detectors

- Muon (charged) + Flux < direction info  
→ HEP Tracking detectors
- Requirements
  - Good angular resolution ( $\sim 1^\circ$ , spatial res. / level arm)
  - **Robustness versus harsh environments**  
(humidity, day/night var., summer/winter cond., transport, ..)
  - Scalability (large surface → shorter exposition time, small < access)
  - **Cost efficient** (large area det., multiple det., industrial appl.)
  - **Low power** operation (in-field applications, caves, volcanos,...)
  - Remote access/control? (if monitoring, if large systems)
- Technologies:  
Emulsion, Scintillators, GasDet.: MM, RPC, Mod.MWPC



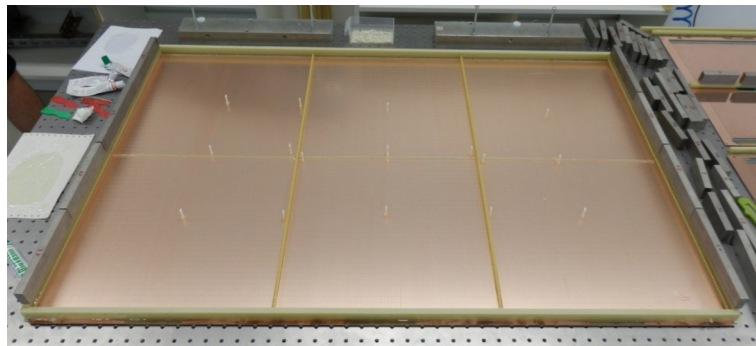
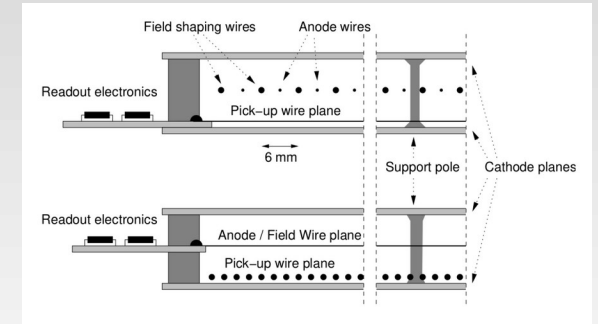
# REGARD - Close Cathode Ch

- **Close Cathode Chamber (CCC)**
- Sense+Field wires, FW on negative potential  
Insensitive to WirePlane distance,
- No robust frame is needed, Lightweight
- Simple construction due to relaxed conditions
- Good position resolution, Low occupancy



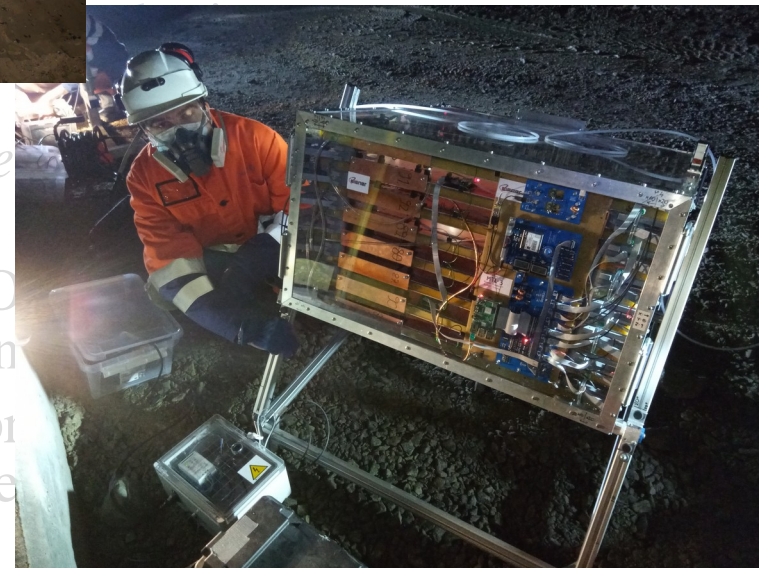
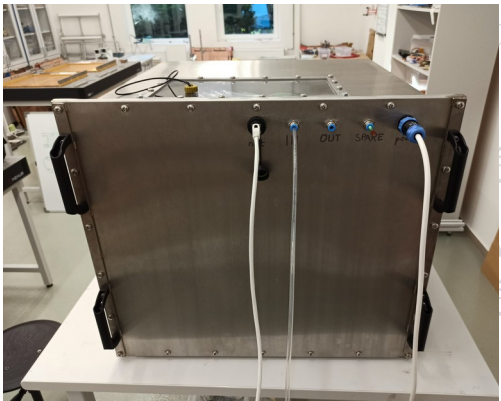
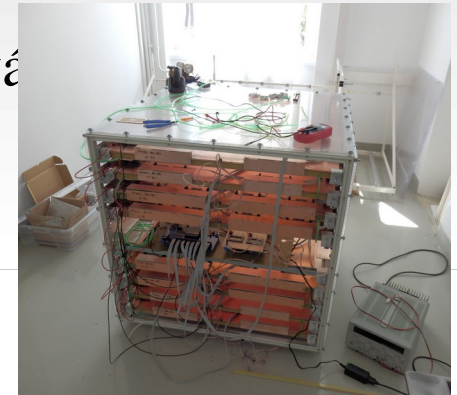
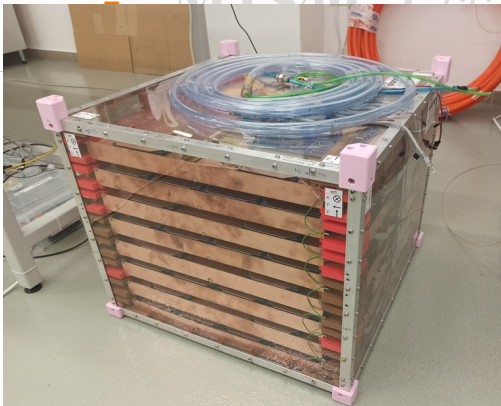
# REGARD : Modified MWPC

- Modified MultiWire Proportional Chamber
- Larger size detectors  $\sim 1\text{m}^2$
- Sense+Field+PadWires : Projective geometry
- Moderate resolution  $\sim 1\text{cm}$ , low n.ch  $\rightarrow$  Few FECs,
- Simple and cost-efficient construction



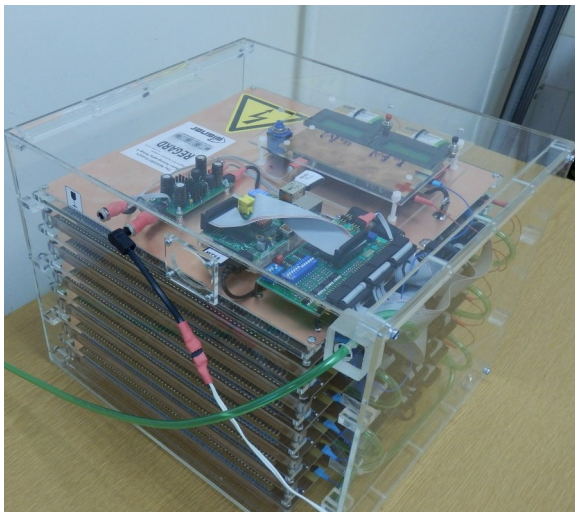
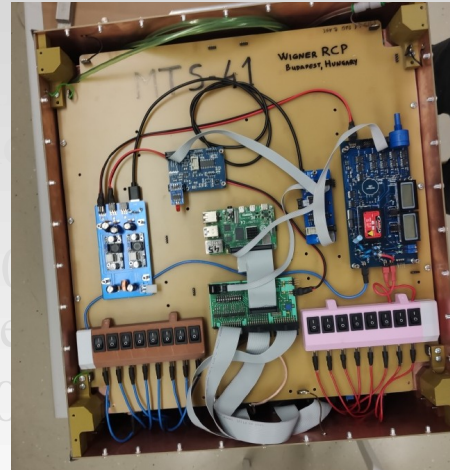
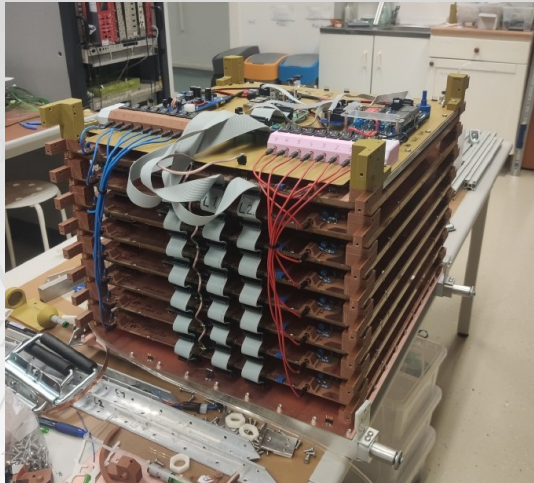
# Müográf Portfólió

- Felhasználási területhez optimalizálható design: méret, fogyasztás, ellenállóság, célterület, fókusztáv, hordozhatóság, vezérlés.
- **MTL-X** : Mwpc-80cm, 6-8 réteg, 80kg, op. Inox burok, állvány  
Bányászat, mély földalatti mérések
- **MTS50** : Mwpc-50cm, 6-8 réteg, 40kg, op. Inox burok, állvány  
Földalatti felmérések, kommersz ajtón átfér



# Müográf Portfólió

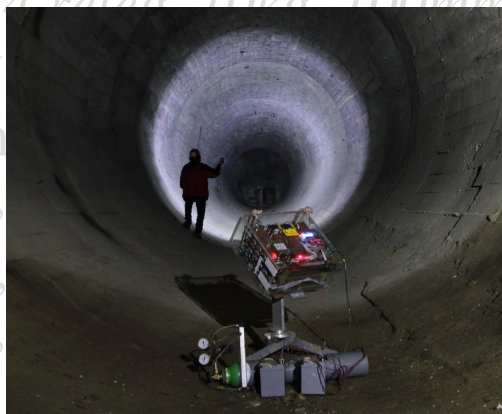
- 
- MTL-X : M  
Bányász
- MTS50 : M  
Földalati
- **MTS40** : Ccc-40cm, 6-8 réteg, 30kg, állvány  
Finom felbontású verzió, közepes mélységekbe
- **MTS25** : Ccc-25cm, 5-6 réteg, 20kg  
Finom felbontás, kis verzió, természetes barlangokhoz



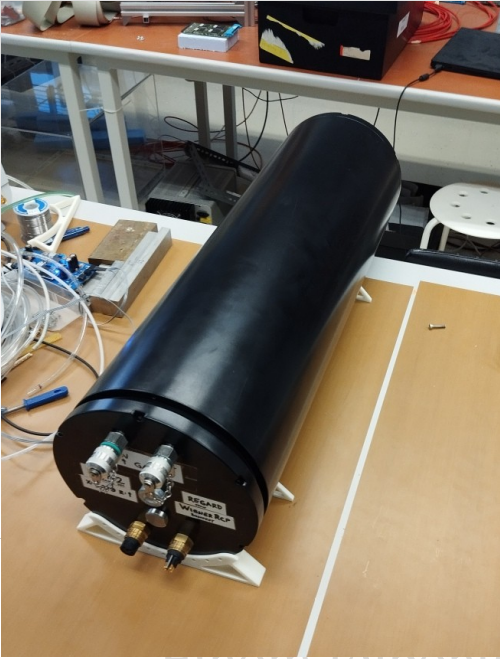
x40, 4 réteg, 16kg, hengeres, vízalatti  
khez, 600m-ig vízálló

cm, 4 réteg, 10kg, 100mm he  
ezett

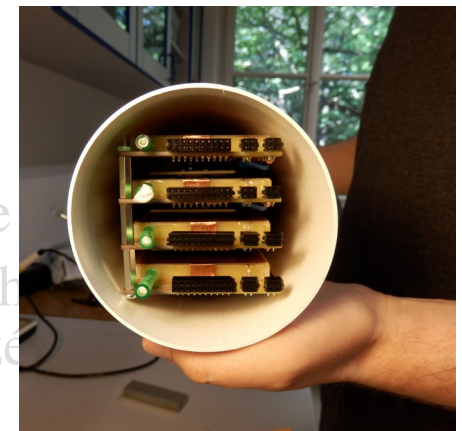
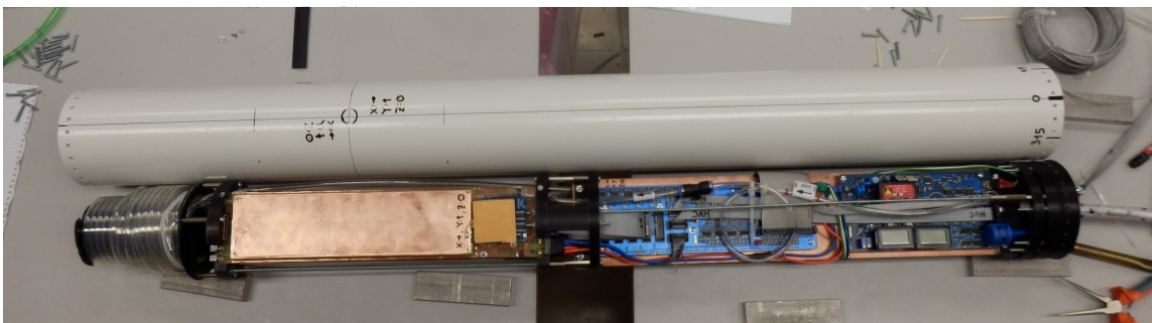
0cm  
hez,  
0cm,  
hez,



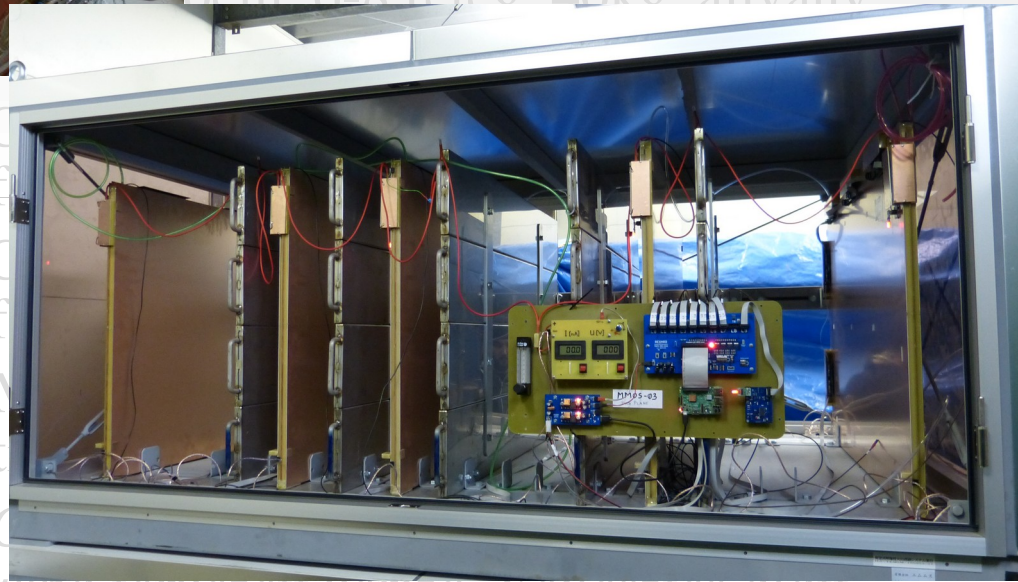
# Műgráf Portfólió



- **MTP-X** : Mwpc-13x40, 4 réteg, 16kg, hengeres, vízalatti  
Vízalatti mérésekhez, 600m-ig vízálló
- **BHD-X** : Ccc-6x25cm, 4 réteg, 10kg, 100mm henger  
*Fúrólyukba tervezett verizó, Fejlesztés alatt*

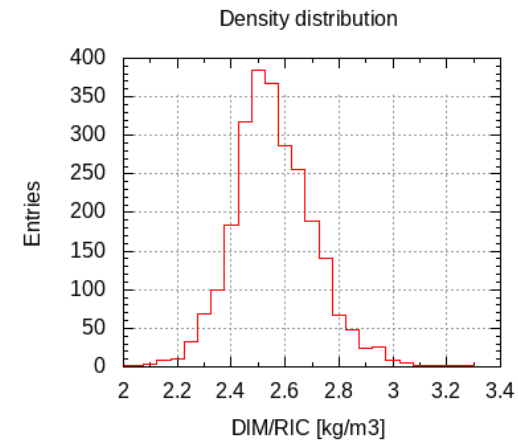
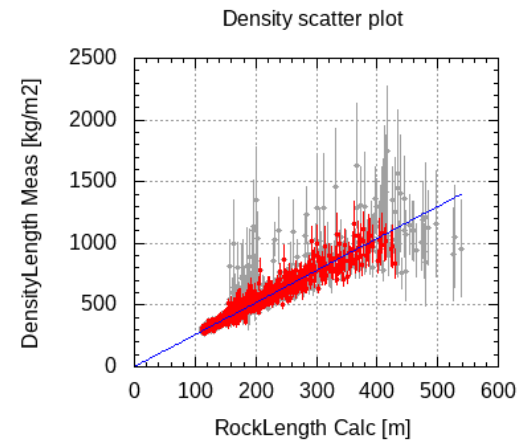
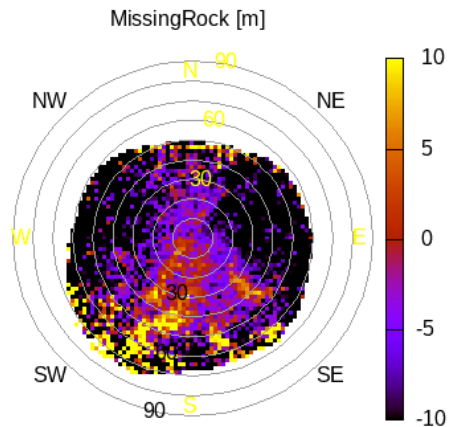
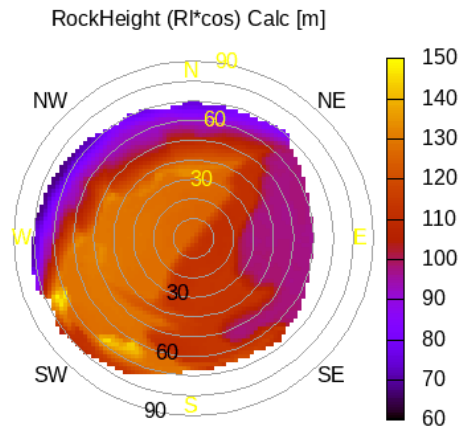
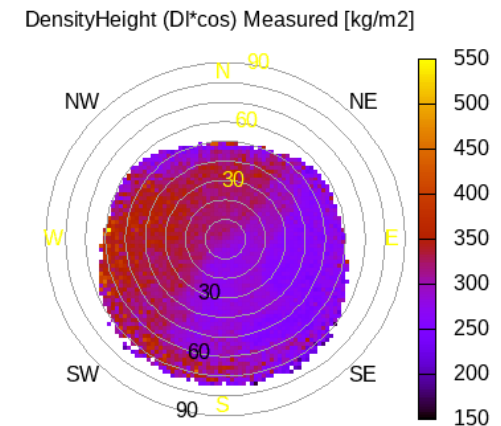
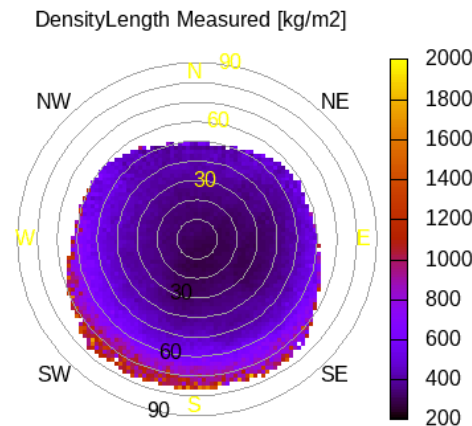
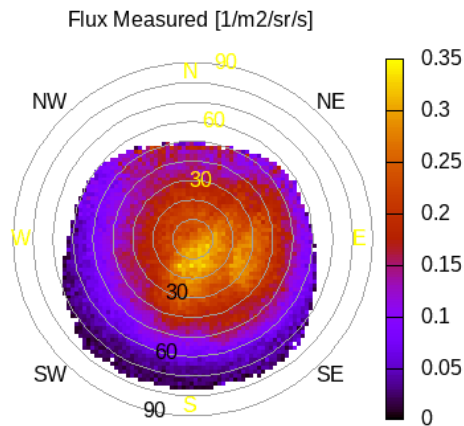
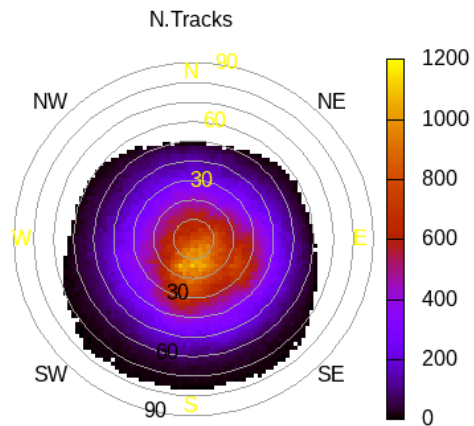
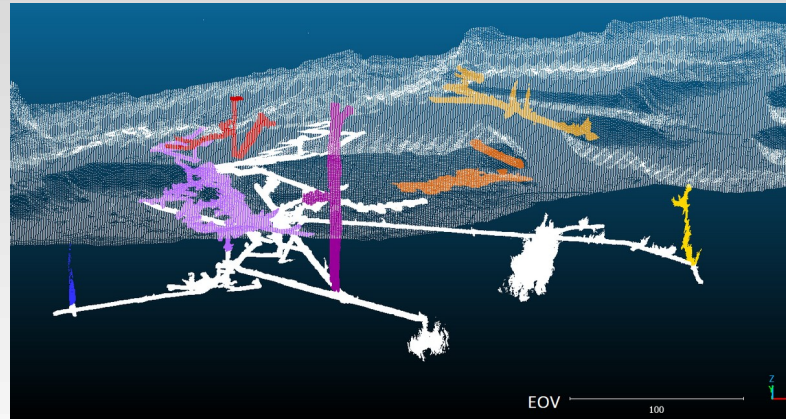


# Müográf Portfólió



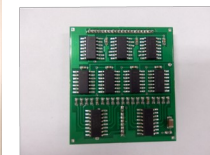
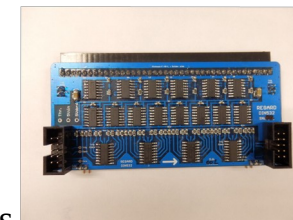
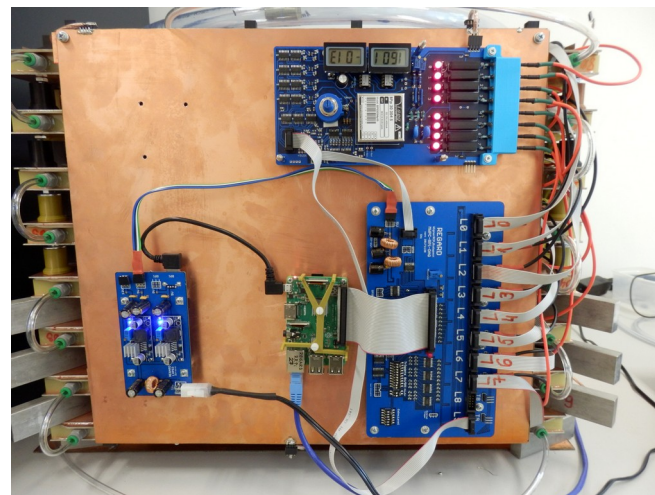
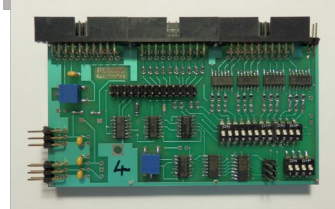
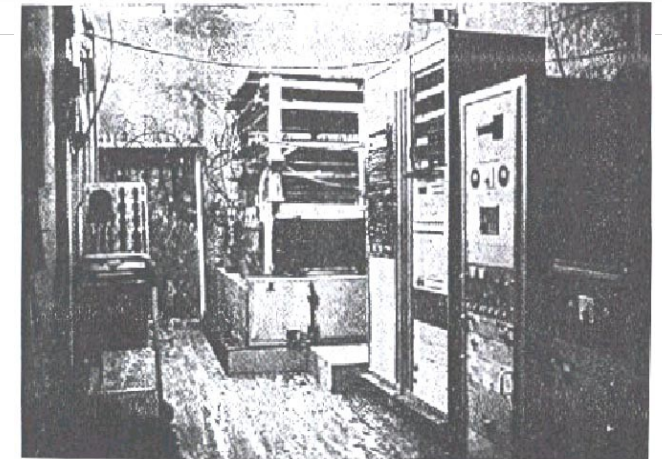
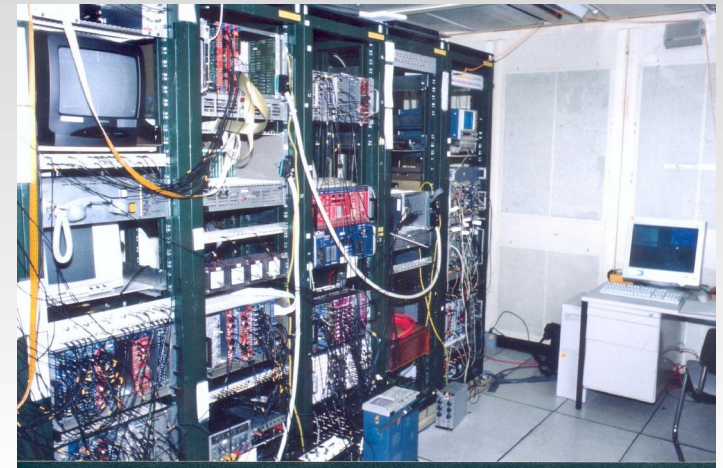
- **MTS40** : C  
Finom f
- **MTS25** : C  
Finom f
- **MTP-X** : M  
Vízalatt
- **BHD-X** : C  
*Fúrólukba tervezett verzió, Fejlesztés alatt*
- **MMOS** : Mwpc-120cm, 7 réteg, SakurajimaMO  
Felszíni mérésekhez, ólom szórólapokkal, rendszerbe építhető
- **MTH-X** : Mwpc-80cm, 6-8 réteg, 60+60kg, lapraszerelhető  
Felszíni mérésekhez, két ólomréteg, lépcsős elrendezés

# Muogram example



# Data Acquisition

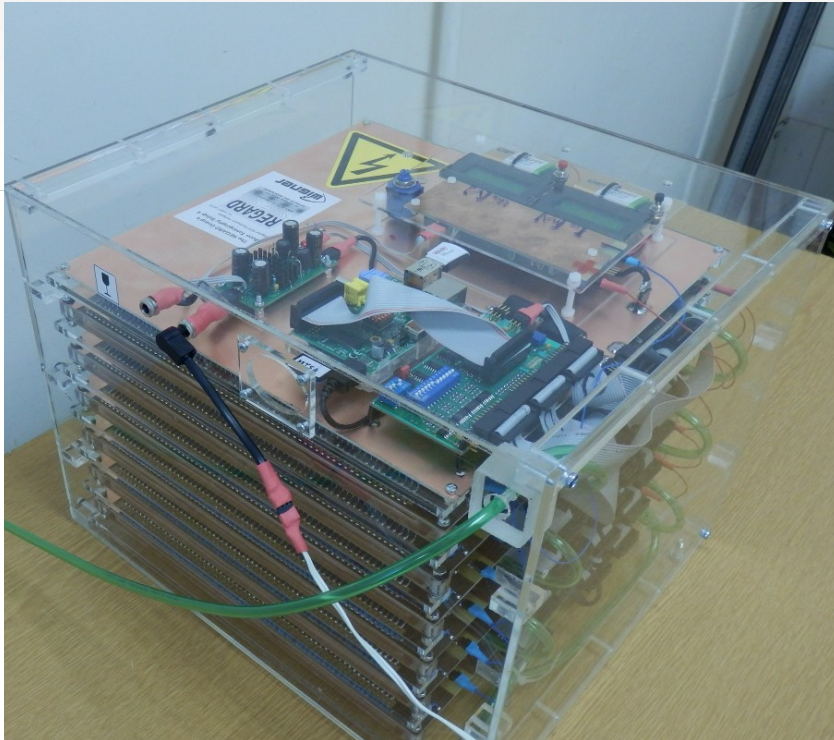
- RaspberryPi microcomputer (low cost)  
ARM CPU + Broadcom  
Peripherals: USB, HDMI, **GPIO**, ...
- DataStorage + Access + Control  
OS eg. Raspbian linux
- GPIO pins (10MHz) adaptable  
for any custom protocol
- FEE: Digital: Preamp+Discrimination  
→ ShiftReg : chainable, simple  
power < 5mW/ch
- Trigger : N-fold coincidence for layers



# Portable Muographs

- **Small-sized Muographs**

Based on CCC chambers, Extra lightweight,  
Compact, One-man-can-carry detectors,  
Mostly used for cave exploration (see later)  
Six layers of 25x25cm<sup>2</sup> CCC



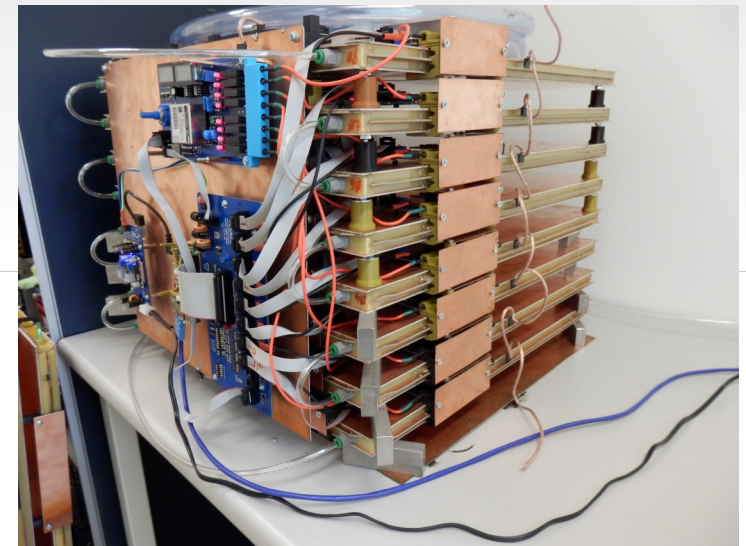
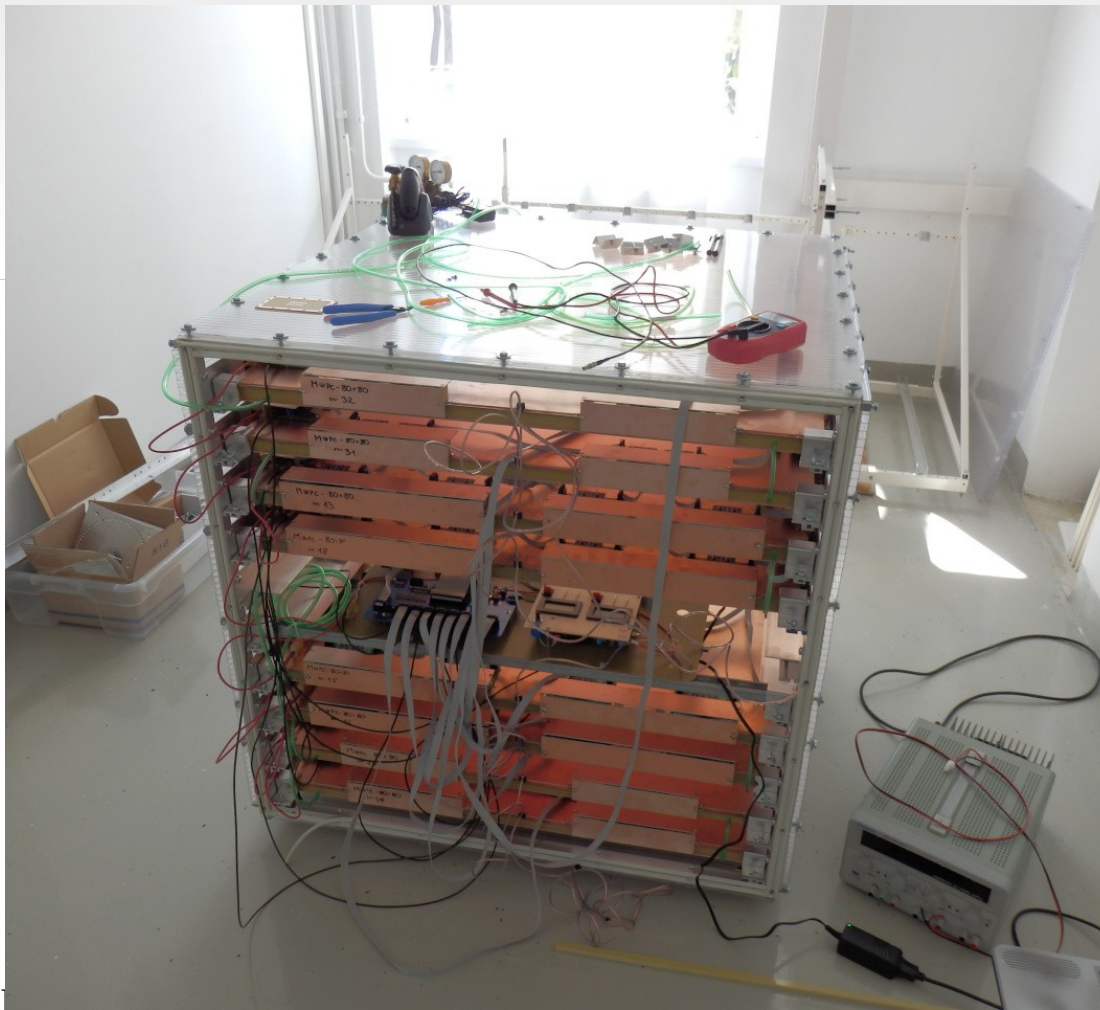
# Portable Muographs

- **Large-size Muograph**

Based on Modified MWPC Chambers,  
Mostly used for easier-access sites (see later)

Eight layers of 80x80 cm<sup>2</sup>

or 50x50 cm<sup>2</sup>



Can be manually carried if needed :)

# Portable Muographs

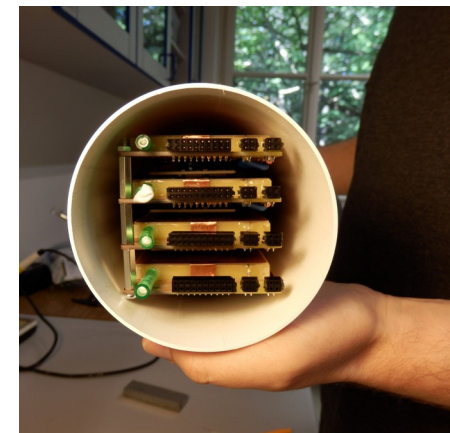
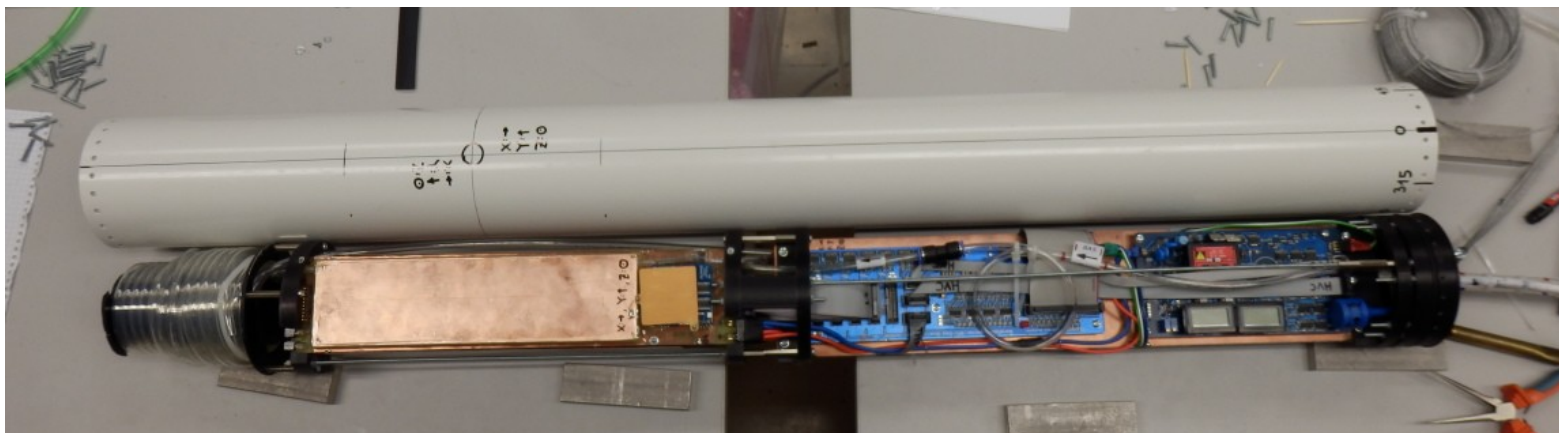
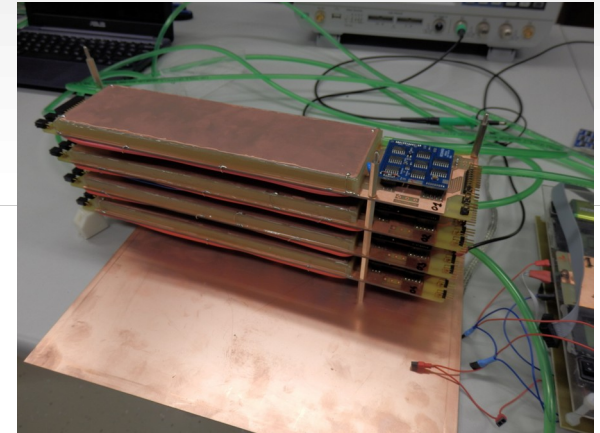
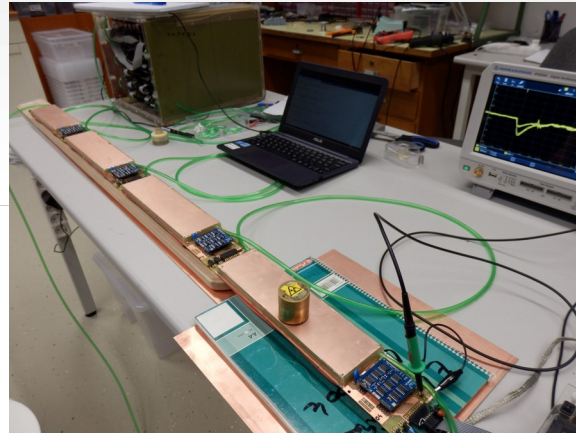
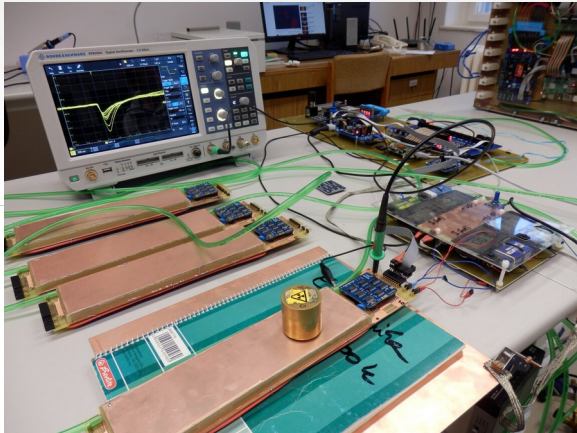
- **BoreHoleDetector**

Fit into tube diam: 100 mm

Four CCC chambers, wire-spacing 3mm,

Extendable: designed like a „Train”

with Locomotive (DAQ) + multiple Wagons (Detectors)



# Portable Muographs

- **MTP 1 and 2**

Underwater muograph, Sealed op., Tube diam: 200 mm  
Four CCC chambers, wire-spacing 4mm, 128x384mm<sup>2</sup> aa.

