Istituto Nazionale di Fisica Nucleare

Imaging with neutrons, muons and protons

Carlo Civinini
INFN-Firenze

Congressino Gr. 5
Firenze, 3 Febbraio 2021

Introduction

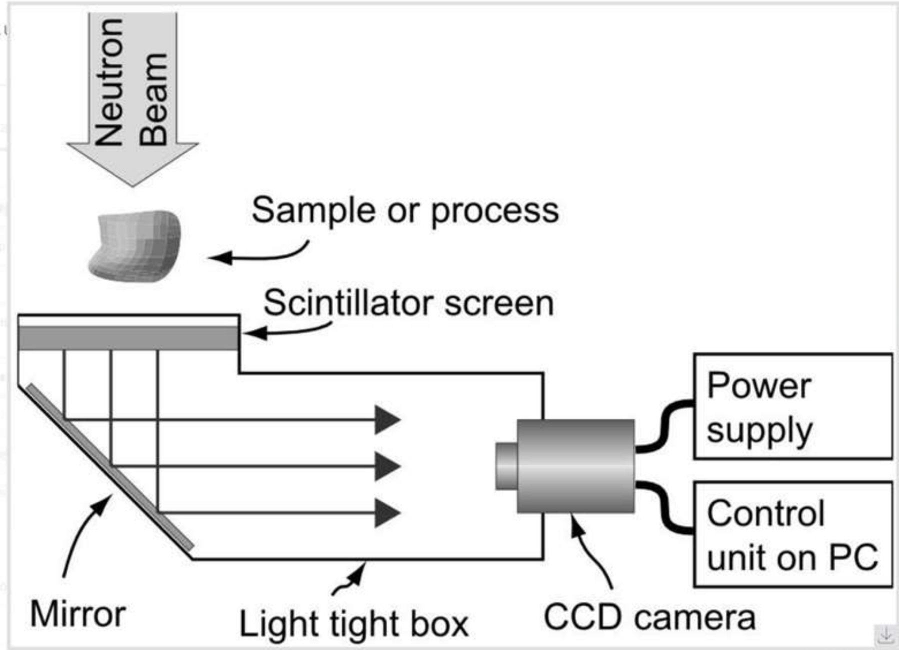
- I will summarize three Gr. 5 experiments, very different from each other:
  - CHNet-NICHE, MITO, XpCalib
- But with a similar purpose: Imaging
  - This is a process through which it is possible to observe the structure and nature of a physical system that is not directly 'visible' from outside
  - The resulting 3D tomographic (or 2D radiographic) images could be obtained using techniques which are mildly, or not at all, invasive.
- In addition to e.m. probes (X-rays, microwaves) or acoustic waves, charged or neutral massive particles are currently emploied:
  - Neutrons → CHNet_NICHE — Cultural heritage (morfology and non destructive analysis)
  - Muons → MITO — Vulcanology, mines, etc.
  - Protons → XpCalib — Tumor therapy with protons or ions beams.

Neutrons

CHNet-NICHE experiment

Experimental method: neutrons

- Radiation source:
  - Thermal or ‘cold’ neutrons’ (moderated by water or liquid hydrogen)
- Baseline L (preferably a vacuum line)
- Collimator:
  - Its diameter D defines the ‘focusing power’ L/D and part of the spatial resolution of the imaging system
- Scintillator to detect the neutrons which are not absorbed nor scattered by the sample under test:
  - $GdO\ -LiF/ZnS$, the thickness and composition affect resolution
- Optics: mirrow and camera lenses
- CCD camera to collect the scintillator emitted light
- Rotating platform for tomographic acquisitions
- Software algorithms to reconstruct the tomographic images starting from the single projections:
  - Mainly FBP (filtered back-projection)



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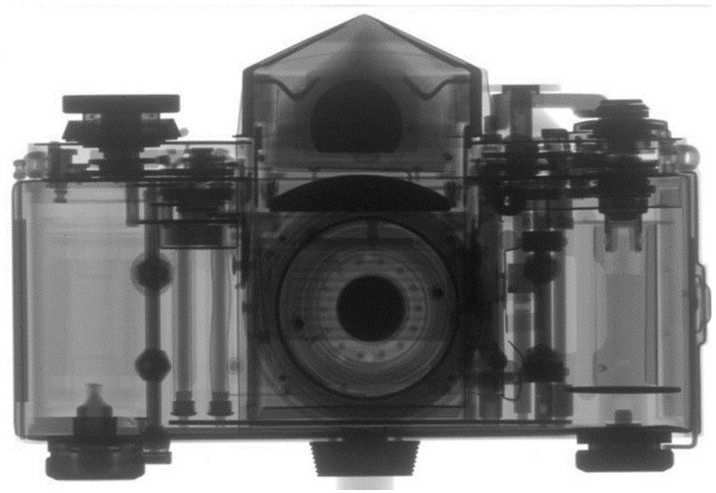
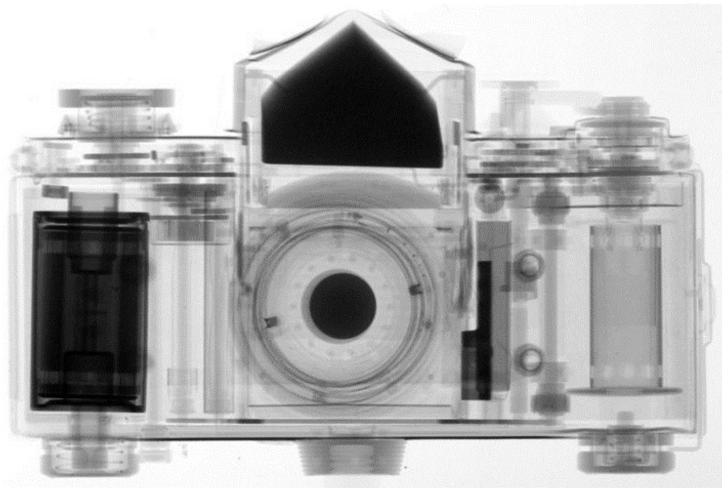
Experimental method: neutrons

- Neutrons have a high sensitivity to the light elements (organic or hydrogen-rich materials) and a high penetrability in the heavy elements (metals)
- On the other hand X rays, much simpler to produce also with higher intensities, have a low sensitivity to light elements and are easily stopped by heavier elements.



X rays radiography



Neutron radiography

Experimental method: neutrons

- Effects of organic materials inside bronze statues

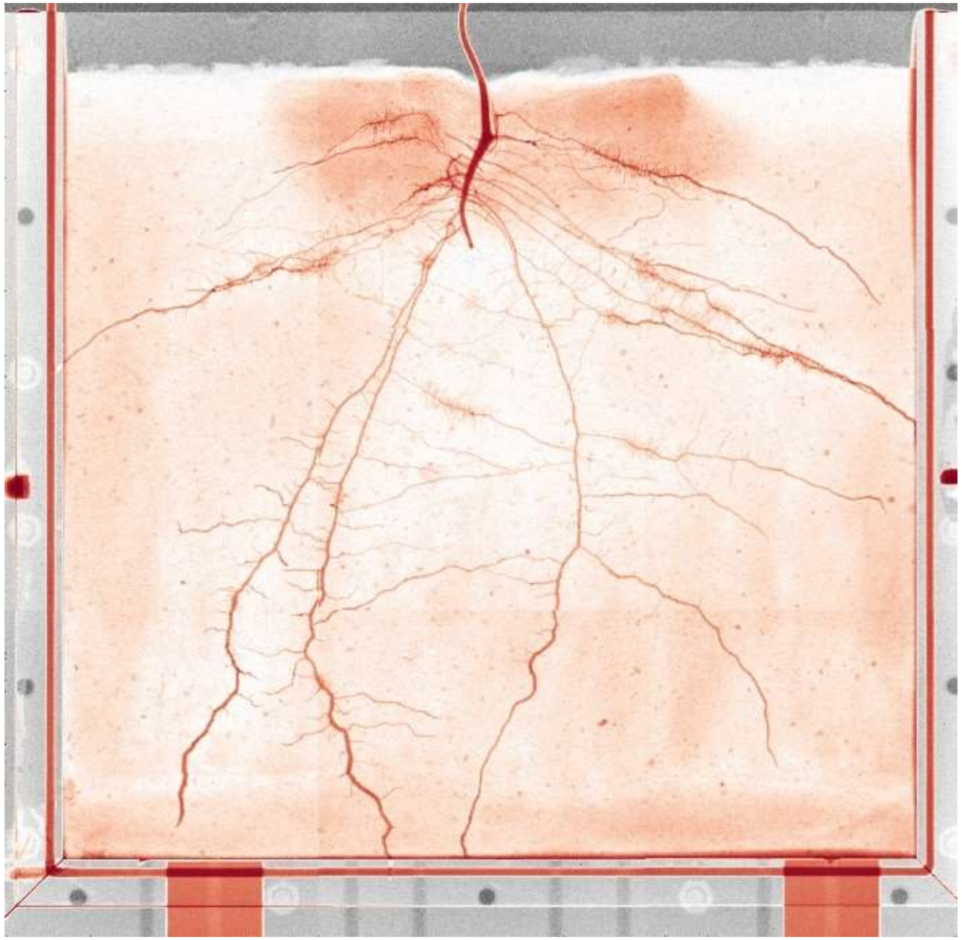
X rays radiography

Thermal neutron radiography

Neutron imaging is the optimal method to study systems made by both organic and heavy element materials.

Experimental method: neutrons

- Light elements examples: organic material (plant roots)
  - Study on the soil water absorpion by the plant roots.



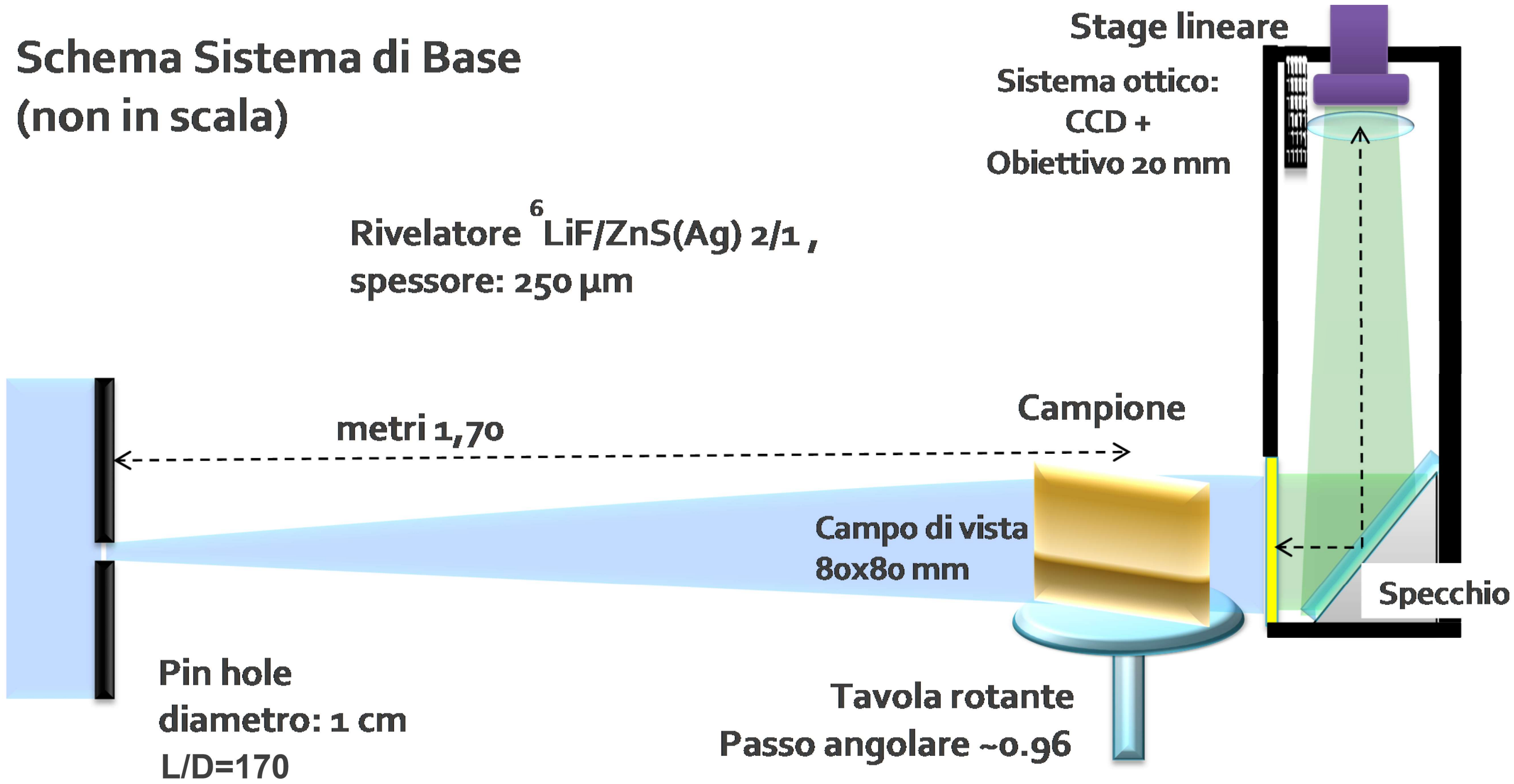
Thermal neutron radiography
(https://www.psi.ch/en/niag/gallery)

CHNet-NICHE experiment

- Cultural Heritage Network – Neutron Imaging for Cultural Heritage
- N. Gelli and F. Grazzi – INFN national resp.
- INFN units: Fi, Pv, Bo, MiB, To
- Project duration: 2 anni

- Target: development and optimization of a thermal neutron imaging system to be installed at the LENA reactor in Pavia.
- Exploit the available beam line of the TRIGA reactor (presently used for 'Prompt Gamma Neutron Activation Analysis' (*PGNAA*) for the CHNet_TANDEM experiment) setting up the first neutron imaging facility in Italy open also to external users and dedicated to analyses in the field of cultural heritage.
- Supplement the diagnostic instrumentation already present within the Cultual Heritage Network CHNet, with a new neutron imaging facility, expanding the range of technologies and equipment available.

Experimental setup: CHNet-NICHE

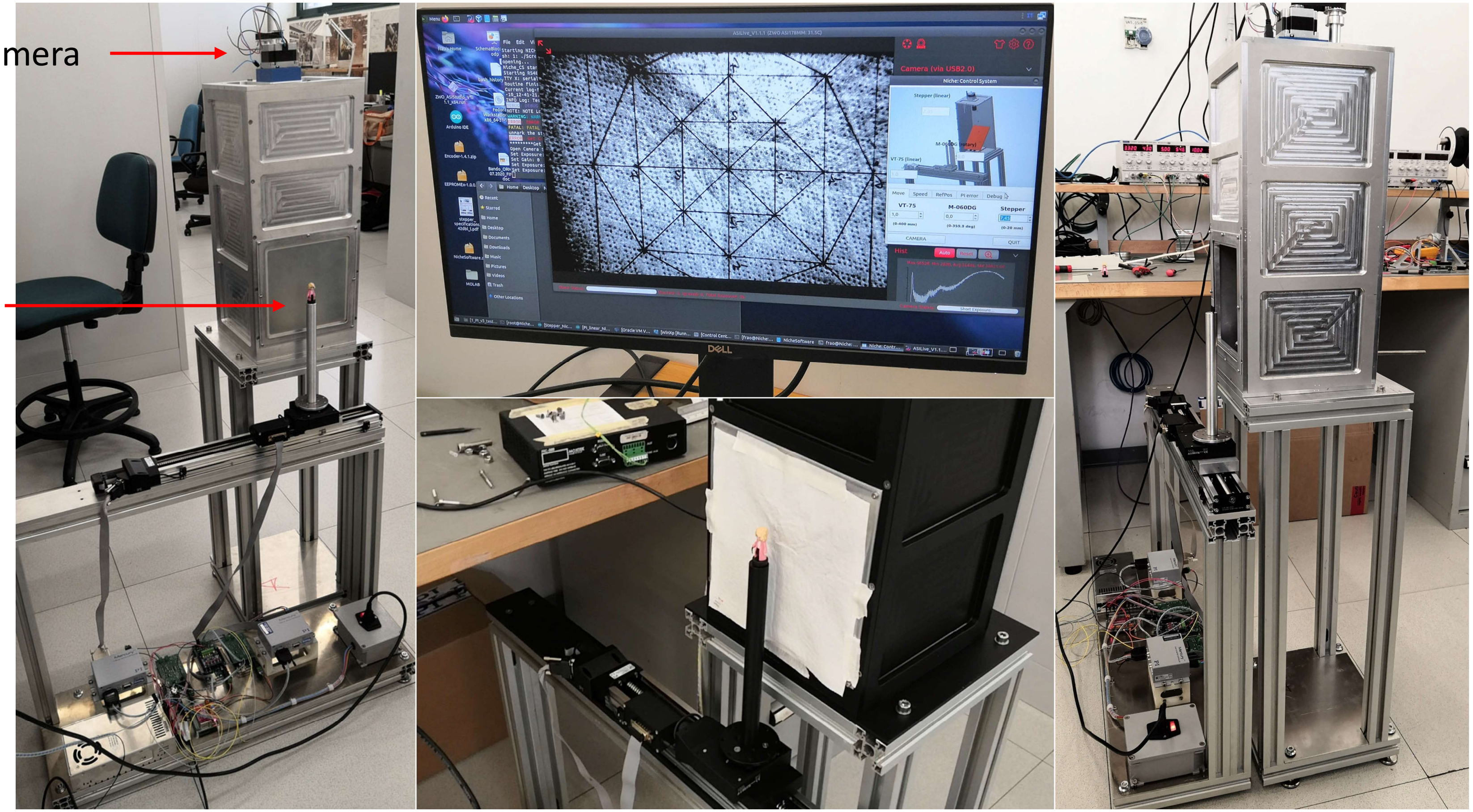


Variable geometry: the coupling between the beam image on the scintillator screen, the mirrow and the camera/lens system is adjustable to optimize the resolution and yield.

Experimental setup: CHNet-NICHE

CCD Camera

Sample holder



CHNet-NICHE: experiment goals

- By the end of 2020
    - **WP1**: production of the basic imaging system, characterization and evaluation of the performance improvement, spatial resolution certification by IAEA standard procedure.
    - **WP2** : beam characterization, measuraments and simulations of the spatial and neutron energy distributions, *beam hardening* evaluation.
- *By the end of 2021*
    - **WP3**: optimization of the different system components. Multi-layered shielding implementation (paraffin, boron, cadmium, lead) to mitigate the radiation damages to the most sensitive components of the system (e.g., camera CCD chip).
    - **WP4**: system implementation whit the commissioning of a *beam limiter* to reduce the environment irradiation and to minimize the background due to the indirect irradiation of the sample.
    - **WP5**: case studies which exploit the peculiarity of the new neutron imaging facility.

- This timescale has been affected by the covid-19 pandemic.

CHNet – NICHE participants

Lisa Castelli 20%
Caroline Czelusniak 20 %
Nicla Gelli 40% (Resp. locale)
Lorenzo Giuntini 30 %
Francesco Grazzi 40%

Marco Manetti 10 %
Mirko Massi 10%
Anna Mazzinghi 50%
Chiara Ruberto 50%
Francesco Taccetti 10 %

Sezione di Firenze CHNet_NICHE **FTE: 2.8**

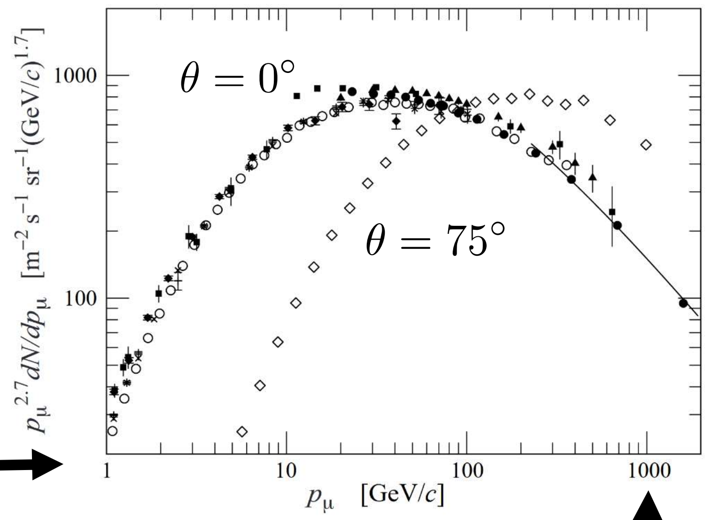
Muons

MITO experiment (& friends)

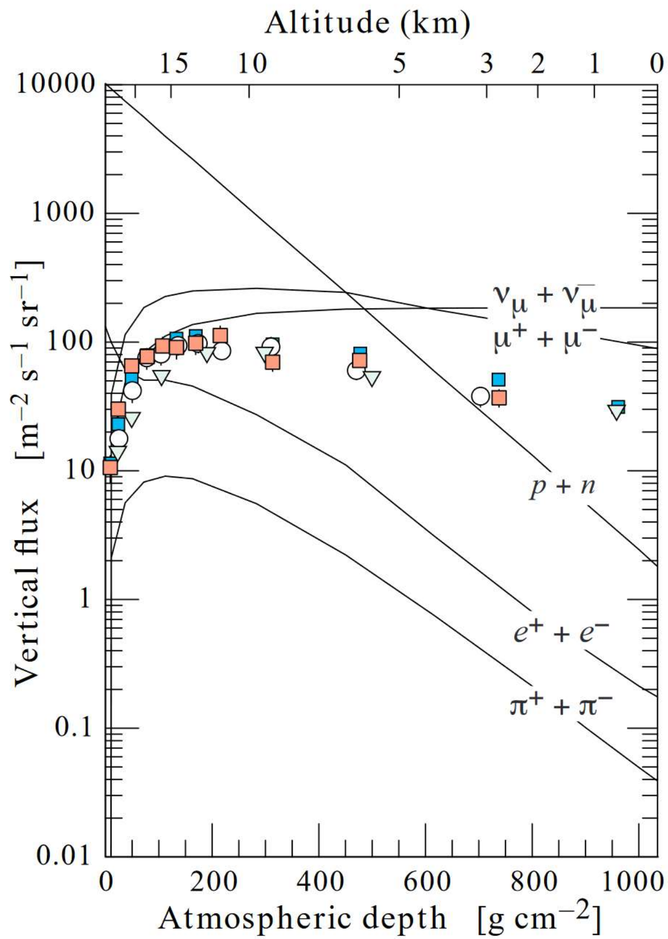
Experimental method: muons

- Radiation source:
  - Cosmic rays (at sea level)
- Detector telescope:
  - Segmented plastic scintillator planes with SiPM (Silicon photomultipliers) readout
- Tomographic/radiographic reconstruction algorithms

- The cosmic ray flux at the sea level is about **100 muons $m^{-2}s^{-1}sr^{-1}$** (around the vertical)
- Sea level muon spectra from two different directions: higher mean energy for muons with trajectories closer to the horizon.



$Range_\mu(1\ TeV) \cong 1\ Km\ (rock)$

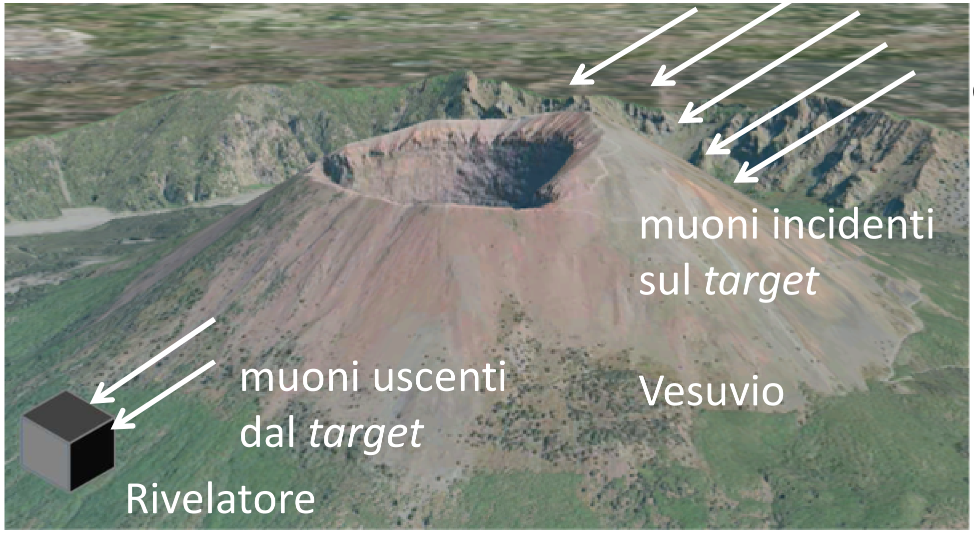


Cosmic rays flux composition at different altitudes

Experimental method: muons

- Muography is an *imaging* technique which uses the flux variation and the trajectory deflections of the muon cosmic rays while they cross an object under test (*target*) to make 2D or 3D images of its internal structure (first used by L. Alvarez, 1970 for Cheops' great pyramid inspection).

Muon radiography



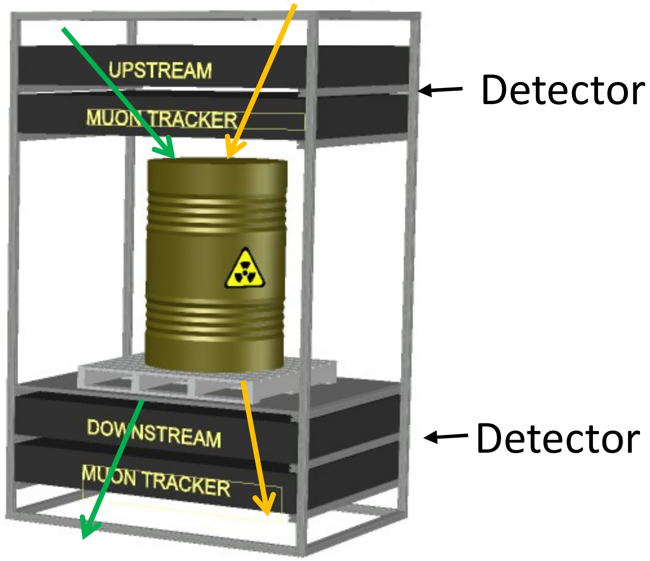
It is based on the muon **absorption** in the material (large volume).
Main applications: geology, archeology, civil engineering.

In both cases the detectors are charged particle trackers

↓

Reconstructions of the muons trajectories

Muon tomograhy

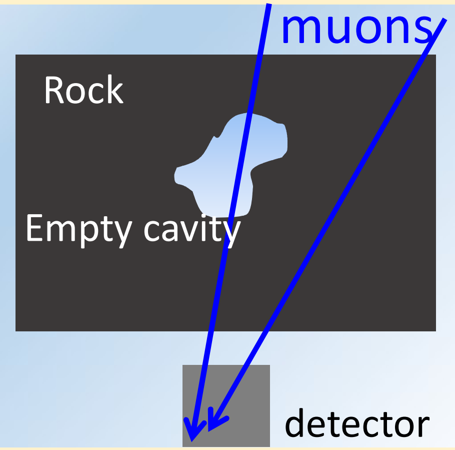


It is based on the measurement of the **multiple scattering** of the muon trajectories in crossing material (small volumes).
Main applicatins: nuclear security, industrial inspections.

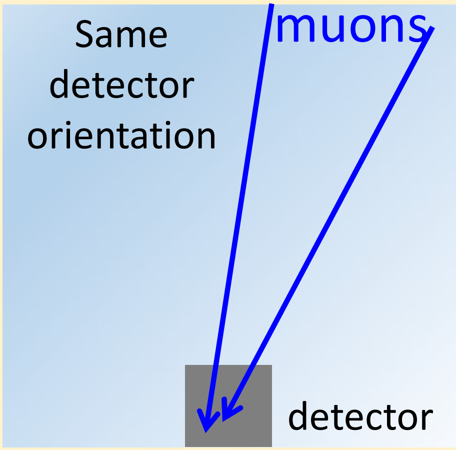
Muon radiography: experimental method

- Starting from a **muon radiography measurement** it is possible to obtaing **2D angular maps of the mean density** of the object under study checking the data against simulation.

➢ ***Target* configuration** (underground)



➢ ***Freesky* configuration** (open-air)

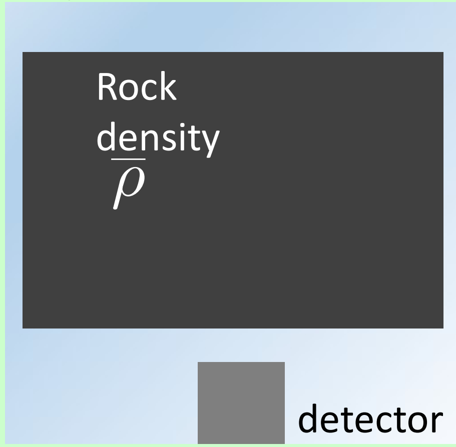


Measured muon transmission $t_{misu}(\theta, \varphi)$

Transmission: fraction of the muons impinging the detector after crossing the *target*

➢ **simulation** in case of a homogeneous target (fixed rock density and no empty cavities):

- *Target* geometry
- Sea level differential muon flux measured by the ADAMO (INFN-FI) magnetic spectrometer



Simulated transmission $t_{simu}(\theta, \varphi)$

Changing the density: $\overline{\rho}(\theta, \varphi)$

$$t_{misu}(\theta, \varphi) = t_{simu}(\theta, \varphi, \overline{\rho})$$

Mean density 2D angular map: $\overline{\rho}(\theta, \varphi)$

MURAVES: MUon RAdiography of VESuvius

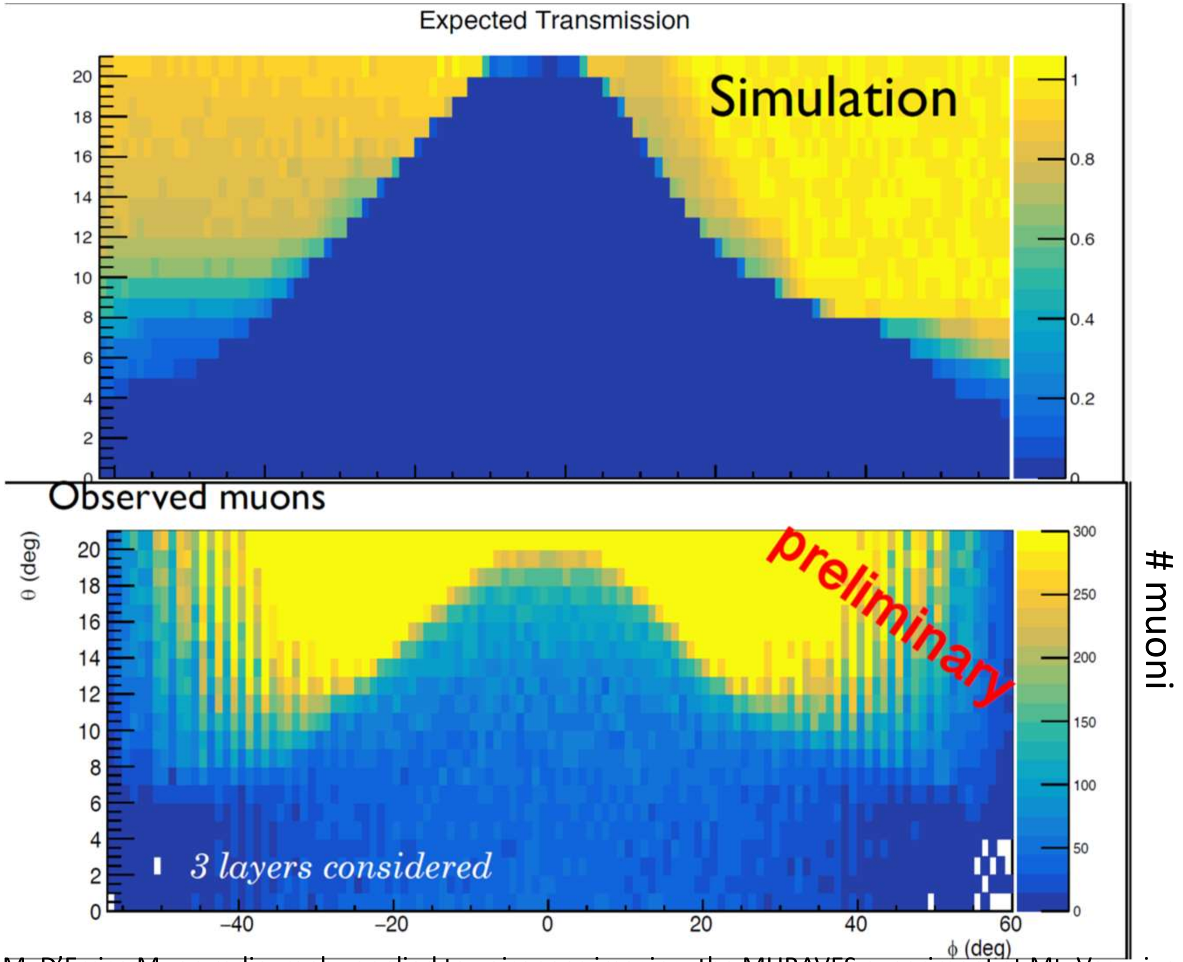
Position: E 14° 24’ 41.76”; N 40° 48’ 36.75” (675 m a.s.l.)

Three muon trackers:
Black – **Red** – **Blue**

PV panels: 18 x 300 Wp

32 Pb batteries (15.7 kWh)

MURAVES: preliminary analysis data



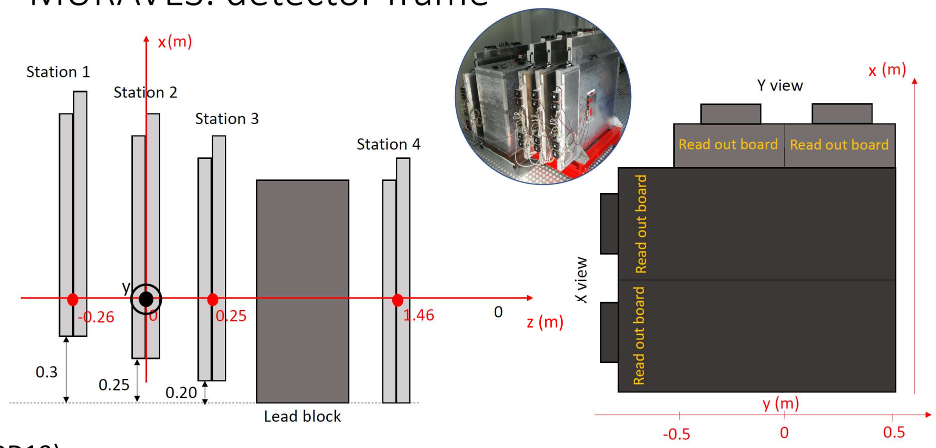
Preliminary measurement:

- One single detector (Black)
- 70 days acquisition statistics

Simulation:

- Software PUMAS (back-propagation)
- Full detector acceptance (4 planes)
- Geometry with lead wall

MURAVES: detector frame

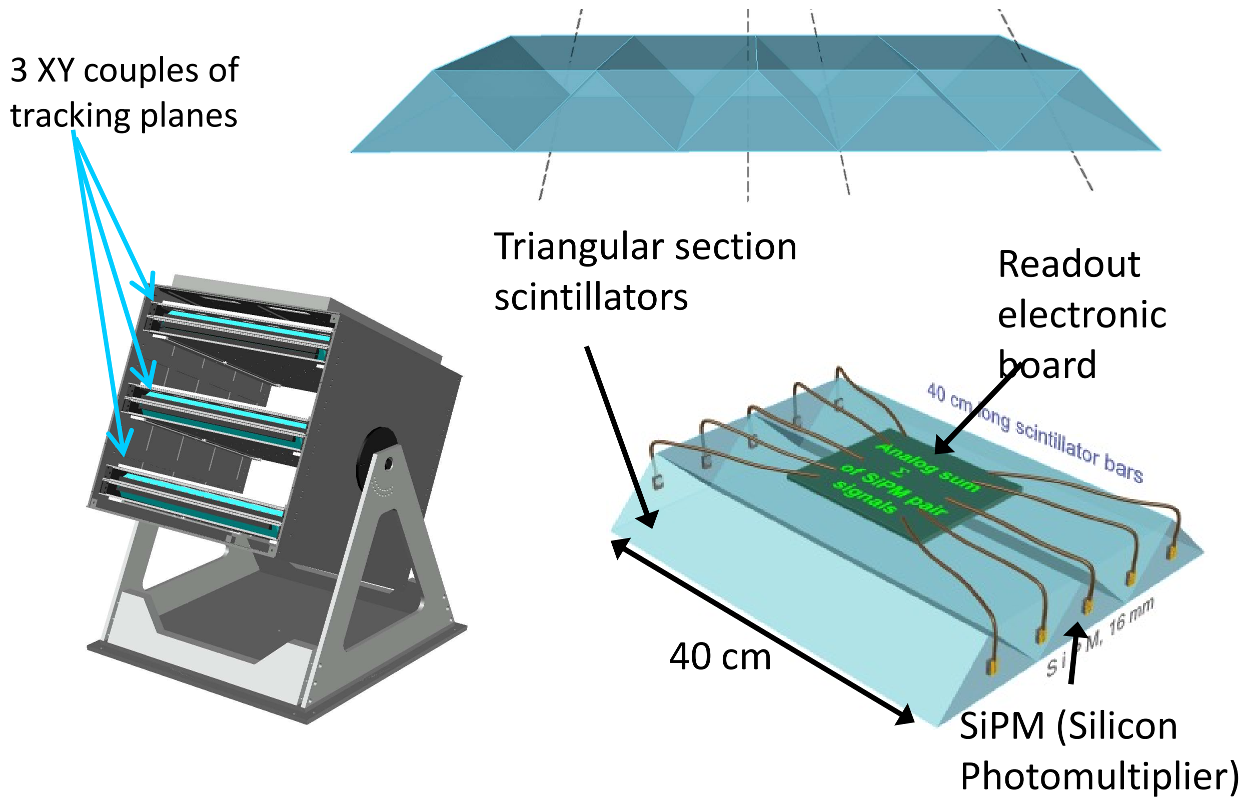


M. D'Errico Muon radiography applied to voicanoes imaging: the MURAVES experiment at Mt. Vesuvius (IPRD19)

The MIMA tracker- Muon Imaging for Mining and Archaeology

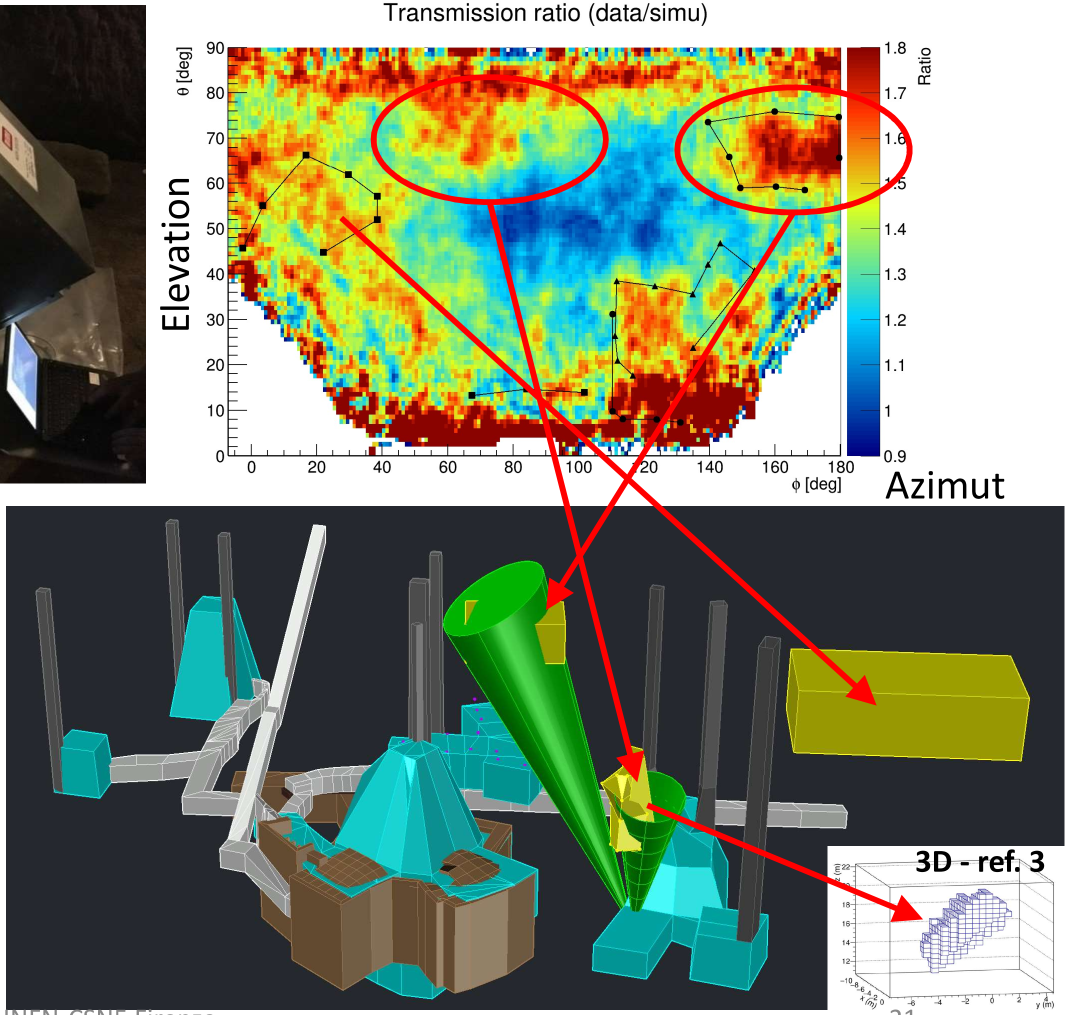
Goal: robust, light, low power tracking for multi-disciplinary muon radiography applications.

Mandatory requirement: ease of installation in harsh environments (e.g., mines, archeological sites, river banks, tunnel etc.)



- R&D: 2016 – 2017
- Tecnology: **plastic scintillator**
- Read-out ~ **MURAVES** (with minimal modifications)
- Total power: ~ **30 W**.
- Dimensions: **50 x 50 x 50 cm^3**
- Weight: ~ **50 kg**
- Angular resolution: ~ **14 mrad** (0.8°)
- Entrance surface: **0.16 m^2**
- Acceptance ~1000 cm^2 sr
- Pointing mechanics: **altazimuth mount**

Archeological applications: Bourbon gallery (NA)



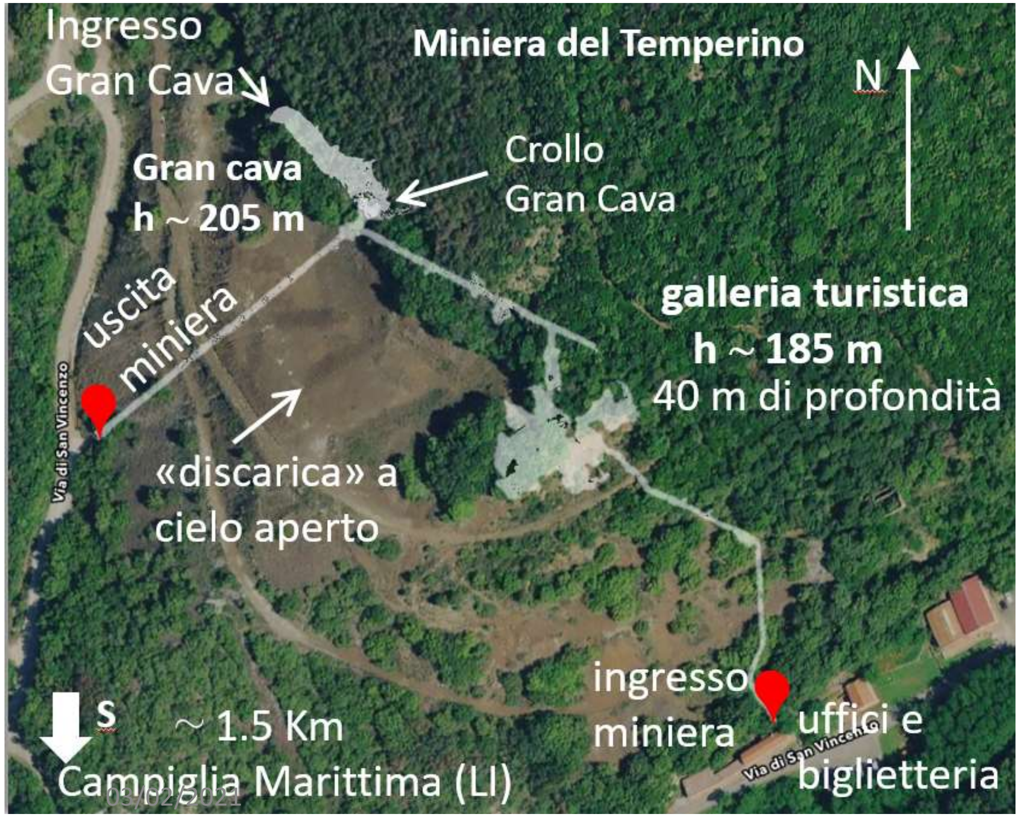
- Three measurements from three different point of view using Mu-Ray and MIMA apparatuses within the **Bourbon gallery** (Napoli)
    - Second half of 2017
    - First measurement with MIMA in complete configuration
    - «Target» meas.: 50 d, rate = 0.55 Hz, N_T = 2.36M
    - «Free sky» meas.: Florence, N_{FS} = 21 M

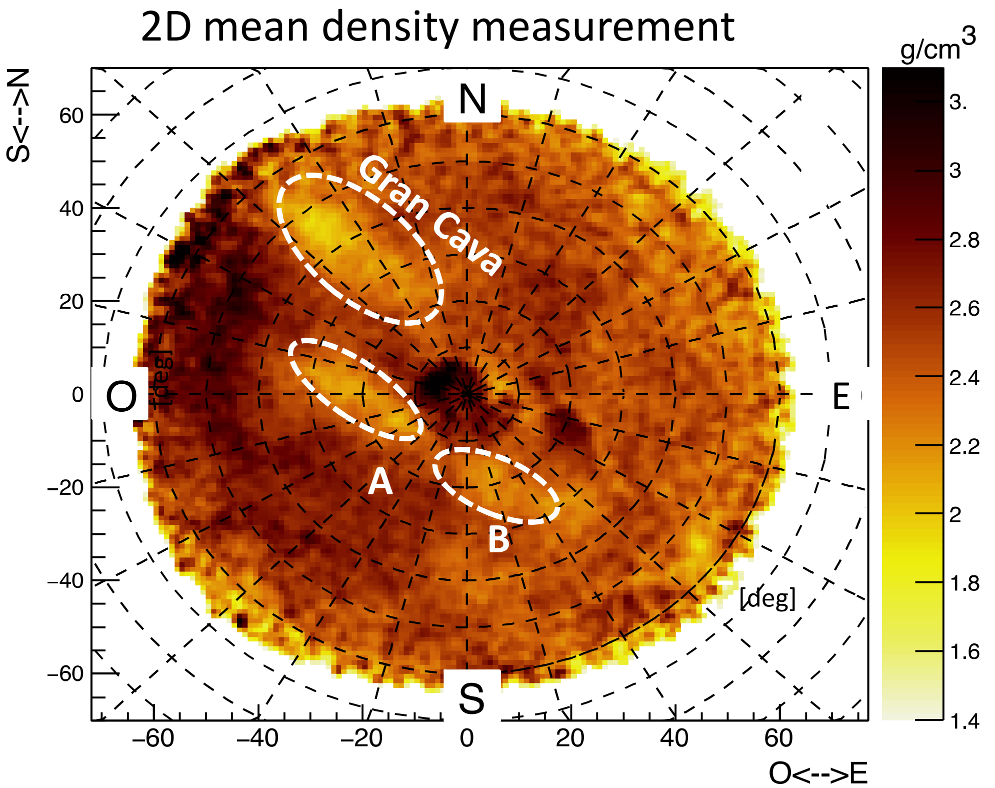
Temperino Mine

Location: Parco Archeominerario di San Silvestro - Campiglia Marittima (LI)

Mining activity: Etruscan origins, Middle Ages period, definitive closure around 1980.

Extraction: Pb, Zn, Ag, Cu and Fe concentrate in a surfacing vein of *skarn* (very hard metamorphic rock)





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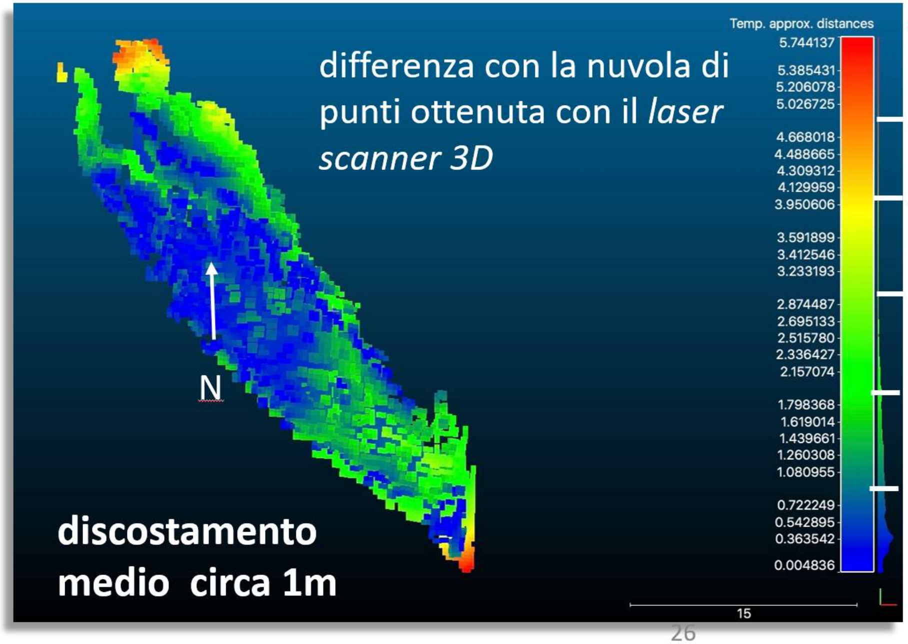
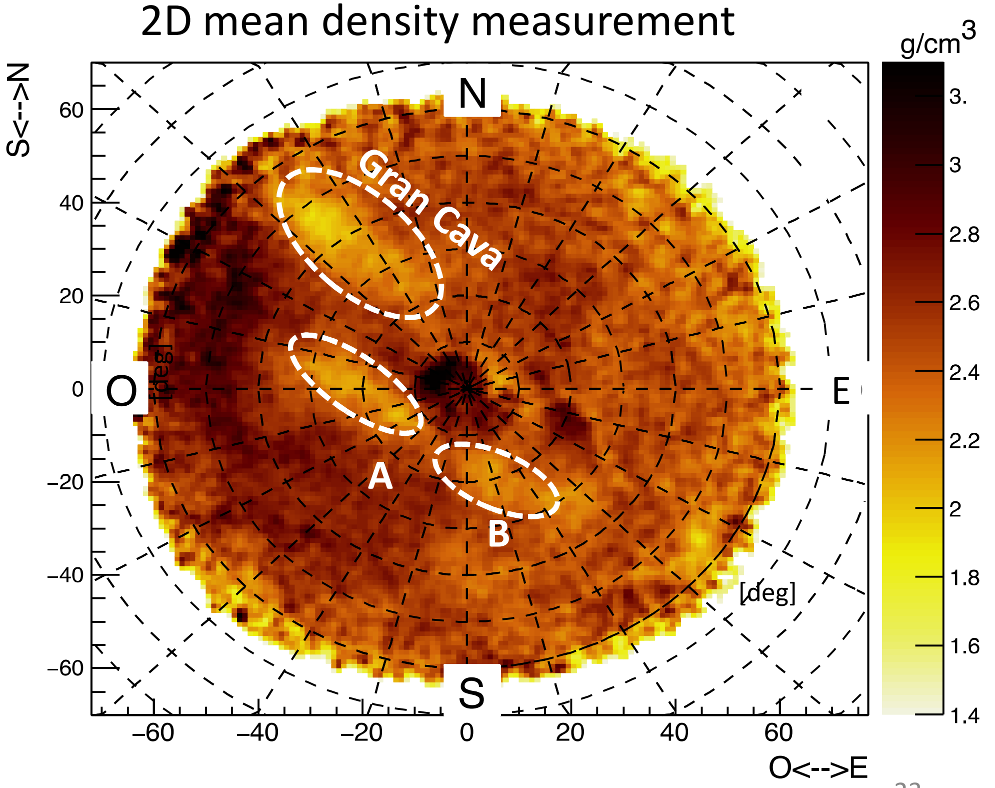


Tomographic reconstruction with the retro-projection method starting from a single radiographic image

2D mean density measurement



MITO experiment participants

L. Bonechi[1;2], G. Baccani[2;1], M. Bongi[2;1], D. Borselli[2,1], D. Brocchini[3], N. Casagli[4], R. Ciaranfi[1], L. Cimmino[5;6], V. Ciulli[2;1], R. D'Alessandro[2;1], C. Del Ventisette[4], A. Dini[7], G. Gigli[4], S. Gonzi[2;1], S.Guideri[3], L. Lombardi[4], N. Mori[1;2], M. Nocentini[4], P. Noli[5;6], O. Starodubtsev[2], V. Pazzi[4], G. Saracino[5;6], E. Scarlini[2], P. Strolin[5;6], L. Viliani[1]

1 INFN Firenze
2 UNIFI, Dip. Fis. Astron.
3 Parchi Val di Cornia (LI)
4 UNIFI, DST
5 UNINA «Federico II», Dip. Fis.
6 INFN Napoli
7 IGG-CNR (PI)

PHYSICS
GEOLOGY
ENGINEERING & GEOPHYSICS
ARCHAEOLOGY

Il team di ambito fisico a Firenze

Other muographic activities:

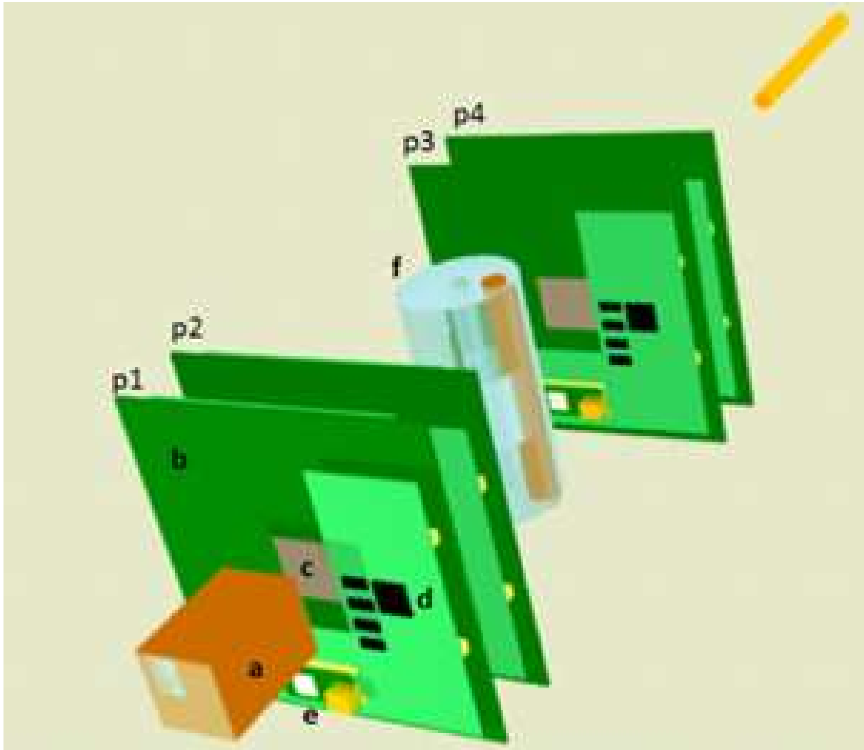
1. River banks studies (torrente Bure, PT)
2. Bilancino dam
3. MIMA-SITES: Temperino mine hidden tunnels search
4. MU-DOME: metal structures search inside the Brunelleschi's dome
5. BLEMAB: Muographic imaging of blast furnaces in steel mills
6. MIMONE: 64x64 cm^2

Protons

XpCalib experiment (& friends)

Experimental method: protons (INFN-system)

- Monoenergetic proton beam
  - $E_{beam} \approx 200 - 230\ MeV$
  - To be used in 'transmission mode'
- Detector
  - Tracker: four planes equipped with 'silicon microstrip' sensors
  - Calorimeter: $2x7$ crystals matrix YaG:Ce
- Rotating platform
- DAQ
  - Single particle mode $(\sim 200 \div 300\ kHz)$
- Recostruction
  - Iterative Algebraic Algorithms running on GPUs
  - 3D maps of Stopping Power relative to water (RSP)



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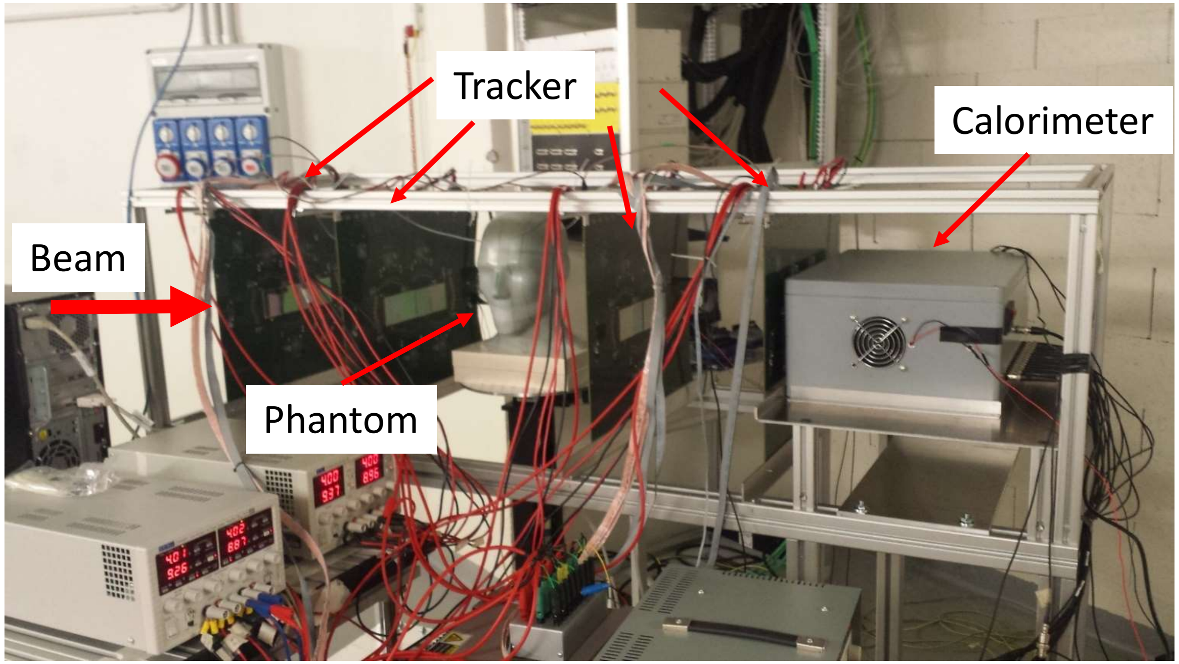


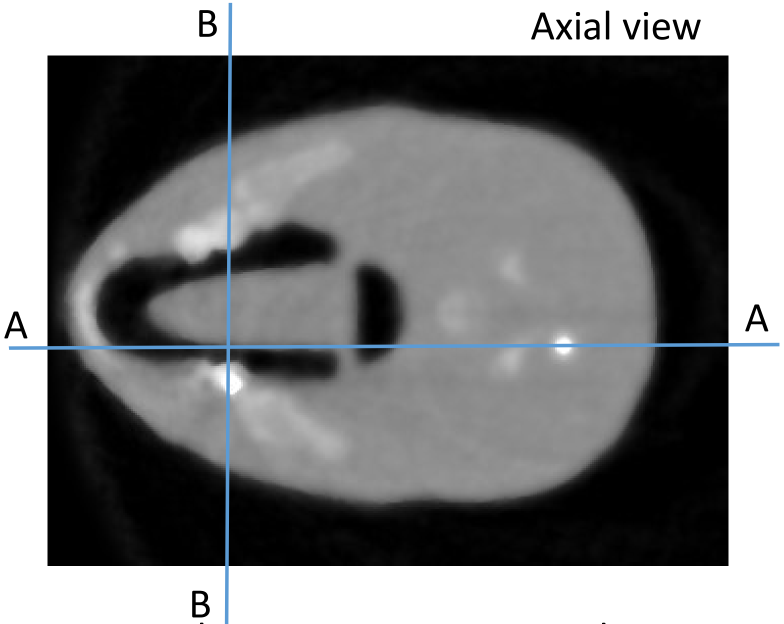
Proton Computed Tomography (pCT) system built within INFN-CNS5 / Miur-premiale (RDH, IRPT) experiments, installed in the Trento APSS proton therapy center experimental room.

Proton tomography: images

- Slices of an <u>antropomorphous phantom</u> tomography reconstructed using data from the pCT INFN apparatus installed on the experimental beam line of the Trento APSS proton therapy center.

Phantom's X-rays radiography

Axial view



Tomographic image reconstructed using iterative algebraic algorithms running on GPU.

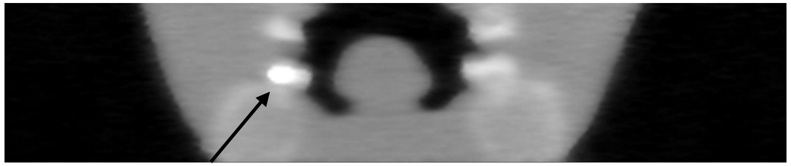
Section AA

Sagittal view

Titanium prosthesys

Section BB

Coronal view



Tungsten dental filling

The grey level are proportional to the voxel RSP value.

Very small metallic prosthesys induced artefacts

Physics in Medicine and Biology
https://doi.org/10.1088/1361-6560/abb0c8

Proton tomography: images

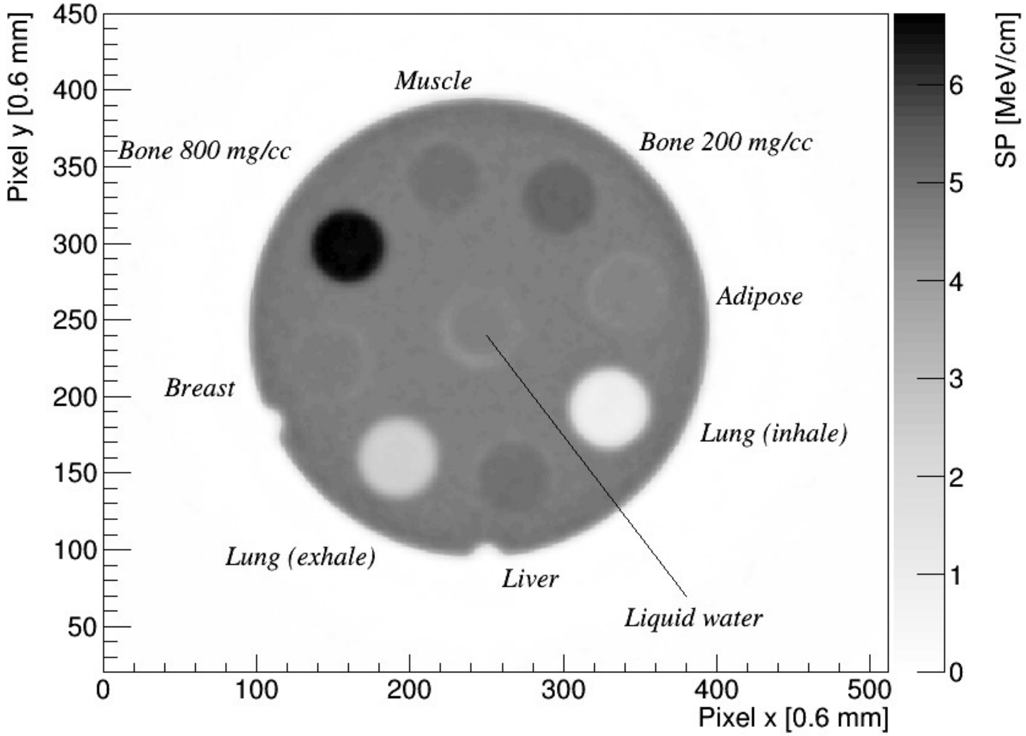
- Slice of a test phantom tomography reconstructed using data from the pCT INFN apparatus installed on the experimental beam line of the Trento APSS proton therapy center.

→8 peripheric insrts:

1) Liver 1.07 gcm^{-3}
2) Lung (exp.) 0.50 gcm^{-3}
3) Breast 0.99 gcm^{-3}
4) Bone 1.53 gcm^{-3}
5) Muscole 1.06 gcm^{-3}
6) Bone 1.16 gcm^{-3}
7) Adipose 0.96 gcm^{-3}
8) Lung (insp.) 0.20 gcm^{-3}

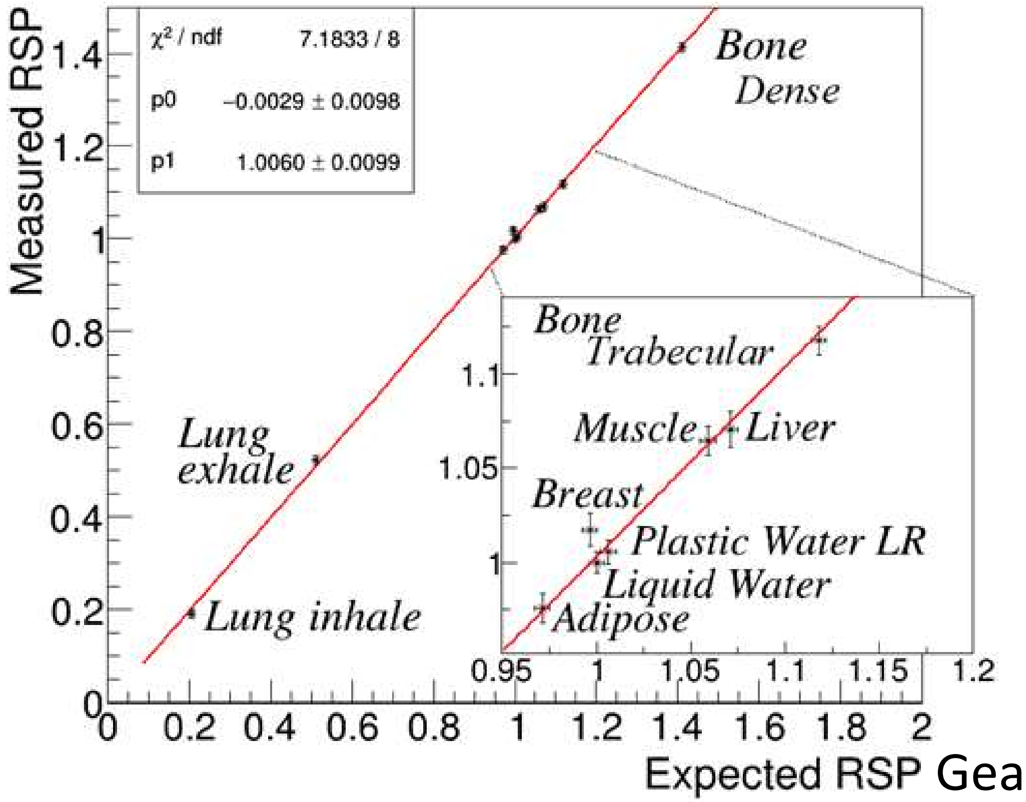
→Central insert:
Demineralized water vial

→Plastic water equivalent matrix.



Proton tomography: images

- The measured Relative Stopping Power are compatible with the expected values (from Geant4 simulation) at a 1% level or less.



Geant4

Accuracy of the RSP measurements:

Absolute error mean on the different materials:

0.54% (pCT meas. – Geant4 sim.)
0.74% (pCT meas. – MLIC meas.)

MLIC: multi layer ionization chamber, it is used as an independent method to measure the RSP values.

Partially funded by CRF

Physics in Medicine and Biology
https://doi.org/10.1088/1361-6560/abb0c8

XpCalib: a possible use of pCT in clinical practice

- Motivation:
  - Implement and test a new x-CT calibration method for precise determination of the patient's RSP 3D maps.
- Goal:
  - Decrease the uncertainty on the particle's range in proton therapy.
- Method:
  - Direct measurements of Relative Stopping Power (RSP) using proton Computed Tomography (pCT) of biological (from animal sample) phantoms.
- Results:
  - Implementation of a new calibration method to be used in 'Treatment Planning Systems' and its verification through independent proton radiographies.

XpCalib: x-CT calibration

- In proton therapy it is essential to precisely know the RSP of the organic material along the regions crossed by the beam.
- An incorrect measurement of these maps has a drastic consequence on the Bragg peak position or a major error on the proton released dose to the tissues.
- To account for these uncertainties the irradiated volume dimension in the beam directions are intentionally over-estimated by a factor which is tipically:

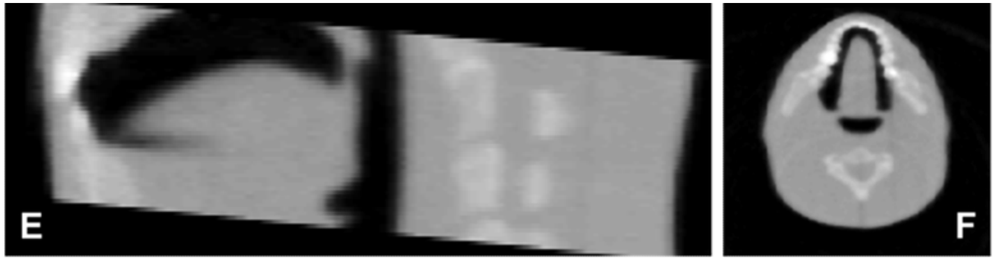
+3.5%*range + 1mm

- This leads to an irradiation of potentially healty tissues which in principlae could be spared making use of a better knowledge of the RSP map of the patient.
- The RSP estimation for each patient is done indirectly with a x-CT: a system which uses X-rays, not protons, and a calibration procedure to translate the measured x-rays attenuation coefficients (HU – Hounsfield Units) into RSP maps.
- This calibration procedure presently makes use of artificial plastic material ('tissue substitutes'), a parametrization of the response of each x-CT system to a certain material and requires the knowledge of the 'mean excitation energies' the quantities present in the Bethe-Block relation which are experimentally measured with a non-negligeable error.

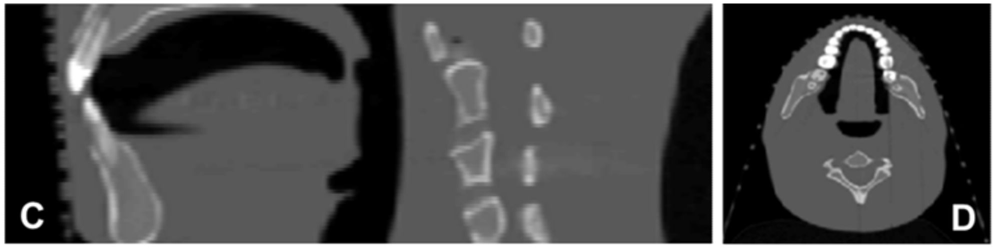
- Each error on the calibration leads to an enlargement of the irradiated volume (the factor 3.5%*range)
  - i.e., **for a tumor at a 100 mm depth → 3.5mm**

XpCalib: a novel calibration of the x-CT for proton therapy

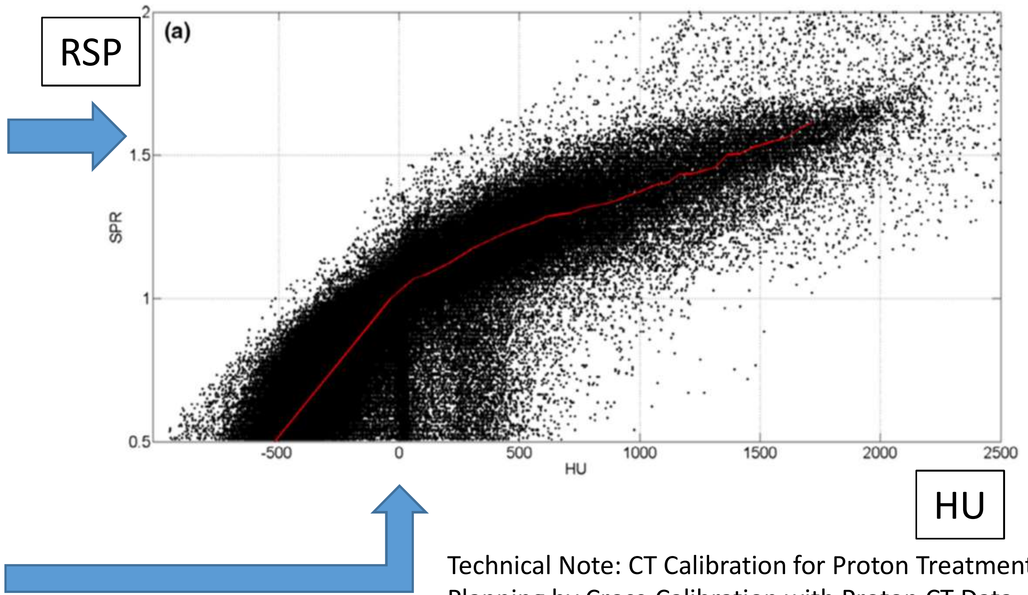
- Using the pCT on biological samples it is possible to measure the RSP distributions without making use of parametrization and computations involving the mean excitation energy values.
- Plotting in a 2D graph the RSP measurements done with an pCT versus the X-rays attenuation coefficients obtained by an x-CT a calibration curve could be obtained and used on the patient's images.



pCT image



x-CT image



Technical Note: CT Calibration for Proton Treatment Planning by Cross-Calibration with Proton CT Data

Paolo Farace *et al.* 2020 *Med. Phys.* In press.
[https://doi.org/10.1002/mp.14698]

XpCalib participants

Project duration: 2 years
2021-2022

- INFN – Firenze
  - Mara Bruzzi 30 %
  - Carlo Civinini 30 % (resp. nazionale)
  - Matteo Intravaia 100 %
  - Monica Scaringella 20 %

  tot. 1.8 FTE

- INFN – TIFPA
  - Francesco Tommasino 30 %
  - Marina Scarpa 20 %
  - Enrico Varroi 10 %
  - Paolo Farace 20 %
  - Stefano Lorentini 20 %
  - Francesco Fracchiolla 20 %
  - Roberto Righetto 20 %

  Medical physicists from the Trento APSS proton therapy center. (Paolo Farace, Stefano Lorentini, Francesco Fracchiolla, Roberto Righetto)

  tot. 1.4 FTE

Conclusions

- Within the INFN-Florence gr. 5 activities, even in very different fields, some interdisciplinary experiments, having as common base the development of imaging techniques, are been carried out.
- These techniques have very important application potentials.
- Historically, it can be said that a good part of what is done in these research lines derives from knowledge that has developed over the years in our INFN section with the participation in high energy, cosmic rays and nuclear physics experiments.

- An example of the functioning of the INFN.