# Considerations on Underground Laboratories

**Aldo Ianni**
Laboratorio Subterrneo de Canfranc Paseo de los Ayerbe S/N 22880 Canfranc Estacion Huesca, Spain
E-mail: aianni@lsc-canfranc.es

**Abstract.** Deep Underground Laboratories are multidisciplinary infrastructures to carry out research on rare events, such as neutrino interactions, proton decay, and dark matter, on geophysics, general relativity, and biology. There are 12 such infrastructures deployed in the north hemisphere. Three new Laboratories are underway, two in the south hemisphere. In the paper some characteristics of the Underground Laboratories are discussed. Synergy between Laboratories is reviewed.

## 1. Introduction

Deep Underground Laboratories (DULs) are research infrastructures with an overburden larger than 1000 meters water equivalent (m.w.e.). At present, there are 13 operating DULs deployed in the north hemisphere. In Fig.1 we show the geographical distribution of DULs [1]. These DULs have different overburden. The reduction of the cosmic ray muons flux in underground is the main characteristic of DULs. In Fig.2 the cosmic ray muons flux in DULs as a function of the equivalent depth under a flat surface is shown. In presenting this plot we underline that in order to compare muon fluxes we use an equivalent depth, due to the fact that some DULs are excavated under mountains and others under flat surfaces. Mountains profile can affect the angular distribution and total flux of muons in underground in a much different way than under a flat surface.

The extreme reduction of muons flux allows to carry out specific research on rare events in DULs such as neutrino interactions from different sources [2, 3], neutrinoless double beta decay [4], proton decay, and interactions of interest in nuclear astrophysics [5].

However, DULs are multidisciplinary research infrastructures. As a matter of fact, DULs are also important infrastructures to carry out research on geophysics [6, 7], biology [8], general relativity [9, 10], and in the next future on gravitational waves. At Kamioka, in Japan, the first gravitational wave detector underground, KAGRA, is under construction [11]. Geophysics and gravitational waves measurements on surface are affected by noise, which is originated by any phenomenon not related to geophysics or a gravitational wave. As a consequence it is better to run the detection apparatus in a location where the signal-to-background ratio can be increased. Signals recorded by set-ups installed on the surface of the Earth show important components related to human activities and environmental factors, such as the wind, rain, temperature changes, etc. In addition, as far as gravitational waves are concerned, the so-called Newtonian noise in underground is reduced. As an example of an installation for geophysics in operation underground we mention that at the Laboratorio Subterraneo de Canfranc (LSC) two laser strainmeters are installed to carry out research on rare events. The strainmeters are sensitive to


**Figure 1.** Deep Underground Laboratories worldwide. In red small solid circles the infrastructures under construction or proposed.

local (hydrologically-induced deformation, ocean loading tides, tectonic deformations, seasonal changes) [12] and global events (free oscillations of the Earth triggered by large earhquakes, free oscillations due to atmospheric motions and wind-driven ocean waves, seismic core modes, free core nutation due to coupling between core and mantle, due to coupling between inner and outer core), which cannot be detect on surface.

At the LNGS, a ring laser in underground to measure the Lense-Thirring effect has been installed [10]. This is an unique installation for expanding the research activity in DULs in the framework of general relativity. At Boulby, a program to develop deep geological mapping by muon tomography is underway. In DULs, it is also possible to identify and characterize microbial communities living in the rocks deep underground and in extreme conditions. In addition, living organism in the absence of cosmic rays radiation can be studied in a unique way in DULs [8]. Indeed DULs are important multidisciplinary research infrastructures and the different geographic location is an advantage to carry out comparisons to disentangle the impact of different environmental parameters on physics phenomena.

Extensions and new excavations are planned for DULs. In particular, we mention the extension of the SURF laboratory in the framework of DUNE [13], a long-baseline neutrino experiment based on liquid argon. Two new excavations are planned in the coming few years, namely, SUPL in Australia and ARF in South Korea. With SUPL the DULs network will expand in the south hemisphere. This is a fundamental expansion to probe dark matter model-independent signatures, such as the annual modulation due to the motion of the Sun about the center of the Galaxy [14]. In a longer timescale (2025-2027) a new DUL is foreseen between Chile and Argentina, ANDES. In Fig.1 we show the geographical location of the new DULs with respect to the ones in operation.

With the expansion of SURF and the inclusion of the new DULs the total excavated volume is of order of $10^6$ m$^3$. In Fig.3 we show the distribution of the underground volume in DULs. More information on some DULs in operation are reported in Tab.1 [1]. In this table we report about the most important parameters in DULs, namely, depth, underground volume, accessibility, and radon. Radon is an important parameter in DULs. Radon level is reduced by forced ventilation to comply with restrictions imposed by the law. The level of radon by ventilation is measured to be less than 300 Bq/m$^3$ in the worst case. Boulby, in UK, has a radon level of just a few Bq/m$^3$ due to the fact that the underground laboratory is built in a potash and salt environment, which contains much less uranium and thorium than standard rock environments. The access in DULs can be different. In DULs excavated in mines the access is vertical through a shaft. In DULs excavated along train or road tunnels the access is horizontal. In some case the access is through an inclined roadway. Multiple access is also possible as it is the case in CallioLab (CLAB) and in ARF (Astroparticle Research Facility).

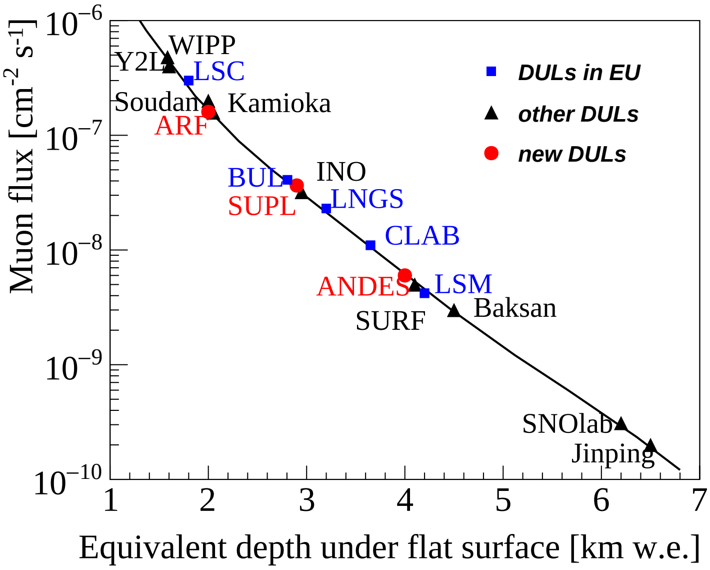


**Figure 2.** Cosmic ray muons flux underground in different DULs. CLAB stands for CallioLab and Jinping for CJPL (China JinPing Laboratory).

**Table 1.** Summary of main characteristics in some DULs. H = horizontal. V = vertical.

| | SNOLab | LNGS | LSC | BUL | LSM | CallioLab | Baksan | SURF | CJPL | Kamioka | Y2L |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Canada | Italy | Spain | UK | France | Finland | Russia | USA | China | Japan | South Korea |
| since | 2003 | 1987 | 2010 | 1989 | 1982 | 1995 | 1967 | 2007 | 2009 | 1983 | 2003 |
| Volume (m$^3$) | 30000 | 180000 | 10000 | 7200 | 3500 | 1000 | 23000 | 7160 | 300000 | 150000 | 5000 |
| depth (m) | 2070 | 1400 | 850 | 1100 | 1700 | 1440 | 1700 | 1500 | 2400 | 1000 | 700 |
| access | V | H | H | V | H | V+inclined road | H | V | H | H | drive in |
| Average Rn (Bq/m$^3$) | 130 | 80 | 100 | <3 | 15 | 70 | 40 | 300 | 40 | 80 | 40 |

Depending on the overall underground volume and access a specific access protocol to the underground experimental area is put in place. At SNOLAB the underground experimental area is turned into a global class 2000 clean room environment. At SURF a less stringent protocol makes the underground area class 3000. Larger DULs, such as LNGS and CJPL, make use of a number of clean rooms for activities which require high cleanliness standards.

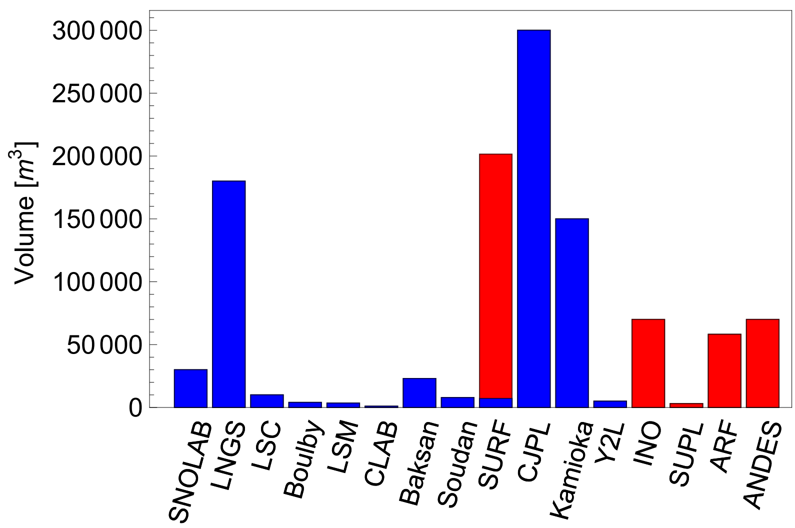


**Figure 3.** Underground volume for present (blue) and future (red) DULs. The extension in SURF is for DUNE, the long-baseline neutrino experiment.

## 2. Ancillary infrastructures in DULs

A number of common crucial facilities are at work in DULs [1]. These facilities give support to experiments in operation underground. The most crucial facility is a gamma spectroscopy screening laboratory for radio-purity assay. This is accomplished by underground installation of high purity germanium (HPGe) detectors. These detectors at present can reach in the best case a sensitivity of the order of 10-50 $\mu$Bq/kg in uranium and thorium. HPGe screening is supported with $\alpha$ counters and mass spectrometers (ICP-MS). At present, in the DULs network we count 53 HPGe detectors at work. This number is expected to increase to 65 in a few years.

Copper is an important component of many detectors in DULs. The material bulk radio-purity can be significantly increased by electro-forming copper [1]. Therefore, copper electro-forming facilities are being installed in DULs. At present, SURF and LSC have used such a process to make detectors components. SNOLAB, CJPG, and ARF are planning to deploy a copper electro-forming facility in underground. Underground installation is the best option in order to reduce the cosmogenic activation.

In recent years the idea to build in underground crystal growing facilities has been taken into consideration. At ARF, a facility to grow NaI scintillators is in the layout of the new DUL. At CJPL a facility to grow germanium crystals is under consideration.

Radon abatement systems, which can produce radon-free air at the level of 1 mBq/m$^3$, are being deployed in all DULs. These systems can make up air for radon free clean rooms or facilities where low radon air is needed. Sensitive radon monitoring detectors are usually coupled with the abatement systems to guarantee the proper operation of the plant [15].

Environmental monitoring is at work in a number of DULs. At the LSC, as an example, convergence measurements are carried out every month to monitor the rock stability in the underground cave. In addition, radon, temperature, and humidity are regularly recorded. In Fig. 4 we show the correlation between radon and humidity measured at the LSC.

Special cleaning facilities might be needed to reach high level cleanliness standards in as-built fluid handling and purification plants, which are used for large Cherenkov or scintillator detectors [1]. These custom-made facilities are crucial to reduce radioactivity coming from dust and particulate due to machining of detectors components.

Water purification and organic scintillator purification plants are installed in a number of

DULs to carry out research on neutrino physics and dark matter. A number of instrumented water tanks, filled with purified water and working as muon detectors, are built to shield detectors for neutrino physics and dark matter. New DULs foresee the deployment of similar equipments.

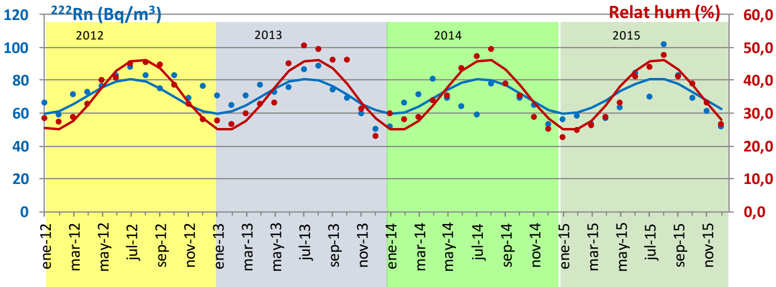


**Figure 4.** Correlation between radon in air and humidity measured at the LSC.

## 3. Synergy and networks for DULs

Interactions and exchange of expertise between DULs can be extremely valuable. A number of attempts are underway. An important example is DULIA, a network between European DULs. DULIA aims to enhance the collaboration between different infrastructures in DULs, to standardize procedures on safety and science assessment, environmental policy, etc. SNOLAB and LNGS are putting forward a proposal for an Underground Global Research Infrastructure (UGRI), which is currently under evaluation.

Synergy between DULs are underway in the framework of an international project where the Super-Kamiokande detector is filled with water and a small amount of gadolinium salt [16]. In this specific case Kamioka, LSC, and Boulby are participating to a huge screening campaign, which is crucial to load the detector with a high radio-pure gadolinium salt. Another example is offered by DarkSide-20k. Three DULs, SNOLAB, LSC, and LNGS, are involved in this project to develop a multi-ton liquid argon detector for direct dark matter search [17]. Different facilities from the three laboratories are at work for this common interest.

A network between DULs could also boost some physics case, such as the directional detection of dark matter. The CYGNUS Collaboration [18] is proposing to deploy the same TPC detector in different DULs to enhance the sensitivity for this specific research, which depends on the geographic location of the detector.

Outreach activities can profit of a collaboration between DULs. An outreach program to make muon telescopes and develop an APP for cellular phones (Cosmic Ray Lives) has been put forward by LSC and LNGS. SNOLAB is joining this network in the near future. In Fig.5 we show some features of the mobile APP developed by LNGS and LSC. At present, similar muon telescopes are deployed on surface at LNGS, LSC, and NYU in Abu Dhabi. The APP allows to see muons detected in real time at different locations. In the next future, some telescopes will be installed in underground as well.

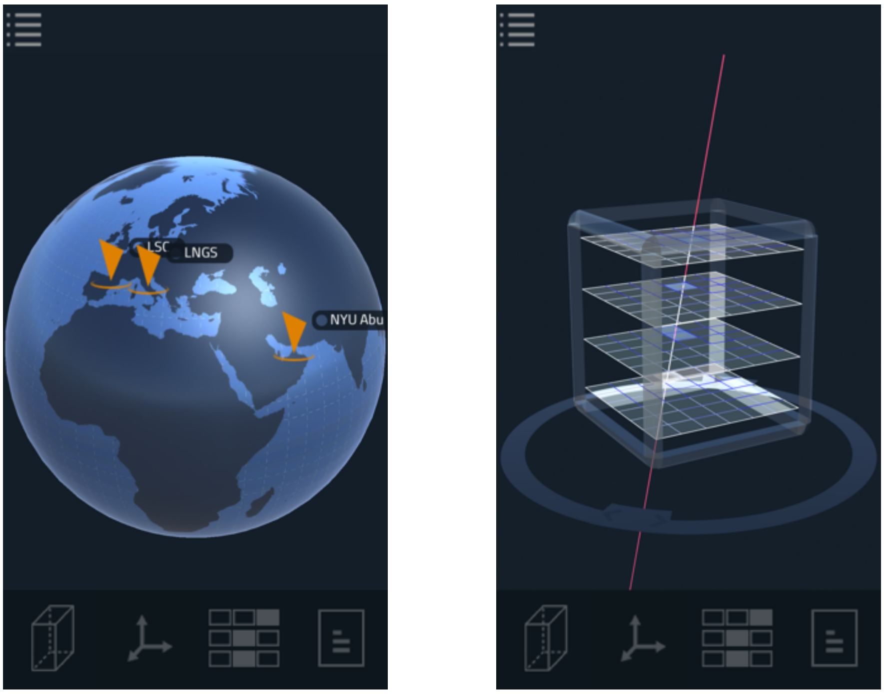


**Figure 5.** Images from the mobile APP developed for outreach activity by LNGS and LSC: an example of collaboration between DULs. Right: present geographic deployment of similar muon telescopes. Left: one muon event detected by a portable telescopes made of four scintillating planes.

## 4. Conclusions

At present there are 12 DULs in operation in the north hemisphere. Four new DULs are planned, two in the south hemisphere, to be completed in a time window between 2019 to 2027. DULs are multidisciplinary research infrastructures equipped with high technology detectors. Some free space is available in a number of DULs including Boulby, LNGS, LSC, CallioLab, and SNOLAB. A new important expansion is foreseen in SURF for the long-baseline proposal, DUNE. About 720 on-site Staff are supporting research in DULs. All together DULs offer an impressive radio-purity screening network with 53 HPGe at the present time. Interactions between DULs are underway to establish a global network to enhance the scientific program and exploit common new technologies. The research program in DULs is broad and offers important opportunity. As a matter of fact, neutrino mixing and oscillations have been observed in DULs, among the most important discoveries. The physics program in the next years is very important in particular for neutrinoless double beta decay and direct dark matter research.

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