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To Callio Lab and beyond – update on the deep underground research centre in Finland

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Underground physics has been conducted at the Pyhäsalmi mine in Finland for over 20 years and it was one of the sites in FP7 LAGUNA and LAGUNA LBNO design studies. In 2015, the University of Oulu established the Callio Lab multidisciplinary research centre, which began coordinating scientific activities on-site. Since then, they have hosted and conducted research in disciplines ranging from particle physics and geosciences to underground food production and remote sensing. The operating environment would also suit studies in circular economy and space and planetary sciences, which are being explored by the Callio SpaceLab initiative. Together with the easy tunnel and elevator access, low seismicity, which has been observed to decrease dramatically since the conclusion of underground extraction, and the flat 1.43 km overburden (~4100 m.w.e.), the site is a potential candidate for future physics experiments. Callio Lab is a founding member of the European Underground Laboratories Association, a member of the DULIA network, and an EPOS and national FIN-EPOS research infrastructure. Underground mining ended in 2022 and re-purposing of the mine by the Pyhäjärvi town-owned CALLIO - Mine for Business concept is ongoing.

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1. History and legacies: CUPP and LAGUNA

Callio Lab is a University of Oulu coordinated multidisciplinary research centre operating at the Pyhäsalmi mine in central Finland. Callio Lab was established in 2015, but underground physics has been conducted at the site for well over two decades. In 1997, physicists from the University of Oulu and University of Jyväskylä began exploring the possibility of doing underground science at the site, and in 1999 the Centre for Underground Physics in Pyhäsalmi (CUPP) began operation [1]. CUPP- era projects included the MUG, MUD, EMMA and C14 experiments [2–4] and participation in two FP7 design studies (DS) of a pan-European Infrastructure for Large Apparatus for Grand Unification and Neutrino Astronomy (LAGUNA) and subsequent LAGUNA-LBNO (Long Base Line Neutrino Observatory). These were ambitious studies evaluating possible underground sites for next generation neutrino experiments; both studies found the Pyhäsalmi site to be the most ideal location for hosting not just one, but multiple large scale experiments [5–7].

In the end, none of the planned experiments were placed in Europe, however, the produced study material is still relevant today and has served as reference for other projects. The outcome also gave the push to re-examine the CUPP underground science programme and begin considering a more multidisciplinary approach. This was essential to ensure the continuation of science at the Pyhäsalmi mine and aligned well with the objectives of the town-owned Callio business, which had an interest in generating new use for the mine infrastructure. CUPP was dismantled and in its stead Callio Lab was established to take over the coordination of scientific activity on-site. Callio Lab has continued the legacy of CUPP, fostering particle physics experimentation while also expanding into new themes within circular economy, geosciences and mining education. The CUPP-era science also led to the establishment of Muon Solutions, a technology start-up which is utilises and develops muography-based solutions for exploration and imaging of underground structures and deposits [8].

2. Callio Lab operating environment

At the Pyhäsalmi mine, there are three major operators: the mining company (Pyhäsalmi Mine Oy), the reuse operator (Callio) and the scientific coordinator (Callio Lab). The mine was opened in 1962, producing copper, zinc and pyrite. The mine is one of the deepest in Europe, with a maximum depth of 1444 meters. Underground mining came to a close in autumn 2022, after 60 years of operation. The underground mine is being closed for extraction, but the above ground mill will continue processing pyrite from stored tailings until 2025-2026. The mining site includes the underground mine, two open pits, an industrial area with the mill, and a 250 hectare tailing pond area. [9]

Post-mining activities are coordinated by the Pyhäjärvi town-owned Callio, which was established once the closing of the mine started to become more topical and tangible within the local community. Callio works on developing commercial and industrial projects, attracting new users for the mine infrastructure and working towards transitioning the site into an industrial and renewable energy park. For keeping the entire underground mine in working condition, a large industrial operator would be ideal, and one major project explored the possibility of building a pumped hydro storage facility underground. [10]

Callio Lab under the University of Oulu Kerttu Saalasti Institute is responsible for the scientific activity and coordination at the Pyhäsalmi mine [11]. Research space both above and below ground is rented from the reuse operator Callio on a project basis. Callio Lab has approximately two permanent staff members and around 40 visiting researchers per year, depending on the current project portfolio. Underground laboratory facilities have existed at multiple levels in the mine, from a shallow 85 meters all the way down to Lab 2 at a depth of 1436 meters. Due to the project-nature of Callio Lab activities, once a project finishes, the space is emptied and turned back over to Callio. However, the facility spaces can be reopened and repurposed swiftly as needed.

One major advantage Callio Lab has is the elevator and tunnel access underground. The tunnel incline is 12 km long and takes 40 minutes to drive down, and it is capable of accommodating trucks and 20-foot sea containers. Driving underground requires induction and training, which can be provided for long-term visitors and personnel. The hoist elevator is mainly used to travel from the surface to the main level at 1410 meters, taking only a short 3 minutes and with room for up to 20 people. The elevator can be used more freely now that it is not hoisting ore anymore; personnel are allowed to operate the elevator themselves after completing training. Logistically, the Pyhäsalmi site is ideally located along central transportation routes, with even train tracks arriving directly to mine site from the Kokkola port. Support facilities, such as electrical and mechanical workshops are available both above ground and at the main level underground. The main level also hosts a cafeteria, office spaces, toilets, and the world's deepest sauna.

Underground the temperature stays between 22-28 °C, with relative humidity in the 30-70 % range. Fresh air is provided from above ground through the ventilation system at rates of up to 130 m^3/h. Radon levels vary from 20 Bq/m^3 to 300 Bq/m^3 depending on location and ventilation [12, 13]. The muon flux was measured at different depths during the CUPP-era, resulting in a maximum m.w.e. of 4100 at level 1436 [2], which is the second deepest overburden found in European deep underground laboratories. Updated measurements would be needed, however, as the density structure of the overburden between levels 990 and 1436 may have changed due to extraction and backfill.

The Pyhäsalmi Zn-Cu ore deposit belongs to one of the best-understood ore deposit types, the volcanogenic massive sulphide class of deposits. Investigation of the geology and rock mechanics of the deep parts of the mine are available in the LAGUNA Design study. The mine has an extensive microseismic monitoring network (measurement range –2 Mag to 2 Mag, bandwidth 3 - 2000 Hz) and monthly seismic reports are made available. Since underground mining ended, the seismicity has been observed to settle quite dramatically, with preliminary reports suggesting a 70-90% decrease in the number of seismic events.

Due to the long history of the Pyhäsalmi mine, a considerable amount of site descriptions and data sets are available to use for research and validation purposes. Together with the mining company, Callio Lab has ensured that critical historical mining data has been put into safekeeping and won't be lost during mine closure. Extensive site characterisations have been done during previous Callio Lab projects, including natural background radiation characterisation, as well as, technical and organisational characterisations. Available data sets include neutron and gamma flux, gamma ray background [12, 13], radioisotope content in rock and water, and 3D point clouds [14]. And as mentioned previously, the LAGUNA LBNO site investigations are available on request.

3. Current activities

In recent years, Callio Lab projects have been heavily profiled in environmental monitoring and remote sensing, with a focus on the above ground mining environment. Callio Lab's role has been to provide ground truths and reference data, evaluate piloted techniques and assist in installation and preparations. Being familiar with the operating environment and protocols, Callio Lab is well-positioned to aid in defining measurement areas and regions of interests and guiding through the approval process for conducting research on the mining company grounds.

Callio Lab was a partner in the 10.7 M€ H2020 Innovation Action project GoldenEye, which lasted three years and ended in October 2023. It developed a platform for satellites, drones and in-situ sensors to collect high-resolution data to be converted into actionable intelligence for enhancing safety and productivity of mine sites. The main objective was to allow for more efficient exploration, extraction and closure [15]. Callio Lab served as a field trial site [16], similar to it's role in the new Mine.io project, which began in January 2023 and will run until summer 2026. It is a 14 M€ Horizon Europe –project focused on industrialization, informatization and sustainable development of the mining sector [17]. The University of Oulu partners will develop and apply a combination of electric resistivity imaging and active- and passive-source seismic imaging to map the subsurface structure of tailings embankment and retrieve hydrogeological and elastic parameters.

Callio Lab also hosts art residencies and public events underground, most recently the Creative Europe funded More-than-Planet project, which re-examines the way people understand and picture the planetary environment as a conceptual whole. It develops societal awareness of environmental concerns and facilitates collaborative, transdisciplinary research through exhibitions, open calls and publications. Their aim is to develop art-driven innovative approaches with critical and creative tools for addressing current global issues. [18]

For particle physics, Callio Lab can offer facilitation and assistance with experiment deployment, installation and maintenance. A benefit of our long-standing history on-site is the already well-established operating methods enabling fast deployment of new activities, especially as a site for Proof-of-Concept research. An example is the NEMESIS and subsequent NEMESIS 1.4 dark-matter experiments, which looked at DM-like anomalies in neutron multiplicity spectra, first at the 85 meter level and later with an upgraded setup at Lab 5 on the 1410 main level [19]. Lab 5 also houses the C14-experiment, which is currently in between funding applications. This experiment measured radioactive purity of liquid scintillator samples and it has been used to test neutrino detector samples for Jiangmen Underground Neutrino Observatory (JUNO) and for the JUNO pre-detector OSIRIS.

Callio Lab work includes fostering cooperation between underground facilities through the European Underground Laboratories association, which is a continuation of the work begun during the Baltic Sea Underground Innovation Network project. In addition to collaborating with the CELLAR network and being an EPOS - and a FIN-EPOS Infrastructure [20], Callio Lab is an active member of the DULIA network and its work in developing cooperation between underground laboratories. Positioned at an intersection of science and industry, Callio Lab is able to connect academia with project collaborations, mine stakeholders and society in general to foster more open and transparent dialogue. In addition, Callio Lab has recently launched the Callio SpaceLab initiative, which is exploring possibilities for space and planetary sciences [21]. The extremely

confined and isolated environment has potential to be used as a test site to simulate human space exploration, space research in extreme environments, as well as analogue astronaut training. One step towards this is through MIMAG (Multidisciplinary International Moon Assessment Group) and it is an open group for space enthusiasts, and experts in various fields, such as planetology, engineering, physics, and architecture. The group is working on proposals for moon base site selection criteria and proposal of a subsurface moon base, with Callio Lab as an analog example.

4. Discussion

As mining has ended, available space underground is increasing and the mining-activity induced seismicity is decreasing, creating possibilities for deployment of both horizontal and vertical gravitational wave detectors. The central location along major routes together with the elevator and tunnel access to the underground levels provide easy, fast access for personnel and equipment. Reuse and re-purposing of the underground infrastructure is in the best interest of the re-purposing operator Callio, and through them excavation and refurbishment of new caverns and tunnels can be arranged. The technological capabilities underground are being updated in 2024 through Callio's FutureMINE project, which includes 5G investments enabling connectivity, IoT, battery charging, remote operations, digital services, and training events [22].

Considering all the benefits of the Callio Lab site, with the 4100 m.w.e. overburden, easy access underground, support facilities, established operating methods and long-standing, positive rapport with the mine and local community, it leads to wonder how come there is not already large scale physics experiments running or even a low-background screening facility. This is due to a few challenges, the first being the current funding model. Callio Lab funding is entirely project-based and admittedly, this has its merits, such as the expansion of networks, increased visibility, and flexibility in building a project portfolio. And as a result, the Callio Lab team is highly experienced in drafting and succeeding in international project proposals. However, project-based funding places restrictions on opportunities for laboratory and infrastructure development.

Another hindrance no doubt, has been the uncertainty of underground mine future the past few years. As a result, the long term projects Callio Lab has applied for are heavily focused on above ground activities. This has been done to ensure Callio Lab's continued, active, scientific presence on-site independent of the future of the underground sites. The arrival of a large industrial (or scientific) underground operator would be significant, as they would bear the majority of the upkeep costs, which can run up to 2 M€ annually. This would obviously make it easier to continue smaller scientific activities underground as well.

Lastly, the LAGUNA projects stir up bittersweet memories in Finland, and the results undoubtedly disheartened the national physics community. This may be partly to blame for the difficulties in stirring up national support and interest in developing the particle physics programme at Callio Lab and Pyhäsalmi mine, which would be essential for progress and credibility when lobbying within international physics communities. Irregardless, it was due to the LAGUNA investigations that the Pyhäsalmi mine was put on the map as a contender for large scale experiments. Which still holds true today, if not even more so, and despite the aforementioned challenges, the Callio Lab team continue to seek out new collaborations and possibilities for realising the potential that their deep underground environment is best suited for: low-background particle physics.

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