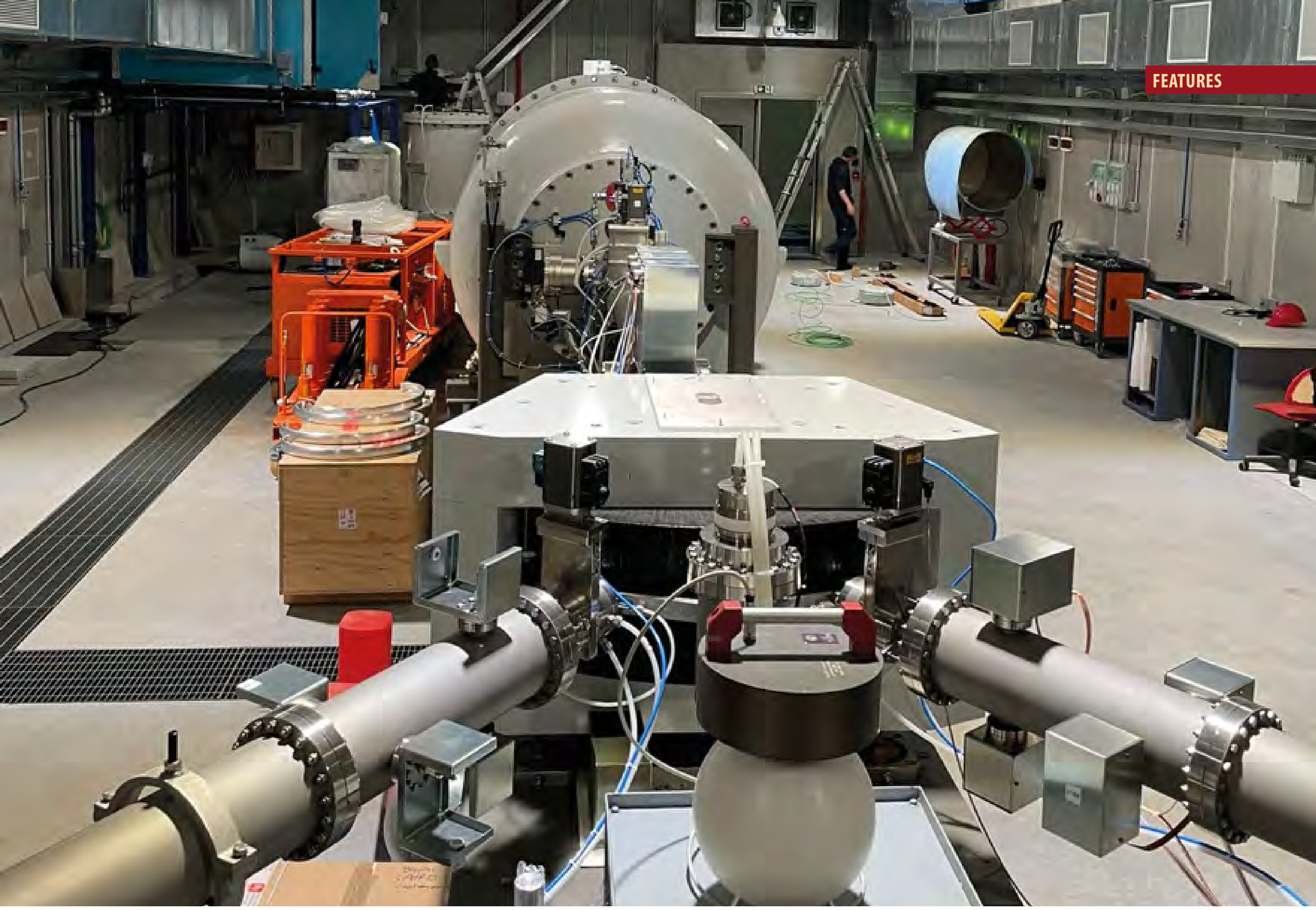

▲ Bellotti Ion Beam Facility of LNGS, a 3.5 MV Singletron machine (courtesy of M. Junker (LNGS)

CURRENT DEVELOPMENTS IN LNGS UNDERGROUND PHYSICS

A. Formicola[1], A. Ianni[2], G. Imbriani[3], M. Laubenstein[2], S. Pirro[4] and E. Previtali[4]

[1] INFN, Sezione di Roma, Italy

[2] INFN, Laboratori Nazionali del Gran Sasso (LNGS)

[3] INFN, Sezione di Napoli and Università degli Studi di Napoli Federico II,Italy

[4] INFN, Laboratori Nazionali del Gran Sasso (LNGS) and Università degli Studi di Milano Bicocca, Italy

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The Gran Sasso National Laboratory in Italy (LNGS) is at present the largest deep underground laboratory in the world. LNGS has been in operation for 35 years. It has a rock overburden of 1.4 km which reduces the muon flux from cosmic rays by a factor of one million.

The core purpose of LNGS [1] is frontier research in the domains of Astroparticle Physics: low energy solar neutrinos, neutrinoless double-beta decay, dark matter searches, rare nuclear decays, and of Nuclear Astrophysics. LNGS is operated as a research infrastructure open to international users. The laboratory is equipped with several laboratories and facilities to support the experimental activities, in this contribution we have selected four of them.

STELLA a laboratory for large-scale-state-of-the-art-material screening

The study of rare events with a specific experiment requires a very low level of radioactivity in all •••

••• detector components to disentangle the signal from the background. Therefore, in addition to locating the experiment deep underground, radio-purity assay of used materials is essential. The activity is carried out in dedicated facilities. For this purpose STELLA (Fig.1) was built at LNGS [2]. STELLA is equipped with 15 high-purity germanium (HPGe) detectors, which allow very sensitive measurements by means of gamma-ray spectrometry. Four of these HPGe detectors are custom-made ultra-low background detectors built by the Max-Planck Institut für Kernphysik (MPI-K) in collaboration with LNGS. They can reach a world record sensitivity of the order of 10 μBq kg^{-1} on natural radioactive isotopes. In addition, STELLA also hosts four detectors for alpha spectrometry as well as two liquid scintillator counters. The main task of STELLA is to offer a professional and unique laboratory for material selection to all experiments installed at LNGS, and to provide support to research activities carried out in other underground laboratories. The radio-purity assay is performed in synergy with the Chemistry laboratory at LNGS, which uses inductively coupled plasma mass spectrometry (ICP-MS). To clearly identify the various contributions to the source of materials background they are divided into three categories: *primordial radionuclides and natural decay chains* (40K, ^{232}Th, ^{235}U, ^{238}U, ^{87}Rb …); *cosmogenic radionuclides*, produced through interaction of secondary and tertiary cosmic-rays with matter (^{3}H, ^{14}C, ^{7}Be, ^{11}C, ^{57}Co, ^{39}Ar…); and *anthropogenic radionuclides*, artificially produced mainly through nuclear reactions (^{60}Co, ^{85}Kr, ^{137}Cs, …). A complete radio-purity assay requires the use of different complementary techniques, which are working in synergy. Primarily, these techniques are gamma-ray spectrometry, ICP-MS, alpha/beta spectrometry, and Radon emanation measurements [3]. In STELLA on average the analysis throughput is 100 samples per year. At present, an important upgrade for STELLA is ongoing. It aims at making available underground laboratory space surrounded by neutron shielding and 5 cm of steel for background reduction purposes. It is expected that this, together with other small modifications on the HPGe detectors themselves, will further decrease the environmental natural background of detectors in order to reach enhanced sensitivities needed for next-generation experiments for rare events.

▼ **FIG. 1:** Stella Laboratory equipped with 15 HPGe detectors (courtesy of Massimiliano De Deo (LNGS))

The NOA innovative low background infrastructure

NOA is a new infrastructure of the outside laboratories of LNGS. NOA which is funded in the framework of PON Ricerca e Innovazione 2014-2020 and RESTART CIPE n. 49/2016, is a unique facility worldwide. worldwide. It comprises a 421 m^2 ISO 6 clean room (Fig.2) which can be operated in virtually Radon-free mode using a Radon abatement system. For this reason, it was built with stainless steel walls, ceiling and floor to reduce possible emanation or diffusion of Radon. In addition, the air ventilation system is engineered to reduce Radon emanation. The design is similar to that of other Radon-free clean rooms operated underground at LNGS [4]. NOA is equipped with a custom-made Radon detector with 1 mBq m^{-3} sensitivity for monitoring the activity concentration. A Radon-free clean room is crucial for dark matter experiments to avoid plate-out of ^{210}Pb on surfaces during the assembly of crucial parts of the detectors. NOA is divided into two main volumes: one with 3.0 m in height and 353 m^2 dedicated to testing and packaging of photodetectors based on SiPMs; another with 5.8 m in height and 68 m^2 area for large volume detector assembly. The two main volumes can be operated separately both in normal and Radon-free mode. The packaging area is equipped with a flip chip bonder, a wire bonder, a dicer, and a cryoprobe to test SiPMs at liquid nitrogen temperature where their intrinsic noise is strongly reduced. The activity is crucial for next-generation cryogenic experiments where SiPMs will be commonly used. Right now, NOA will be used for the mass production of photosensors for DarkSide-20k.

The Bellotti Ion beam Facility

The Bellotti Ion beam facility is a new 3.5MV accelerator devoted to nuclear astrophysics and applied physics. It is the result of the synergy between the LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration[1] and the LNGS, thorough a funding of the Italian Ministry of Research[2]. The Bellotti Ion beam facility is equipped with a 3.5 MV Singletron machine [5] manufactured by High Voltage Engineering Europe (HVEE). The machine can deliver intense proton, helium, and carbon beams (about 1, 0.5 and 0.15 mA respectively) with excellent energy resolution and stability, optimal for precision nuclear astrophysics measurements. The new accelerator is

▲ **FIG. 2:** A detail of the SiPM packaging facility in NOA equipped with a flip chip bonder, a wire bonder, a dicer, and a cryoprobe, which can be operated at 77 Kelvin.

currently installed in the hall B of the underground laboratory (see full page picture). A key research area of this facility is the experimental Nuclear Astrophysics studies, the exploration of low energy nuclear reactions related to various stages of stellar evolution and nucleosynthesis. The LUNA collaboration was the first to propose a new approach to nuclear astrophysics, by exploiting the extremely low background inside the LNGS. A pioneering experiment was proposed 1992 to LNGS and a 50 kV accelerator (LUNA-50kV) was installed underground. A 400 kV Singletron accelerator - LUNA-400kV – is in operation since 2000 and still plays a fundamental role for experimental nuclear astrophysics. The LUNA experiments have established underground nuclear physics as a powerful tool for determining nuclear reaction rates at Gamow peak energies, which represents the energies where most of the reactions take place in the interior of a star at a given temperature. Thanks to the presence of the two accelerators with complementary energies and taking advantage of the many years of LUNA collaboration in managing experiments with underground accelerators, the new Bellotti Ion Beam facility, which has a Program Advisory Committee to select and monitor the experiments, will open new frontiers in astrophysics nuclear power and nuclear physics research.

Ieti, the low noise - low radioactivity milliKelvin cryostat for Qubits characterisation

An increasing number of experimental evidence is suggesting that environmental radioactivity could be a limiting factor for the performance of future quantum computers based on the technology of superconducting circuits. Cosmic rays, as well as the decay products of radioactive isotopes naturally present in the laboratory environment, can interact with the chip hosting the quantum processor (Qubit). Such an interaction would limit the ●●●

[1] https://luna.lngs.infn.it

[2] Progetto Premiale 2012 and 2013

▸ FIG. 3: Ieti cryostat hosting a Superconducting Qubit. The Qubit is framed inside the second magnetic shield just below the inner Lead shield of the cryostat.

• • • coherence of the quantum system, *i.e.*, the time in which it retains its quantum behaviour. Moreover, it would induce simultaneous errors on multiple Qubits deposited on the same chip, spoiling the protocols for quantum error corrections.

The Ieti facility[3] is the first cryogenic platform enabling the test of superconducting qubits in an ultra-low radioactivity environment (Fig.3). Ieti offers the ideal environment to test novel qubit prototypes with an experimental volume of 5500 cm^3, a dual magnetic shield to prevent disturbances in quantum processors caused by fluctuations of the magnetic field, and a lead/copper shield system to reduce significantly the influence of environmental radioactivity inside the laboratory. In 2021 the facility hosted the first underground measurement showing the impact of radioactivity on a quantum circuit [6]. In 2022 Ieti was used to benchmark a Qubit fabricated with a new material (Granular Aluminum) by the Karlsruhe Institute of Technology [7]. The Ieti facility is presently hosting members of the SQMS (Superconducting Quantum Materials and Systems) Center, led by Fermilab, to develop a novel quantum processor. Thanks to Ieti, it will be possible to test the SQMS prototypes in an extreme "low noise – ultra-low radioactivity" environment and push their performance to new limits.

Some new improved facilities were realised during the last few years at LNGS aiming at the improvement of experimental sensitivities for Astroparticle physics experiments and to explore new fields of research. At LNGS the development of beyond-state-of-the-art instrumentation, combined with the implementation of novel and original approaches will provide a unique support for future advanced experiments in fundamental physics researches. ■

[3] https://ieti.sites.lngs.infn.it/index.html

About the Authors

Alba Formicola is senior scientist at INFN Rome and served as Head of Research Division at LNGS from 2015 to 2021. Since 1998 she is a member of the LUNA collaboration working mainly in nuclear astrophysics.

Aldo Ianni worked as Director of the Canfranc Underground Laboratory from 2015 to 2018. In 2019 he became manager of research at LNGS and head of Office for Scientific Strategy and International Collaboration between underground laboratories.

Gianluca Imbriani is full professor of Experimental Nuclear Physics at the University of Naples Federico II (https://www.docenti.unina.it/gianluca.imbriani). He is currently spokesperson for the international collaboration LUNA.

Matthias Laubenstein is head of the underground ultra-low level laboratory STELLA of LNGS.

Stefano Pirro is senior researcher at LNGS. Currently, he works on the Cryogenics on the Cryogenics of ET and in the Qubit underground characterisation.

Ezio Previtali, PhD in Physics (1993), in 2019 full professor at Univerisità degli Studi Milano Bicocca. From 2021 to present he is Vice President of the HPC4ND consortium on High Performance Computing. Currently, he is Director of Gran Sasso National Laboratory of INFN.

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