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Report on the Demonstrator

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Abstract

This document describes the development of the prototype sensor unit. It includes the modelling and simulation of the γ detector and discusses the implications found. Based on that the structure of the Sensor Unit and its associated Transmitter Unit is discussed. The results of the prototype tests and the production of the Early Demonstrator, produced in six units follows. Finally the deployment of the units in selected locations in Italy, Greece and Switzerland is discussed as well as the lessons learned leading to an improved Advanced demonstrator currently under development.

Inhalt

1 Introduction

This document describes the development, realization and commissioning of the first prototypes of the sensor units of the artEmis project. The development is based on the requirement specifications given in document D1.1.

In close collaboration with the group working on WP3 and intense discussions with the experts of WP4 and literature studies, the requirements for the sensor system had been worked out. The sensor system shall comprise of a network of low-cost radiation sensors preferentially deployed in ground-water sites. The primary goal of the sensors is the detection of the characteristic gamma and/or alpha radiation following the decay of radon (Rn) in water, respectively the location-dependent variation of the Rn activity within the network. As much as reasonably possible other parameters like temperature and hydrologic head (pressure) should be measurable with the same sensor device.

The core of the sensor device is a CsI(Tl) scintillation detector to efficiently detect gamma radiation. The same or another scintillator will be used to detect alpha radiation. The scintillation light is being read out in any case by silicon photomultipliers (SiPMs). Highly-integrated signal forming and processing electronics shall be arranged at the detector units. Adequate computing power will be made available on-board of the detector unit as well as bias generators, environmental controls like temperature sensors, and appropriate communication channels. Here, the projects relies on the latest electronics and data acquisition (EDAQ) developments available from large nuclear physics experiments. Relying on the experience of the groups involved, the mechanical structure of the sensor-unit will be optimized for underwater operation in the wanted depth range.

Gamma energy spectra and other sensor's information will be collected and transmitted in suitable intervals, e.g. every ten minutes for further analysis employing control units coupled to a network. These units and the network are being developed and realized within WP3.

The device must be able to operate autonomously without human supervision. Introducing machine-learning concepts shall allow for innovative, autonomous, unsupervised operation, calibration and control of the detection system, constituting a smart radiation detector.

The artEmis project relies on the availability of a few sensor units at the earliest possible time, but with limited sensor capabilities. Therefore, it was agreed to produce 6 sensor units (early demonstrator) from available components within the first six months of the project. After 12 months, an advanced demonstrator should be available with additional features and improvements derived from the early operations. Finally, after 24 months the full demonstrator with 100+ units should be available for deployment. As it is assumed that the development of a proper alpha detector requires long development time, it will be only available at that stage.

The technical specifications as well as the timeline are provided in document D1.1.

Together with the partners in WP1, a concept for the three demonstrator phase has been developed. Initially the following sensor elements were considered:

gamma detector: CsI(Tl) scintillator with size between d:1 cm l: 2 cm and d:2 cm l: 6 cm (matter of simulations) and SiPM readout, i.) self-made or ii.) from the specialized company Scionix at a rather high cost of 800 €.

Temperature sensor: Options i.) on board CPU/FPGA (simple and cheap, but may not show water temperature accurately), ii.) stand-alone plug-in board (cheap, several variants available), iii.) included on another sensor board (simple and cheap), iv.) self-made electronics with sensor chip or PT100 (cheap but some effort)

Pressure sensor: Options i.) Water pressure sensor with plug-in board (easy to implement but expensive) ii.) air pressure sensor with elastic membrane (needs some thoughts on the membrane, but cheap plug-in boards are available). The type GY-68_BMP180 costs <20 €.

Conductivity sensor: Required range estimated to be 5µS/cm…5 mS/cm with 5µS/cm resolution. Critical is the long-term stability affected by fouling/deposits. Options: 2-pole, 3-pole, 4-pole, inductive. Most sensor geometries turn out to be too big. Costs vary strongly from 20 € up to 400 €.

It was agreed to test in the early demonstrator phase the different options to gain experience on accuracy and reliability. Closer investigations of conductivity sensors revealed that most units need regular re-calibration and are not suitable for permanent placement in water. The industrial models fulfilling our requirements had to be excluded for budgetary reasons. Therefore, it was decided to develop a suitable conductivity sensor within the project. However, the necessary development time excluded it to be incorporated into the early phase. Instead, it was decided to enlarge the scope of the pressure measurement to **shocks and acoustical noise** introducing 3D gyroscopes and a special microphone.

Fig. 1.1 shows the layout of the sensor unit. It consists of the actual Sensor Unit, which contains all sensor elements, the signal shaping and digitizing electronics and two CPUs for data processing and control. This system is mounted in a watertight casing connected to a Transmitter Unit through a RJ-45 cable for data and power transmission. While the Sensor Unit is located in the well or source to be monitored, the Transmitter Unit is mounted outside the water close by, e.g. at the rim of the well. This structure minimizes the size of the underwater unit and its power consumption respectively heat production.

While the cable length between Sensor and Transmitter needs to be short (a few meters) for technical reasons, the distance between Transmitter and Gateway can be several 10s of meters long. This enables placing the Gateway optimally for connecting it either to an available Wi-Fi, LAN or G2/G4 mobile net to internet access. The Gateway Units are provided by WP3 and are not described in this document.

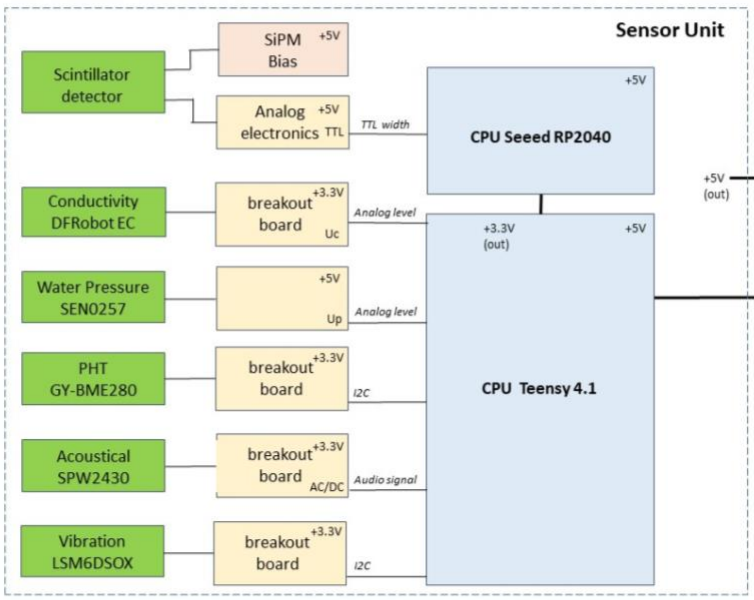

Fig. 1.1: Layout of the Sensor Unit.

Planning for three CPUs in the Sensor Unit guarantees sufficient computing power and storage capability to enable the intended smart operation of the units. For the early phase, it is assumed that all deployment locations provide stable electrical power and regular internet access. Internet interruptions can be handled by buffering the data. The power consumption of the whole system is being minimized to enable battery backup and operation with solar power. The latter is planned for the third stage of the deployment.

2 Realization and testing of the sensor demonstrator

2.1 Modelling and Simulation

The main sensor element concerns the detection of radon in water. The novelty of our approach lies in measuring γ radiation from the radioactive decay of radon daughters directly in water. To be able to determine the optimal size and geometry of the detector, modelling and simulation with the GEANT-4 package was performed. Fig. 1.2 shows the basic geometry employing a 60 mm long CsI(Tl) scintillation crystal detector with 20 mm diameter (grey) in an idealized sensor housing (pink). Electronics components and other material inside the housing has only a small impact on the simulation and is therefore not considered. The γ response of the simulated detector shows the characteristic triple line structure between 0.2 MeV and 0.4 MeV γ energy and the prominent line at 0.6 MeV. The spectrum has not been folded with the finite detector resolution to ease the analysis. The strong dominance of the Compton continuum in the spectrum is characteristic for a water environment, causing Compton scattering of most of the γ quanta before entering the detector. Only a few of the quanta mostly from close distances survive with their full energy.

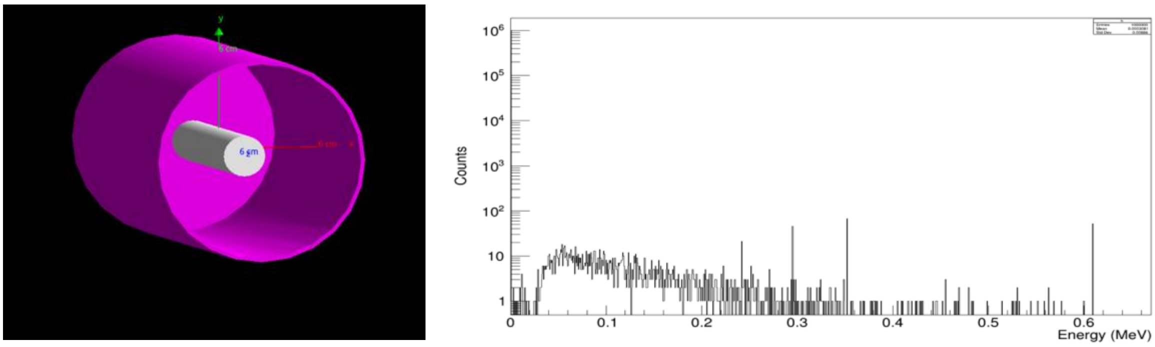

Fig. 1.2: Basic geometry of the γ detector in the sensor housing (left) and simulated detector response for radon-loaded water (right).

By varying the CsI(Tl) dimensions as well as the geometry of the water volume representing the well, the sensitivity of the detector was investigated. One important finding was the confirmation of the size parameters given before. Another one the water volume dependence shown in fig 1.3. To reach maximal sensitivity the radius of the water sphere around the detector should be around 50 cm. For lower radii, the sensitivity drops while still larger water reservoirs will not add to the count rate any more.

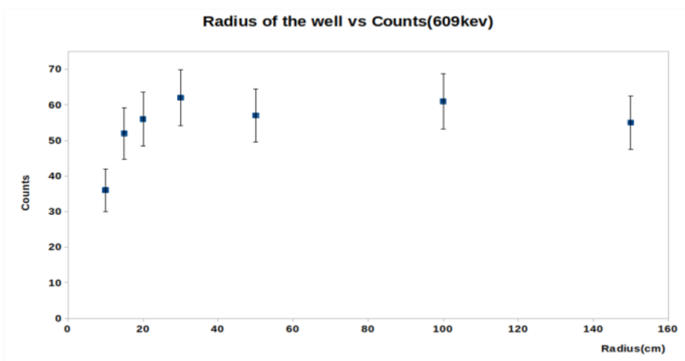

Fig. 1.3: Radon count rate in the detector as function of the radius of the water sphere.

Based on these findings the Sensor Unit was developed. Besides the crystal geometry also aspects like the optimal depth of the unit and hence the required pressure resistance of the housing was determined. The prototype unit was characterized in summer 2023 in a water tank at SURO and confirmed the estimated sensitivity of 1 Bq/ 10 minutes. The calibrated radon water sources of SURO turned out to be essential to measure the response of the γ detector in this unusual environment.

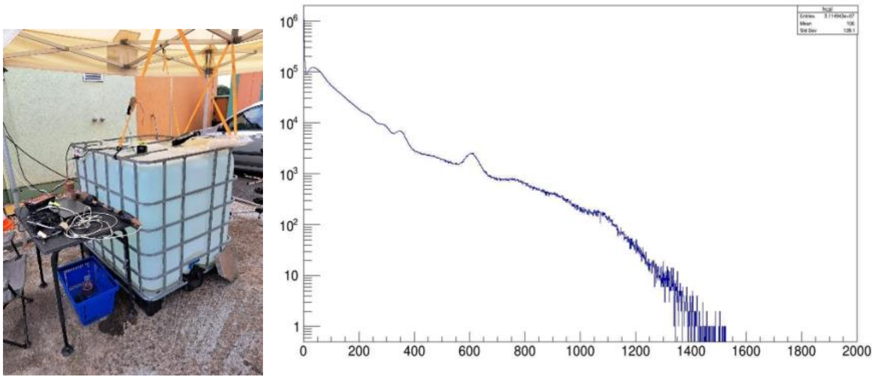

Fig. 1.4: One m^2 test water tank at SURO (left) and obtained radon γ spectrum (right).

The γ spectrum shown in fig. 1.4 is strongly dominated by radon lines and corresponding γ Compton scattering in the water, while usual radiation background from natural radioactivity of the environment is strongly suppressed by the shielding effect of the water. This becomes impressively visible in the energy range around 1460 keV, which in airborne spectra is dominated by environmental ^{40}K. This shielding effect adds to the sensitivity of the method as essentially the full spectrum can be used and not only the peaks. The latter, in particular the line at 609 keV, serve mainly as control of the integrity and gain stability of a detector.

2.2 Prototyping and production of initial sensor network

After a proof-of-principle using the first prototype, a pre-series of six sensor systems was planned to be realized. The realization was affected by overlong delivery times of some electronics components.

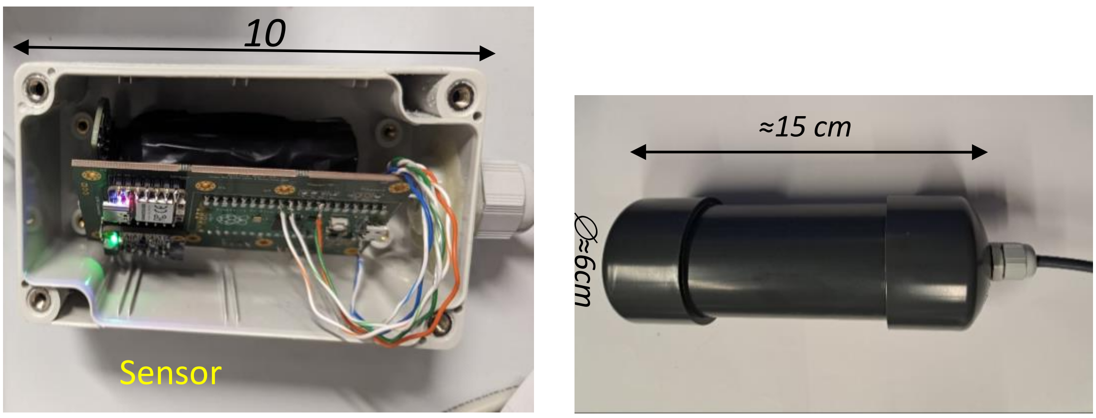

Fig. 1.5: Two versions of the Sensor Unit.

Fig. 1.5 shows two different versions of the sensor unit optimized for deployment in tanks (left) and water with varying depths (right). While the sensor units were equipped with different sensor elements to be able to study their suitability in the field, the Transmitter Unit (see fig. 1.6) was built in one version only.

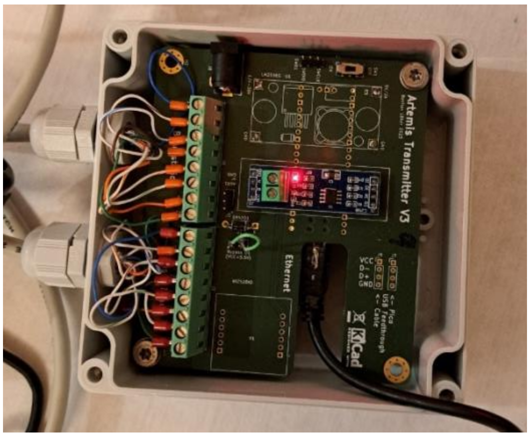

Fig. 1.6: Transmitter Unit before closing.

Connection between Sensor Unit and Transmitter Unit was provided by a RJ-45 cable soldered to the main pcb of the Sensor and screwed to a terminal on the Transmitter side. This allowed for minimal cable length on site. The sensor units were sealed with epoxy resin against water leakage.

Basic features of the on-board control system were developed and implemented on the respective processing units. This includes power and temperature control as well as automatic data buffering. More advanced features like gain control of the γ detector and self-calibration are in development.

Data analysis routines for the γ detector were developed and implemented. Analysis routines for other sensors like pressure shocks are currently being developed.

The development of the units went smoothly without major technical challenges. However, the unpredictable and overlong delivery times for common electronics components became an issue and finally caused a delay of about 3 months with respect to the original production plan. The most important points are:

- The internal time plan for the production of the six units of the Early Demonstrator version of the Sensor system was delayed by 3 months.
- The delay was due to overlong delivery times of some electronic components.
- The delay caused a delayed deployment of the units and therefore also a delayed availability of the first field data. However, the field installations are still much earlier than originally planned. This was achieved by starting the roll-out already with the early demonstrator phase (see section 3).
- The deviation has no additional impact with respect to the original effort and budget of artEmis.
- To reduce the dependence on delivery times respectively availability of electronics components in general, for the Advanced and Full demonstrator production, components will be ordered on stock, and in different varieties although this costs extra effort for modification of electronics schemes and printed circuit boards.

3 Deployment of initial sensor series

The plan in the proposal to start deployment of sensor units only with sensor units of the fully developed demonstrator was changed to allow for early availability of field data. For that purpose, three categories of demonstrator units have been defined:

- Early demonstrator, 6 units with basic detection capability.
- Advanced demonstrator, 30 units with the full detection capability but α.
- Full demonstrator, >60 units including α detection if applicable and customized units, e.g. high-temperature operation in thermal springs.

After thoroughly testing the various units, the installation of the Early demonstrator units took place in Q1 2024. Units no. 1-3 were deployed in the region of l'Aquila in Italy, no. 4-5 on the island of Lefkada in Greece and no. 6 in the Bedretto laboratory in Switzerland. Table 1.1 shows deployment details.

Table 1.1: Early demonstrator field installations:

System no.	**Site**			
	location	type	water depth	min. wall distance
1	3 - SW Gran Sasso tunnel drainage	basin	2 m, varying	0.5 m
2	2 - NE Gran Sasso tunnel drainage	tank	0.5 m	0.4 m
3	8 - Giardino spring	spring	0.3 m	0.5 m
4	Brunello/Lefkada	well	0.5 m	>0.3 m
5	Komilio/Lefkada	well	0.5 m	>0.3 m
6	Bedretto	tank	0.5 m	0.5 m

Fig. 1.7: Installation of sensor systems 1, 5 and 6.

All installations were successful and the experience gained turned out to be very useful. Fig. 1.7 shows examples of spring, well and tanks sites with sensors installed. A typical radon γ spectrum obtained within a few minutes from such sites is shown in fig. 1.8.

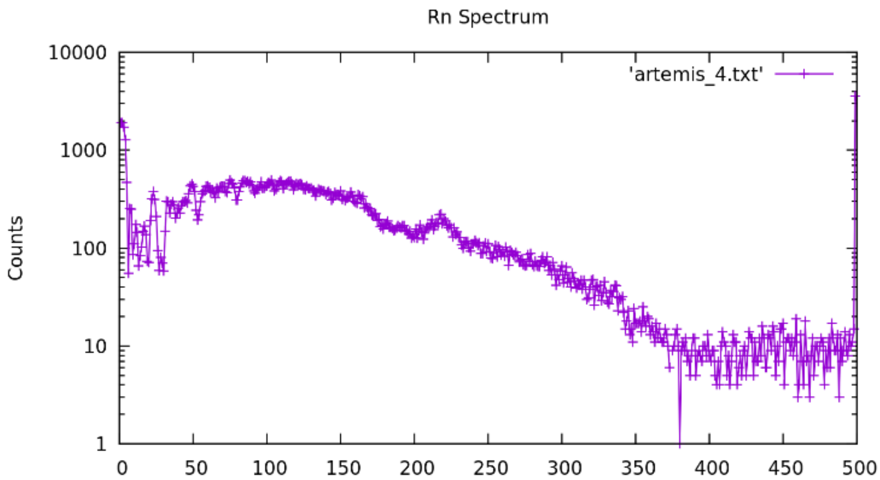

Fig. 1.8: A typical radon γ spectrum from a well.

3.1 Adaptions and enhancements during field application

Taking advantage of the availability of operating Early demonstrator sensor units, improvements of the production efficiency, reliability and cost-efficiency have already started and will become effective with the Advanced demonstrator units, which are currently in preparation.

This includes:

- Using confectioned RJ-45 cables with socket connectors on the pcbs on sending/receiving side
- Using only standard size cables
- Optimizing electronics schemes and pcb layouts
- Outsourcing of standard tasks like soldering components to pcbs
- Reducing the size of the γ detection scintillator to 45 mm length and 20 mm diameter following a lean production scheme

For the standard Advanced demonstrator units the external pressure sensor will be replaced by the internal one, which turns out to be sensitive enough.

As the commercially available conductivity sensors for long-term installations without maintenance are too expensive for the project, a dedicated sensor is under development.

Provisionally it is planned to start deployment of the Advanced demonstrator units in Summer 2024.