Einstein Telescope: Exploring the Universe from the Underground

P. Lamas
EMC[2] Consortium – Amberg Engineering, Brussels, Belgium

R. Houhou
EMC[2] Consortium – Amberg Engineering, Paris, France

ABSTRACT: The Einstein Telescope is a 5th-generation interferometer, an instrument capable of measuring gravitational waves which will help the scientific community better understand the complexity of the universe. A competition to win the right to host such a project is currently ongoing, the choice to be made between two different sites, the cross-border region of The Netherlands, Germany, and Belgium (the Euregio Meuse-Rhine region , EMR), or a particular territory in Sardinia, Italy. A feasibility mission has been awarded to the consortium EMC2 to study the technical viability of the planned infrastructure in the EMR. One of the current project's layout consists of a 30 km tunnel forming a triangle, with large caverns at its vertices to host the facility. This infrastructure will be located underground at around 250 to 300 m depth to ensure the lowest degree of gravitational waves' signal perturbation possible. The design of this unique infrastructure is both as demanding as it is exciting. The scientific requirements for the instrument's operation impose constraints that are not common practice within the tunnelling industry, pushing designers to explore the limits of technical feasibility. Additionally, constructing this infrastructure will have a significant impact on the area. Planning for the construction works will be equally challenging from both constructability and logistics perspectives. Lastly, environmental and social constraints will also add to the difficulties the project will be dealing with. A comprehensive technical assessment will be conducted to ensure the project's feasibility. Our engineers will leverage innovation and inventiveness to enhance the project and prove its technical and financial feasibility. The endeavor to bring the Einstein Telescope to the EMR marks the commencement of a thrilling journey, poised to establish a new benchmark within the tunnelling community.

1 INTRODUCTION

The Einstein Telescope (ET) is an exciting project set to become Europe's leading third-generation gravitational wave observatory. This advanced research facility, built underground, will explore the universe by detecting gravitational waves, the ripples in spacetime. ET will consist of three interconnected interferometers, capable of identifying a wide range of gravitational wave frequencies with exceptional accuracy. This endeavor not only promises to reveal new cosmic insights but also marks a significant step forward in the fields of astrophysics and cosmology.

The decision to build the Einstein Telescope underground is driven by the need to achieve unparalleled precision in detecting gravitational waves. By situating the telescope deep beneath the Earth's surface, it will be shielded from a myriad of surface-level disturbances, including seismic activity, human-made noise, and atmospheric variations. However, bringing this ambitious project to fruition involves overcoming significant engineering and logistical challenges.

Among the various defying tasks within the project is the excavation of extensive tunnels and large caverns at considerable depths. Furthermore, the project's success requires ensuring both the technical feasibility of these infrastructures and an optimal interferometer's sensitivity. Overcoming both challenges is critical to ensuring the observatory's performance and its potential to revolutionize our understanding of the universe.

2 GENERAL CONTEXT

2.1 *An underground facility*

Interferometers have long been essential tools in the field of physics, and have traditionally been constructed on the surface. However, there is a growing interest in building interferometers underground due to the benefits this approach offers.

The interest of building ET underground relies on the aim of reducing the impact of seismic noise and gravity gradient noise induced by seismic waves and compression waves of the surrounding air. Furthermore , the underground operation will allow to extend the frequency band of the observatory down to a few Hz (ET steering committee et al, 2020).

By mitigating seismic and gravity gradient noise, ensuring stability, and protecting from environmental factors, the underground location will enable the ET to perform with unprecedented precision. The move towards building interferometers underground represents a significant step forward in enhancing the accuracy and reliability of these essential scientific instruments. The several outpointed advantages collectively make a compelling case for subsurface construction.

2.2 *The sites*

One of the consequences of the extension of the observation band towards lower frequencies is that environmental disturbances and therefore the quality of the observatory location is ought to play an increasingly important role (ET steering committee et al, 2020).

Evaluating the site selection for the Einstein Telescope involves a comprehensive and holistic approach. The key criteria include the impact on the infrastructure's longevity, the observatory's sensitivity and operational efficiency, and the preservation of the site quality. Additionally, considerations must cover the construction costs and the socio-economic benefits to the surrounding community. Technical feasibility plays a crucial role, ensuring that the chosen site supports the advanced requirements of the observatory, consequently optimizing both performance and sustainability.

Two candidate sites have been identified for a detailed site-characterization: one in the north of Lula in Sardinia, and one in the Meuse-Rhine Euroregion , locations showed in Figure 1.

Figure 1. Possible sites under evaluation for ET

2.3 *Site selection methodology*

The site characterization process has been planned in several steps (ET steering committee et al, 2020). A preliminary survey has already been conducted at both candidate sites in Sardinia and the Meuse–Rhine Euroregion for preliminary site characterization. This survey relies mainly on surface measurements and existing site data.

At the EMR, a borehole campaign is currently ongoing to obtain information about the local geology, groundwater conditions, and underground seismic spectra. This information will be used to do a first feasibility assessment on construction , including logistics assessment and preliminary construction cost estimates. Moreover, characterization of environmental noise over at least one year will be conducted to make accurate noise predictions for ET.

Once the site is chosen, extensive borehole studies and engineering design of the future ET site will be necessary for construction planning and for a detailed cost estimate.

3 TECHNICAL SPECIFICATIONS

3.1 *The ET layout*

The layout details to be evaluated in order to assess feasibility are yet to be defined. However , two configurations are being analyzed from a physics and engineering point of view.

For the first scenario, the subsurface configuration of tunnels forms a triangle with an approximate side length of 10,798 meters, excluding the access options. The schematic reference layout, is illustrated in Figure 2.

Access for the assessed scenario is facilitated through either (a) vertical shafts or (b) inclined access tunnels, connecting the surface to the main caverns. The surrounding area at the corners of the triangle includes several caverns with varying geometries near the intersection points. Additionally, a lined borehole, located away from the crucial and vibration-sensitive cavern structure, is proposed for water management during operation.

The described layout foresees a main big cavern for each corner point, measuring 190 m long, having a 20m span and a 30m height. Several smaller caverns and connecting tunnels are planned surrounding this main cavern. At the end of the main tunnel, a vertical borehole is planned to dewater the Access Area separately. The length of the “Dewatering Tunnel” is contingent on the vibrational impact of the hydraulic pumping system and the tolerable water infiltration.

The second scenario would foresee an L structure , with 15km long legs , which angle is fixed at 90°. For this detector to perform 2L detectors should work in cooperation , and therefore two detectors should be built.

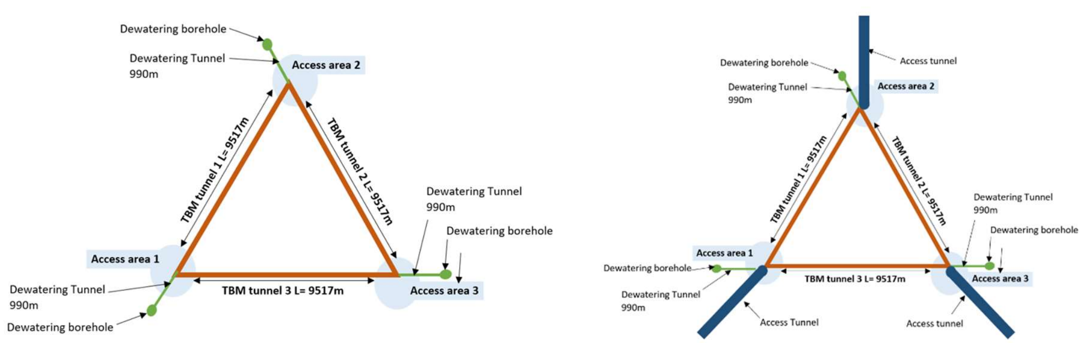

Figure 2. Schematic reference layout based on (a) left , and (b) right

3.2 *EMR geological context*

The EMR buildup of the geological context aims at laying out the geological foundation of the region, from a structural, stratigraphic, geohydrological and geotechnical perspective.
The exploration specifically addresses three key aspects of regional geological derisking :

- A regional tectonostratigraphic assessment. The aim of this assessment, essentially consisting on the review of 3-5 parallel cross SE-NW directed sections aims to elucidate how deep rock layers are distributed in space and depth throughout the ET-search area. This assessment will also look forward to illustrating the position, and as far as possible the features of the main faults and thrust planes.
- An evaluation of rock properties, particularly focusing on geotechnical aspects. This will result in a catalogue of encountered and expected rock types in the area.
- Construction of a baseline monitoring network and a general description of the hydrological interactions between the Paleozoic and the overburden.

Based on the assessment of the geological context of the area of study, rock formations originating from the Devonian Famennian age have better quality than the overlaying Namurian Upper-Carboniferous rock. An uplift or up thrusted area has been identified in the Netherlands – Belgium border region, where the Famennian formation can be observed at + 50m NN/TAW.

A first borehole campaign including 10 boreholes is currently ongoing for a better identification and assessment of this rock mass. An overview of the subsurface conditions for one of these boreholes, at Aubel location, is presented in the following chapter §4.1, together with a preliminary review of the most suitable construction methods related to this geological context.

3.3 *Borehole Aubel*

The borehole intersects the following sedimentary formations from top to bottom:

- 0-1 m: Soil material
- 1-21.5 m: Namurian rocks with black shale and few quartzite layers
- 21.5-27.9 m: Breccia zone corresponding to contact between Namurian and Dinantian formations
- 27.9-45m: Dinantian rocks with limestone and dolomite
- 45- 250m: Upper Devonian series with lithological sequence of shale, siltstone, and sandstone

The weathering level is approximately 27 m deep, with further local weathering levels presumed to appear up to 100 m deep. The RQD results show that most of the borehole is of good quality rock (RQD >75%). Between 150m to 250m depth, the rocks are strong to very strong (R5) except in the fault zones. The uniaxial compressive strength values are higher than 100 MPa (up to 266MPa) except for one outlier of 41 MPa at 246 m where some argillite fillings were found.

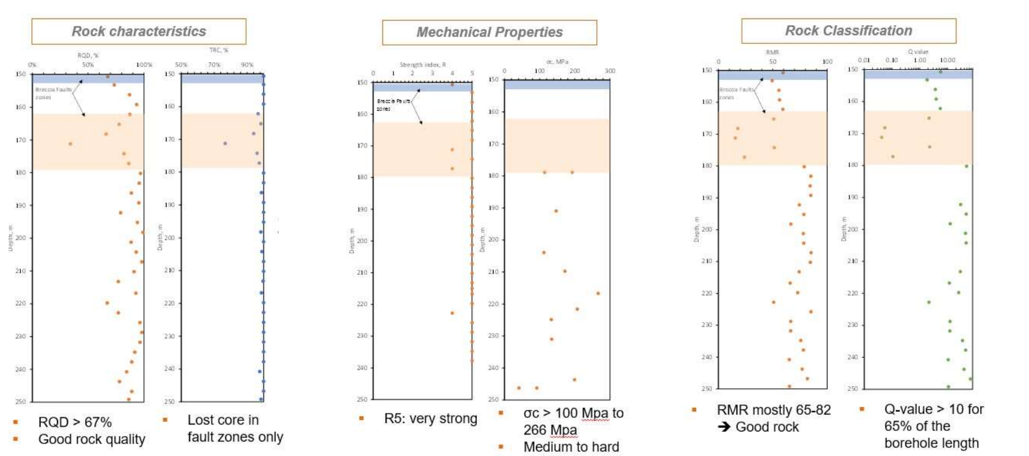

Figure 3. Rock characteristics, Mechanical properties and Rock classification for Aubel's borehole.

The Q values distribution in Figure 3 shows that the quality rock index ranges from poor to fair until a depth of 180 m. Namely, the quality rock index for the fault zone identified between 150 m to 180 m depth is classified as extremely poor.

However, the values distribution in Figure 3 indicate that the rock quality ranges between good and very good for a depth below 180 m, so good perspective since the caverns and the tunnel will be executed below 180 m depth. It is noted that, locally, one area (221.3 to 224.3m) shows a rather poor quality. It corresponds to the transition between Montfort and CLT formations where the joint augmentation is associated with the presence of a locally highly fractured heterogenous sandstone layer. The cavern levels should eventually be defined taking in account the presence of this interface and avoiding it being set at the cavern's vault level if this location will be considered for the construction of ET.

Tunnelling and excavation techniques have been revised, taking into account Aubel's borehole geotechnical context and the following conclusions have been withdrawn :

- Single open shield or gripper excavation stand out, as these methods are both suitable for the geotechnical conditions described in chapter §4.1 and logistically, time and cost-effective. Excavation through these methods might have to be combined with associated measures such as pre-grouting and water pumping, together with support installation.
- Drill and blast is the most suitable and convenient method for excavating the caverns. This method has the disadvantage of inevitably damaging the surrounding rock mass. This damage could result in the development of a network of blast-induced cracks in the surrounding rock mass that would therefore need the implementation of further support (short bolting for small block anchoring and shotcrete). These countermeasures should be taken in account while doing the cost estimation.
- Regarding shaft excavation, numerous methods can be used, some are time-consuming but cost-effective (drill and blast) and some are time-efficient but costly and require large surface installations, complex logistics, limited versatility and flexibility and skilled operating team (SBC and blind shaft). Water pumping and probably grouting around the shaft until the bedrock is reached is required. A further assessment taking into account surface environmental restrictions, excavation safety and stability works planning and budget shall help the project owner choose the most suitable solution for the project requirement.

4 CIVIL ENGINEERING FOR ET FEASIBILITY

4.1 *Design requirements for construction*

The design requirements taken in account for this preliminary review of the concept design relate therefore to geotechnical, dimensional or operational requirements of the Einstein Telescope. Feasibility constraints due to surface exigences have not been taken in account at this stage .Boundary conditions or design requirements for feasibility stage are listed in Table 1 below:

Table 1. Project requirements and general tasks for ET project subsurface infrastructure construction

Project design general main domain requirements	Project design requirements expected outcome from project definition phase (feasibility)
Geology & Hydrogeology	Tunnel alignment definition Corner points emplacement
Engineering	Technically feasible layout
Logistics	Accessibility analysis Construction site logistics
Environmental aspects	No go restrictions to be considered
Timeline	Determine project's timeline Construction planning
Cost and financing	Rough cost estimation envelope
Health and safety during construction	Preliminary review of compliance of preferred layout
Functionality and operation	Definition of the set of minimal requirements for ET operation
Operational health and safety	Not to be addressed at this stage

The design requirements identified during this first review will be further developed to define design specifications. The design specifications will define the precise characteristics of the Telescope Einstein that make up the concept design and allow evaluation of the conformity of the project with the construction requirements. The definition of these design specifications conforms the scope of a later more detailed mission, which will analyze the design alternatives for the Einstein Telescope project.

Because the design specifications are strongly dependent on the design, and because several design solutions can exist for a given component (reference design and alternative designs), different design scenarios shall be defined, allowing a clear identification of which scenario each design specification applies to.

4.2 *Design approach for civil engineering*

4.2.1 *Lifetime approach*

The design approach for civil engineering is to be based on the following steps :

- Prefeasibility studies: Aiming to define the project's requirements. In the EMR region, 3 boreholes have been drilled and preliminary studies have been carried out on several fields (namely noise, geology and hydrogeology) to explore the project's potential. The first preliminary layout was defined in 2020.
- Feasibility studies: Starting in Q1 2024 they aim to validate feasibility for a specific chosen emplacement. A concept design, a preliminary cost estimate and a construction schedule are expected as an output. To enhance the geological and hydrogeological knowledge of the region a borehole campaign is currently ongoing.
- Technical design: Further studies will develop one and only design scenario up to the detail of detailed design. Construction schedule and budgeting are to be conducted.
- Tendering: Environmental assessment and validation, tender documents preparation and call for tenders. Depending on the tendering scheme selected, part of the technical design might be developed during the constructor's mandate.
- Construction: A contractor is awarded with the project's construction mission and therefore responsible for the construction of ET.

4.2.2 *Ongoing feasibility studies*

The design approach at the feasibility stage has been based on an up-to-down methodology. The main steps of the design are summarized below:

- The preliminary layout and the geometric definition of the caverns and shafts, especially the configuration of adjoining caverns
- Definition of the geological and geotechnical context of the area where the project will be built. This study is based on the available information (borehole information at our disposal as reference, laboratory or in-situ tests, geological plans, etc…) and on the judgement of expert geologists. It is to be noted, that an underground context is a highly heterogeneous environment. This heterogeneity is usually encountered even within the same geological formation or within the same geotechnical unit. In consequence, a certain degree of incertitude will always exist, and it means that the characterization of the mechanical parameters of the geotechnical units should follow a probabilistic approach.
- Full preliminary design of the underground caverns and tunnels considering the geological and the geotechnical context, the design loads, and the preliminary definition of the project.
- Optimization of the project design (tunnels and caverns support, geometric definition, etc…) based on the results of the preliminary studies.

Some of the general design requirements for deep underground works that need to be considered are the following:

- Ensuring an adequate lifetime for the constructions.
- Considering the construction design codes in effect.

- Following the advice of trustable recommendations as underground works are not fully described in the construction design codes.
- Identifying any missing geological and geotechnical information deemed essential for the design.
- Developing a design adapted to an observational excavation approach in case of huge geological and geotechnical uncertainty. It means, that several excavation and support methods need to be defined to be prepared for all the potential scenarios.
- Ensuring the feasibility from a logistic point of view. It means that the shaft and the ET dimensions need to be large enough to allow all equipment (e.g. ventilation ducts, laser pipes) to be installed and operational facilities to be emplaced.
- Ensuring that the crossings between galleries and caverns or galleries and shafts are large enough to allow the rotation of the longest operational facilities.
- Ensuring enough escape routes for workers during construction and limiting the length of dead-end galleries if any.
- Ensuring geometrical layout to meet ventilation and fire safety requirements. Safety at this stage, refers only to structural resistance of the infrastructure to the design loads. No further measures regarding safety will be assessed at this stage of the concept design analysis

5 EXPECTED CHALLENGES

5.1 *Technical hurdles*

One of the principal technical challenges for ET construction is related to the complex nature of the ET layout. Corner points hosting multiple caverns have been identified as a highly critical aspect regarding feasibility.

Multiple recesses along the tunnel alignment pose extra technical challenges since they are likely to be excavated by traditional methods. Impacts on costs shall be taken into account. It is important to note that considering insufficient spacing between caverns may lead to pillar instability issues.

Restrictions regarding water flow within the infrastructure to ensure proper operation might well determine water tightness criteria of caverns and tunnels, which will determine inner lining requirements as well as the expected effort for pre-excavation grouting works. In case the tunnels must remain flat, and thus no slope is allowed, dewatering management will pose a significant challenge. Defining these outstanding issues will help reduce the level of uncertainty the project is currently facing.

5.2 *International context and stakeholder engagement*

The EMR site is strategically positioned at the intersection of three European countries: Belgium, Germany, and the Netherlands. This prime location offers significant opportunities for funding and technological collaboration. Ensuring the success of the project is therefore set as the top priority for everyone at the ET EMR Project's office.

However, the alignment of the scientific community's objectives with the engineering feasibility of the project presents a significant challenge despite collaborative efforts. Overcoming this challenge will require a unified approach and for both engineers and scientists to push the limits of their respective state-of-the art.

5.3 *Environmental aspects*

The construction of the Einstein Telescope must ensure minimal disturbance to the protected areas of the EMR region. This involves adhering to stringent guidelines on noise, vibration, and air quality. Furthermore, there must be a focus on maintaining the hydrological balance of the area. Alterations to the water table caused by the excavation and construction processes could adversely affect the delicate ecosystems within the Limburg's Natura 2000 sites. Therefore, hydrological studies and sustainable water management practices will play a determinant role regarding feasibility.

International collaboration and engagement with stakeholders, including environmental organizations and local communities, are imperative for navigating the legal and ecological complexities of this project. Only through continuous dialogue and compromise to environmental regulations can the Einstein Telescope project proceed responsibly, ensuring the preservation of the natural heritage while advancing scientific knowledge.

6 CONCLUSIONS

Located at the strategic intersection of Belgium, Germany, and the Netherlands, this project aims to achieve groundbreaking advancements in gravitational wave detection, all while addressing the complex combination of technical challenges, environmental compliance, and cost efficiency.

However, this project also presents an opportunity to innovate and find cost-efficient solutions that do not compromise quality or sustainability. Collaborative efforts between engineers, scientists, and financial experts will be vital in optimizing resources and achieving the desired outcomes.

The challenge of aligning scientific requirements with tunnelling feasibility is an opportunity to push the boundaries of technology. A holistic and collaborative approach will help to create a truly unique and groundbreaking project that will inspire both the tunnelling industry and the scientific community, redefining the possibilities of underground use and setting a milestone on how large-scale scientific endeavors can be realized responsibly and sustainably.

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