Preparatory Phase for the Einstein Telescope Gravitational Wave Observatory

Milestone XX.XX
Deliverable 6.2

The Vacuum Pipe of ET

Lead beneficiary:
Delivery Date:
Dissemination level: internal
NAME : ET-PP-Milestone-XX.XX
NAME : ET-PP-Deliverable-XX.XX
Version: X.X

This project has received funding from the European Commission Framework Programme Horizon Europe Coordination and Support action under grant agreement 101079696.

Document information

Grant Agreement Number	101079696
Acronym	ET-PP
Start date of project (Duration)	01/09/2022 (48 months)
Document due date	09/2024
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Deliverable/milestone number	6.2
Deliverable/milestone name	Vacuum pipe design
WP	6

Version	Date	Author	Description
v 0.1			Creation
v 0.2			Revision
v 0.3			Revision
v 1.0			Revision including all partners' contributions. Final approval by ET-PP coordinator

EXECUTIVE SUMMARY

This document, D 6.2 Vacuum pipe design, is a deliverable of the ET-PP Project, which is funded by the European Commission Framework Programme Horizon Europe Coordination and Support action under grant agreement 101079696. It outlines the design and operational strategies for the Einstein Telescope's ultrahigh vacuum pipe system, which is a critical part of the laser interferometers, providing an environment with minimal residual gas and photon scattering.

List of acronyms and abbreviations

UHV	Ultra-High Vacuum
TIG	Tungsten Inert Gas
MIG	Metal Inert Gas
CF	ConFlat
NEG	Non-Evaporable Getter
TMP	Turbomolecular Pump
SIP	Sputter Ion Pump
BA	Bayard-Alpert
RGA	Residual Gas Analyser
CDR	Conceptual Design Report
TDR	Technical Design Report
ET	Einstein Telescope
LF	Low Frequency
HF	High Frequency
TIG welding	Tungsten Inert Gas welding
PAW	Plasma Arc Welding
FT-IR	Fourier Transform Infrared spectroscopy
XPS	X-ray Photoelectron Spectroscopy
EDX	Energy-Dispersive X-ray
SEM	Scanning Electron Microscope
QA	Quality Assurance
GWT	Gravitational Wave Telescope

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1. Overview and assumptions

The Einstein Telescope (ET) vacuum pipes are metallic tubes through which laser beams propagate in an ultrahigh vacuum (UHV) between the input and end mirrors of the interferometers. The vacuum pipes are equipped with conical baffles to reduce noise caused by scattered photons from mirrors and are held and aligned by supports that also serve as ground vibration dampers. The ET's vacuum pipes are located within tunnels, with their extremities positioned at the entrances to the experimental caverns. Sector valves at these locations separate the room-temperature vacuum pipes from the cryotraps installed before the experimental towers, defining the limits of the vacuum pipes.

In the ET's triangular configuration, each 10 km side contains four vacuum pipes arranged in two stacks of two, leaving a central passageway. In the L configuration, each tunnel's branch houses two vacuum pipes, either stacked or positioned on either side of the central passageway near the tunnel walls. This report provides technical inputs that remain largely independent of the tunnel configuration, except in specific instances where the configuration is explicitly mentioned. On the other hand, the tunnel's infrastructure is one of the critical factors defining the vacuum-pipe design as it is outlined in the following chapters.

By design, ET has two types of interferometers referred to as high frequency (HF) and low frequency (LF). Even if the required vacuum performance differs [1], at the present stage, the vacuum pipes of the two types of interferometers are considered identical, both fulfilling the most stringent requirements.

This technical report gives a thorough description of the vacuum pipes from conceptual design to operational procedures, including fabrication details, surface treatments, and installation considerations. The logistics are also addressed. The entire production cycle, from raw material to final commissioning, is evaluated with a focus on safety, sustainability, and costs.

In the following paragraphs, we frequently use technical terms that are here clarified:

- 'Vacuum pipe system' comprises the vacuum pipe, its vacuum systems, optical baffles, and mechanical supports.
- 'Tube units' are the pieces of vacuum pipe that are assembled to compose the whole vacuum pipe system. This is the unit of production, storage and transport.
- 'Vacuum sector' is the part of the vacuum pipe included between two sector valves.
- 'Pumping modules': the vessels equipped with pumping ports for instrumentation and pumping.
- 'Tube string': the vacuum pipe included between two pumping modules..
- 'Outgassing rate' is the net quantity of gas spontaneously released per unit time by materials in vacuum.

- 'Bakeout' is the *in-situ* heating of the vacuum pipe to accelerate water desorption and, as a consequence, the achievement of the ultimate pressure
- 'Vacuum commissioning' is the sequence of actions that bring the pressure in the vacuum pipes from atmospheric to the required one (i.e. around 10^{-10} mbar).

2. Functional specifications, scientific requirements and technical constraints

The functional specifications detail what the ET's vacuum pipe system must provide. They describe the expected behavior, features, and interactions with the other systems, focusing on what the ET scientific program needs. Both scientific requirements and technical & legal constraints contribute to defining the functional specifications. Requirements outline the desired functionalities, while constraints determine the boundaries within which those functionalities must be delivered.

The main requirements for the vacuum pipe system are:

- Clipping losses in the Fabry-Perot cavities must be less than 10^{-8} of the stored power.

  This requirement, along with assumptions regarding the maximum laser beam offset (5 cm), the radial height of the optical baffles (8 cm), and the potential for future upgrades has led to the conclusion that the ET's vacuum pipes must be 1-meter inner diameter cylindrical vessels [1].

- All sources of noise correlated with the vacuum pipe systems must jointly contribute to less than 10% of the ET's amplitude noise spectral densities.

  - **Residual gas pressure**: The 10% requirement implies upper limits on the residual gas pressures in the vacuum system. These limits were estimated in the CDR and are reported in Table 1 [2]. At this stage, they are considered a guideline. Refined values were provided in [1], which takes into account the calculated pressure distribution for a given pumping layout.

Gas species	Maximum residual gas pressure [mbar]
H_2	1×10^{-10}
H_2O	5×10^{-11}
CO	10^{-11}
N_2	10^{-11}
C_xH_y with more than 100 amu	$< 1\times10^{-14}$

Tab. 1: *Indicative maximum values for the partial pressures in the vacuum pipes. More precise estimates are given in Tab. 8 once the pumping layout is defined and the additive effects of multiple gas species are considered.*

  - **Light scattering from mirrors' surfaces**: Reducing the noise well below the 10% threshold requires a detailed study of the baffle geometry, positioning along the vacuum pipe, as well as surface reflectivity and dust particle effects. This TDR incorporates input from the current baffle technical drawings [3], theoretical installation locations [4], and guidelines for the maximum tolerable dust particle concentration [5]. These factors influence the vacuum pipe technical design, fabrication and installation procedures. A technique to ease baffles installation is proposed, and ISO-6 standards (reference to ISO 14644-1) are imposed to limit dust contamination during all post-cleaning steps where the vacuum pipes' inner surfaces are exposed to air. The suppression of light scattering requires limiting vibration transmission at the baffle positions [1], which leads to a dedicated design of the supports and their transmission matrix.

- The vacuum pipe system lifetime must be longer than 50 years.

  The required long lifetime and the lengthy operational downtime caused by air venting of the vacuum pipes system necessitate the use of materials, joining techniques, and vacuum components that are corrosion-resistant to the typical chemical species found in underground tunnels. This applies not only to the materials of the tubes but also to any electrical feedthroughs required for operating vacuum pumps and instrumentation. The long lifetime requirement also demands a rigorous quality assurance plan and thorough follow up of any non-conformities that may arise during the fabrication process.

The external factors that impose limits on time, budget, resources or technology that constraint the beampipe technical design are:

- Related to safety and sustainability:
  - All activities related to the vacuum pipe systems must comply with the safety regulations in place at the time and location of the associated work. This influences the installation process (e.g., transport and welding in the tunnel). Additionally, the beampipe bakeout must take into account electrical safety considerations and constraints associated with maximum temperature limits for the tunnel air (30°C) [1].
  - The selection of raw materials, fabrication methods, logistics, installation, commissioning, and operation must consider environmental impact.

- Related to compatibility with the ET infrastructure:
  - ET infrastructure significantly impacts vacuum pipe design. For instance, the available electrical power in the tunnel affects the way bakeout procedures are conducted. The space available in experimental areas and/or access shafts limits the maximum length of the tube units, while the space within the tunnel

directly influences the design of the supports. These aspects will be discussed in the following sections.

- Related to budget and time limitations:
  - The vacuum pipe system is one of the most expensive components in the ET cost breakdown, second only to civil engineering. Every cost-saving measure has a significant impact on the overall project budget, potentially freeing up resources for gravitational wave detection systems. From the choice of raw materials to operational efficiency, each step of the process must be optimized. As a guideline for defining cost reductions, we adapt to ET the design adopted for Virgo [6] and LIGO [7], therefore considering as cost reference for the tube unit a lip-welded 15-meter-long pipe made of air-fired, 4-mm-thick AISI-304L stainless steel, reinforced with circumferential stiffeners.
  - The time required for fabrication, installation, and commissioning is a critical aspect of the vacuum pipe design that is not fully analyzed in this TDR, as several inputs are still under development. As a guideline, we assume that the installation and commissioning phases will take **three years**. This duration is used to formulate an installation plan and procedure, which are described in the following paragraphs.

3. Material for the vacuum pipes

3.1 Introduction

Austenitic stainless steels are standard materials for UHV applications and, among them, AISI 304L is the default structural material in scientific equipment. Indeed, more than 30 years ago, this stainless steel was selected for Virgo and LIGO. More recently, AISI 304L was also considered for the construction of the ET vacuum pipe system [2].

AISI 304L would certainly meet the ET requirements. However, austenitic stainless steels are known for their high hydrogen outgassing rates at room temperature, the highest among typical UHV structural materials used in scientific applications (i.e., copper, aluminum, beryllium, and titanium alloys). This unfavorable characteristic originates during the hyperquenching of the material, when hydrogen dissolved in the liquid metal is trapped within the volume available in the face-centered cubic lattice. This compact crystallographic structure, typical of austenite, reduces hydrogen mobility during mild temperature treatments such as in-situ bakeout. The practical result is that high-temperature heating is required to remove hydrogen from the bulk of these materials, consequently achieving specific outgassing rates in the range of 10^{-13} to 10^{-15} $mbar \cdot l \cdot s^{-1} \cdot cm^{-2}$, depending on wall thickness and the partial pressure of H_2 during the treatment. These degassing treatments, referred to as firing, are regularly applied either in vacuum (typically at 950°C for 2 hours) or in air (about 450°C for several tens of hours) [8], as was the case for Virgo and LIGO. Nonetheless, regardless of their feasibility, the integration of such degassing treatments at the scale of ET would represent a bottleneck in the production flow, incur significant costs, and have a high environmental impact.

In contrast, ferritic steels, such as mild steels, present a more cost-effective alternative with inherently lower residual hydrogen content. The hydrogen mobility in these materials is orders of magnitude higher, which enables more efficient degassing at relatively low temperatures. This results in a very low hydrogen outgassing rate, as has been demonstrated in recent experiments [9]. Despite these advantages, mild steels face limitations due to their susceptibility to deep oxidation and corrosion, posing risks for applications requiring longevity.

Beyond outgassing properties, material selection for ET’s vacuum pipes must also consider factors like availability, formability, weldability, strength, ductility, corrosion resistance, and cost. After a preliminary evaluation of various ferritic steels, only those meeting the industrial availability requirements in terms of form and dimensions were considered for final selection. Based on these criteria, ferritic stainless steel AISI 441 [10] (EN 1.4509 [11]) emerged as the most suitable material for ET’s vacuum pipes.

Ferritic stainless steels, which are low-carbon Fe-based alloys with ferrite as the main phase, have vacuum properties particularly well-suited for this application. Characterized by a body-centered cubic structure, as already reported above, these steels offer lower hydrogen solubility and higher diffusivity than austenitic stainless steels, resulting in reduced hydrogen outgassing. Experimental measurements [10] reveal that AISI 441 exhibits a hydrogen outgassing rate lower than vacuum-fired or air-baked AISI 304L following low-temperature bakeouts (80°C–150°C).

In terms of availability, AISI 441 is widely produced in cold-rolled strip and sheet forms with thicknesses up to a few millimeters and a maximum width of 1500 mm. Delivered in the annealed condition with a 2B surface finish (pickled and skin-passed), this material meets ET's requirements for large-scale manufacturing. Its typical chemical composition and mechanical properties are provided in Tables 2 and 3, respectively.

Ferritic stainless steels like AISI 441 also offer advantageous formability and weldability. They are compatible with common UHV welding methods, including laser and arc welding, with or without filler materials. Additionally, the chemical composition of AISI 441 is optimized with stabilizers (titanium and niobium) to prevent chromium carbide precipitation (resistance to sensitization) and unwanted martensitic transformations in weld zones. Proper welding procedures that control heat input and optimize cooling rates result in minimal grain coarsening, yielding welds with ductility and toughness comparable to the base material. These welds have been systematically verified through metallurgical examination and non-destructive testing, ensuring compliance with UHV standards.

The corrosion resistance of ferritic stainless steels is another critical advantage. High chromium levels promote a passive oxide layer that protects against oxidation and corrosion, while their low nickel content minimizes susceptibility to chloride stress corrosion cracking. While ferritic steels generally exhibit lower corrosion resistance than austenitic types, AISI 441's optimized composition, with low carbon and high chromium, improves its corrosion resistance, giving it a pitting resistance equivalent number (PREn) around 21 [13].

Additional specifications concern grain size and inclusions. The equivalent grain size number according to ASTM E112 shall be, in average, equal or greater than 4. The grain size shall be homogeneous within the range of ± 0.5 equivalent grain size number around the true average value. The amount and definition of inclusion shall meet standard ASTM E45, Method A, with severity level number not more than 2.

Lastly, cost is an important consideration in the choice of materials for ET. Ferritic stainless steel is generally less expensive than austenitic grades, and the ability to skip high-temperature degassing during UHV conditioning further reduces both costs and energy consumption.

C	Mn	Si	P	S	Cr	Nb	Ti
≤ 0.030	≤ 1.00	≤ 1.00	≤ 0.040	≤ 0.015	17.5 -18.5	[(3xC) + 0,30] - 1.00	0.10-0.60

Tab. 2: *Composition (wt. %) of the AISI 441 (EN 1.4509) according to EN 10028-7*

Yield Strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation at break A_5 (%)
≥ 230 (long.) ≥ 250 (tr.)	430 to 630	≥ 18

Tab. 3: *Mechanical properties of the AISI 441 (EN 1.4509) according to EN 10028-7*

4. Mechanical design of the vacuum pipes

The tube unit has a cylindrical geometry with a nominal inner diameter of 1 meter. Its nominal length of 15 meters was chosen to ensure compatibility with transport options by rail or standard road vehicles. Constructed from AISI 411 ferritic stainless steel, two technical solutions for the tube units have been evaluated. The primary option, taken as the baseline, follows the VIRGO design and incorporates a smooth tube reinforced with stiffeners (Fig. 1). An alternative approach has also been explored considering a thin-walled, corrugated chamber design (Fig. 1).

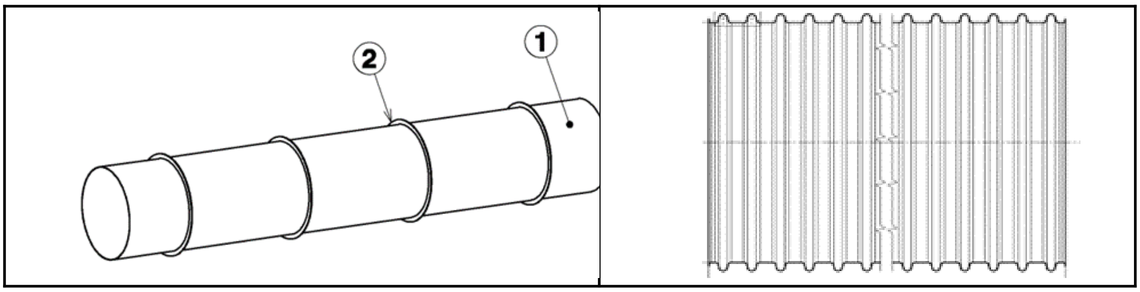


Fig. 1: *Schematic design of the smooth tube unit reinforced with stiffeners (left side) and a section of the corrugated tube (right side).*

4.1 Smooth reinforced vacuum chamber

This design comprises a tube with a nominal inner diameter of 1 meter and a wall thickness of 4 mm, reinforced by stiffeners attached with intermittent welds (according to ISO 2553). The stiffeners, spaced 1.5 meters apart, stabilize the tube's unsupported length against external atmospheric pressure. Each stiffener consists of a circular bar with a rectangular cross-section, measuring 6 mm in width and 50 mm in height. The tube itself is manufactured using a full-penetration butt seam weld, while the stiffeners are attached with non-penetrating, staggered intermittent welds. The reinforcement material requirements may be relaxed, allowing for less stringent specifications on chemical composition and inclusion content. This non-penetrating weld must leave at least 50% of the original tube thickness intact, ensuring the stability of the chamber.

4.2 Thin-walled corrugated vacuum chamber

To potentially reduce vacuum system costs, an alternative thin-walled design, with a typical wall thickness of 1.5 mm, has been proposed. This design integrates corrugations into the chamber wall, providing the necessary strength to withstand external pressure. This approach offers several notable advantages: it reduces the amount of raw material, directly impacting the cost and sustainability of the vacuum chamber. A thinner wall also might require lighter forming equipment and eliminates the need for additional reinforcement steps, further reducing production costs. The bakeout of the vacuum chambers is conducted through Joule heating, and the reduced wall thickness lowers both the current and energy requirements for this process. Additionally, the corrugations help absorb thermal expansion, mechanical tolerances, and misalignment during bakeout, eliminating the need for bellows between chambers.

The corrugation profile is optimized for stability against external pressure, with a typical convolution height of 35 mm. A flat section between each corrugation accommodates baffle interfaces and simplifies tooling insertion if required. Two options are available for forming the corrugations circumferentially: annular or helical. Annular corrugations offer superior mechanical performance, enhancing stability and avoiding axial or torsional coupling. Helical corrugations, however, simplify manufacturing by allowing corrugation formation before tube shaping and reducing the risk of detergent or water retention during chemical cleaning and rinsing.

4.3 Ancillaries on the vacuum chamber

The tube units are equipped with survey target supports to enable precise position measurement and alignment of the system. These target interfaces are welded onto the chambers at their extremities, aligned within the same plane as the baffle supports.

To facilitate the bakeout process, the tubes are covered with rigid thermal insulation segments. A 10 cm layer provides a thermal resistance of 0.30 W m^{-2} K^{-1}. The insulation material must be compatible with the tunnel environment, meet fire resistance requirements, minimize dust generation, and be capable of relocation between sectors. This relocation feature could reduce material usage and cost. Removable insulation also simplifies leak detection, should a leak occur.

Pumping modules are positioned along the interferometers (see Chapter 5). These modules are constructed from 4 mm thick, reinforced AISI 441 ferritic stainless steel tubes with a length of approximately 750 mm. The modules integrate ports for vacuum components, such as valves, pumps, and gauges. These ports include sleeves made from AISI 441, welded internally to the module wall, and are fitted with DN200 CF flanges made of vacuum-fired, 3D-forged 316LN stainless steel.

4.4 Vacuum chamber connection

Two options are considered for connecting the tube units. The first one involves a radial lip weld, with an optional 90° flared extremity. The second one utilizes a fillet weld, joining a 2 mm thick external sleeve made of AISI 441 to the tube units A comparison of these options is provided in Table 4. Optimisation of the local thermal insulation may be needed to ensure a uniform temperature profile.

4.5 Baffle integration

The vacuum chambers incorporate optical baffles to intercept scattered laser light. Each baffle is designed as a truncated cone, fabricated from a 1.5 mm thick stainless steel sheet, with a serrated internal edge measuring 850 mm in diameter. The precise grade of the steel and its surface treatments are still a subject of study.

The conical section is welded to a circular flat plate with dedicated holes to facilitate mechanical assembly within the vacuum pipes. To support this assembly, an additional circular flat plate is welded inside a selected number of tube units, providing a mounting base. These support rings have radial protrusions along their outer diameter to ensure local contact with the chamber walls, reducing the risk of contamination or liquid retention during cleaning. Six M6 threaded holes are provided for assembly, along with two diametrically opposed bored holes.

	Radial lip 	**External sleeve** 
Tolerances:		
Length	Required	Not required
Perpendicularity	Required	Not required
Diameter (developed length)	Not required	Required
Risk of contamination during welding/cutting	High	Low
Repair/cutting possibility	Limited	High
Alignment requirement	1-2 mm	~ 1 mm for a 0.2 mm radial gap
Others	• Additional step during manufacturing: cost ↗ • Compatibility with simple leak testing?	External side of the extremities must remain clean.

Tab. 4: *Characteristics of the two methods for tube units connections*

The theoretical longitudinal positioning of the baffles is determined based on the mirror and baffle geometries, as well as their distances from the mirrors. The spacing between baffles varies along the length of the interferometer, with closer spacing near its extremities. The first baffle downstream of the cryotrap, transition module, and sector valve is positioned approximately 60 meters from the mirror. The baffles are installed at the ends of selected 15-meter tube units, as close as possible to their ideal theoretical positions.

4.6 Supports

A preliminary integration of the chambers and their supports within the 6.5 m diameter free-aperture tunnel is illustrated in Fig. 2. A passage approximately 2 m wide is available between the two rows of chambers. Further studies are required to optimize the vacuum pipe integration and the overall ET design.

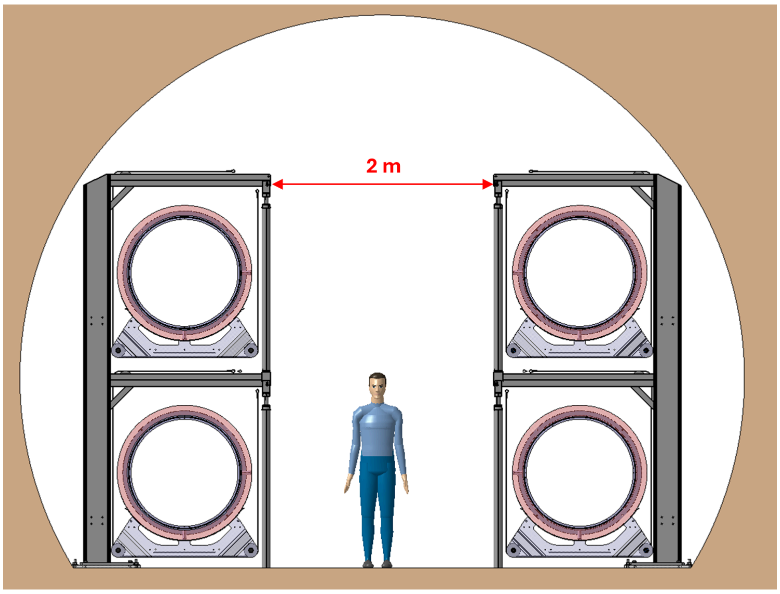


Fig. 2: *Integration of the four vacuum pipes in the tunnel*

4.6.1 Suspension of the vacuum chambers

The support system relies on the suspension of the vacuum chambers, functioning as a low-pass filter in both vertical (spring/mass system) and lateral (pendulum) directions. The natural frequencies for these directions are given by $\frac{1}{2\pi}\sqrt{\frac{k}{m}}$ and $\frac{1}{2\pi}\sqrt{\frac{g}{L}}$, where L and k represent the length and stiffness of the pendulum, respectively, m is the suspended mass, and g is the gravitational acceleration. The parameters of the suspension system are optimized to reduce these natural frequencies while staying above the global wave-induced low-frequency seismic noise present up to 0.4 Hz at the surface and 0.3 Hz underground (see Fig. 3). The length of the pendulum is approximately 1.5 m.

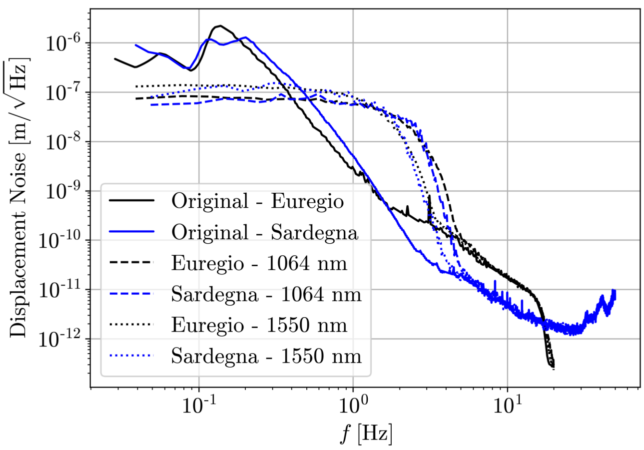


Fig.3 *Displacement noise amplitude due to seismic activities and conversion for the different laser wavelengths [4].*

The suspension cable consists of high-strength synthetic ropes, offering low stiffness (resulting in a lower natural frequency in the vertical direction) and likely some damping. A nominal diameter of 6 mm is foreseen for the ropes. This ensures a nominal safety margin of 5.5 against the average breakage load, considering a linear weight of 145 kg·m^{-1} (insulated corrugated chamber with rail support).

4.6.2 Supporting frame

The vacuum chambers are suspended from supporting frames anchored to the ground (Fig. 4). These frames are constructed using welded standard steel beams—IPN240 for the pillars and UPE100 for the transverse crosspieces. The supporting frame has two levels to accommodate the installation of one vacuum line above the other. A lightweight, cost-effective design has been implemented; however, to prevent high bending stresses in the supports due to the weight of the chambers, an additional leg support has been added on the passage side. When removing the lower chamber while the upper chamber remains installed, an additional temporary support structure must be considered.

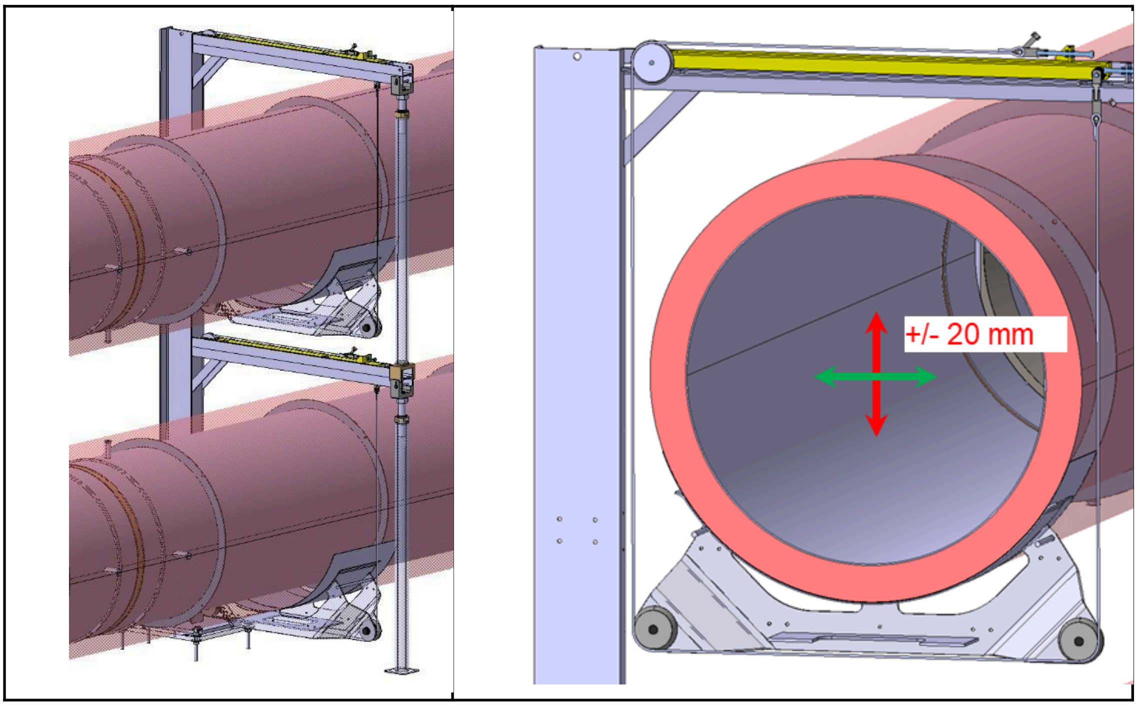


Fig. 4: *Design of the supporting frame (left) and its adjustment capability (right). The red ring around the tube represents the thermal insulation material.*

The position of the vacuum chamber can be adjusted freely within ±20 mm in both directions (Fig. 5-right). The interface between the suspension system and the frame includes an intermediate crosspiece. Equipped with bearings, this crosspiece can slide laterally within the frame, with its lateral position adjusted by a screw (Fig. 5-left). The two ends of the suspension ropes are attached to this crosspiece, with one end adjustable to modify the pendulum length, and consequently, the vertical position of the chambers (Fig. 5). Both vertical and lateral adjustments are accessible from the passage using two screws. Any misalignment in the longitudinal direction between supports and vacuum tube will be absorbed by the supporting cables

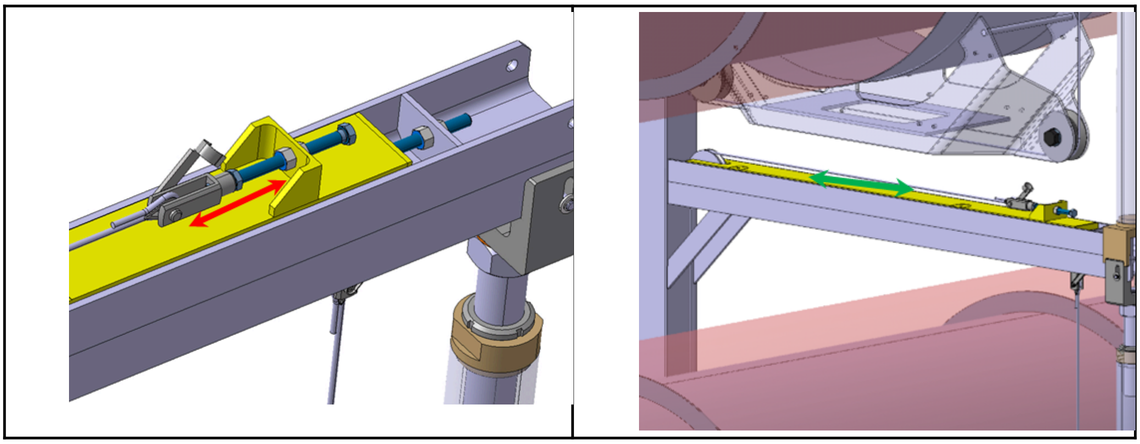


Fig. 5: *Adjustment of the vertica (left)l and lateral positions (right)*

4.6.3 Cradle

The interface between the suspension system and the chamber consists of a cradle. Two localized cradles, each 30 cm long, are installed underneath each smooth, reinforced, and insulated vacuum chamber. For corrugated tubes, which have limited bending stiffness, additional supports and cradles—or a continuous cradle along the full length of the pipe—are required to prevent significant sagging; its analysis is still a subject of development. Lateral dampers are incorporated between the cradles and the vertical pillars to attenuate vibrations from direct external forces.

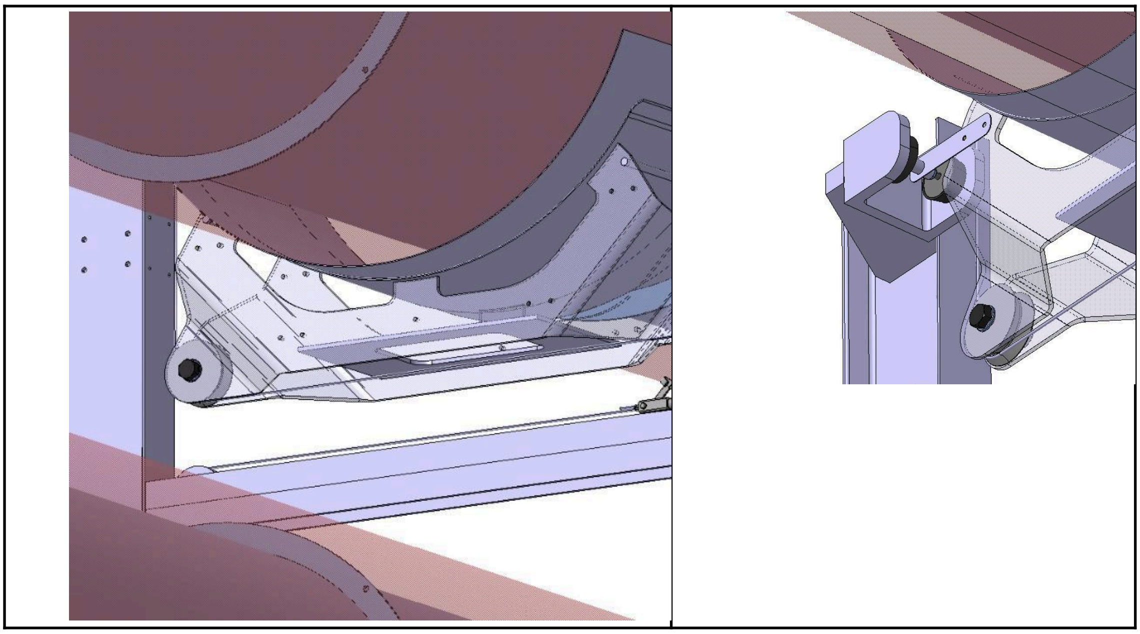


Fig. 6: *Design of the cradle (left) and the lateral damper (right).*

The thermal insulation is compressed between the chamber and the cradle. If long-term geometric stability cannot be maintained or if flexible insulation such as mineral wool is used, spacers, such as those made from glass fiber-reinforced epoxy (GFRE), can be added through the insulation.

4.7 Vacuum sector extremity – bellows expansion joints

The suspended chamber solution requires decoupling from all components directly fixed to the ground, such as sector valves located mid-interferometer and near the cryogenic traps. Thin-walled decoupling bellows (0.6 mm thickness) are required, with typical stiffness values of 25 N/mm in the axial direction and 70 N/mm transversally. These bellows are made from stainless steel. When using an austenitic stainless steel grade such as 316L, a high-temperature degassing is necessary to reduce the specific hydrogen outgassing rate to approximately 10^{-14} mbar·l·s^{-1}·cm^{-2}.

In the case of stiff vacuum tubes, such as smooth configurations, bellows are also needed to accommodate the thermal expansion occurring during bakeout. With a bakeout temperature of 150°C, thermal expansion is estimated at 1.7 mm/m, totaling 25.5 mm per tube unit. To address this, it is proposed to install one bellow for every two tube units, as this is within the operational range of the bellows and does not necessitate any additional vacuum pipe variants.

4.8 Mechanical behavior of the proposed vacuum pipes

In this chapter, the mechanical behavior of the smooth and corrugated vacuum chambers is presented. The geometry of the smooth pipe is detailed in Section 4.1. For the corrugated chamber, a possible profile for annular corrugations is provided in Section 4.2. If a helicoidal solution is chosen, the stiffness will be reduced, and the corrugation parameters will need to be updated to ensure the chamber's stability.

The mechanical analyses have been conducted using a conservative elastic modulus of 190 GPa.

4.8.1 Buckling instability

The mechanical design of the vacuum chamber is primarily driven by the buckling stability against external pressure. For the reinforced smooth chamber, the parameters of the stiffeners are defined to ensure a minimum safety factor of 3 for elastic eigenmode analysis and to identify the vacuum chamber's instability in the non-supported length. A mode 5 is observed, occurring at 3.6 bars (Fig. 7). For the chamber with annular corrugations, a mode 2 is also observed.

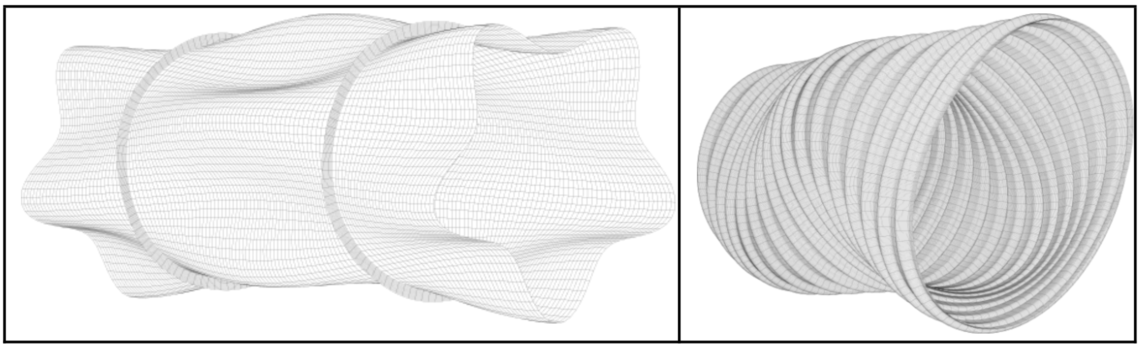


Fig. 7: *Main buckling mode of the smooth (left side) and corrugated vacuum pipes (right side).*

4.8.2 Smooth reinforced chamber

The effects of intermittent welding on the stiffeners and the weld-induced prestress due to weld shrinkage have been considered; however, their influence on buckling pressure is found to be insignificant (approximately 1%).

The influence of wall thickness on buckling pressure is shown in Fig. 8 and exhibits the expected t^3 dependence.

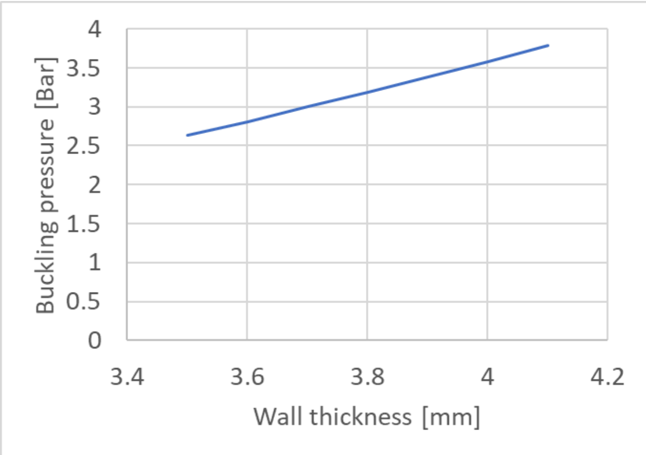


Fig. 8: *Influence of the wall thickness on the buckling pressure*

The effect of initial imperfections was studied using a defect parameter range from 0.1 to 2 mm, corresponding to half the cylindricity tolerance, as illustrated in Fig. 9. The deformations and maximum Von Mises stresses are presented as functions of external pressure in Fig. 9-left and Fig. 9-right, respectively. For an initial defect parameter of ±2 mm, the instability pressure is reduced to approximately 2.3 bars, though the deformation at a differential pressure of 1 bar is about 0.8 mm. The stresses remain limited to about 30 MPa at both 1 bar and at the instability pressure, which confirms the occurrence of elastic buckling.

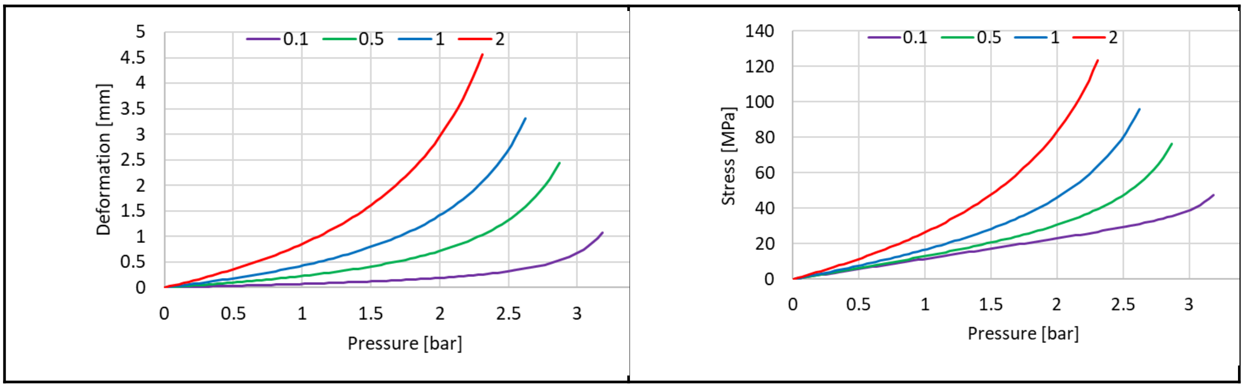


Fig. 9: *Effect of initial imperfections as a function of pressure on deformation (left) and stress (right).*

4.8.3 Helicoidal corrugated chamber

An alternative method for producing a corrugated chamber is to form the convolutions on the sheet band before tube rolling. This approach results in a specific helical angle determined by the coil width and the number of convolutions per band width. The typical first buckling mode is shown in Fig. 10; it exhibits a helicoidal shape. The influence of the number of convolutions per band width on different corrugation profiles is evaluated in Fig. 11. This factor has a significant impact and should be carefully considered when defining the profile and thickness, whenever a helicoidal corrugated vacuum pipe is chosen.

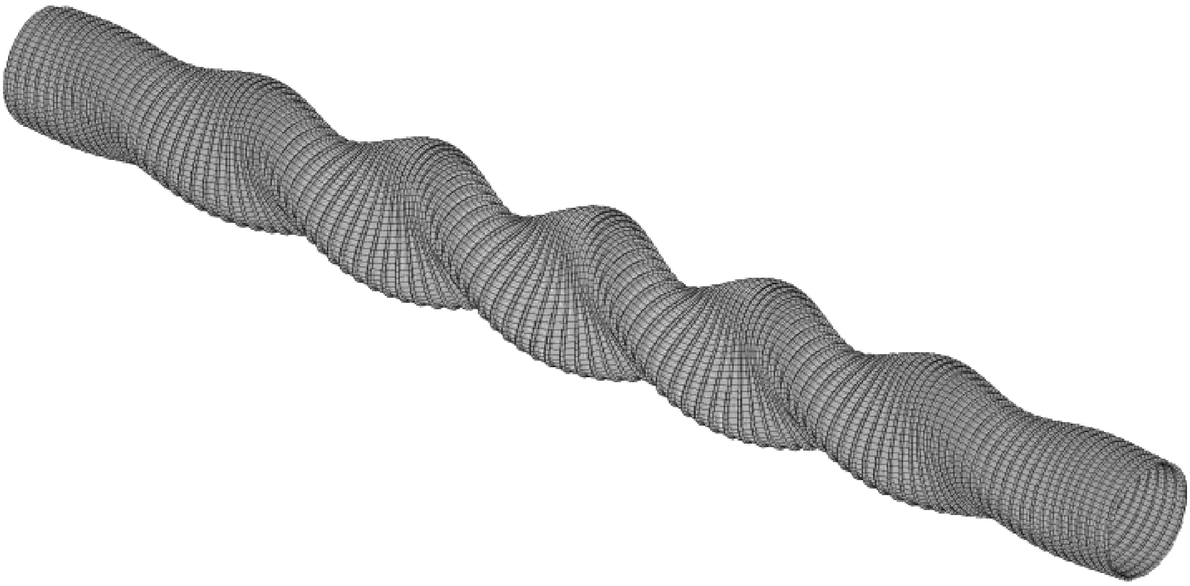


Fig. 10: *Buckling mode of helicoidal corrugated pipe*

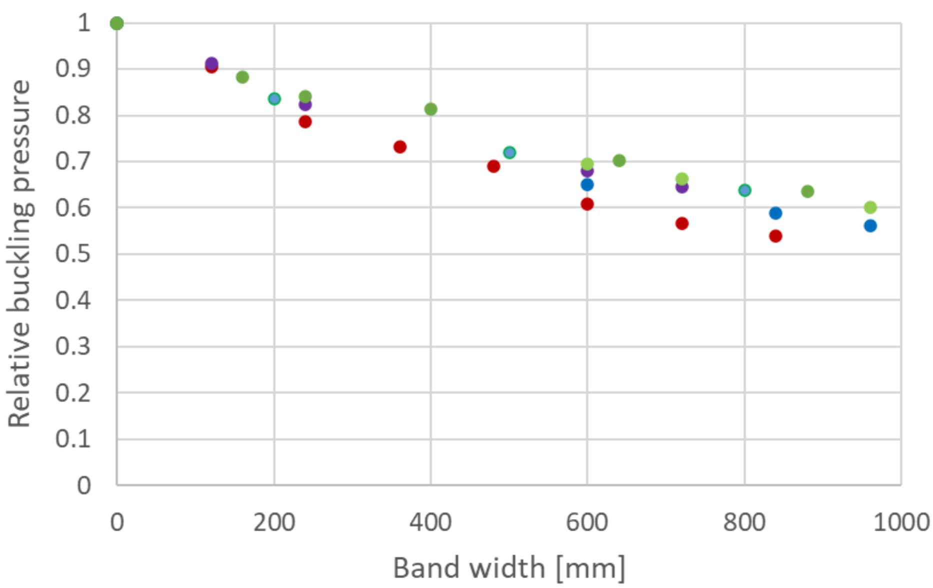


Fig.11: *Influence of band width (helical angle) on the relative buckling pressure for different convolution parameters.*

4.9 Vibrations

Minimizing vibrations of the integrated optical baffles is an important requirement for the vacuum pipe system.

4.9.1 Eigenmodes of a single suspended chamber

A vibration analysis was conducted using a finite element model. Shell elements were applied to model the smooth tube and stiffeners, while the corrugated vacuum chamber was represented as an equivalent smooth tube with shell elements. In this approach, material properties were defined to maintain the same mass distribution and both longitudinal and circumferential stiffness as the actual corrugated chamber. The effect of vacuum on chamber stiffness was also taken into account.

The eigenmodes for a suspended smooth chamber with a baffle at one end are shown in Fig. 12. The initial modes correspond to pendulum and spring/mass oscillator behaviors, with frequencies of 0.42 Hz and 2.61 Hz, respectively. At higher frequencies, bending modes of the chamber are observed.

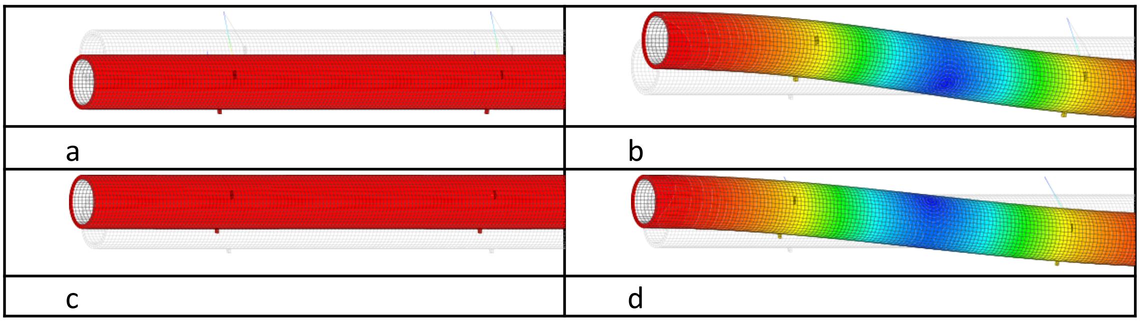


Fig.12: *First two modes for the smooth chamber: in lateral direction at 0.42 (a) and 11.2 Hz (b); in vertical direction at 2.6 (c) and 11.5 Hz (d).*

Similar modes are obtained (see Fig. 13) for the suspended and supported corrugated vacuum chamber.

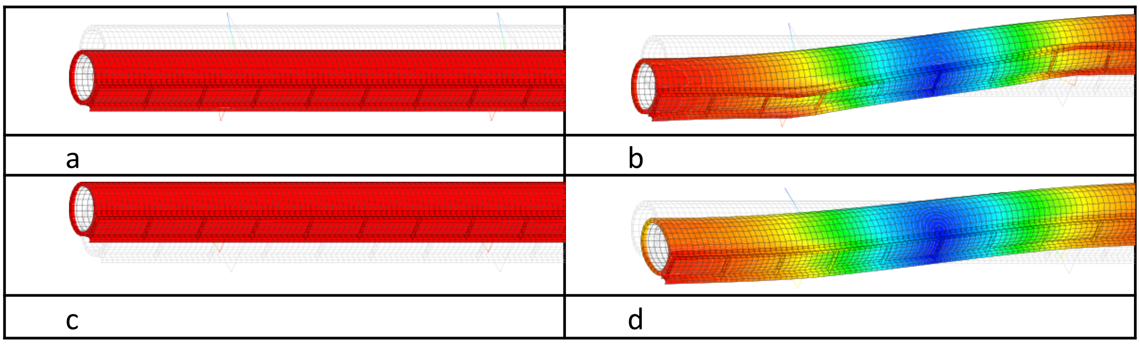


Fig.13: *First two modes for the corrugated chamber: in lateral direction at 0.42 (a) and 4.9 Hz (b); in vertical direction at 2.3 (c) and 5.2 Hz (d).*

4.9.2 Transfer functions along a 500 m long vacuum pipe

A 1D beam model was developed to evaluate the vibration transfer functions from the ground to the baffles along a 500 m long string of superposed vacuum pipes. For the reinforced smooth vacuum pipes, a decoupling bellows is placed at one end (fixed side) and then every two tube units. Pumping modules are located at both extremities.

Ground motion is applied to the support base plates and the bellows end at one extremity, considering both vertical and lateral displacements. Baffles, weighing 12 kg each, are positioned at distances of 15, 30, 75, 120, 195, and 315 m from the extremity. Loss factors of 0.01 were applied for the insulated chambers, pumping modules, and ropes, while a factor of 0.005 was used for the bellows and supporting frames.

The vertical (V) and lateral (H) transfer functions are shown in Fig. 14 and 15 for both lines (top (t) and bottom (b)) and the six baffles (with the first baffle located on the fixed end). A maximum amplitude ratio of about 13 and 30 is estimated for the first eigenfrequency in both vertical and lateral directions, at 0.4 Hz and 2.5 Hz, respectively. In the lateral direction, multiple modes are observed in the 1 to 2 Hz range and around 5 Hz, corresponding to modes with near-rigid body displacements of the chambers, with the bellows acting as hinges. From 5.3 Hz onward, a significant amplitude attenuation is observed. The influence of the end bellows is only significant for the nearest baffle.

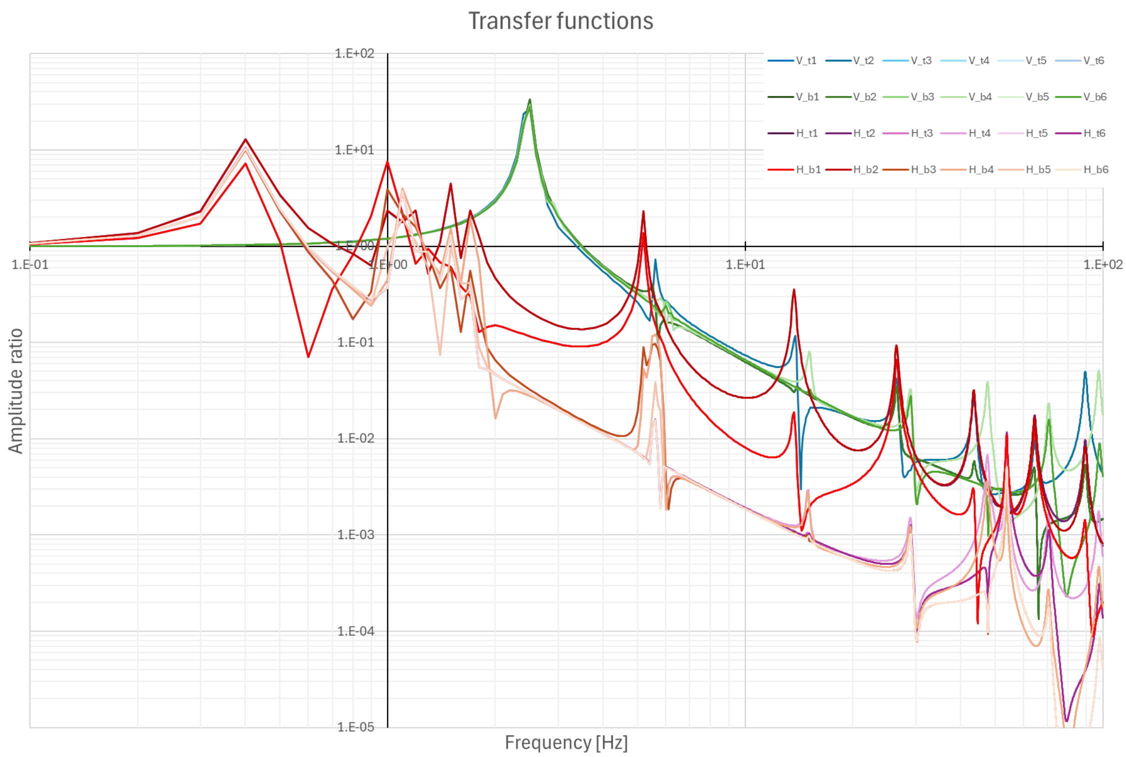


Fig.14: *Transfer function from ground to baffles for the suspended reinforced smooth tube*

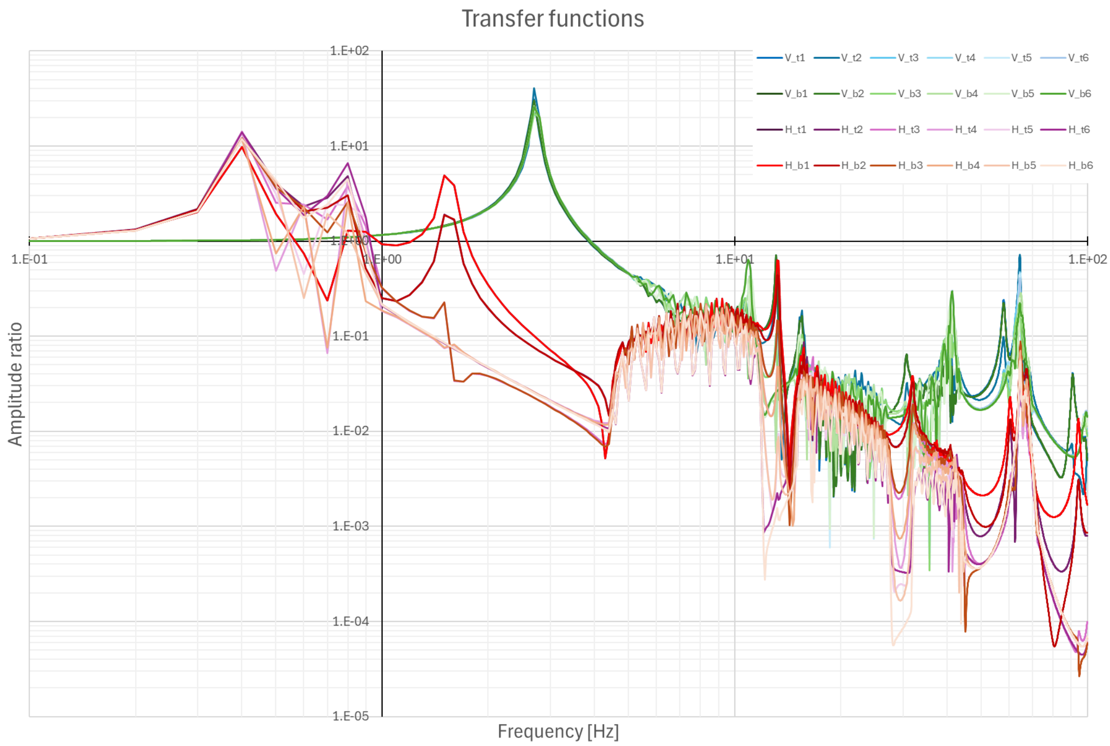


Fig.15: *Transfer function from ground to baffles for the suspended corrugated tube*

4.9.3 External force

The effect of acoustic noise on the vibrations of the vacuum pipes was assessed. A uniform force per unit length with a spectral amplitude of 10^{-4} $N \cdot m^{-1} \cdot Hz^{-1/2}$ was applied [1]. The amplitude spectral displacement and the integrated RMS displacement were calculated in both vertical and lateral directions along the 500 m pipe section. The displacements of the baffle located 195 m from the end are shown in Fig. 16.

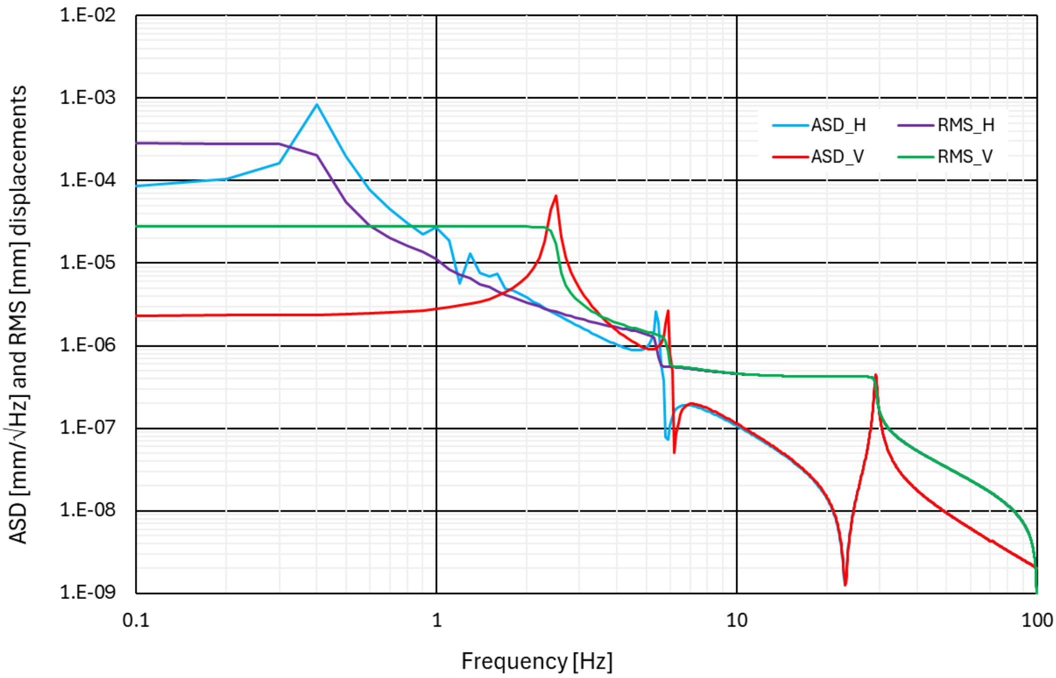


Fig. 16: *Displacement of the suspended reinforced tube under acoustic noise*

5. Fabrication and surface treatments

For the fabrication of the tube units, as outlined in the design section, it is essential to optimize both forming and welding processes to meet UHV requirements. Given the extensive length of the vacuum pipes (120 km), a continuous and efficient fabrication process is critical. The length of individual tube units must be compatible with standard constraints for road transportation, handling, cleaning, and installation. For smooth pipes, bellows need to be installed approximately every two tube units, or every 30 meters, whereas this requirement does not apply to corrugated pipes. Additionally, baffles must be installed inside the vacuum pipe as specified in the previous section.

Considering these constraints, straight pipe sections can be fabricated using one of two primary approaches. The first approach involves rolling flat sheets and performing one or multiple longitudinal welds to produce long pipe sections, as illustrated in Fig. 23-a. The second approach uses spiral forming and welding of the material. Both methods support a continuous fabrication process, allowing for significantly longer pipe sections. Special attention must be paid during forming to ensure the raw material width aligns with the selected grade.

For corrugated pipes, the fabrication process includes an additional step to form the corrugation. Tube fabrication can follow one of the two aforementioned methods, with corrugation subsequently applied either circumferentially or helically, as shown in Fig. 23-b. For large-scale production, a continuous process that combines forming, welding, and corrugation is preferred for both cost efficiency and production speed. Regardless of the approach, it is crucial to maintain the straightness and roundness of the pipe sections within the tolerances specified in the design.

Regarding welding, methods compatible with UHV, such as TIG welding, PAW, or laser welding, must be employed. Autogenous welding should be used whenever possible, as filler materials can compromise vacuum properties and increase welding costs. All joints must be butt-welded with full penetration through the material thickness. Post-weld modifications, such as grinding or machining of the weld beads, should be avoided. Meticulous weld preparation is necessary to ensure smooth weld face and roots, enabling effective UHV cleaning. Welding must follow approved Welding Procedure Specifications (WPS) according to EN ISO 15609-1, and Welding Procedure Qualification Records (WPQR) compliant with EN ISO 15614-1 (Level 2) or EN ISO 15613. All welds are subject to non-destructive testing, with 100% inspection using radiography, ultrasonic testing, or other suitable methods, and must meet the requirements of EN ISO 5817 Level B standards. This approach is essential to prevent vacuum leaks, as demonstrated by previous experience [15].

Finally, dimensional control of the pipes is necessary to verify the straightness and roundness of each section. The outer diameter and wall thickness of each pipe must be measured at both extremities using appropriate measurement techniques.

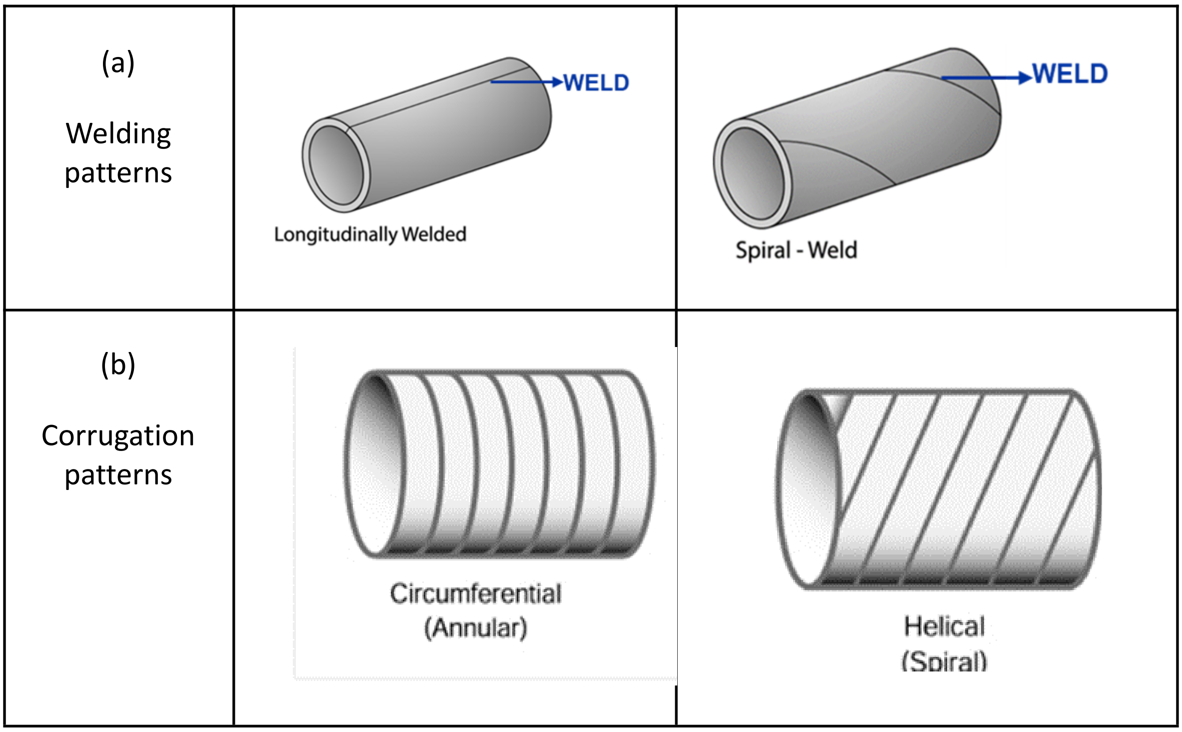


Fig. 23: *Welding methods for smooth (a) and corrugated (b) tube units*

The surface treatments planned for the ET components are designed to meet the necessary functional specifications, particularly in achieving the residual gas pressure defined in Table 1 and maintaining dust contamination at or below ISO-6 standards. Additionally, at intermediate stages, these treatments are intended to enhance working conditions, improve material characteristics for subsequent production or assembly processes, and facilitate the final cleaning. Quality control is an essential tool for anticipating, tracking, and identifying any deviations from the specified requirements, particularly with regard to organic and particulate contamination. The specific control measures are described in each subchapter. Key aspects such as production rate, safety, and environmental impacts of each option presented in this TDR have not been fully addressed and require further analysis. However, at this stage, all options are considered technically compatible with these considerations..

5.1 Considerations about contaminants on raw materials

AISI 441 ferritic stainless steel responds similarly to AISI 304L during degreasing, whether using alkaline water or organic solvent-based processes. In addition to the preferred 2B surface finish, the specifications for the tube elements must identify unacceptable contaminants, as these may necessitate specific cleaning procedures that could increase processing costs. Indeed, any materials and lubricants in contact with the vacuum pipe's raw material must be free from halogens, silicone, graphite, and dry lubricants such as molybdenum disulfide (MoS_2).

Samples of the raw material must be made available before procurement and with each purchased batch to assess surface contamination compliance. The detailed procedure is described in Section 5.5.

5.2 Surface treatments and pipe manufacturing

Similarly to raw materials, it is essential to list all substances used during fabrication and avoid those known to be challenging to remove with standard surface treatments, as previously discussed.

For both smooth and corrugated vacuum pipes, wet cleaning processes are similar; however, corrugated pipes require higher electrical energy for drying after rinsing.

Samples of the pipes, or witness samples processed through the same assembly steps, must be provided before purchase and with each purchased batch to assess compliance with surface contamination standards.

5.3 Cleaning facility

In general, cleaning techniques are categorized as either wet or dry. Wet processes are characterized by effective transport properties, including the removal of dust particles. Within wet techniques, choices include the type of cleaning agent and whether to use an open or closed facility.

For stainless steel, the most suitable cleaning process is water-based, consisting of two steps: an initial treatment with a detergent solution to remove organic contaminants, followed by a rinse with demineralized water (ASTM D1193-99 Type II) to remove detergent residues, allowing components to dry without leaving residues. One main drawback of water-based cleaning is the need to locally produce demineralized water and manage wastewater, a requirement that must be integrated into the facility's design phase. Another wet method uses organic solvents, which do not require wastewater processing but may leave higher levels of organic residue on vacuum pipe surfaces.

Open facilities are less expensive, offer higher processing capacity, and are compatible with continuous fabrication processes. However, closed facilities are easier to integrate into a cleanroom environment. Hybrid facilities can incorporate both open and closed equipment, such as when vacuum is applied to dry the vacuum pipes.

To meet ET requirements for dust contamination, dry techniques like laser and plasma cleaning require auxiliary methods, such as vacuum cleaning or clean gas jets, to remove particulates from surfaces. These dry cleaning techniques are particularly suitable for integration in continuous pipe fabrication processes. For fully manufactured vacuum pipes, dry techniques are less promising, as they ideally need to reach the entire pipe length without direct surface contact.

The choice and validation of cleaning techniques, cleaning agents, and facilities should be based on preliminary trials, using appropriate cleanliness assessment techniques as described in Section 5.5.

Packaging methods for cleaned vacuum pipes depend heavily on fabrication and cleaning processes. Packing materials must protect against particulates, organic contamination, and, as much as possible, mechanical shocks and adverse environmental conditions.

5.4 Control of the cleaning process

To avoid drifts in the cleaning quality, the first precaution consists in monitoring the cleaning process working parameters and maintaining recording logbooks. For wet processes, this includes bath composition, working temperature, conductivity, processing time, and identification of the processed components or batch.

Cleanliness assessments are implemented through two main methods. One approach involves tracking samples from the same raw material that undergo the pipe cleaning procedure. These samples do not need to be analyzed for each individual tube unit, but they should be identified, kept clean, wrapped in aluminum foil, and stored in a plastic box in a dry environment. The control frequency should align with the estimated risk level.

The other method uses direct extraction from cleaned components. Here, a suitable solvent is applied to a defined surface area (typically 1 dm^2) of the cleaned component by wiping or rinsing. This method offers data directly from the component, though it may be limited by the small surface area sampled. The control frequency for this method is also based on the estimated risk.

Particulate cleanliness assessment should be performed after pipe manufacturing and degreasing. This assessment is valuable only if the final cleaning and packaging are carried out in an environment that meets project requirements, ideally ISO Class 6 or cleaner.

5.5 Cleanliness control techniques

Assessment methods are used at various stages of production and after cleaning to identify contaminants and validate compliance of raw materials, cleaning processes, and the final surface state of components. Acceptable contamination levels, as measured by FT-IR spectroscopy and XPS, are listed in [16], with both techniques achieving a sensitivity in the 0.1 mg/cm² range. EDX spectroscopy is also available to complement these methods.

Currently, FT-IR and XPS are used at CERN to meet surface contamination requirements for ultrahigh vacuum applications. FT-IR enables a semi-quantitative evaluation of organic contamination on a surface, performed either directly on the component or on a tracking sample. Contamination is extracted by wiping the surface with a solvent-soaked PTFE membrane or by rinsing directly with solvent, allowing posterior analysis on an FT-IR instrument. By defining the surface area from which contamination is extracted, results can be compared to a predefined acceptance threshold. A preliminary test should determine the solvent’s efficiency with existing contaminants. Further details on this technique are in [17].

XPS provides additional information by identifying chemical elements on the surface of a control specimen, such as a tracking sample, and can detect both organic and inorganic contamination. A key limitation is that the controlled part must be small (maximum around 40x40 mm^2) to fit into an ultra-high vacuum system, and it must have minimal organic contamination to avoid polluting the instrument. The typical detection limit is below a single molecular layer, with surface sensitivity depending on the excitation source energy, electron emission angle, and other instrument settings, as detailed in [16].

EDX, when paired with a SEM, offers a powerful tool for identifying contaminants by providing qualitative and semi-quantitative chemical composition for elements with an atomic number greater than three. The detection limit for EDX in SEM varies by sample composition but generally falls within the 0.1-0.5 wt% range. Combined with automatic particle analysis software, EDX characterizes the morphology and chemical nature of particles from nanometers to micrometers. This is especially useful for samples collected during installation on known substrates, such as silicon wafers or carbon-based stickers, with results presented through particle classification schemes. EDX can also be integrated with dust counters and other tools to validate procedures during installation. Substrates used must fit the SEM chamber, with typical dimensions around 50 mm by 50 mm.

6. Vacuum layout

The vacuum layout identifies the vacuum sectorization and defines the type and positions of pumps, instruments and valves.

6.1 Sectorization

Large DN1000 FKM-sealed, pneumatically actuated gate valves (sector valves) are used to isolate sections of the vacuum pipes. These valves are installed at the extremities of the arms to separate the vacuum pipes from the experimental areas' vacuum system. Additionally, they are installed midway along the vacuum pipe, as shown schematically in Fig. 17, to facilitate the commissioning phase and reduce the impact of air venting.

Since the sector valves expose a significant surface area to vacuum, their body and gate are air-fired at 450 °C for one week to minimize their contribution to the overall outgassing rate [14]. To mitigate the risk of malfunctioning of the central sector valve, which could become stuck in a permanently closed or undefined position over the 50-year operational period, an alternative solution proposes installing two central sector valves spaced about 20 m apart with mechanisms facing each other. This precaution allows maintenance on a faulty valve while venting only 20 m of vacuum pipe to air. If this safety measure is implemented, the vacuum pipe will consist of three sectors: a central one of about 20 m and two other sections approximately 4990 m long. In the next chapters, we neglect the shortest sector and we consider the vacuum pipe sectorised only in its midpoint.

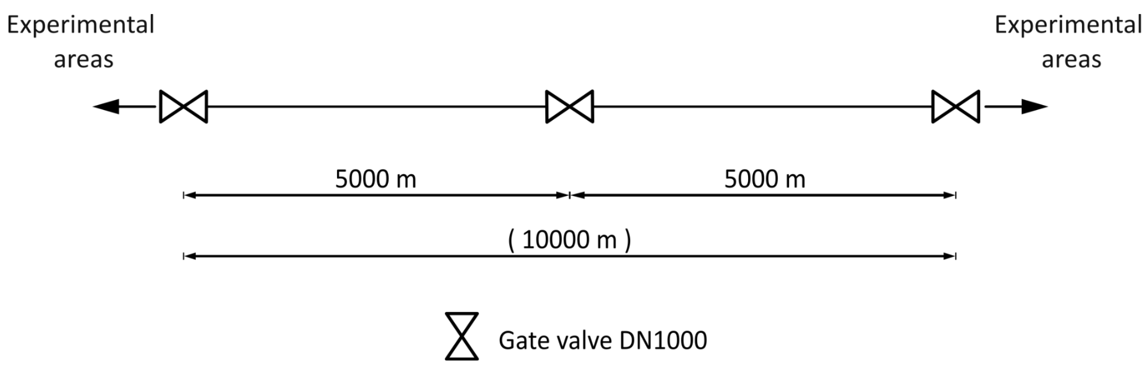


Fig 17. *Sectorisation of a 10 km arm.*

6.2 Pumping ports

The vacuum pipe includes pumping modules with DN200 ConFlat (CF) flanged pumping ports, spaced 500 m apart, for operational pumping and diagnostics. A separate pumping port, used only for rough pumping, is located 50 m from the gate valves near the experimental areas. Each pumping port must be equipped with an FKM-sealed, manually or electro-pneumatically actuated gate valve, allowing pumps or instruments with an intolerable leak to be isolated safely. This setup enables repairs or replacements of faulty components without venting an entire vacuum sector. To minimize impact on the outgassing rate budget, the valves' body and gate are vacuum-fired prior to assembly.

6.3 Vacuum layouts

The vacuum layout of an ET vacuum pipe sector is optimized for pumpdown and each commissioning phase according to the needs and requirements.

6.3.1 Layout during rough pumping

In the pumpdown phase, which involves evacuating the atmospheric gas, the layout is shown in Fig. 18. This evacuation is carried out using two commercial mobile rough pumping groups positioned at 1500 m from the vacuum sector extremities, comprising a 90 m^3/h roots pump. The use of such pump size, will guarantee no drag and lift of dust particulate during the evacuation phase. Given the beamline arrangement in the tunnel, the mobile rough pumping group must be connected to the tube via a flexible metallic hose (see Fig. 19). The required instrumentation (a Pirani gauge) and venting tools for this commissioning phase can be positioned on a fitting between the flexible hose and the pumping port.

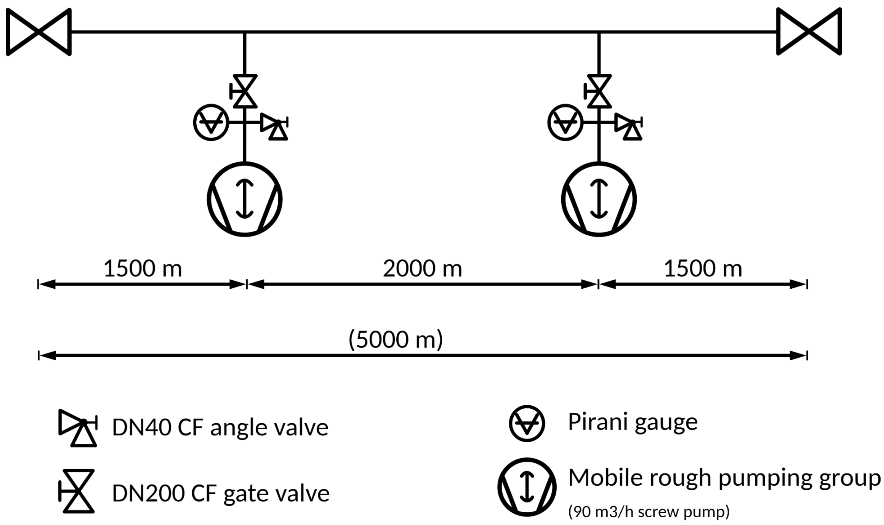


Fig. 18: *Layout of the mobile rough vacuum pumping*

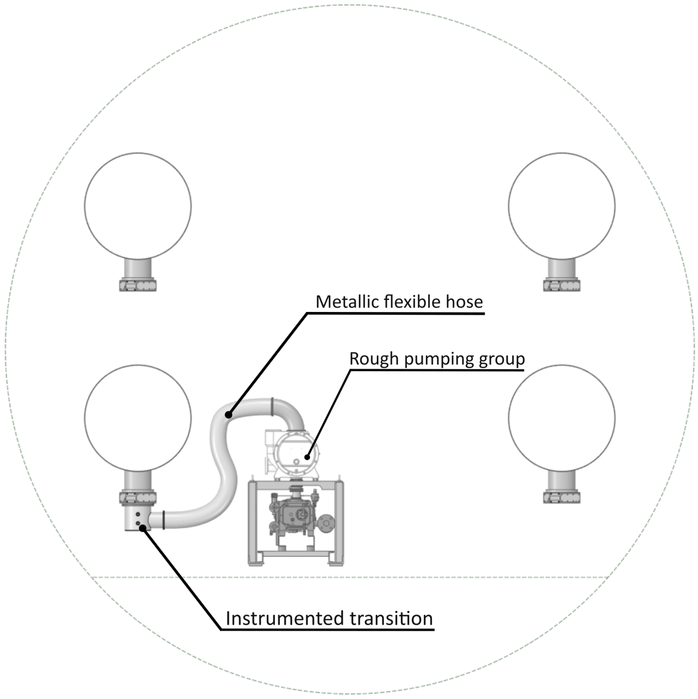


Fig. 19: *Schematic of the mobile rough vacuum pumping group connection to the pumping ports. The size and configuration of the rough pumping group should be intended as an example.*

6.3.2 Layout during intermediate pumping

Once rough pumps reach their intrinsic pressure limit, they are valved off and mobile turbomolecular pumping groups enable the system to achieve high and ultrahigh vacuum regimes. Each mobile pumping group comprises an air-cooled 800 l/s Maglev turbomolecular pump (TMP) backed by an 11 l/s dry roots pump, with groups spaced 2000 m apart, as shown in Fig. 20. To maximize pumping speed, the TMPs will be mounted on the pumping port via a short, instrumented DN200–DN40 CF cross reducer. A metallic hose connects the TMP exhaust port to the backing pump.

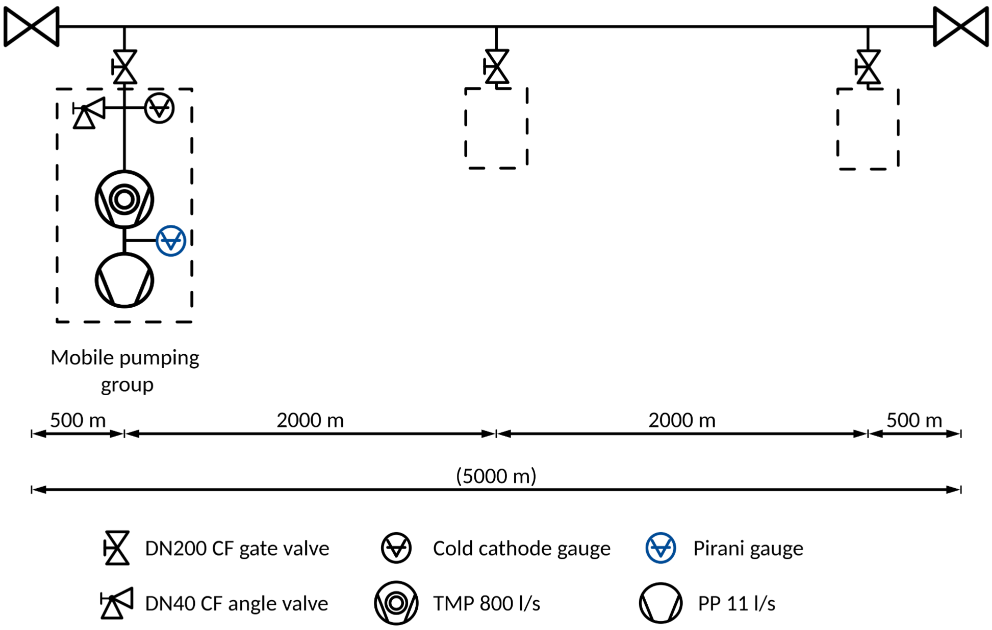


Fig. 20: *Vacuum layout during intermediate vacuum pumping.*

6.3.3 UHV vacuum layout

To ensure vibration-free operation, low power consumption, and high reliability, UHV pumping is primarily achieved using non-evaporable getter (NEG) pumps, supported by ancillary sputter ion pumping. The UHV pumping units, spaced 1000 m apart, consist mainly of a DN200 CF custom chamber housing a 2000 l/s (nominal H_2 pumping speed) NEG cartridge and a 300 l/s (N_2-saturated nominal N_2 pumping speed) sputter ion pump (SIP) (see Fig. 21). Each pumping module is also equipped with two DN40 CF ports designed for a Residual Gas Analyzer (RGA) for gas composition monitoring, a Bayard-Alpert gauge (BA) for total pressure measurements, and a DN40 CF all-metal angle valve for controlled venting equipped with a particle filter and a protection pinch-off.

If all ion pumps are off except those at the extremities, the Ar partial pressure profile due to air leak would be linear from the point of the leak to the extremities and the RGAs should be able to localize the position of the leak quite accurately if they are calibrated. In this respect, the installation of Ar and He calibrated leaks would be an option.

As shown in Fig. 22, pumps and instruments are positioned within the space between the two vacuum pipes, staying within the tube's lateral limits. This arrangement ensures that no pump or instrument protrudes into the passageway, thereby minimizing the risk of accidental collisions.

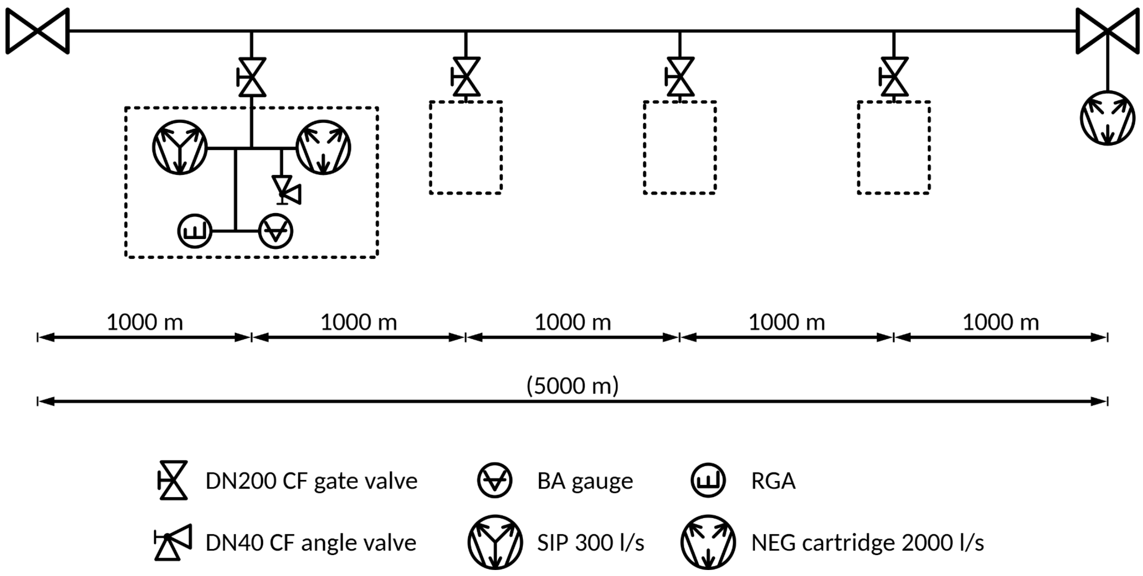


Fig. 21 - *UHV vacuum layout*

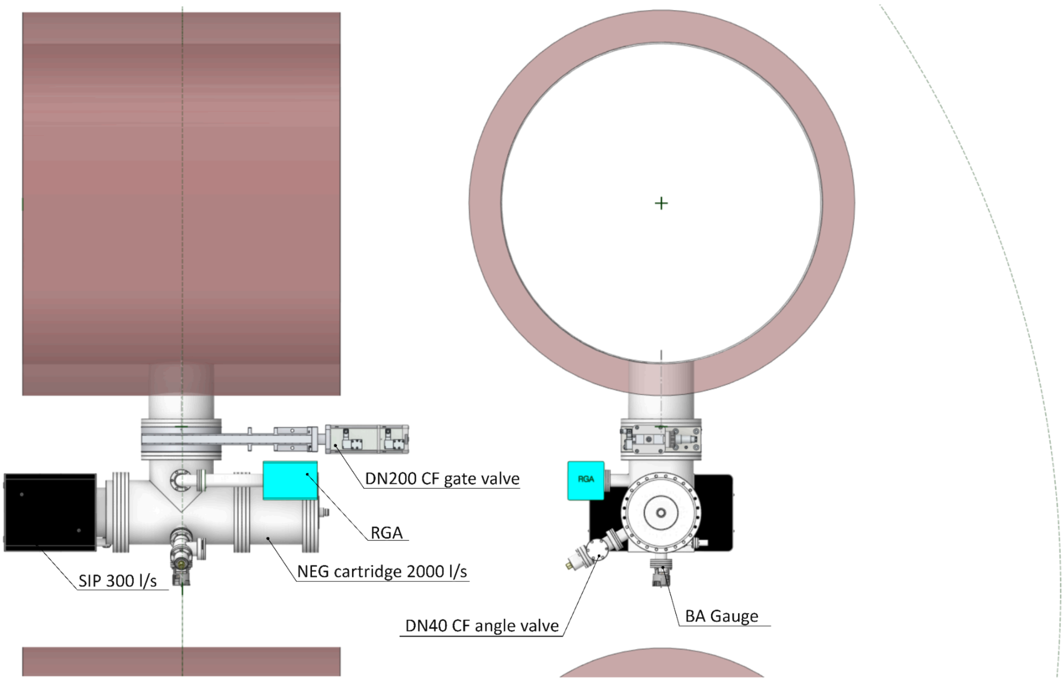


Fig. 22: *3D schematic of an UHV pumping group assembly. The arrangement shown is one of many possible.*

7. **Installation**

In this chapter, we assume that the 15-meter-long tube units are prepared and ready for entry into the tunnel. These units have been cleaned according to the required standards, and the dust environment is continuously monitored post-cleaning to maintain optimal conditions. Additionally, a comprehensive quality assurance (QA) protocol is in place, tracking each tube unit from the raw material stage through to its final protection before arrival at the tunnel.

The tunnel, with a 6.5-meter internal diameter, is initially empty, and access is limited to two entrances located at the extremities, which are connected through the experimental caverns. This chapter outlines the installation phase of the tube units in the layout presented before, including the steps taken to ensure quality control throughout the process. The installation and operation of mobile pumping groups, along with the pumpdown procedures, are detailed in Chapter 10 on 'Vacuum Commissioning’.

7.1 Space requirement for installation

The room occupied by the vacuum pipe system is shown in Fig. 2 of Chapter 4. The space limits are defined by the vacuum pipes’ supports, leaving about a 2 m-wide pathway at the center of the tunnel. The welding process requires at least 50 cm of clearance around the tubes to install tools and the welding robot in the assembly area. This space is also necessary for conducting helium leak detection. In the position of assembly, the space between the tubes and the nearer tunnel’s wall is occupied by customized laminar airflow units.

7.2 General description of the installation procedure

After cleaning, the tube units are protected against recontamination and moved to storage areas before being transported into the tunnel. Prior to the installation sequence, all dust-generating activities must be completed. This includes drilling the concrete walls to secure cable trays, electrical sockets, and vacuum pipe supports. Before installation, the tunnel floor is cleaned to minimize airborne dust during personnel movement and material transport. Before the installation of the vacuum pipes, ventilation ducts, cable trays and any other service occupying space in the tunnel must be completed.

The vacuum pipe installation begins at the center of the tunnel, either along one side of the triangle or a branch of the L-shaped configuration. The main assumptions made here are:

- The tube units are 15 meters long.
- Two connections are made per working day per team, resulting in 10 connections per week per team, on average.
- Two teams work simultaneously on one side of the tunnel, moving in opposite directions.
- Installation and testing take place only during standard working hours (8 hours per day).
- Transport of tube units and supports in the tunnels is carried out outside of working hours.

In the triangle configuration, each team will need to travel a maximum of 5 km in the tunnel to reach the working point. The transport of personnel and materials will occur in an empty tunnel, and the estimated maximum travel time for personnel from the experimental cavern (the point of underground access) to the installation front is 15 minutes.

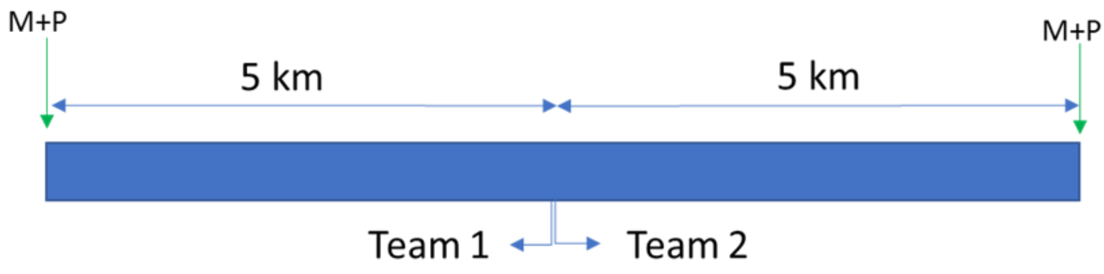


Fig. 23: *Schematic view of the tunnel (triangle version of ET) with the two installation fronts starting from the center. Personnel (P) and material (M) enter the tunnel from the extremities.*

This results in approximately 670 connections per vacuum pipe (i.e., 2,680 assemblies per tunnel side, and 8,040 for the entire triangle). Based on the assumptions above, it will take the two teams around 134 weeks to complete the installation of the four vacuum pipes for one side of the triangle. Considering a learning phase with a progressive increase in welding rate, it is reasonable to estimate that the installation of one side—and by extension, the entire triangle—will take approximately three years, assuming parallel activities on each side.

In this scenario, six welding teams are required. The installation rate is 12 tube units per day, which defines the minimum number of tube units that must be available daily to ensure continuous installation.

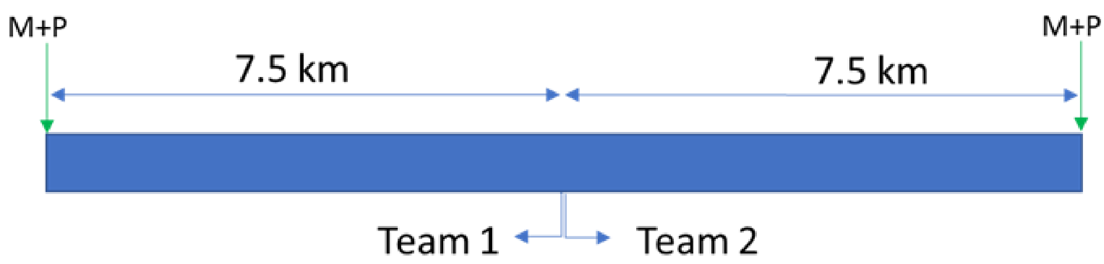


Fig. 24: *Schematic view of the tunnel (L version of ET) with the two installation fronts starting from the center. Personnel (P) and material (M) enter the tunnel from the extremities.*

In the L configuration, which spans two different sites, the same rationale is applied to each branch of the L. Teams will have to travel a maximum of 7.5 km to reach the working front. If installation begins at the center of the L's branch, the transport of personnel occurs in an empty tunnel, with a maximum travel time of 20-25 minutes to the installation front.

As the total length of the vacuum pipes remains the same (i.e., 120 km), the number of connections also remains unchanged. With four teams working per site (two on each side of the L), the installation of a complete interferometer would take around two years. If installation occurs simultaneously at both sites, eight teams will be required to complete the installation within two years. In this scenario, 16 tube units must be available each working day.

7.3 Limitation and assessment of recontamination by dust and hydrocarbons

The tube units are assembled as shown in Chapter 4. The protection at the extremities, the positioning of the tubes, and the insertion of the sleeve—when this solution is chosen—are carried out under a laminar airflow generated by customized wall modules. The technical personnel responsible for the installation are trained in handling UHV components in controlled dust environments. No dust-generating activities or mechanical exhaust systems are permitted during the assembly phase.

The effectiveness of dust and hydrocarbon contamination control is monitored using witness samples clipped to the extremities of all tube units. These samples are removed just before assembly, stored in appropriate containers, and later tested for dust analysis and surface composition.

7.4 Installation of pumping modules

The pumping modules are assembled at the positions defined in Chapter 6, i.e. roughly every 500 m. During transport and installation in the tunnel, all flanges are tightly sealed to prevent recontamination. Pumps, gauges, and RGAs are mounted on the pumping modules before the installation of the thermal insulation wrapping. A laminar airflow is generated by customized wall modules at the installation site.

8. Bakeout: thermal insulation, electrical configuration and procedure

Bakeout is a critical step in vacuum conditioning, primarily aimed to accelerate water vapor outgassing by heating the external surface of evacuated vacuum pipes. The temperature and duration of this in-situ thermal treatment are chosen to achieve the required ultimate pressure once the vacuum pipe returns to room temperature. Bakeout temperature is a significant factor in the mechanical design, as it determines the maximum thermal expansion of the tube, which, in turn, influences the quantity and dimensions of the bellows in the smooth pipe design. Both the bakeout temperature and duration impact the electrical energy consumption required for heating. For this TDR, we assume a bakeout cycle of 150°C for one week, providing sufficient time at the target temperature, with controlled temperature ramp-up and ramp-down phases.

8.1 Direct Joule-effect bakeout and thermal insulation material.

Given the dimensions of the vacuum pipe, the bakeout is conducted through direct Joule heating. The electrical resistivity of AISI 441 at the bakeout temperature is comparable to that of AISI 316L, with $\rho(150°C) = 8 \times 10^{-7}\ \Omega$ m [18]. For a smooth vacuum pipe with a 4 mm wall thickness and an internal diameter of 1 m, the resistance during bakeout is R(150°C) = $6.4 \times 10^{-5}\ \Omega\ m^{-1}$.

The thermal insulation considered at this stage of the TDR is a 10 cm layer of mineral wool with high fire resistance and a thermal conductivity of λ(150°C)=0.05 W $m^{-1}K^{-1}$. This choice serves only as a basis for thermal calculations, with no considerations regarding dust generation yet. To address this point together with fire resistance, an alternative solution based on cork derivatives is presently under study.

Assuming a conservative convection coefficient of h = 5 W $m^{-2}K^{-1}$ (natural convection in calm air) and an ambient temperature of 20°C, a current of 1800 A is required to heat the vacuum pipe sections to 150°C. If a 1.5 mm thick corrugated profile is used instead, the required current decreases to 1100 A.

For both vacuum pipe profiles, the thermal power required, based on the insulation's performance and thickness, is approximately 210 W/m. In the event of simultaneous bakeout of two vacuum sectors, the maximum tunnel temperature at the end of the heating plateau will reach 23°C (see Fig. 25).

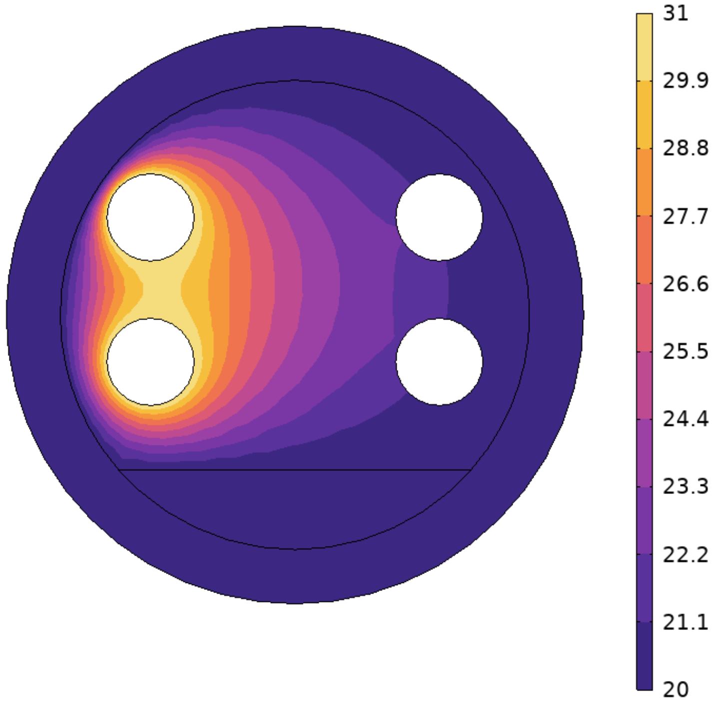


Fig. 25 - *CFD simulated temperature distribution after 7 days of simultaneous bakeout at 150°C of two ET vacuum sectors. The average temperature in the tunnel is 23°C, (tunnel's walls at 20°C).*

8.2 Electrical circuit configuration

An efficient bakeout procedure involves simultaneously heating both superposed vacuum pipes, using each pipe as part of the forward and return current circuit. This configuration eliminates the need for costly high-section return conductors. High-section DC cables are necessary to connect the positive and negative poles of the high-current power supply to the two pipes. Additional connections using the same DC cable section must be made at earthing points to close the circuit with minimal resistance, preventing high currents from flowing through the earth circuit. To ensure proper connection, busbars should be available at defined positions on the chambers.

For a current of 1.8 kA, a copper section of 1000 mm² is recommended, while 2000 mm² is required for 3.6 kA connections. Figure 26 illustrates the electrical connections between the high-current power supplies and the two superposed vacuum pipes. The voltage drop along the vacuum pipe is a limiting factor concerning both electrical safety and available power.

In terms of electrical safety, international standards, such as EN 50191, specify that DC voltages under 60 VDC are safe in dry conditions. Therefore, without special measures to prevent direct contact with the vacuum pipes, the voltage drop must not exceed this limit. This voltage drop also defines the maximum safe circuit length. Given a resistance of 5.37×10^{-5} Ω/m and a current of 1.8 kADC, the maximum circuit length to remain under 60 VDC is 620 m. If the power supply is connected midway between two earthing points, the vacuum pipe should be earthed every 1240 m. In this configuration, the voltage of the upper vacuum pipe will reach +60 VDC relative to earth, and the lower pipe -60 VDC.

The power supply must deliver 3.6 kADC at 120 VDC, equivalent to 432 kW. For a complete 5 km vacuum sector, four parallel power supplies are needed, totaling 1.7 MW. However, 432 kW industrial DC power supplies are uncommon. Lower-power units are more readily available and offer the advantages of flexibility and spare part availability. Reducing the power per supply reduces the voltage drop and, thus, the circuit length. Although more units are required, this allows for better distribution of AC power along the tunnel and better temperature control due to smaller circuits. The overall power requirement remains at 1.7 MW, with an expected efficiency of 0.9 and a power factor close to 1, leading to a total power draw of about 1.9 MW from the grid or auxiliary systems. These high-current power supplies also require high-power 3-phase sockets.

During bakeout, vacuum equipment located between two earthing points must be isolated either by an isolation transformer or complete disconnection to prevent high currents from flowing through earth connections. Special attention must be paid to the pumping groups.

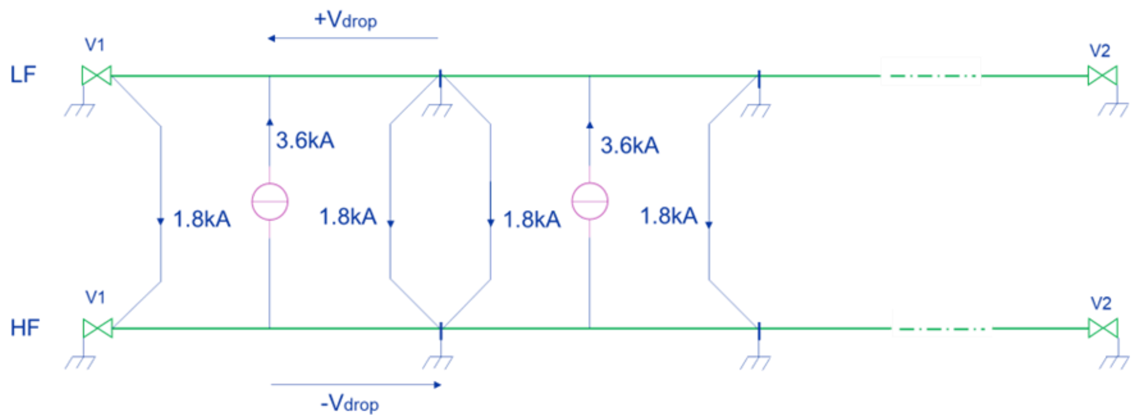


Fig. 26: *Electrical connections of the high current power supplies to the chambers.*

8.3 Temperature measurement

Temperature monitoring is essential for controlling bakeout conditions. Temperature sensors should be installed in representative positions, considering anticipated hot and cold spots. With four sensors placed at four clock positions every 50 m, each vacuum sector will require 400 sensors, amounting to a total of 9600 sensors for all of ET's vacuum pipes.

Temperature data acquisition will be managed through a distributed architecture with PLCs positioned at each sector valve. The PLC responsible for temperature control is connected to the high-current power supply, with control achieved through either digital/analog input/output signals or a fieldbus interface (e.g., Profibus, Profinet, Modbus, etc.).

8.4 Standard bakeout (heaters)

The sector valves and all the vacuum components installed on the pumping ports, including sputter ion pumps and gauges are heated in the range 150°C to 350 °C for 1 week using standard heaters (heating jackets, bands, wires and collars). Mobile bake out racks are placed at these locations during the bake out process. Each mobile bakeout rack provides regulated power and temperature sensors reading for temperature control. During the bakeout process, each mobile bakeout rack will be connected to the local field bus provided by the PLC. This allows the full remote control and monitoring of the bakeout process, including data logging.

9. Vacuum control system

9.1 Vacuum control architecture

The vacuum control architecture is closely related to the vacuum layout. As shown in Fig. 17, each 10 km line has 3 DN1000 gate valves, one at each end and one in the middle, creating two vacuum sectors (neglecting the suggested short sector generated by two facing sector valves at midway). The DN1000 gate valve in the middle will also be equipped with a NEG pump (2000 l/s).

Each vacuum sector will have 3 pumping ports, separated by 2000m, equipped with a DN200 gate valve dedicated to the connection of mobile turbomolecular pumping groups (see Fig. 20). In addition, each vacuum sector has 4 other pumping ports, separated by 1000 m, equipped with a DN200 gate valve dedicated to operational pumping and vacuum instrumentation, including a NEG pump (2000 l/s), a SIP (300 l/s), a B-A gauge, an RGA and a DN40 angle valve (see Fig. 21).

Tab. 5 summarizes all the permanent operational vacuum equipment that needs to be controlled for the whole vacuum pipe systems based on the proposed vacuum layout.

Equipment	Type	Number
Gate valve	DN1000	36
Gate valve	DN200	168
Angle valve	DN40	96
Sputter Ion Pump	300 l/s	96
NEG pump	2000 l/s	108
Gauge	Bayard-Alpert	96
Residual Gas Analyser	-	96

Tab. 5: *Total number of permanent vacuum components for the whole vacuum pipe system, considering 7 pumping ports per sector (3 for intermediate pumping, 4 for permanent pumping), 3 DN1000 gate valves per line, and one NEG pump on the central DN1000 gate valve.*

9.2 Racks and controllers

Racks containing controllers are situated in the tunnel inside the frame of the vacuum pipe system, managing vacuum equipment. Each rack, with respect to its position, controls the superposed vacuum pipes on both the left and right sides. Near each DN1000 gate valve position, a rack includes a PLC to control the DN1000 gate valves and to acquire temperature sensor data. Close to each permanent pumping set, a rack is equipped with a PLC, a BA four-channel controller, and a SIP four-channel controller, which controls four BA gauges, four SIPs, and four DN200 gate valves, as well as collect temperature sensor readings. Near each pumping port designated for mobile turbomolecular pumping groups, a rack integrates a PLC to control four DN200 gate valves and to acquire temperature sensor data. Residual Gas Analyzers (RGAs) are directly connected via Ethernet, while BA and SIP controllers connect to the local fieldbus provided by the PLC, dedicated to permanent equipment. Temperature sensors are distributed and connected to various PLCs.

To standardize setup, each rack measures 14U/19” (60 cm high), providing ample space for additional controllers, equipment, and patch panels, primarily for temperature sensors. Each PLC is equipped with a local fieldbus dedicated to mobile equipment, including power supplies for NEG activation, TMP groups, the standard bakeout rack, and the high-current power supply for bakeout. This setup allows full remote control, monitoring, and data logging of the process.

For NEG activation, NEG pumps are powered by a mobile rack with a dedicated power supply for optimal power and temperature control. Mobile pumping groups are used for primary and turbomolecular pumping and connect at designated pumping port positions. If infrastructure supports a wireless network (e.g., 4G LTE), mobile equipment can connect wirelessly.

Each rack position requires a 230VAC/10A power outlet for the controllers, a 230VAC/16A power socket for local NEG pump activation and turbomolecular pumping groups, and a three-phase 32A power socket for the standard bakeout rack. An Ethernet outlet is also needed for PLC and RGA connections. Tab. 6 summarizes the permanent controllers, racks and cables required for the entire ET vacuum system.

Equipment	**Type**	**Number**
BA controller	4 channels, 3U	24
SIP controller	4 channels, 4U	24
PLC	19’’/3U	51
Rack	19’’/14U	51
BA cable	Triax Low current (collector)	96
SIP cable	Coaxial high voltage	96
DN1000 gate valve cable	Multicore low voltage	36
DN200 gate valve cable	Multicore low voltage	168
Temperature cable	Thermocouple/PT100	9600

Tab. 6 - *Summary of the total number of permanent controllers, racks and signal cables.*

9.3 SCADA

All controllers and mobile equipment permanently or temporarily installed in the tunnel will be remotely controlled and monitored by a SCADA system. The SCADA presents data to operators using graphical user interfaces (GUI) to check the process, react to alarms and interact with the equipment. It also archives historical data so that operators can review what has happened in the past. All PLCs and RGA will be connected to the Technical Ethernet network, from which the SCADA server is connected. Operators can connect to the SCADA directly from the Technical Network, or Personal Computers on the General Purpose Network (GPN) via terminal servers. There are several SCADA software packages on the market. Most scientific installations use EPICS (Experimental Physics and Industrial Control System) or Tango. Industrial standards include systems based on WinCC-OA (Open Architecture) from Siemens. Fig. 27 shows a possible control architecture from the field device layer to the SCADA layer.

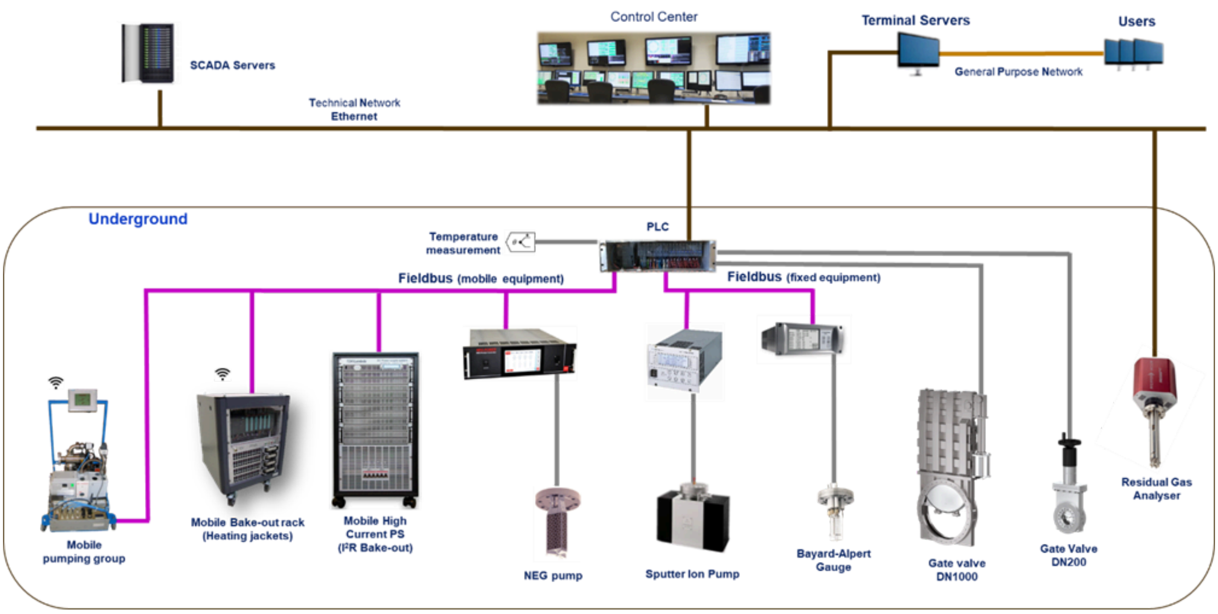


Fig. 27: *Possible vacuum control architecture.*

10. Vacuum commissioning

The commissioning of the ET's vacuum pipe system is executed sector by sector. During this phase, the central sector valve must remain closed until the neighboring sector is conditioned to the UHV regime. Similarly, the sector valves at the extremities of the ET's arms must stay closed until vacuum conditioning in both areas is complete. All pumping groups and necessary fittings should be installed on the pumping modules in a clean condition compatible with the ISO-6 standard.

10.1 Rough vacuum regime

The evacuation of air, performed with the pumping group described in Sec. 6.3.1, brings the sector from atmospheric pressure to the low 10^{-1} mbar range in about 12 days (see Fig. 28).

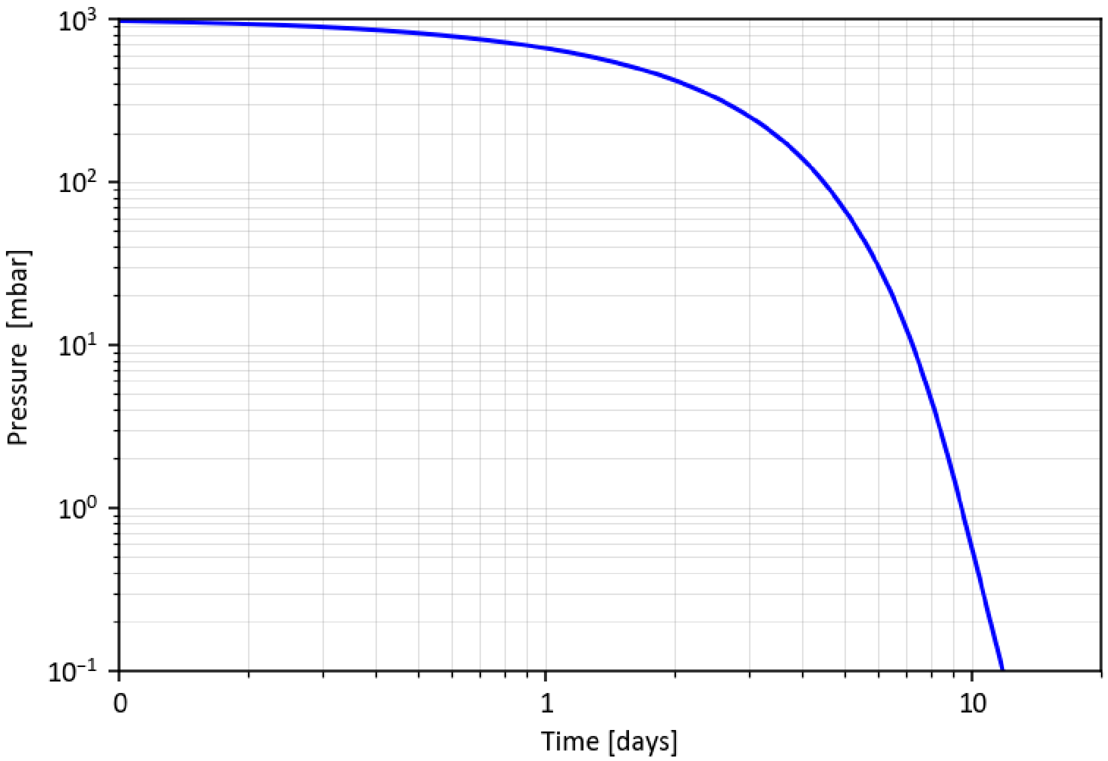


Fig.28: *Analytical rough-pumping curve of an ET sector from atmospheric pressure to 1 x 10^{-1} mbar.*

10.2 Intermediate vacuum regime

Once pressures in the 10^{-1} mbar range are attained, the mobile turbomolecular pumping groups are turned on, and the rough pumping group is valved off, vented to air, dismounted, and installed on another vacuum pipe. The sector is then pumped down for a few days before the bakeout process begins. During this pumping period, global leak detection and the installation of the thermal insulation are carried out in parallel. If no leaks are detected, the bakeout can commence when the pressure is below 10^{-5} mbar. RGA spectra can be recorded before the start of the bakeout to check the residual gas composition, particularly for the anomalous presence of hydrocarbon species. All instrumentation should be turned off when the temperature ramp begins, except the pressure gauges in the TMP pumping groups.

As already mentioned, the bakeout is planned to occur at 150°C for 7 days (see Fig. 29). The ramp-up and cooldown should each take at least 24 hours to ensure uniform temperature distribution and avoid abrupt thermal expansions that could lead to leaks. The NEG pumps are activated two days after the beginning of the bakeout and reconditioned at the end of the highest temperature plateau. At this time, the SIPs, BA gauges, and RGAs undergo the standard degassing procedure. Prior to cooldown, all instrumentation and pumps are operational.

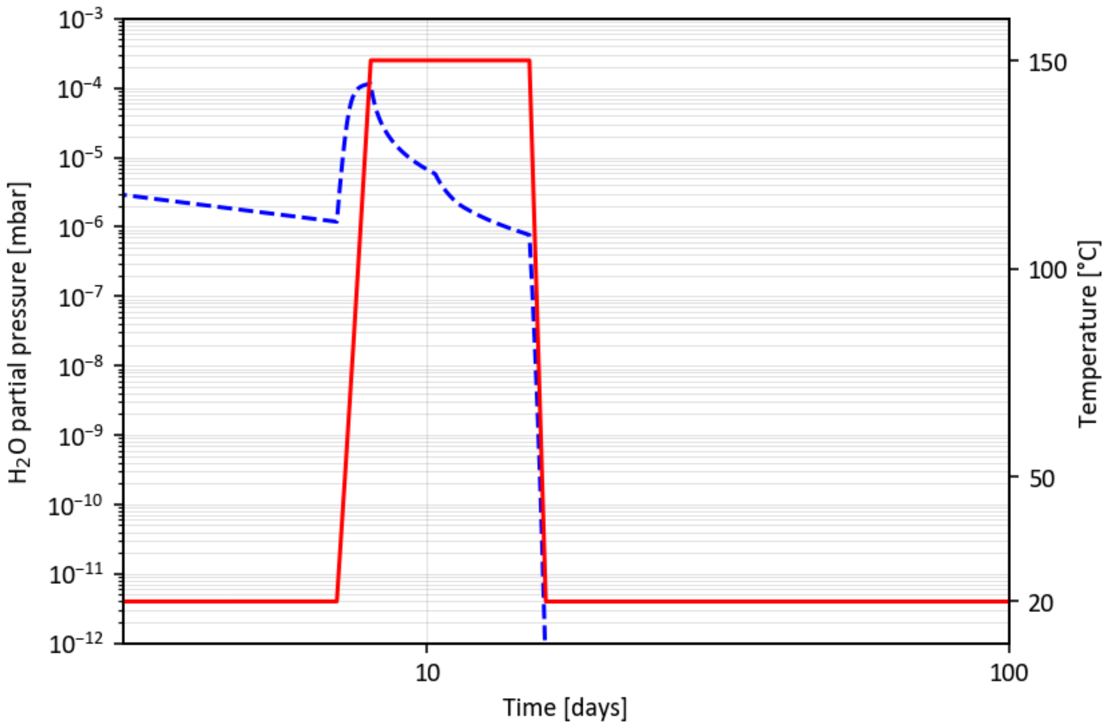


Fig.29: *Simulated pressure during bakeout of an ET vacuum sector (dashed line). Maximum pressure reached between two NEG pumps spaced 1000 m; solid line: temperature profile.*

10.3 UHV regime

Once the vacuum sector is brought down to room temperature, the gate valves at the location where the mobile turbomolecular pumping group is connected are closed, allowing the pumping groups to be safely vented, removed, and installed elsewhere. The now-free ports are sealed with DN200 CF blank flanges and pinched-off in ISO-6 cleanroom conditions. Before the delivery of the vacuum sector, 48 hours after the end of the bakeout, the gas composition and ultimate pressures are checked using the dedicated instrumentation.

Considering the specific outgassing rates of AISI 441 as reported in Tab. 7 and the proposed layout, the upper limits of the partial pressures in the vacuum sectors have been calculated and are reported in Tab. 8; the pressure profile along the vacuum pipe is plotted in Fig. 30.

Gas	Specific outgassing rate [mbar l s^{-1} cm^{-2}]
H_2	< 1.0 x 10^{-15}
CH_4	< 1.0 x 10^{-17}
CO	< 3.7 x 10^{-17}
CO_2	< 1.4 x 10^{-17}

Tab. 7: *Experimentally measured specific outgassing rates from AISI 441 specimens after a 2-day bakeout at 150°C. The values represent upper limits, as the measurements were constrained by the sensitivity of the system. [Data currently in the process of being published]*

Gas	**Max pressure [mbar]**
H_2	6.0 x 10^{-11}
CH_4	2.2 x 10^{-12}
H_2O	2.6 x 10^{-13}
CO	2.9 x 10^{-12}
CO_2	1.3 x 10^{-12}

Tab. 8; *Maximum ultimate partial pressures in the ET beam pipe after a 7-day bakeout at 150°C, following the layout presented in section 6.3.3. The ultimate pressures reported should be regarded as upper limits.*

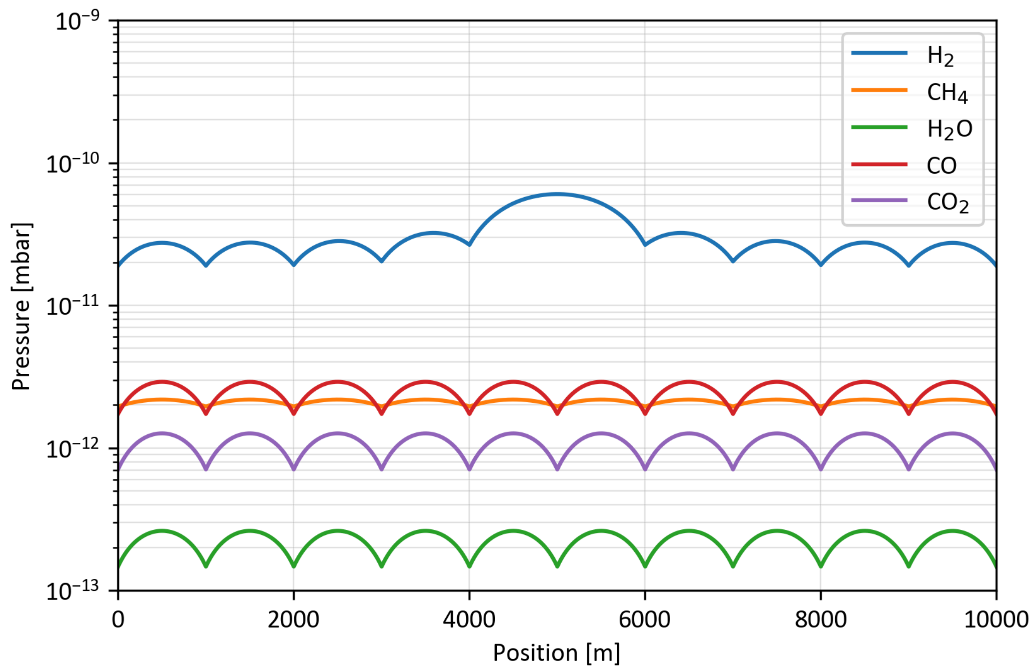


Fig. 30: *Distribution of partial pressures in the ET vacuum pipe after a 7-day bakeout at 150°C, following the layout presented in Section 6.3.3. The ultimate pressures depicted should be regarded as upper limits. The bulge of the H_2 pressure profile at km 5 is due to the outgassing rate of the sector valve (the total outgassing rate reported in literature is given in H_2 equivalent) [14].*

11. Vacuum operation and maintenance

To ensure the correct functioning of the ET's vacuum components over their expected lifespan, yearly maintenance must be performed. The pumping port's gate valve should be opened and closed, and the mechanism maintained to preserve the gate's isolation functionality. Similar service must be performed on the sector valves, which should be closed during the yearly technical stops. This operation, conducted with the SIPs off, allows the accumulation of gas species that are not pumped by NEG, notably Ar; their pressure rise monitored by the RGAs can be used to check for the presence of leaks undetectable during operation.

In the event of a failure of an instrument or pump, the pumping group valve should be closed, and the pumping module vented with a ppb dry nitrogen flow. Air injection should be performed via a filter cartridge to avoid the introduction of unwanted particulates into the pumping module. Component replacements and re-installation must be done in an ISO-6 compatible environment while continuing the injection of ultradry nitrogen. Pumpdown is ensured by a pre-baked mobile TMP group via the DN40 CF angle valve. This procedure should avoid the need for an additional local bakeout of the pumping module; if not, local rebaking is necessary. Prior to opening the pumping port gate valve, the quality of the vacuum should be assessed by RGA spectra.

12. Quality assurance plan

The Quality Assurance (QA) plan is essential for ET, notably for its vacuum pipe system. The primary goal of a QA plan is to ensure that every component and process meets strict quality standards from material selection to the final pressure.

Most of the steps in the QA have been already introduced in the previous chapters. Here, the purpose is to give a global picture that underlines the adopted strategy.

The first critical element in the QA process is the control of the raw materials used for the construction of the beampipes. This comprises the measurement of material composition, grain size, distribution of inclusions, surface state, mechanical properties, and outgassing rates all of which affect the final performance. Ensuring that materials meet specification standards helps minimize the risk of mechanical failure, corrosion issues over time, vacuum leaks at welding joints and unduly high ultimate pressure. This control is further supported by material certification processes, ensuring that only high-quality materials are used. This check, done before issuing the order, is repeated at each delivery batch.

Welding is another crucial aspect of the construction process, especially for components that must be vacuum-tight for more than 50 years. To guarantee the quality of the welds, the QA plan includes several controls:

- Preliminary radiography and metallurgical analysis are conducted on prototypes to validate the welding protocol and the competence of the welders.
- On-line monitoring of the welding joint to detect drifts in the joints' quality as early as possible. This control is applied to the welding of the whole set of tube units.
- During the pre-series phase, the welded tube units undergo radiography and full leak detection to identify any potential weaknesses. The number of tubes in the pre-series should be around 100 elements to eliminate systematic errors.
- In the series phase, sampling is done for both radiography and leak detection to avoid production deviations. A typical sampling would be one tube unit per batch of 60, which is roughly the number of tube units required per week to feed the installation in the triangle option. This sampling amounts to roughly 130 tests in the period of production.

Once components are fabricated, cleaning is a critical step to prevent contamination. Several QA checks are involved:

- FTIR and XPS assessments are performed on witness samples to ensure that the cleaning process complies with specifications. These techniques are also used during the series production to sample the quality of the cleaned surfaces. FTIR is also applied directly to the cleaned tube units. During the preseries, the cleaning of all tube units is qualified, while during the series production sampling is applied.

- Components are dried under laminar airflow that complies with ISO6 standards, preventing dust particles from settling on the inner tube unit surfaces. Dust-tight protection is used for storage and transport to protect against recontamination. Dedicated samples are installed inside the tube units to qualify and quantify the concentration of dust particles on the surface by optical techniques and EDX.

During the pre-series phase, the outgassing rate of a few tube elements is measured (less than 10). To perform such a test, endcaps have to be welded on both tube's extremities. The purpose of this measurement is to identify virtual leaks generated by porosities in the welds' joints.

Each bellow, installed every second tube unit, and pumping module (about 250, installed every 500 m) undergo a QA similar to that of the vacuum units.

During installation, critical quality controls continue to be implemented. For instance:

- Witness samples are extracted just before welding of tube units to check for dust and surface contamination.
- Leak detection is performed after every installation of a pumping module.
- A global leak test is conducted to check each complete vacuum sector (5 km length) for any potential issues before it is fully operational.

Following the bakeout process of a vacuum sector, final performance testing is conducted:

- The ultimate pressure is measured to ensure the system meets the required vacuum standards.
- A residual gas analysis is performed to detect any remaining contaminants that could interfere with telescope operations.

The QA plan for the Einstein Telescope (ET) must be recorded in a dedicated database to ensure that every stage of production and installation is meticulously documented, reported, and approved. This database serves as a central repository for all quality control data, from material selection to final system testing, providing traceability and accountability throughout the project. Each component within the system is assigned a unique identification code that allows for precise tracking of its production history, including any potential issues or deviations from the required standards.

12.1 Non-conformities and their treatment

In any large-scale engineering project non-conformities (i.e., cases where a component or process does not meet specified standards) are an unavoidable part of the production process and they must be identified, documented, and tracked in the dedicated QA database.

When a non-conformity is identified, it should trigger a formal process that follows key steps:

1. Identification and classification of non-conformity.
   Non-conformities are first categorized based on their severity and potential impact on ET's performance. Minor non-conformities might involve small deviations from design specifications that do not significantly affect the component's functionality, for example, small virtual leaks or small deviation in surface chemical composition. Major non-conformities could compromise the performance of ET and require immediate attention, and they could require an immediate stop of the production or installation phases; this could be the case of important vacuum leaks or hydrocarbon contamination.
2. Documentation in the QA Database.
   Once a non-conformity is detected, it is logged in the QA database along with detailed information about the affected component or process, the nature of the deviation, and any initial observations. This documentation is crucial for maintaining traceability and understanding the issue. The systematic documentation of non-conformities and their resolution in the QA database provides a valuable record that can be used to improve future production cycles and upgrades of ET.
3. Evaluation and Decision-Making.
   After the non-conformity is documented, it undergoes a thorough evaluation to assess its impact. This evaluation is used to decide the appropriate action, which generally falls into one of two categories:
   - Rejection and disposal: If the non-conformity is severe and cannot be corrected (e.g., unacceptable presence of inclusions or irreversible defect in welds), the part is rejected. This decision is typically made when dealing with raw materials out of specifications or when reworking or adjusting components would pose too great a risk, either in terms of performance or cost-efficiency.
   - Adjustment and rework protocols: In cases where the non-conformity can be corrected, an adjustment protocol is applied. These protocols must be clearly defined before production begins and may involve additional machining, cleaning, or re-welding.
4. Root cause analysis and preventive measures.
   In cases of recurring or significant non-conformities, a root cause analysis is conducted to identify the underlying issue responsible for the deviations. For example, this concerns systematic leaks during the pre-series, residual contamination after cleaning, or excessive presence of dust on the witness samples. Understanding the root cause is essential for preventing similar non-conformities in subsequent phases. Once the cause is determined, corrective and preventive actions are implemented to modify the production or installation processes. These actions are recorded in the QA database to ensure that future production runs are adjusted to prevent the recurrence of the issue.

12.2 Procedure for vacuum leak detection

Among all QA tests, leak detection is the most critical one due to its significant personnel requirements, and impact on production and installation schedule. The best way to prevent leaks is to integrate engineering practices by design that are known to reduce the risk of tightness failure. The experience gained during the fabrication of vacuum pipes for existing GWT [15] and accelerators suggests that vacuum leaks are avoidable if material quality and welding processes are appropriate and continuously monitored by experts.

The leak detection process for the ET consists of three steps. The first concerns the tube units and pumping modules, for which pre-cleaning might be required to conduct a reliable test. The second step applies to a tube string between two consecutive pumping modules (i.e., about 500 meters of vacuum pipe composed of 33 tube units). Finally, a whole 5-kilometer vacuum sector must be tested.

In the first step, leaks may occur in the longitudinal welds (spiral or straight) of the tube units and pumping modules. Material defects such as through-wall porosity, inclusions, or damage could also result in leaks. In the second step, circumferential welds are a potential failure point, while degradation due to transport and corrosion during the storage period is another potential source of issues. During the global test, vacuum pumps and instrumentation are additional potential locations for failure.

Based on previous experiences [19], which indicate a maximum failure rate in the order of one per thousand, the maximum expected number of leaks in ET vacuum pipes should be on the order of ten to twenty, assuming a total of around 15,000 welds. The cost of repairing this number of components must be compared to that of performing a systematic 100% leak check on all components, including approximately 8,000 tube units. The leak detection strategy proposed in the previous chapter is a tradeoff aimed to be as cost-effective as possible.

Another important aspect of leak detection is the response time of the vacuum system to helium signals. When a tube string of 33 tube units is tested, the characteristic response time (Volume/Pumping speed) is 11 minutes if the applied effective pumping speed is 600 l/s. This means that testing a full tube string would take at least a full working day. If a similar response time is required for the global test, the vacuum sector would need to be pumped at each pumping module with the same pumping speed, which could reduce the intensity of the detected signal at the position of the leak detectors.

Leaks could also appear after bakeout or during operation, which would result in increased signals detected by the pressure gauges—indicating the presence and possible location of the leak. In the worst-case scenario, this could increase noise in the GW detection system. If such a situation occurs, a leak detection campaign must be initiated. Given the sector's size and the dynamics of leak detection, the campaign must focus on the weakest points, which are typically welded joints, flanged components, or areas showing signs of localized corrosion. Specific tools (such as clam shells) could be used to deliver helium directly around the joint to confine the gas spread within the tunnel. Multiple leak detectors can be installed around the suspected area to improve localization. Pre-localization by calibrated RGA, monitoring Ar or N_2 mass peaks, could be beneficial.

The maximum leak rate that can be tolerated during operation has been calculated. The pressure profile and strain noise increase due to a localized air leak with a throughput of 1×10^{-7} mbar·l/s are shown in Fig. 31 and 32, respectively. The resulting strain noise is a factor of two below the ET's upper limit.

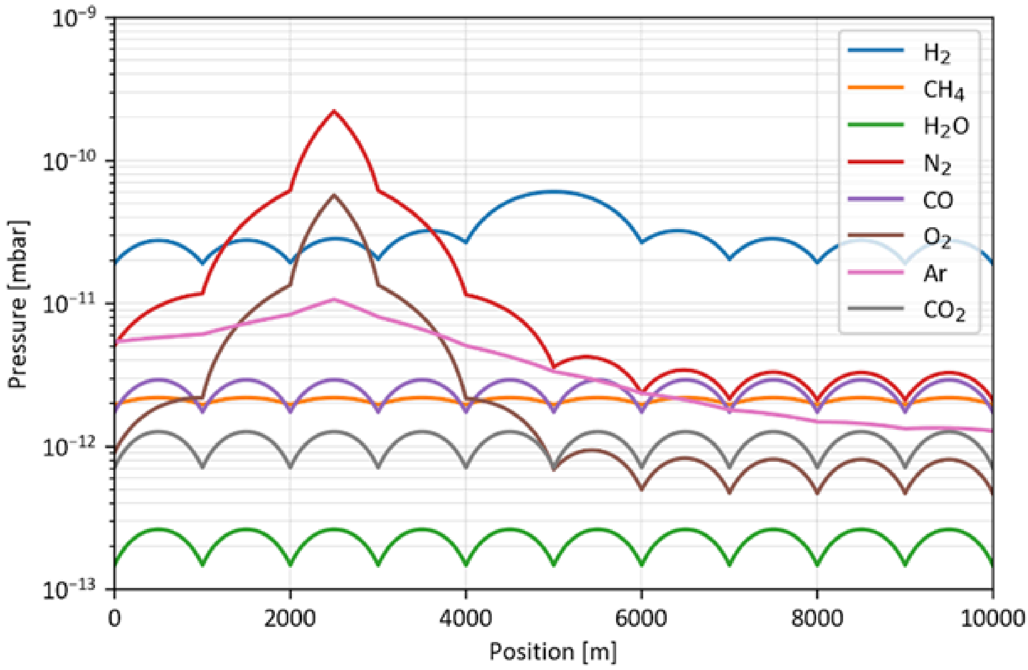


Fig. 31: *Calculated partial pressure profiles when a leak of 1×10^{-7} mbar l s^{-1} is localized in the middle of a vacuum sector. The outgassing rates for N_2, O_2 and Ar are arbitrary assumed as $q_{N2} = 3.7 \times 10^{-17}$ mbar l s^{-1} cm^{-2}, $q_{O2} = 1 \times 10^{-17}$ mbar l s^{-1} cm^{-2} and $q_{Ar} = 1 \times 10^{-18}$ mbar l s^{-1} cm^{-2}.*

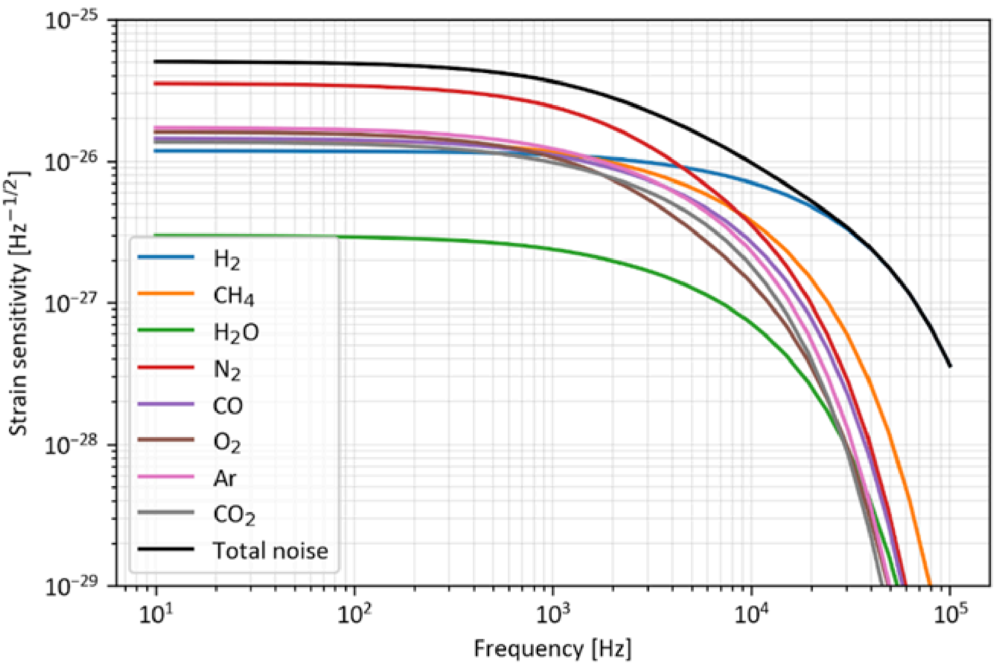


Fig.32: *Strain noise as a function of frequency for an air leak of 1 × 10^{-7} mbar l s^{-1} for ET-LF. Similar results apply to ET-HF. The optical polarizability for N_2, O_2 and Ar are taken from the NIST CCCBDB database.*

Although the system can operate with leak rates in the order of magnitude of 10^{-8} mbar l s^{-1}, it is strongly recommended that the leaks be repaired, as their size could increase over time and saturate the getter pumps. The method for fixing a leak depends on its rate. Standard procedures include using liquid silicone sealant, resins, putty sealant, local rewelding, or differential pumping. In the worst-case scenario, where the leak cannot be repaired or mitigated, the affected component must be replaced. This is a major intervention requiring thorough engineering analysis due to the limited space in the tunnel compared to the installation phase (see Fig. 33 and 34).

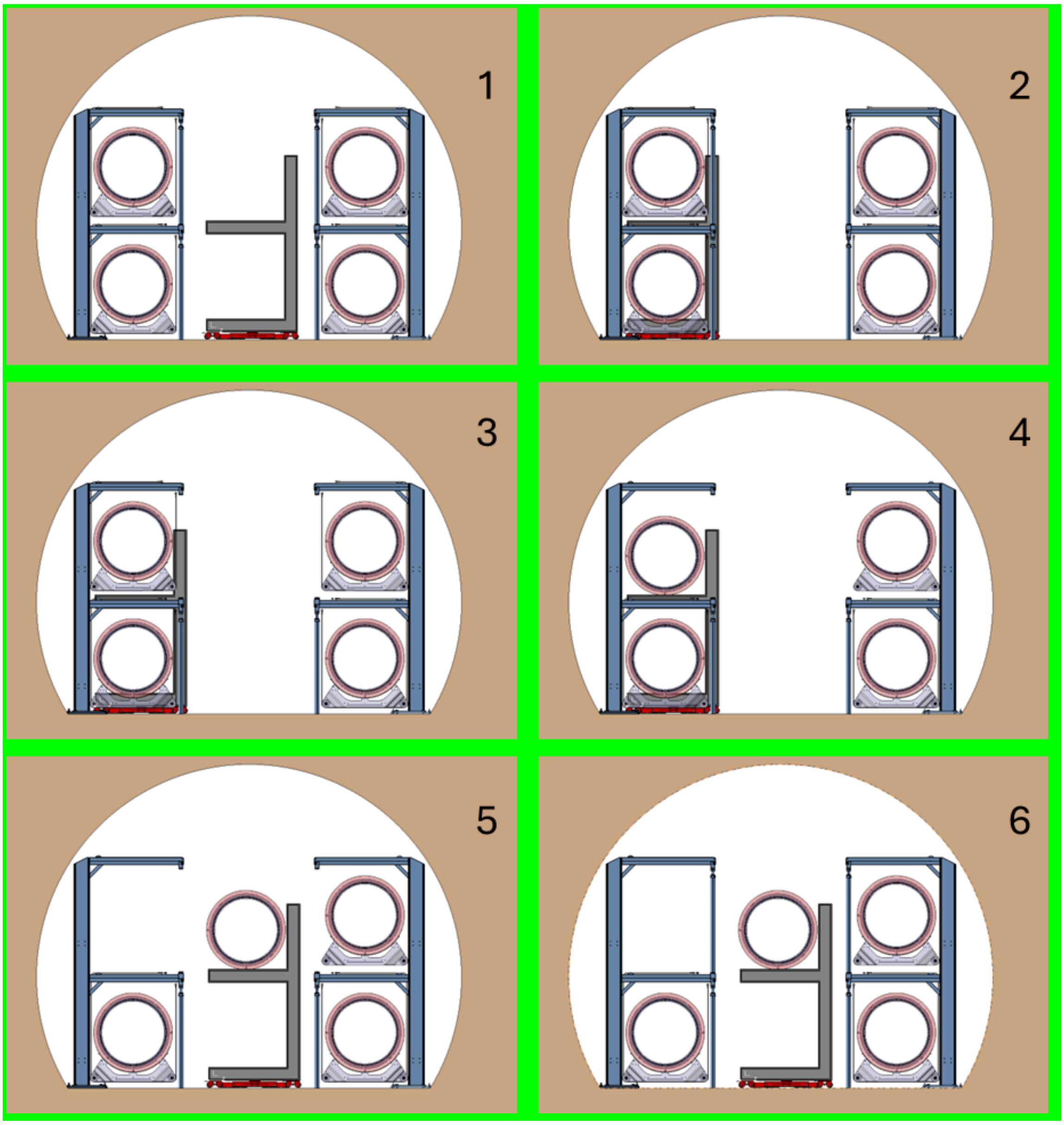


Fig.33: *Conceptual sequence to remove a tube unit after cutting its extremities.*

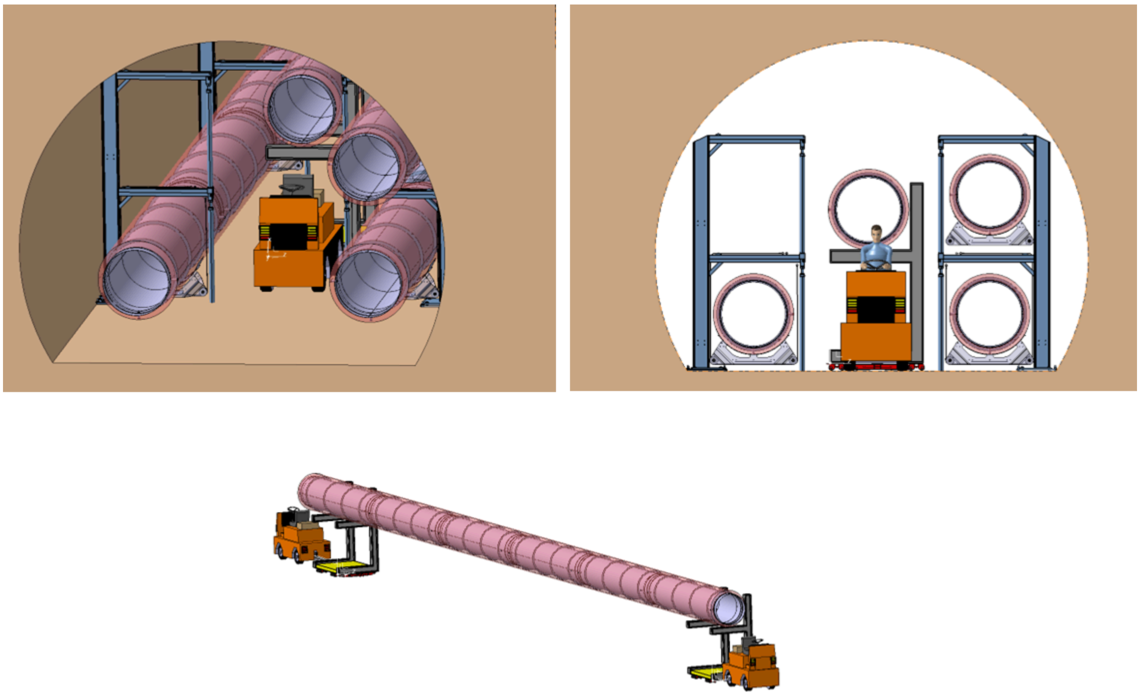


Fig.34: *Conceptual sequence to remove a tube unit after cutting its extremities. View of the towing tractors during the transport in the tunnel.*

A preliminary feasibility study indicates that such a replacement is feasible within the proposed layout. In the specific case of a failure in a tube unit, the circumferential joints at both ends must be cut, minimizing dust contamination as much as possible. The tube must be extracted under a laminar airflow to counteract dust ingress from the open ends. Once removed, the extremities are protected with cleanroom-compatible sheets. The replacement tube is then installed and welded in the dedicated space.

Following installation, pumpdown and bakeout procedures must be repeated, including leak detection for the entire vacuum sector. As previously mentioned, this is a lengthy intervention that would significantly impact interferometer operation unless carried out during a planned shutdown. Therefore, it is crucial to develop methods to mitigate the leak's effect on the physics program while waiting for a scheduled stop in operations.

13. Risk management

Risks associated with the vacuum pipe system concern the safety of both personnel and equipment during all phases of the project and operation. Contamination, mechanical failure, or vacuum degradation could result in significant downtime, degraded performance or even irreversible damage to the ET interferometers.

This chapter presents a preliminary risk analysis that addresses potential technical failures and prioritizes safety of the personnel involved in the production, installation, and maintenance of the vacuum pipe system. Handling large vacuum components and working in limited spaces with sensitive materials pose various risks, including exposure to fumes during welding, physical injury during installation, and electrical and thermal hazards during bakeout. By employing a structured risk analysis approach, we aim to anticipate and mitigate both operational and safety-related risks throughout the vacuum pipe's lifecycle. This chapter is a contribution to the ET global risk management.

The primary risks associated with the design, construction, and operation of the vacuum pipe system have been identified with their potential causes and the associated mitigation strategies are highlighted. Risks have been classified according to the nine ET risk domains (Technical, Financial, Schedule, Scope, Safety, Organizational, Environmental, Communication and Political) based on their potential impacts. Only risks related to the Technical, Scope, Financial, Schedule and Safety domains have been reported in this TDR.

13.1 Technical Risks

The main technical risks are those engendering poor performance and failures in the vacuum system that arise from the complexity of design, the manufacturing processes and the installation and alignment activities as detailed in the following table.

Technical Risk(s)	Risk cause(s)	Mitigation(s)
Poor performance	Dust contamination due to improper cleaning or handling of components during installation and maintenance.	Rigorous **testing and quality assurance** during manufacturing and assembly. Implementation of **cleanroom procedures** during assembly and maintenance to prevent contamination. **Continuously monitor** for dust during construction and installation, especially during maintenance activities. Adequate and mandatory training of the personnel.

Technical Risk(s)	Risk cause(s)	Mitigation(s)
	Hydrocarbon contamination due to improper cleaning of components prior to installation or inadequate sealing during installation and maintenance procedures.	Rigorous **testing and quality assurance** during manufacturing and assembly. Implement **validation protocols** that include surface contamination tests like FT-IR and XPS analysis. Implement procedures with strict **sealing protocols**, including the use of ISO 6 cleanroom environments for assembly, protective packaging during transport, and regular inspections of seals to prevent recontamination. Adequate and mandatory training of the personnel.
	Imperfections during the manufacturing process, the Installation and alignment activities.	Apply strict **quality control** measures throughout production and establish detailed **manufacturing, installation and alignment protocols** conducting frequent audits, and use automated systems for precision.
	Unanticipated environmental conditions or design flaws impacting the vacuum system	**Comprehensive modeling** and simulation during the design phase.
Failures in the vacuum system Failure to attain ultra-high vacuum (UHV) conditions.	Thermal expansion/contraction issues due to Improper thermal management or uneven heating of components during bakeout or normal operations.	**Comprehensive modeling** and simulation during the design phase to understand and manage expansion effects. Implement an **active control** of the rate of temperature increase during bakeout to minimize thermal stress.
	Vacuum Leaks due to welding or manufacturing defects in the vacuum pipe or components.	Rigorous **testing and quality assurance** during manufacturing and assembly. Perform rigorous leak testing using helium leak detectors during fabrication and installation.
	Vacuum leaks at joints, valves, or connectors.	Rigorous **testing and quality assurance** during manufacturing and assembly. Perform rigorous leak testing using helium leak detectors during installation.
	Vacuum leaks due to failure in seals (e.g., O-rings or flanges).	Use **UHV seals** (e.g., ConFlat flanges) that are compatible with ultra-high vacuum (UHV) conditions.

Technical Risk(s)	Risk cause(s)	Mitigation(s)
	Vacuum leaks due to thermal expansion, local corrosion or contraction leading to material stress.	Schedule **periodic inspections** and maintenance to detect and fix small leaks as early as possible.
	Virtual leaks due to improper fabrication or material imperfections.	Design components to **avoid cavities** where gas can be trapped. Use smooth surfaces and appropriate welding techniques. Subject all components to **vacuum bakeout** procedures to remove trapped gasses before installation.
	Virtual leaks due to trapping of liquids used during surface treatments.	Perform **thorough cleaning, rinsing and drying.** Avoid by design the presence of open cavities.
	Failure of sector valves due to mechanical wear or actuator failure.	Perform **routine operational testing** and servicing of sector valves to ensure they function properly under vacuum conditions. Install **redundant valves** in critical sectors to allow for continued operation if one fails.
	Control system failures due to software malfunctions or control system errors.	Application of the **rigorous testing** and implementation of automated fault detection.
Loss of vacuum due to an electrical power cut.	Loss of electrical power will stop the operation of the UHV pumps.	**Use of NEG pumps** allows power cuts durations up to more than a month

Tab 9: *Technical risks, causes and mitigations*

13.2 Scope Risks

The main scope risks are related to issues with the requirements and their change during the project execution. Additionally, problems with integration and definition of boundaries are part of this class of risks.

Scope Risk(s)	Risk cause(s)	Mitigation(s)
Incomplete or vague requirements	Insufficiently defined project specifications and unclear performance requirements for the vacuum pipe system.	Develop **detailed design documentation**, ensuring that all functional and technical specifications are well-documented. Use **gate reviews** and updates of requirements to ensure they align with project goals.

Scope Risk(s)	Risk cause(s)	Mitigation(s)
Scope creep	Adding new features, technologies, or subsystems that were not part of the original project scope during the design. Requests for additional capabilities, modifications, or upgrades to the vacuum system as the project progresses.	Implement a **change management process** that evaluates the impact of any proposed scope changes on cost, schedule, and performance. Define clear **scope boundaries** at the outset and communicate them to all project stakeholders to manage expectations. Conduct regular **scope reviews** with ET Organization to prevent unauthorized changes.
Inadequate definition of project boundaries	Failure to clearly define which components, subsystems, or processes are included within the scope of the vacuum pipe system.	Clearly delineate **project boundaries** in terms of infrastructure, subsystems, and interfaces with other systems (e.g., cryogenics, sensors, or optics). Develop detailed **interface control documents** to manage interactions between different systems and subsystems.
Integration with other systems	Challenges in aligning the vacuum pipe system with other critical ET systems, such as optical, cryogenic, and detection subsystems.	Create a **detailed integration plan** that outlines how and when the vacuum pipe system will interface with other subsystems.
Inadequate documentation of scope and requirements	Poorly documented project goals, scope, and requirements, leading to misunderstanding during execution.	Ensure that all aspects of the project scope, including requirements and specifications, are **well-documented, regularly updated** and accessible to all team members.

Tab 10: *Scope risks, causes and mitigations*

13.3 Financial Risks

The main financial risks, essentially overcosts, are detailed in the following table.

Financial Risk(s)	Risk cause(s)	Mitigation(s)
Overcosts	Changes in design specifications during the project can cause cost overruns due to re-engineering and potential delays.	Ensuring thorough initial **design reviews** and strict **change control processes**.

Financial Risk(s)	Risk cause(s)	Mitigation(s)
	Cost of raw materials such as steel can fluctuate due to market conditions, affecting the budget.	Mitigations include **long-term contracts** with suppliers, **careful material selection** (e.g., using less expensive grades like ferritic steel), and optimizing design to reduce material use.
	Delays in manufacturing could increase labor costs and extend timelines.	Use modular **off-site manufacturing** where possible and ensure efficient logistics for transporting components to the construction site.
	Misalignments or improper installations can lead to costly reworks.	Detailed planning, **rigorous training** for personnel, and implementing robust **quality control** at each stage.
	Transportation of large pipe sections and equipment may incur higher-than-expected costs due to logistics constraints.	Optimized transport routes considering **local manufacturing** or storage facilities to reduce transport distances.

Tab 11: *Financial risks, causes and mitigations*

It should be noted that some mitigations might contradict each other. In this case, a risk reassessment will have to be carried out once the choice of the site to host the project will be finalized.

13.4 Schedule Risks

The main schedule risks derive from design changes**,** delays in material procurement, manufacturing, installation, logistical challenges, integration of complex components, coordination of diverse teams and business failure as detailed in the following table.

Schedule Risk(s)	Risk cause(s)	Mitigation(s)
Delays due to design changes.	Unanticipated design revisions due to incomplete specifications, technical issues, or changes in scientific requirements. Late identification of design flaws that require re-engineering.	Implement a rigorous **design review** process with cross-disciplinary teams to identify potential issues early. Use simulations and modeling to **validate the design** before the fabrication phase. Establish a clear **change control process**, limiting changes after the design is finalized unless necessary.

Schedule Risk(s)	**Risk cause(s)**	**Mitigation(s)**
Material procurement delays	Long lead times for specialized materials (e.g., vacuum-compatible stainless steel) or parts like valves and pumps. Supply chain disruptions due to external factors such as market fluctuations, geopolitical issues, business failure, or shipping delays.	Develop **long-term contracts** with suppliers to ensure material availability. Source **multiple suppliers** for critical materials to reduce dependence on any single source. Plan for **buffer stock** or early procurement of key materials with long lead times.
Manufacturing delays	Manufacturing defects or bottlenecks in fabrication facilities. Inadequate quality control leading to the rejection of parts, requiring rework or remanufacturing.	Implement continuous quality assurance and non-destructive testing during the manufacturing process to detect issues early. Outsource manufacturing to multiple vendors to distribute the load and minimize bottlenecks. Build in extra time for unforeseen manufacturing delays in the project timeline.
Installation Delays	Challenges in assembling and aligning long vacuum pipes within the tunnels. Unexpected site readiness issues, such as incomplete civil engineering works or tunneling.	Ensure that installation teams are well-trained in alignment protocols and have the necessary tools and support. Use modular prefabricated sections to streamline installation, reducing time spent on-site.
Logistical Delays	Delays in transporting large and heavy components, especially to remote or underground locations. Coordination issues between multiple teams (civil engineering, mechanical, and electrical teams) working in parallel.	Develop a comprehensive logistics plan that includes transport routes, timing, and storage options near the installation site. Schedule regular coordination meetings between different teams to avoid conflicts and ensure alignment.

Tab 12: *Schedule risks, causes and mitigations*

13.5 Safety Risks

The main safety risks are related to fire hazards, electrical hazards, confined space hazards, exposure to hazardous materials, mechanical and structural hazards, pressure-related risks and handling of heavy machinery-related risks as detailed in the following table.

Safety Risk(s)	Risk cause(s)	Mitigation(s)
Fire hazards	Equipment overheating during bakeout processes and electrical faults in high-voltage components.	Implement **thermal insulation** of high-risk components. Install **temperature sensors, interlocks** and alarms to detect and block overheating early. Conduct regular **fire risk assessments** and ensure that fire extinguishing equipment is easily accessible in critical areas.
	Welding operation.	Place **fire-resistant curtains** around the welding area to contain sparks and molten metal. Ensure that suitable **fire extinguishers** (e.g., for Class A, B, or C fires) are readily available. Implement a **hot work permit** system to ensure that all welding activities are properly assessed and authorized.
Electrical hazards	High current operations during the bakeout processes. High voltage operations during pumping processes. Faulty electrical connections or poor insulation can lead to short circuits or electric shocks.	**Limit the presence** of people in the tunnel during the bakeout processes. Implement strict adherence to **electrical safety standards** and regular inspections of all wiring and connections.
Confined space hazards	Workers entering confined spaces, such enclosed pipe sections, where there could be oxygen depletion or accumulation of harmful gasses.	Implement strict **confined space entry protocols**, including continuous atmospheric monitoring and ventilation systems. Ensure workers are **trained in confined space** entry procedures and emergency evacuation. Provide appropriate personal protective equipment (**PPE**) such as oxygen masks, communication devices and oxygen deficiency detectors (ODH).
Exposure to hazardous materials	Inhalation or contact with hazardous chemicals (e.g., cleaning agents or coolants) used during pipe cleaning or welding.	Use environmentally safe and **non-hazardous chemicals** wherever possible. Ensure **proper ventilation** and provide PPE like masks and gloves to protect workers. Conduct regular **health and safety training** on the proper handling of hazardous materials and safe disposal methods.

Safety Risk(s)	Risk cause(s)	Mitigation(s)
Mechanical and structural hazards	Improper alignment or structural instability of vacuum pipe sections, which may cause collapse or equipment damage. Falling objects during installation or failure of support structures.	Use precision **alignment tools** and follow strict **installation protocols** to ensure structural integrity. Provide workers with adequate **training** and use cranes, lifts, and scaffolding that meet safety regulations. Regularly **inspect** the supports and joints for signs of wear or fatigue, and install **protective barriers** to minimize falling object risks.
Pressure-related risks	Sudden loss of vacuum (vacuum failure) due to leaks, which could cause implosions or other mechanical failures.	Conduct regular **vacuum leak testing** (e.g., helium leak detection) to identify potential points of failure. **Train** personnel on the safe handling of vacuum components and the risks of sudden pressure changes. Install pressure sensors and **safety valves** to monitor and control pressure levels.
Handling of heavy machinery-related risks	Improper use of heavy equipment (e.g., cranes, lifts) during the installation or repair of vacuum pipes.	Provide **regular training** on the safe operation of heavy machinery. Use modern machinery with **built-in safety features** such as automatic shut offs and load sensors.

Tab 11: *Safety risks, causes and mitigations*

14. Logistics and Sustainability

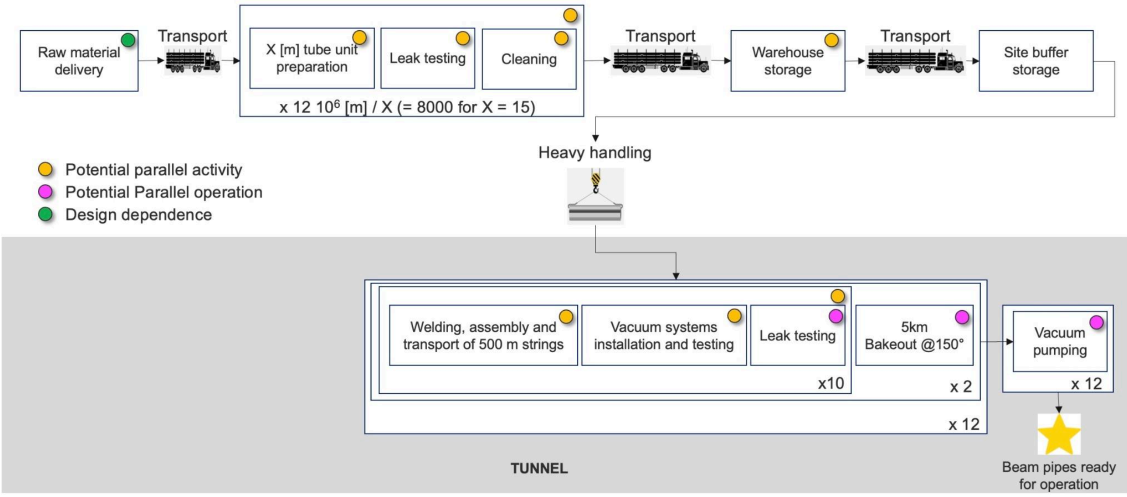
14.1 Logistics

The logistics for the ET's vacuum pipe system with its 120 km of 15 m tube units, pumping modules, bellows, supports, instrumentation and pumps present significant challenges. The overall flow has been modeled and several options have been analyzed and four are reported in this chapter: off-site, on-site, in-tunnel and in-tunnel quasi-continuous manufacturing. The final process will be finalized once the installation site is selected.

The model indicates the main tasks and the related handling and transport activities. In addition, the eventual design dependencies, the potential parallel activities and the potential parallel operations have been highlighted. The time required to execute each task will be developed at a later stage and they will be used to size the manufacturing and storage facilities. The off-site manufacturing scenario is described in detail and it will be used as a reference compared to the others.

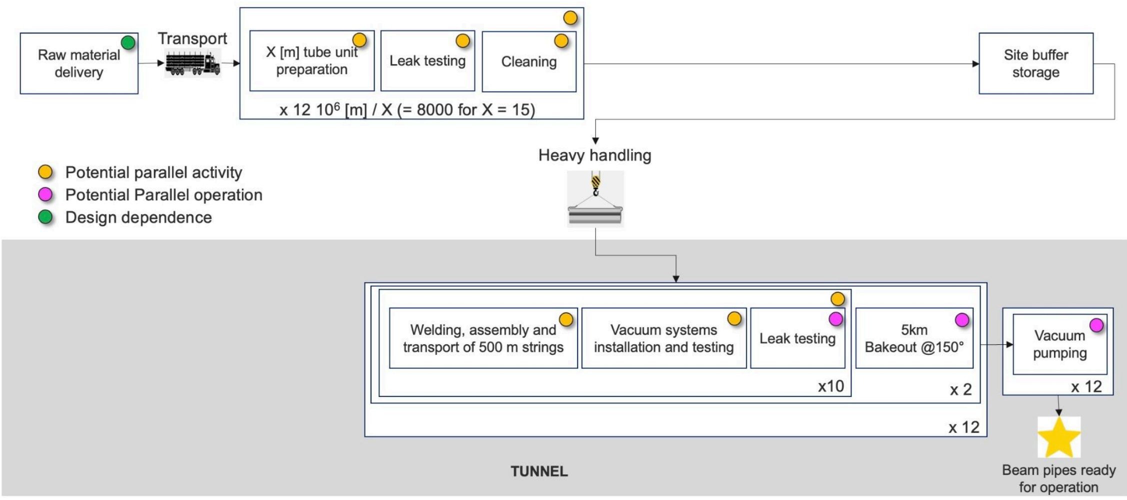
14.1.1 Off-site manufacturing scenario.

In the off-site manufacturing scenario, the manufacturing of the tube units is carried out at one or more off-site facilities. After the manufacturing, leak testing and cleaning, the tube units are conditioned for transporting and warehousing and then transported to the installation site. At the site, they will be stored in a buffer area before being vehicled to the tunnel. Once in the tunnel, the tube units will be transported to their installation slot where they will be welded in tube strings of 500 meters. Bellows will be installed every second tube unit and pumping modules every 500 meters (see Section 12.2). Ten tube strings will compose a vacuum sector of 5 km that will be baked at 150°C. Two 5 km sectors separated by sector valves will compose a 10 km arm. This process will continue for the 12 arms.



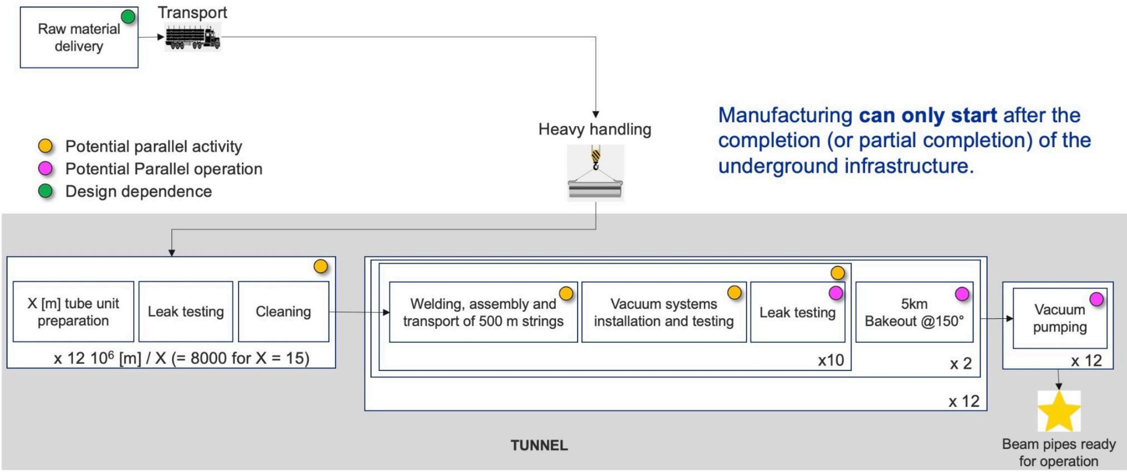
14.1.2 On-site manufacturing scenario.

In the on-site manufacturing scenario, the main difference is that the manufacturing facility is located on-site. Since the raw material is transported directly on-site, the number of transport legs is reduced from 2000 legs (8000 unit pipes / 4 x transport) to 314 legs (628 coils of raw materials / 2 x transport): a factor of 6.4 reduction.



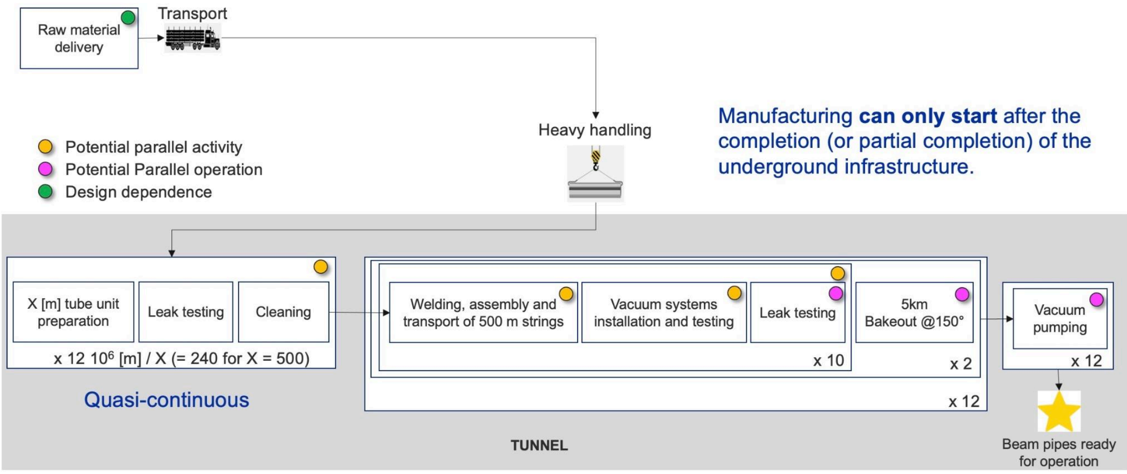
14.1.3 In-tunnel manufacturing scenario.

In the in-tunnel manufacturing scenario, the benefits of the reduction of the transport analyzed in section 14.1.2 are also complemented by the reduction of space required for the manufacturing and buffer storage on the surface (considering that the manufactured unit pipes will be placed in their final position after manufacturing).
However, these benefits are offset by the need for space allocation underground and the safety constraints that would apply for the underground activities.



14.1.4 In-tunnel quasi-continuous scenario.

In the in-tunnel quasi-continuous manufacturing scenario a full string of 500 m is fabricated underground and then assembled in the tunnel. The main benefit is a drastic reduction of the unit pipes weldings with the reduction of the risk of leaks and alignments. Considering the benefits highlighted in the sections 14.1.2 and 14.1.3, this scenario is the optimal choice for reducing transports, unit pipe transport and storage conditioning and for reducing the risks of leaks and alignments during the assembly activities. However, the feasibility of this scenario is not yet validated and its technology is still in the conceptual phase. More development is required.



14.1.5 Preliminary conclusions

The preliminary conclusions from the analysis of these scenarios are:

- The amount of transport legs increases dramatically with an off-site manufacturing facility: this scenario also increases the conditioning of the tube units for transport versus storage.
- With tube unit sections of 15 m in length, a considerable number of individual units and careful planning for their movement to the installation site will be required to accommodate road and rail transport.
- The risk of schedule delays increases in underground production due to space constraints.
- In all scenarios, the complexity of assembling and aligning the numerous tube units within the tunnel has an inherent risk of schedule delays.
- The final design and the eventual sustainability assessment based on the transportation means (road, sea and rail) and transportation routes, detailed handling procedures, storage requirements, and the sequencing of installation activities depend on the site selected to host the project.
- The evaluation of the environmental impacts of the logistic activities should quantify CO_2 emissions and address potential environmental concerns associated with material sourcing, manufacturing processes, energy usage during operation, and waste management.

14.2 Sustainability

The ET's vacuum pipe design prioritizes sustainability by using resources efficiently, minimizing waste, and reducing environmental impact. The ET vacuum pipe system is developed with sustainability at its core. Its main sustainability objectives in the technical design are to minimize energy consumption, to reduce greenhouse gas emissions and minimize its environmental impact by the selection of construction materials and by optimizing the activities during the construction, installation, conditioning and operational phases.

The **Material Selection** for the vacuum pipe allows to address both the minimization of the energy consumption and the reduction of the greenhouse gas emissions.

The AISI 441 ferritic stainless steel was chosen for its reduced hydrogen outgassing, which eliminates the need to fire bake at 450 °C the raw material. This choice translates to lower energy consumption and potentially reduced thermal insulation material needs.

The **Design Optimization** for the vacuum pipe with the thin-walled corrugated vacuum chamber design option allows to address both the minimization of the energy consumption and the reduction of the greenhouse gas emissions by:

- The reduction of the material – The thickness of the corrugated vacuum chamber is reduced by a significantly thinner wall thickness (typically 1.5 mm)

compared to smooth reinforced tubes (4 mm). This reduced thickness translates into a lower overall mass for the tube units.
- The reduction of the material - Smooth reinforced tubes require bellows to accommodate the thermal expansion that occurs during bakeout. Corrugated pipes, however, can inherently absorb this expansion within their corrugations, eliminating the need for bellows.
- A simpler manufacturing - The corrugated pipes require lighter forming machines and fewer manufacturing steps compared to smooth reinforced tubes, resulting in lower energy consumption during production.
- A less-energy intensive method for the handling and transportation - Due to their lower mass, corrugated pipes could potentially be transported using less energy-intensive methods.

The **Design Optimization** of insulation thickness allows to minimize the thickness for the insulation layer by showing that increasing the thickness of the thermal insulation beyond a certain value does not significantly reduce the current required for bakeout. This reduction of insulation materials not only optimizes energy consumption but also reduces the overall materials with an indirect reduction of the greenhouse gas emissions.

The **Material Selection** for the insulation material points to cork, a natural material derived from the bark of cork oak trees, as it offers several potential advantages:
- Low embodied carbon footprint - Cork's natural origin and minimal processing result in lower CO_2 emissions compared to many synthetic insulation materials.
- Excellent thermal insulation properties - Cork is a highly effective insulator, potentially further reducing energy consumption during bakeout.
- Fire resistance and durability - Cork possesses natural fire-retardant properties and is known for its long-term durability, making it suitable for the demanding tunnel environment.
- Reduced CO_2 Emissions - Being a Renewable Material, it has a lower embodied carbon footprint compared to synthetic alternatives. Cork is harvested from the bark of cork oak trees without harming the tree, allowing for continuous regeneration. This natural process makes cork a highly sustainable resource.
- Lower environmental impact - Cork is biodegradable and has less harmful effects on ecosystems during their production and disposal compared to materials derived from fossil fuels. In addition, cork production involves minimal processing and does not rely on energy-intensive chemical reactions, contributing to its lower environmental impact.

The **Design Optimization** of the bakeout process needed for the material conditioning is designed to heat both the low-frequency and high-frequency chambers simultaneously. This approach avoids redundant heating cycles and reduces overall energy use and enhances overall efficiency.

The **Design Optimisation** of the Vacuum Pumping System also contributes to the minimization of the energy consumption as the UHV pumping system relies solely on getter pumps, which are known for their low power consumption and high reliability.

The **Design Optimisation** of the Vacuum Control System enables precise monitoring and control of the vacuum system. This level of control can help optimize pumping cycles, minimize energy use, and ensure long-term system stability.

The **Design Optimisation** of the cleaning process addresses the use of sustainable chemicals designed to minimize negative effects on the environment.

Finally, the **Design Optimization** of the logistic activities will have an impact on the overall sustainability. However, this will depend on the site selected to host the project as many parameters are site-specific: namely, transportation means (road, sea and rail) and transportation routes, detailed handling procedures, storage requirements, and the sequencing of installation activities.

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