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# Cryopump concept development for the cryogenic mirror region of the Einstein Telescope – the future gravitational wave observatory

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**Abstract.** The Einstein Telescope (ET), the planned gravitational-wave observatory for Europe, will increase the sensitivity and expand the observation band to lower frequencies. The main optics of the ET-Low Frequency (LF) interferometer will be cooled to cryogenic temperatures below 20 K and the whole system, consisting of the beam pipes, the suspension towers and the cryostat containing the mirror, requires high to ultra-high vacuum conditions.

To fulfill the vacuum related requirements the use of tailor-made in-situ cryopumps is envisaged. Simulations at KIT, performed with the in-house Test Particle Monte Carlo code ProVac3D and a simplified model of the system, considered the three main gas sources from the neighbouring systems and the sinks by pumping stations distributed along the pipe arms, the cryogenic pump sections close to the mirror and the cryogenic mirror environment. These simulations showed different needs for the pumping of hydrogen (to lower the residual pressures) or heavier species like water (to lower the frost formation on the cryogenic mirror surface) – depending on the position related to the mirror. With these findings, the development of a pump arrangement concept was worked out.

In parallel, the outgassing rates of the inner walls of the beam pipe tubes, influencing strongly the vacuum pumping demands, have been varied to investigate the potential use of mild steel as a beam pipe material of reduced costs.

This paper describes the developed pump arrangement concept, utilizing cryogenic pumps integrated into the beam pipe tubes of 1 m diameter, with their individual objectives regarding pumped species and needed temperatures.

Furthermore, the key parameter of frost formation on the cryogenic mirror, important for long operational phases without pause and maintenance, being also a design driving demand, is derived from the predicted residual pressure of sticky gases like water.

## 1. Introduction

The Einstein Telescope (ET), as the planned third-generation, underground gravitational-wave observatory for Europe, will increase the sensitivity compared to the current advanced detectors (Virgo, LIGO, KAGRA) and expand the frequency band to lower frequencies. Proposed as an equilateral triangle with 10 km long vacuum pipe arms, the Einstein Telescope will consist of three laser interferometers for high (HF) and low frequencies (LF) each.

The main optics of ET-LF will be cooled to cryogenic temperatures below 20 K in order to reduce thermal noise for sensitivity optimization. The whole system, consisting of the beam pipes (120 km length in total), the suspension towers and the cryostat containing the cryogenic mirror, requires high to ultra-high vacuum conditions [1, 2]. Along the beam pipes, residual gas has to be reduced as much as possible to avoid e.g. optical noise, while around the mirror the pressure minimization is mainly motivated by the fact that gases like water will be adsorbed as frost on the cryogenic mirror surface and thus degrade its optical performance.

In order to fulfill the vacuum related requirements and to consider thermal radiation aspects from the warm interferometer to the cryogenic mirror, the use of tailor-made in-situ cryopumps seems indispensable. This paper describes the different simulations performed at KIT and the resulting pump arrangement concept which fulfills all requirements.

## 2. Simulation approach

The approach to come from a collection of pressure requirements, gas source flows and geometric boundaries to a sound concept of different pumps in the system, followed the usual way to iteratively implement all gas sources and surfaces with a certain sticking coefficient into the model and simulating the resulting pressures until requirements are met. These simulations have been performed with the KIT in-house Test Particle Monte Carlo code ProVac3D [3] and a simplified model of the system was used. Due to the disadvantegous geometry of the system, with a beam pipe of 1 m diameter but up to 2000 m length, the computational effort required the use of High-Performance Computing with ~10,000 cores.

The gases of main interest for the simulation of ET have to be separated in hydrogen and heavy gases since they behave differently at a cryopump. The specie of heavy gases of highest impact to the system and largest fraction in the source flow is water. Consequently, simulations of hydrogen and water have been performed separately since ProVac3D can handle one specie only at the same time.

## 3. Outgassing of beam pipe material

The 10 km long beam pipe at the right of the cryostat will act as a gas source due to the homogenous outgassing of the entire inner pipe wall. Warm pumping stations will be installed, distributed equidistantly along the beam pipe length, to reduce the residual gas pressure. Since outgassing of steel strongly depends on the pre-treatment and the material itself, a dedicated variation of this parameter in the simulation was performed. This was done to investigate the feasibility of using mild steel as beam pipe material for cost reduction reasons. Fig. 1 shows a typical pressure profile simulated for the beam pipe of the first 2000 m with this outgassing variation - assumed for the long beam pipe and leading to different pressure profiles which are mainly not compatible with the beam pipe pressure requirement of $1 \cdot 10^{-8}$ Pa for hydrogen.

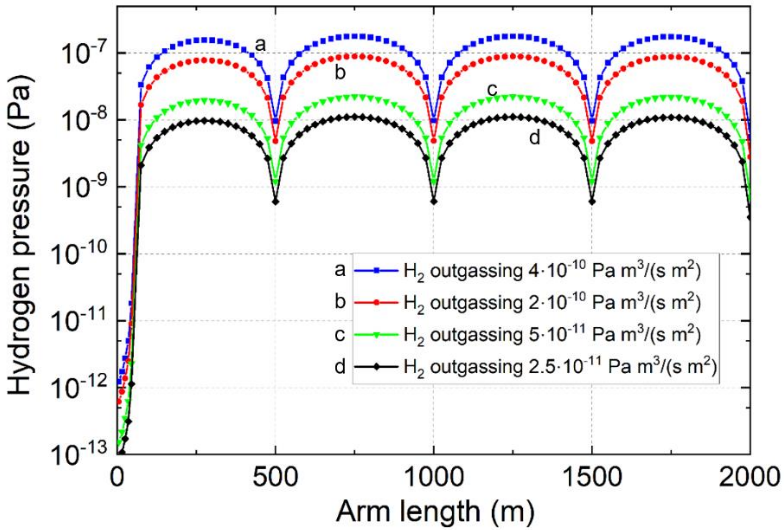


**Fig. 1**: Pressure profile along the beam pipe at different outgassing levels of the pipe wall. It can be seen that the profile is repetetive after 1000 m which is consequently the reduced simulation length.

With these findings, the following different conclusions can be drawn. Firstly, the pressure of the beam pipe is strongly decoupled from the cryostat vacuum condition due to the strong pumping of the cryopump (see Fig. 2). Secondly, by varying the pumping speed (up to 125 $m^3/s$) and distance (down to 100 m) of the warm pumping stations distributed along the beam pipe, it was demonstrated that a sufficiently low residual pressure along the beam pipe has to be established by a sufficiently low outgassing of the beam pipe material and not with an excessive pumping system. This effect can be seen comparing Fig. 1 and 2: while the pumping speed of the warm stations along the beam pipe is enormous 125 $m^3/s$ in Fig. 1, this value is only 5 $m^3/s$ in Fig. 2. But the result of this excessive pumping speed is only a reduced pressure locally around the pump station and not a reduction of the peak pressure due to the low conductance of the 500 m pipe length in between.
However, since the beam pipe pumping will be a distributed system of more or less conventional pumps (but at least warm pumps), and since it is decoupled from the cryostat region, this area is not investigated further but separated to another work package beside cryo/vacuum. Therefore, only the cryostat and its proximity are further studied towards a cryopump concept.

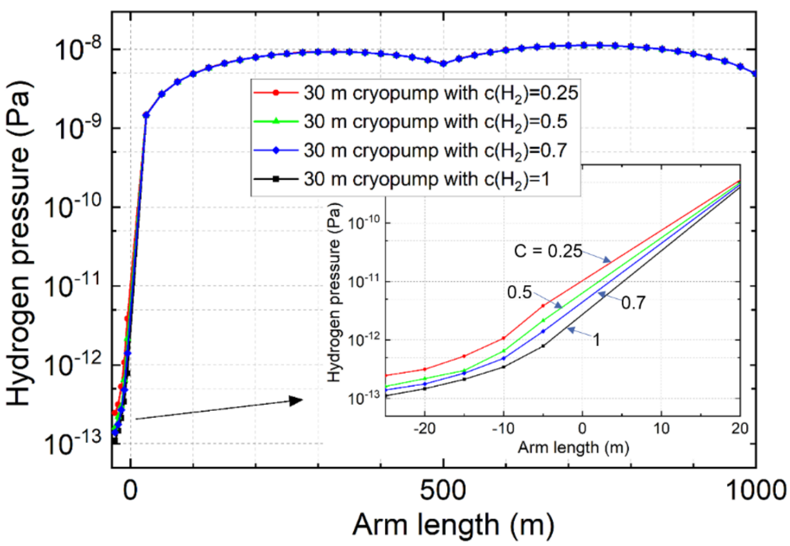


**Fig. 2**: Pressure profile with a variation of the sticking coefficient of the cryopump installed between cryostat and the 10 km beam pipe. The decoupling of the beam pipe from the cryopump region is visible.

## 4. The model

ET-LF consists of a cylindrical cryostat around the cryogenic mirror and a beam pipe of 1 m diameter at both sides each. Fig. 3 shows a sketch of the simplified model established for the simulations comprising three gas sources which have to be considered for a sound simulation. These are the flow from the 10 km long beam pipe (S1), the upper suspension tower (S2) and the adjacent tower 50 m on the left (S3). The major simplification was to omit the suspension system of the mirror. This complex structure is expected to influence the gas distribution in the cryostat not significantly. However, the so-called marionette, part of the suspension system above the mirror, was considered since it may also be at cryogenic temperatures and therefore contribute to the pumping.

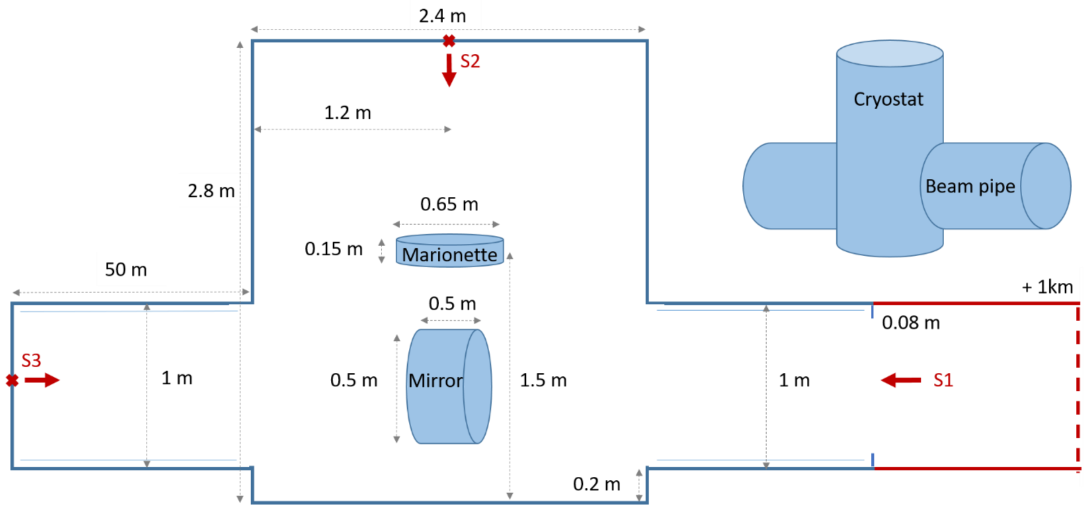


**Fig. 3**: Sketch of the simplified model of cryostat with cryogenic mirror and the beam pipes left and right. S1, S2 and S3 represent the different gas sources (with dedicated sections below) to be managed by the cryopumps installed in both beam pipes.

### *4.1. Gas source S1 – the 10 km beam pipe*

Even with the finding of a beam pipe decoupled from the cryostat region, the model comprises 1 km of it to create a distributed gas source at the warm side of the cryopump under consideration of the warm pumping stations in the pipe. Herewith, a very low outgassing value of $2.5 \cdot 10^{-11}$ $Pa \cdot m^3/s/m^2$ was assumed for the inner pipe wall and used in the simulation, which is demanding but demonstrated successfully in recent gravitational observatories like VIRGO. The already described split between hydrogen and water simulation assumes that both species contribute identically to the overall outgassing value.

### *4.2. Gas source S2 - upper tower*

Above the cryostat with the cold mirror, the upper tower is located which hosts the complex seismic isolation system of the mirror suspension. This upper tower is > 10 m high, packed with sensitive hardware and therefore not bakeable. Consequently, the pressure in the upper tower would be two orders of magnitude higher than the pressure requirement in the cryostat. A full isolation of both systems is not possible since the suspension wire, on which the marionette and the mirror hang, requires an opening of ~ 20 mm diameter. Here, a first concept was developed, to reduce the resulting gas flow by two measures. Firstly, the pressure in the upper tower will be reduced by at least one order of magnitude with additional pumping there, e.g. in-situ or ex-situ cryopumps, developed separately. Secondly, by a mechanical solution of a long pipe with an adaptive orifice around the suspension wire, which drastically reduces the conductance between upper tower and mirror region while maintaining the non-contact and the freedom of alignment. With the separate simulation of this draft concept, the reduction of the resulting gas flow to $2 \cdot 10^{-9}$ Pa·m$^3$/s for hydrogen and water each was found to be reasonably achievable. This value is the used gas source contribution by the upper tower for the simulation of the entire system.

### *4.3. Gas source S3 - adjacent tower*

The adjacent tower is a warm tower left from the cryostat in 50 m distance, connected via the standard 1 m diameter beam pipe, which releases very high gas loads of hydrogen and water with $10^{-7}$ Pa·m$^3$/s and $10^{-6}$ Pa·m$^3$/s respectively. Consequently, also on this side a cryopump is needed which is even more demanding as the right one in order to reduce the high gas flows to a level appropriate for the required conditions around the cryogenic mirror.

## 5. Simulation results

With the geometry and gas flows described above, the system was simulated for hydrogen and water seperately with the focus on the conditions around the mirror and the variation of the left and right cryopump. A result of major importance is the fact that at the right cryopump, towards the 10 km beam pipe, no hydrogen pumping is needed. Fig. 4 shows a fully sufficiently low pressure of hydrogen at the mirror below the requirement of $<10^{-8}$ Pa.

Contrarily, the gas flow from the adjacent tower on the left is of such height, that a hydrogen pumping is unavoidable. However, a very short section of a hydrogen pumping cryopump (1 m) fulfills this need.

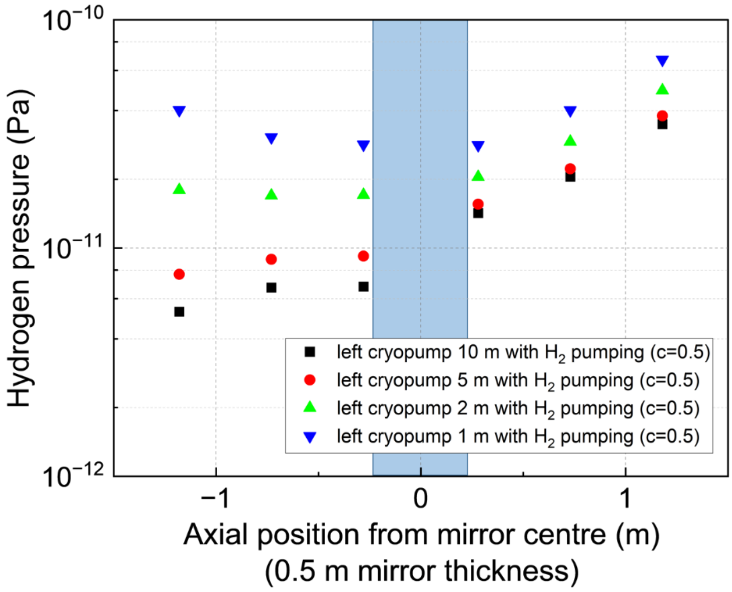


**Fig. 4**: Hydrogen pressure around the cryogenic mirror (blue box). The pressure depends on the length of the hydrogen pumping cryopump section at the left side. At the right, no hydrogen pumping is needed.

Regarding water the situation is different: at both sides large pumping speed for water is needed but not the pressure requirement of $<10^{-10}$ Pa is the driver but the frost formation at the cryogenic mirror surface. Adsorbed water would degrade the optical performance of the mirror, increase optical losses and noise and increase the laser power absorption to unacceptable levels. Therefore, the built-up of one monolayer of water ice at the mirror is the limit given to design the pumping system appropriately. This leads to the driver that the monolayer built-up time is reasonably maximized and minimum one year. Fig. 5 shows the water pressure around the mirror with the related monolayer times and it can be seen that for example a solution with 20 m water pumping cryopump on the left and a 10 m one at the right fulfills all requirements and gives a satisfying monolayer time of ~2 years. From the simulation it was also derived that no significant inhomogeneity of the water deposition at the mirror will occur. Such an effect would reduce the allowed time until a monolayer of water is established, but could therefore be excluded.

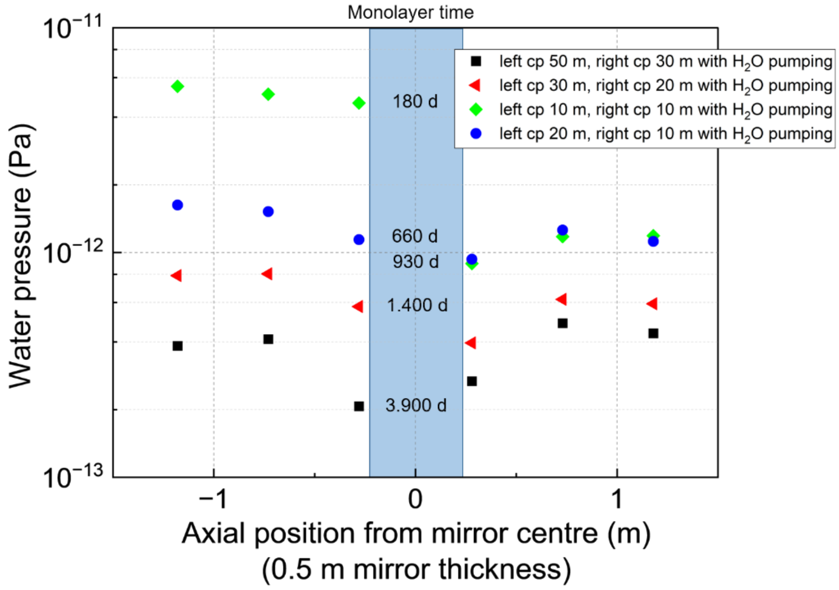


**Fig. 5**: Water pressure around the cryogenic mirror (blue box). The pressure depends on the length of the water pumping cryopumps at both sides. The time values in the center are the monolayer built-up times correlated with the pressure at this level (e.g. 660 days for $1.05 \cdot 10^{-12}$ Pa).

While the water pumping cryopumps are envisaged to be operated at 80 K, the hydrogen pumping section needs clearly a lower appropriate temperature. Two options are available and under discussion currently, the adsorption on bare steel panels at 3.7 K or physisorption at a panel at higher temperature but coated with a dedicated sorbent. For example, activated charcoal could be used to elevate the temperature to ~10 K in order to save energy for the cryogenic supply. Since it is currently not clear, how strict the requirements on dust-free solutions have to be, the conservative assumption is an operation at 3.7 K.

## 6. Resulting pumping concept

With the described variations of 80 K water pumping cryopump lengths at both sides and of the length of the hydrogen pumping section, the pressure requirements could be fulfilled with a significant margin. The need of a long monolayer built-up time is a much more demanding need and driver. For this purpose, long cryopumps at both sides are needed.

With all these findings an appropriate concept was concluded and was proposed to the ET community. This concept is shown in Fig. 6 and consists of a 10 m long 80 K pump at the right side towards the 10 km beam pipe and a 20 m long cryopump on the left side towards the adjacent tower. This left pump again consists of a 1 m section at 3.7 K for hydrogen pumping and further 19 m at 80 K.

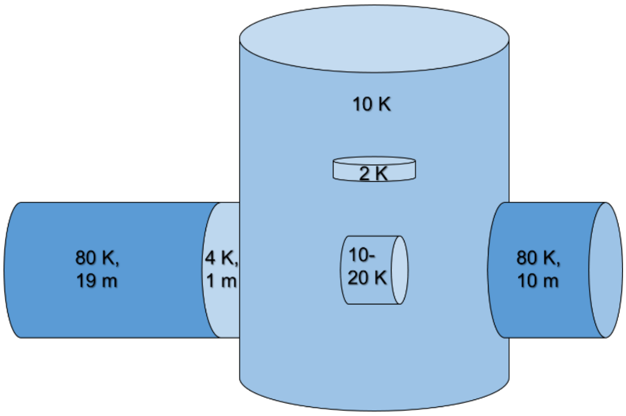


**Fig. 6**: Pump arrangement concept work out to fulfill all pressure requirements and providing a reasonably long monolayer built-up time of water at the mirror.

With this concept in hands, which is sound from a vacuum point of view, the next step is the consideration of thermal aspects. Here, for the start not thermal aspects of a well designed cryopump are meant but the resulting thermal situation for the cryogenic mirror. Since the coating of it is not yet decided and for many coating candidates the absorption behaviour for thermal radiation is unclear, the conservative approach for the moment is to assume that all radiation will be absorbed. Due to extreme limitations in mirror cooling (caused by the 1-2 m long and 2 mm thin suspension wires of silicon) which are the only mechanical contact to keep the 200 kg mirror at cryogenic temperatures) the radiation load has be limited to few 100 mW. Consequently, the design of the pump arrangement had to be detailed in order to optimize the thermal radiation load onto the mirror. Fig. 7 shows the sketch of the recently developed concept of the right cryopump comprising baffles which can be tolerated from an optical point of view but restrict the free opening and mask completely the view of the mirror on the 80 K surfaces. This concept makes clearly only sense with colder baffles, so they are assumed with 10 K.

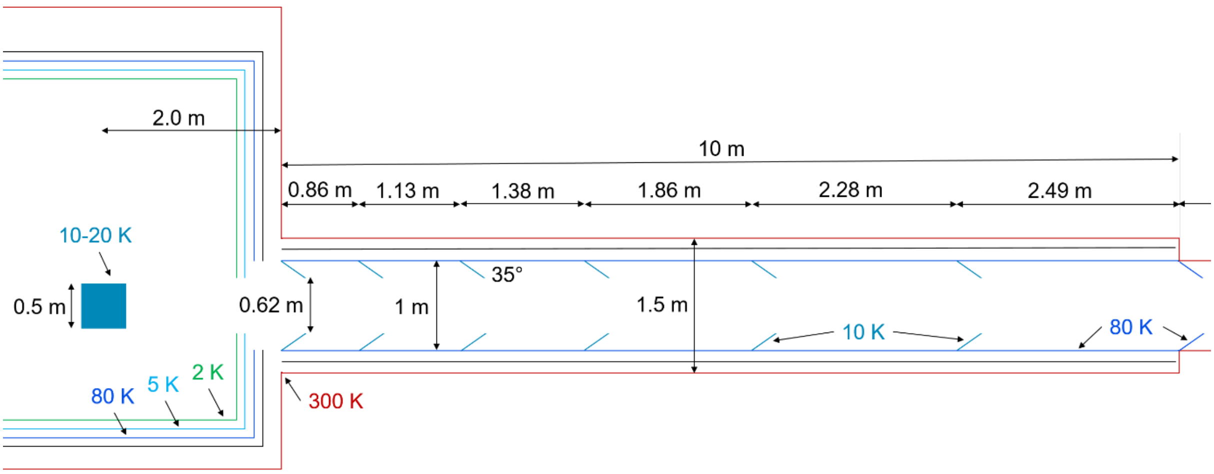


**Fig. 7**: Cryopump concept (80 K) at the right side towards the 10 km beam pipe with integrated 10 K baffles supressing the view of the cryogenic mirror on 80 K surfaces reducing thermal radiation drastically.

From a manufacturing and supply point of view, it is necessary to segment the long cryopumps with the same pattern as the baffles are located along it. Such a cylindrical segment of an 80 K cryopump with integrated baffle could look like the one in Fig. 8. The question how to cool the pump surface (the cylinder mantle), by thermal conduction from attached supply pipes, or by a flow through a hydroformed component, has to be investigated. The hydroformed concept, well established for a number of cryopumps developed by KIT for nuclear fusion devices [4], has to be tested in the future regarding potential vibration of the component caused by the internal cryogenic flow, which could be an issue for the optical noise in the interferometer.

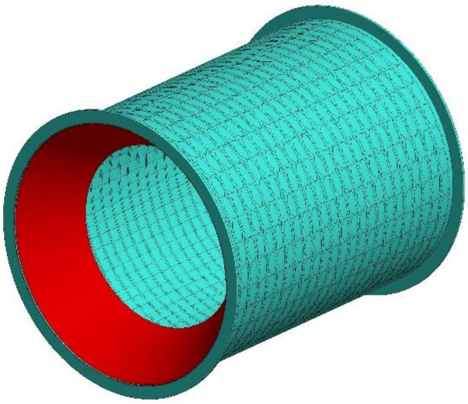

**Fig. 8**: 80 K cryopump segment with integrated baffle. With this segmentation the baffle installation is well feasible and the pump can be assembled and supplied segment-wise.

## 7. Conclusions and next steps

With the described work, a cryopump arrangement was elaborated which fulfills all specific vacuum requirements of ET-LF as pressures, water monolayer times and different demands for hydrogen and water. The developed concept was furthermore detailed to limit the thermal radiation onto the cryogenic mirror.

As a next step, the arrangement of both cryopumps of ET-LF, including baffles, will be investigated regarding thermal loads. Here, the interest is a first rough assessment of the global cryogenic demands of ET to derive cryoplant size and costs (three plants will be needed for the ET triangle configuration). Since the cryopumps (also in ET-HF cryopumps will be needed but they will be similar) are the major cryogenic consumers, a heat load assessment is needed now. To perform this study, the ProVac3D code can be used and the developed model will be adapted to allow the simulation of radiation instead of particles.

With the results of this next step not only the concepts of all ET cryopumps will be available, also the entire cryogenic infrastructure can be assessed.

## 8. References

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