The ROtating Tungsten HElium cooled TArget (ROTHETA) concept

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Abstract. Since the very beginning of the Pre-construction phase (2010-2012) of the European Spallation Source programme, a helium gas-cooled target was proposed, capable of sustaining the beam power of 5 MW and avoiding cladding of tungsten blocks necessary to mitigate corrosion in an analogous water-cooled system. The concept retained during the target selection process is a rotating target filled with tungsten. The choice was driven by different criteria, in which safety and performance were central. The current design effort and its status will also be presented, including some of the major components needed to operate the target. Different arrangements inside the target are proposed and the retained pattern is aiming at providing a robust and reliable design.

1. Introduction: the material and helium coolant choice

The European Spallation Source (ESS) will be a multidisciplinary scientific research center harnessing the world's most powerful neutron source.

The selection of a site to host the European Spallation Source at the end of May 2009 has triggered a renewed interest in the technical implementation of such a facility. The main parameters, which formed the basis of the design of the LINAC, target station and instruments are summarized in the table 1.

Whereas the previous incarnation of the ESS project [1] foresaw two target stations receiving on one a short pulse (1.4 µs, 50 Hz) and on the other a long pulse (2 ms, 16.67 Hz), the current version considers only one long pulse target station motivated by higher neutron fluxes in the thermal and cold neutron energy range (wavelength > 0.9 A) [2]. This move away from the short pulse target station along with operational experience gained in the last decade on MW class spallation targets prompted a re-evaluation of potential target concepts for the ESS.

The Helium Cooled Granular Target concept [3][4] was first developed for the Neutrino Factory. This idea was revisited during the TSCS [5] (Target Station Concept Selection) process and lead to the study of a ROtating Tungsten HElium cooled TArget (ROTHETA) concept. This concept presents several advantages:

- Neutron yield is expected to be high,
- Ease of tuning the cooling and heat removal,

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- Suppression of Tungsten cladding, the conventional way to avoid corrosion of the Tungsten material in the water-cooled alternative
- Larger margin for safety cases compared to water cooling option
- Smaller radioactive inventory

Table 1. The ESS LINAC parameters

Parameter	*Unit*	Value
Average current	*mA*	2
Proton energy	*GeV*	2.5
Repetition rate	*Hz*	14
Pulse length	*ms*	2.86
Beam Profile	-	Parabolic
Beam width	*cm*	14
Beam height	*cm*	5

Table 2. The ESS target parameters

Parameter	*Unit*	Value
Spallation material	-	Tungsten
Wheel outer diameter	*m*	2.5
Peak current density	$\mu A.cm^{-2}$	64
Peak power density (“stationary”)	$kW.cm^{-3}$	~4.8
Peak power density (“corrected”)	$W.cm^{-3}$	~145
Average beam power	*MW*	5
Rotational speed	*rpm*	~25

2. The spallation target

2.1. Geometry and some of the main parameters

The target wheel current proposal (general overview in figure 1) consists of 33 sectors. The beam pulses are synchronized with the target rotation speed to allow an optimization of the flow pattern and target material arrangement. The number of sectors has been chosen:

- To have an outer length large enough for the foreseen beam foot print
- To avoid having a direct view via the He cooling channels in case of desynchronized proton pulse hitting the target in between 2 sectors – it is achieved thanks to the odd number of sectors

The helium channels have identical width, 2mm. The channels on the side, above and below the tungsten blocks have been chosen to provide enough cooling. The top and bottom gaps between the tungsten slabs and the structure of the target are meant to avoid direct contact between the tungsten and the shroud, which could lead to high temperatures in the container.

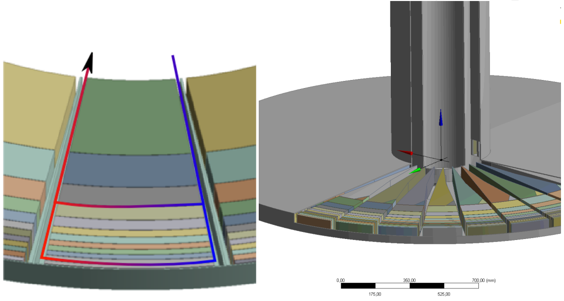


Figure 1. The target geometry and the sectors of tungsten material arranged in a concentric layering of tungsten plates of different thicknesses. The flow pattern follows a U trajectory in the target.

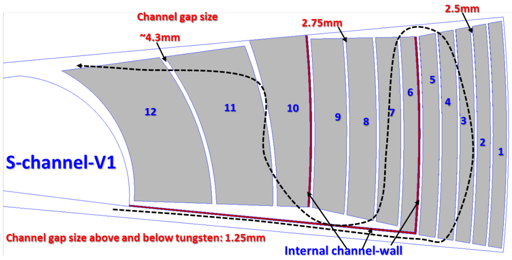


Figure 2. The spallation material arrangement in the S configuration and its associated flow pattern.

This geometry already proposes an inlet and outlet path for the helium (from the shaft). This allows a better pressure loss estimation while taking these regions into account. The helium is flowing from the outer ring of the shaft into the wheel, cooling the tungsten blocks while flowing in between the 2mm channels. The hot helium flows back via a collector into the inner tube of the shaft. The outer part of the shaft holds the structural function of the target assembly. It will retain its length and will not move due to thermal expansion. The inner part will be designed in a manner that the thermal expansion is taken into account without influencing the vertical position of the target.

2.2. Thermo hydraulic and mechanical analysis

Only one of the 33 sectors has been 3modeled, in order to take advantage of the symmetries and improve the calculation speed. In this preliminary model, the supporting structures of the tungsten slabs are not considered. Furthermore, the shroud is taken into account in this Computational Fluid Dynamics (CFD) analysis, but its outer walls are set by adiabatic boundary conditions. Hence, the model considered here is conservative, as the amount of heat dissipated via convection and radiation through the shroud is not negligible. This conservative assumption is acceptable in a first step.

Figure 3 shows the geometry used in the CFD analysis as well as the heat load [6]. In that picture, the green part represents the tungsten whereas the grey part represents the helium. The time averaged peak power density for this sector is 154W.cm^{-3}; the main parameters of the target are summarized in the table 2.

The validity of the CFD tools and estimation performed has been discussed and assessed [7].

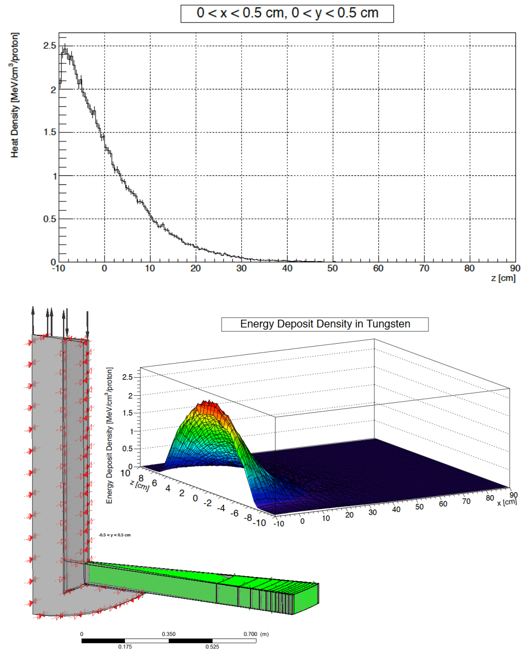


Figure 3. The CFD model of one the 33 sectors showing the inlet, target material arrangement and the outlet.

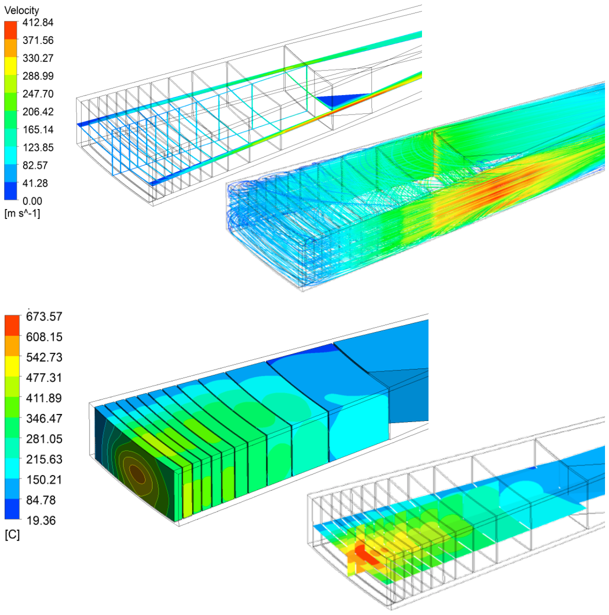


Figure 4. Helium velocity and tungsten temperature distribution in the considered sector.

This analysis is in a first step a steady state analysis. Transient analyses are in progress with the pulsed heat deposition correctly modeled. It is less of a concern for a gas cooling solution, as we do not risk local boiling during pulses. To take the thermal effect on the structure into account, it has been defined as a one-way fluid structure interaction simulation. It means, that pressures, temperatures, convections coming from the CFD analysis are exported into further analysis, but the deformations of the structures are neglected in the CFD simulation.

The Conjugate Heat Transfer (CHT) analysis takes thermal effects and viscosity changes into account via the “total energy” (kinetic energy considered) model, with viscous effects activated. The turbulence model that has been chosen is a Shear Stress Transport (k-ω SST), Reynolds-Averaged Navier-Stokes (RANS) model.

The maximum temperature in the Tungsten (673°C) could be adjusted according to the material requirement and operation requirement. This is also shown in the following paragraph. The highest values of the velocity (400m/s) occur at the exit of the helium from the tungsten slabs; however, this value, mainly due to a not yet optimized outlet channel geometry, has no influence on the overall heat transfer, which will mainly depend on the flow between the tungsten slabs (~80m/s). After passing though the plates the helium density changes and the hydraulic diameter needs to be increased to lower this high velocity; it is a side effect and could be revised and lowered during design optimization.

In order to ensure a better cooling of the BEW, an alternative design with a modified flow pattern is currently investigated. This is performed within the Work Package 4 (WP4) of the Target Station Design Update project (TSDU [8]) collaboration group and especially at KIT, Karlsruhe, Germany [9].

In opposition to the reference design where all the tungsten slabs and the BEW are cooled in parallel, in the S-shaped solution there are two groups cooled in series: the BEW and the first 5 tungsten slabs are cooled first, then a second group of 4 followed by the last 3 slabs (figure2).

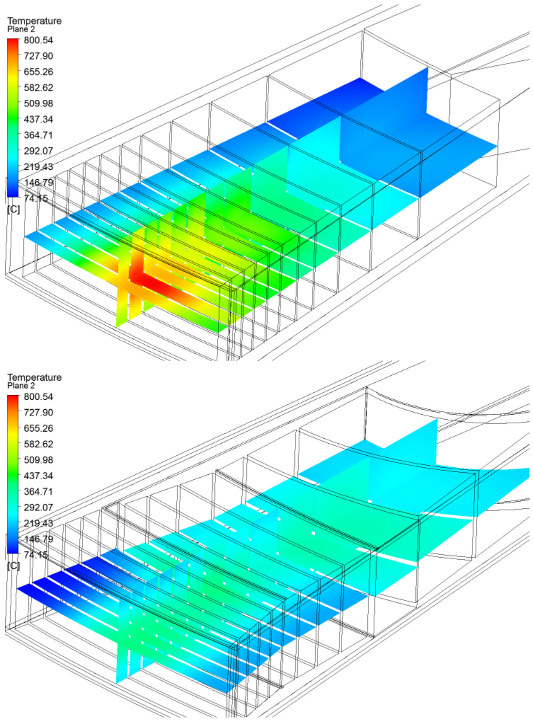


Figure 5. Temperature field in the Tungsten for the U(top) and S(bottom) configuration.

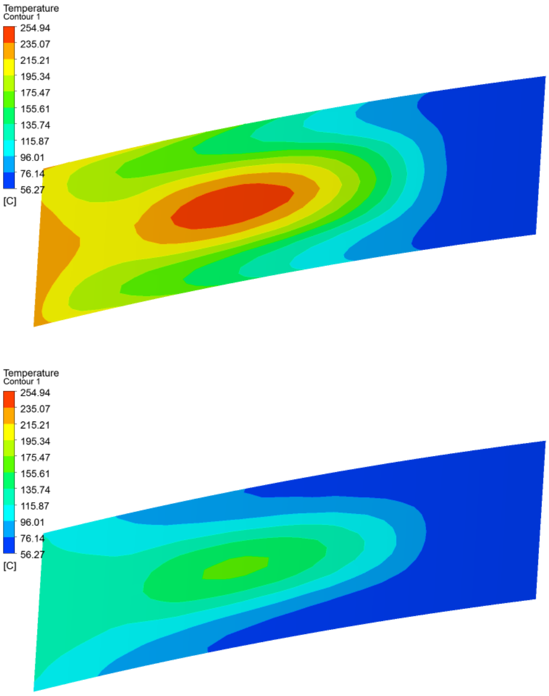


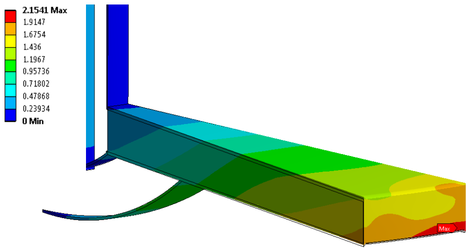
Figure 6. Temperature field in the BEW for the U (top) and S (bottom) configuration.

Figure 5 presents the result of the CFD analysis of this S-flow pattern and especially the reduction of the maximum temperature in the tungsten. The top images show the temperature estimation for the U configuration while the bottom pictures are associated with the S configuration. Further work is planned in order to reduce the pressure drop. The difference in the temperature field in the Beam Entrance Window (BEW), the structural part of the target receiving the protons at the outer diameter of the wheel can be seen in the figure 6. It can be observed from this analysis that the temperature of the tungsten plates could be easily reduced, here from 800°C to 394°C while also moving the hot spot from the second slab to the one in position 7. The peak temperature in the BEW is also reduced from 255°C to 170°C. It is of interest to note that the hot spot at the BEW is dragged to the left side by the flow direction of the Helium along the inside of the window.

This modified flow pattern has the disadvantage that the pressure drop increases from 0.3bar to around 1 bar. The initial pressure loss could be recovered by reducing the flow rate to half (1.5kg/s).

While the BEW and the front slabs temperatures remain low, the helium temperature at the outlet is twice as high as in the reference design with consequences in the design of the supporting structure in that area. Further investigations are currently focused on optimizing the flow pattern to reduce the pressure drop while maintaining the 3kg/s flow rate.

The maximum deformation of the structural part of the target is shown in the figure 7 and is about 2mm. Figure 8 shows the resulting thermal stress in the tungsten slab. It is obvious that these stresses, rather high but not excessive for tungsten, could be reduced further by cutting the slab vertically as drawn in the figure.



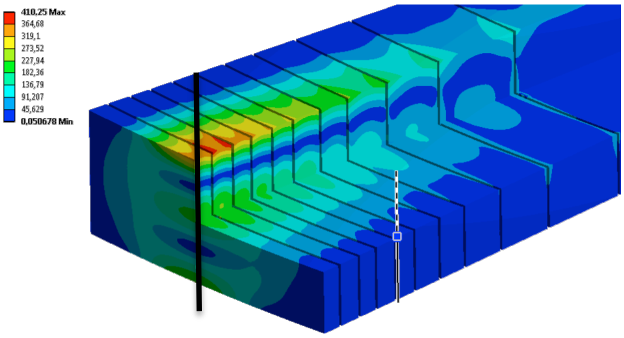


Figure 7. Total deformation (in mm) of the target wheel due to the thermal load and mechanical load (gravity and rotation)

Figure 8. The distribution of the von Mises stress in the tungsten slab arranged and cooled in a U configuration – One quarter of the tungsten block is cut to see the stress level inside the blocks.

3. Helium loop

3.1. Global layout and the main parameters

The loop has a simple layout with a circulator that provides the 3kg/s and compensates the pressure loses in the loop. Two helium-nitrogen heat exchangers are installed before and after the circulator: the one upstream removes the heat generated in the target (3MW) maintaining constant the temperature at the inlet of the circulator; the second heat exchanger removes the heat coming from the compression process inside the circulator keeping the target inlet temperature at the room temperature level. This second heat exchanger ensures that the shaft temperature remains unchanged, thus, maintaining the position of the target with respect to the beam.

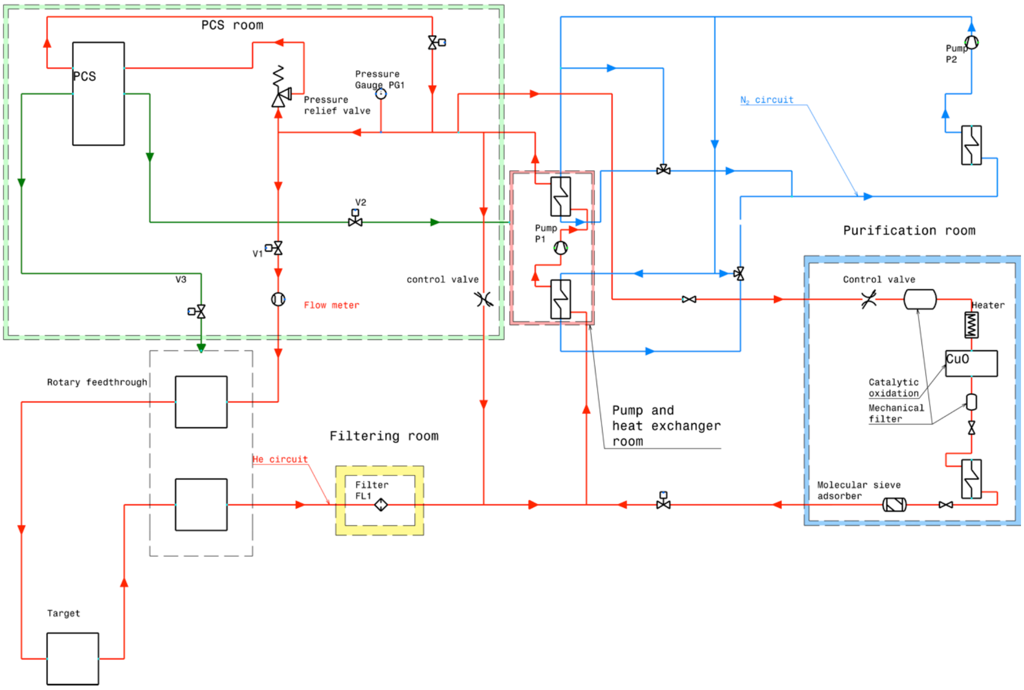


Figure 9. The helium loop and its principal components

The helium loop should deliver a relatively high volumetric flow (~23000m^3.hr^{-1}) at a relatively low pressure (3-4 bar). This aims at releasing constraint on the design of the target envelope and especially the BEW. The structure submitted to the proton flux receives an internal power deposition. The thermal stresses related to this load are directly linked with the thickness of the window. Therefore the aim is to create a BEW with a reduced thickness. However the pressure load from the cooling fluid will contradict this. It is therefore important to minimize the pressure of the cooling fluid.

The top and bottom cover of the target, which are mostly submitted to the pressure load are flat and therefore quite difficult to reinforce against an internal pressure. This is also an important aspect for the optimization of the target, and especially for the neutronic performances of the system.

The high flow rates at low pressure induce high velocity. It is therefore important to assess properly the pressure drop along the loop. Figure 9 presents the global layout of the loop and the place of each component. Table 3 gathers the essential parameters of the helium loop and table 4 summarizes the foreseen pressure drop along it.

Table 3. The helium loop parameters

Parameter	*Units*	Value
Pressure head at the pump	*Bar*	1
Inlet pressure	*Bar*	3
Design pressure (relative)	*Bar*	3.5
Helium mass flow	$kg.s^{-1}$	3
Pumping power	*kW*	800
Bulk temperature at target inlet	*°C*	20
Bulk temperature at target outlet	*°C*	~220
Pipe diameter	*mm*	250 – 300
Pipe total length	*m*	185
Cyclone filter volume	m^3	3.2
Total volume of the loop	m^3	15 – 23

Table 4. Pressure losses along the loop

Pressure drop region	*Units*	Value
The target	Bar	0.3 – 0.4
The shaft	Bar	0.05
Inlet rotating seal	Bar	0.1
Outlet rotating seal	Bar	0.1
Pipes (185m)	Bar	0.1 – 0.2
Filtering system	Bar	0.1
Heat exchanger	Bar	0.2
Total	Bar	~1

3.2. The filtering system

Two kinds of dust filters could be considered. For small particles, standard filters could be used. They should be better placed on bypass loop, as for instance in the so-called purification loop (figure 9). The possibility to use cyclonic filters in the main helium stream is also considered. Such filtering systems are widely used in the industry, even in harsh environment. The high density of tungsten makes it suitable for this type of filter. The products described here are the product from Advanced Cyclone System (ACS) and are the outcome of a pre-design study [10].

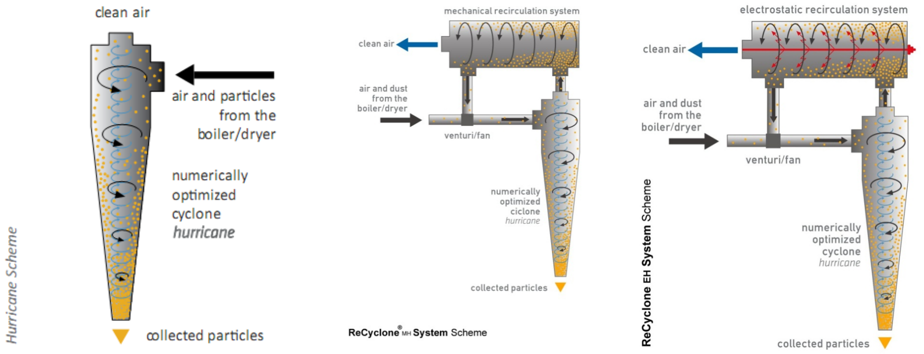


Figure 10. The different systems proposed by ACS increasing the efficiency of particles capture from left to right.

The goal is to capture potential tungsten particles that are flushed away from the target on the helium coolant stream. The proposal consists on the design of a Hurricane System. It is considered to be the simplest, most robust and cost-effective technical solution.

Figure 10 presents the 3 different systems proposed. The efficiency of the global filtering system is increased while adding to a simple cyclone (Hurican) the mechanical ReCyclone. The efficiency could be further increased with an Electrostatic ReCyclone Systems.

The main purpose of the recirculator is to reintroduce the fine non captured particles into the cyclone after those have been driven to the outer walls of the recirculator by centrifugal forces. A ReCyclone MH decreases emissions of Hurricanes alone by 40 to 60%.

The electrostatic recirculation system has successfully proven to further reduce particle emissions. A DC high voltage is applied to the concentrator, allowing the recirculation of very fine particles, more resistant to centrifugal forces, to the cyclone collector. After having been separated in the recirculator and concentrated in the recirculation flow, electrically charged particles are attracted by the cyclone walls, while agglomerating with larger particles entering the system, both promoting an easier capture.

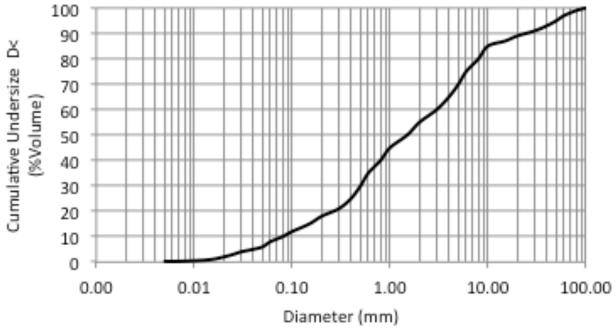


Figure 11. Particle Size Distribution (PSD) used in simulations for the comparison between performance of 3 systems

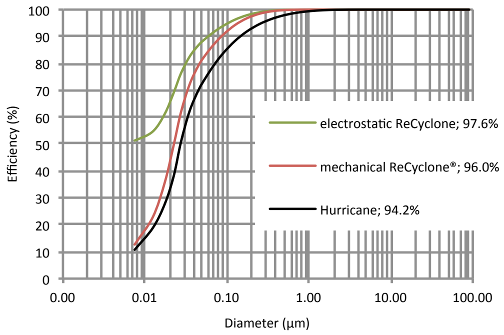


Figure 12. Predicted grade and global collection for tree systems and PSD from figure 11

Table 6. The System specifications and particles emissions

Parameter	Units	Value
Expected emissions	μg.N m^{-3}	0.27
Expected efficiency according to the PSD	%	73.5 to 99.9 (figure 12)
Measured efficiency	%	92.9 to 98.9 [11]
Pressure drop	kPa	1.3

The possibility to have an efficient filtering system with a very low pressure drop to extract the potential dust is demonstrated here (table 6). Some remaining point have to be analysed and especially about the handling issue of the container. There are no showstoppers foreseen in the handling as different system could be proposed. Some key parameters need to be better determined before considering the maintenance routine. The system proposed here has a high efficiency (confirmed by an experience [11]), it is important to highlight that no dust finer than the grain size could be expected (about 10microns). Within this range a simple cyclone arrangement will be very efficient (~100%).

3.3. The pump system

The pump chosen is a multistage helium compressor, as described in the following pictures. This pump is available as a standard product. The price range for the unit required is between 2M€ to 3M€ depending on the customer specification. An important aspect of the compressor performance is the leak rate.

The compressor will have 2 rotating seals where the leak of helium will need to be well controlled. The proposed solution is to have a negative leak rate, so that no Helium from the main loop is leaking out but instead a dedicated supply of helium (green loop in figure 9) provide clean and controlled helium, which is leaking towards the atmosphere. Figure 13 presents the principle of a sealing solution. The enclosure has a pressure of helium slightly higher than the pressure inside the core of the pump. That will insure that the helium would only flow from this enclosure towards the helium loop. Some helium will leak though the last seal towards the atmosphere, but this will be the controlled helium fed by the supply directed to the enclosure. This concept will also be considered for the rotating feed though, which provide the helium from the fixed part of the loop to the rotating target shaft.

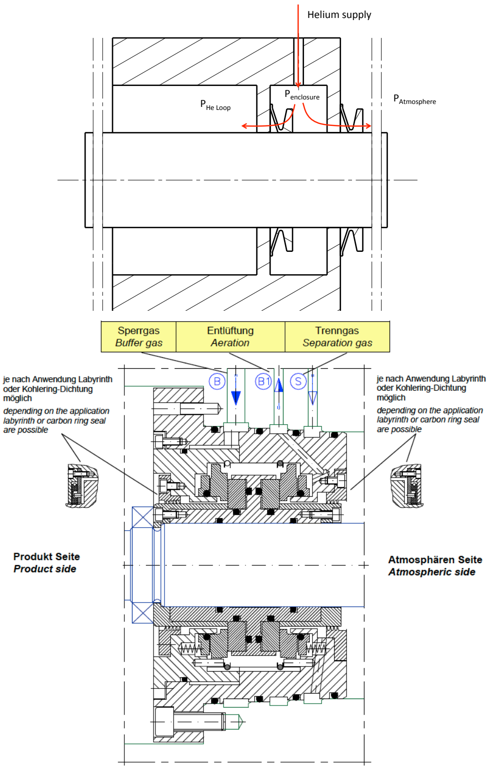


Figure 13. Double seal with a enclosure fed by helium: principle sketch (a) and existing technology from John Crane Ltd.

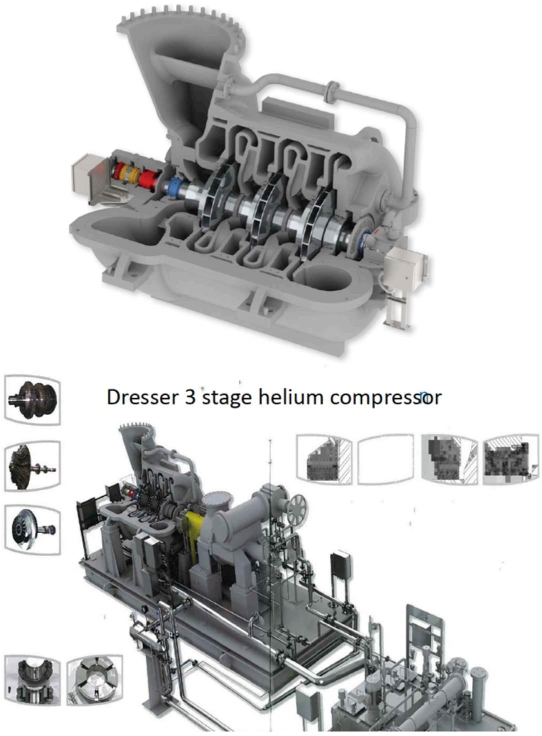


Figure 14. ROOTS Dresser multistage pump

Table 7. The pump of the helium loop

Parameter	Units	Value
Inlet pressure	bar	3
Outlet Pressure	bar	4
Shaft Power	kW	807
Shaft Speed	rpm	11710
Outlet Temp	K	350
Pump system length	m	7.6
Pump system width	m	3.7

Table 8. Leak rate estimation

Parameter	Units	Value
Leak rate	$Nm^3.hr^{-1}$	0.7 - 2.1
Number of 200 bar Helium bottle (50l) for 50 days operation	-	80 - 300
Cost of Helium for 50 days operation	k€	4 - 15

3.4. The leak control system and pressure control

The helium leak tightness is a challenge. The main concept agreed by the ESS design team is to ensure the control of each leak. Where possible the leak will be inversed or negative as previously mentioned.

For instance as described for the sealing of the pump a secondary helium loop link to the Pressure Control and Supply system (PCS) as shown in figure 9. The overload of helium introduced in the loop via this seals will be recuperated in the PCS. This control leak concept will ensure that no helium directly contaminated or in contact with the tungsten will be released. This gas seal system is available technology, especially from John Crane Ltd. The table 8 summarizes the leak rate and the amount of helium required to compensate this leak. A global recuperation system could also be foreseen to reduce the cost impact of the helium leak.

4. Conclusion

The **RO**tating **T**ungsten **HE**lium cooled **TA**rget (ROTHETA) considered, filled with tungsten plates and cooled by low pressure and high velocity helium represents a viable solution for the ESS target. The mechanical comportment of the target structure does not present major issues neither does the spallation material behavior. Further investigations are performed to optimize the cooling performance and reduce the stress level in the structural and the spallation material.

The estimations shown here are only preliminary and detailed analyses of this system are performed within the TSDU project. The ancillaries required for the system are based on good engineering practice and will lead to a robust design.

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