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Progress of the ESS monolith design and engineering solutions for target and moderator systems

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Abstract. The on-going project for construction of the European Spallation Source (ESS), the 5 MW long-pulsed neutron research facility in Lund, Sweden, has entered the phase in which design work and development are focused on realising solutions that shall satisfy well-defined requirements. The Target Station, which converts the pulsed proton beam delivered by the linear accelerator to cold and thermal neutron beams tailored for neutron science applications, consists of several systems. Each of these elements offers unique design challenges for the engineering teams both in terms of providing the necessary primary function and in satisfying complex requirements for physical and functional interfaces between systems. The monolith, which houses the target, the moderators and several other essential systems, shall provide sufficient radiation shielding and retain the internal helium atmosphere properties within specified limits. Some of the associated engineering challenges are to define and meet support and alignment requirements; to find solutions for safe, robust and efficient replacement of components; to choose appropriate yet cost effective materials for the shielding structures; and to create a design that allows the construction to respect a tight installation plan. Within the monolith, the moderator and target systems, whose optimal performance is critical to the overall performance of the facility, present similarly complex design challenges. This paper presents the progress and status of the design work for the ESS target monolith as well as summarising the engineering solutions adopted for the target, moderators and other components and parts of the monolith.

1. Introduction

1.1. Brief description of the ESS project context

The ESS target station, being one of the main parts of the facility, is managed as a project within the ESS programme. Starting with the site decision in 2009, a suite of dedicated sub-projects were executed which through the so called Target Station Design Update (TSDU) project resulted in the description of the target station in the ESS Technical Design Report (TDR) [1], by April 2013. After extensive planning efforts the construction project started in the beginning of 2014 aiming at finalising the facility for delivery of the first neutrons to instruments in 2019.

1.2. General description of the ESS target station [1]

The function of the target station is to convert the intense proton beam from the accelerator into several intense neutron beams, for use by neutron science instruments. This conversion is achieved by the interplay of a number of basic functions. In the heavy metal target the impinging proton beam radiation from the accelerator is converted via the spallation process into fast neutrons as the useful product, while generating a large amount of heat, radioactive isotopes and prompt radiation as unavoidable by-products. The moderator-reflector assembly surrounding the target transforms the fast neutrons emitted by the target into slow neutrons, which are the final form of useful radiation provided by the neutron source, while further radioactive waste is produced by the absorption of neutrons by various target structures. These two neutronically active systems are surrounded by a radiation shielding system of approximately 7000 tons of steel, in order to contain the extreme level of highly penetrating gamma and fast neutron radiation created in the target and its vicinity. The beam extraction system provides intense slow neutron beams through beam guides, which traverse the target shielding. These neutron beam guides are accessible at the surface of the shielding, for delivery to and use at the neutron-scattering instruments facing the beam ports at variable distances. The proton beam window separates the high vacuum in the accelerator from the atmospheric-pressure inert helium gas inside a large container vessel, in which all of these systems are housed. They form, together with the tight container, the target monolith, which takes the shape of an 11 m diameter and 8 m high cylinder.

At ESS, the proton beam will deliver 5 MW power in the form of kinetic energy. About 10% of this energy is converted to mass through the nuclear reactions in the spallation process that produces neutrons, other nuclear fragments, isotopes and gamma radiation. The energy of these particles makes up the remaining 90% of the proton beam energy, and it is almost all deposited within a distance of 1 m from the site of proton beam impact in the target. Different cooling circuits in the target monolith remove this large amount of heat from the target itself (3 MW), from the moderator-reflector assembly (1.2 MW) and from the monolith shielding (0.3 MW). The proton beam window is directly heated by the traversing beam and requires cooling of about 6 kW, though this value is strongly dependent on window design details.

Radiation damage and fatigue limit the lifetime of the three most strongly affected systems: the target, the reflector-moderator assembly and the proton beam window. All of these systems will need to be changed multiple times during the lifetime of the facility, with frequencies ranging between 6 months and 5 years, as conservatively estimated on the basis of available experience at spallation sources. The removed used components represent a considerable amount of radioactive waste. The other part of the radioactive waste consists of gases, volatiles and airborne particles, which will be continuously captured by a variety of efficient filters and traps.

2. Progress in engineering and evolution of the system design

The following subsections describes the current progress and evolution of the design of the monolith systems, the target systems and the moderator and reflector systems, compared to the design concepts for these systems set forth in the TDR [1]. The paper reflects the status of the engineering designs of the systems during the initial phases of the construction project in the autumn of 2014. It should be acknowledged that it is a phase of continuous development towards the preliminary design and further on the final design and construction of the facility.

2.1. Modifications to the monolith systems and choice of concepts

The main functions of the monolith can be summarized as providing shielding sufficient for personal protection and for reduction of signal background for the neutron science instruments as well as confining radioactive inventory both during normal operation and in off-normal situations. In order to satisfactorily perform these main functions several additional supporting functions have to be defined and assigned to the monolith systems. The most important supporting functions are to remove excess heat deposited in the monolith structures during operation, to provide structural support for intrinsic components, plugs and shielding blocks with appropriate and repeatable alignment precision and to allow access for maintenance and replacement in accordance with expected lifetime and reliability of each component and part.

Figure 1 shows the layout and configuration of the monolith systems and the intrinsic target components that were presented in the TDR [1]. This previous design concept featured, so called, light shutters internal to the a large confinement vessel. These internal shutters were envisaged to be operated with drives located on top of the monolith via pull rods penetrating the confinement vessel. The large confinement vessel was also equipped with many other covers and penetrations, separately for each main internal components. Notably the target drive was to be contained in a quite tight housing located very near the cover above the moderator and reflector plug.

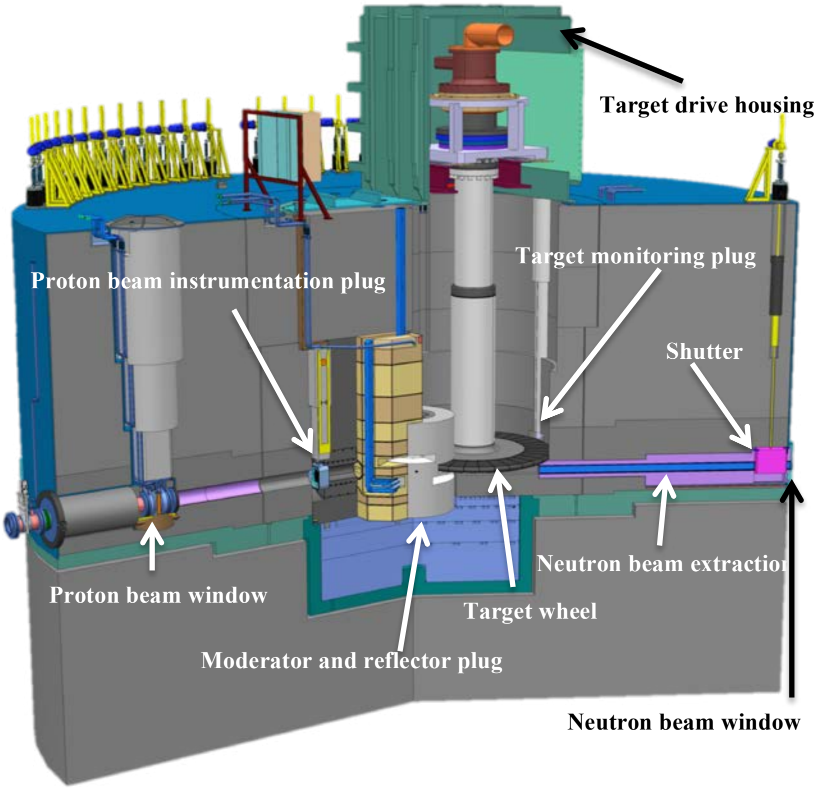

Figure 1. Layout of the monolith as presented in the TDR [1], April 2013.

2.1.1. *Important modifications of the confinement system*. The large diameter of the confinement vessel was found to be inconvenient during the initial planning of the installation since it was located very close to the building concrete structures. In order for the monolith installation to become independent from the building construction works to a larger extent it was decided to consider a smaller diameter for the confinement vessel. The decision to decrease the diameter of the confinement vessel is coupled to the choice of making the light shutters external to the vessel. At the same time it was concluded to be advantageous to merge most of the covers and penetrations into a larger dome with one common vessel head and a cylinder wall with permanent penetrations for pipes, cables and optical paths. The diameter finally chosen for the confinement vessel is approximately 6 m, see the light blue structure in figure 2.

2.1.2. *Shielding system changes*. The most significant evolution of the shielding system, i.e. the steel shielding blocks and parts is the introduction of a lower support cylinder structures for supporting the mass of the upper monolith parts and distributing the forces down to the concrete foundation and base slab. It was decided to pursue an engineering design with well defined steel structures in order to be able to sufficiently predict the behaviour and qualify all parts for all events and load cases, such as installation and test loads, normal operation loads as well as extreme conditions like seismic events.

The introduction of the three support cylinders, together with the central column, as can be seen in figure 2 leads to a significant advantage in that the permanent bulk shielding in between these cylinders does not need to provide any load bearing function. The bulk shielding can therefore be optimized from both a shielding and cost perspective.

An additional advantage of the decrease of the confinement vessel diameter is that requirements on cleanliness and corrosion resistance can be somewhat relaxed for the upper outer parts of the monolith, which is a quite large fraction of the permanent bulk shielding.

Finally, after further and more detailed shielding calculations it was concluded that the optimal diameter of the monolith steel shielding is 11 m, complemented by half a metre of concrete.

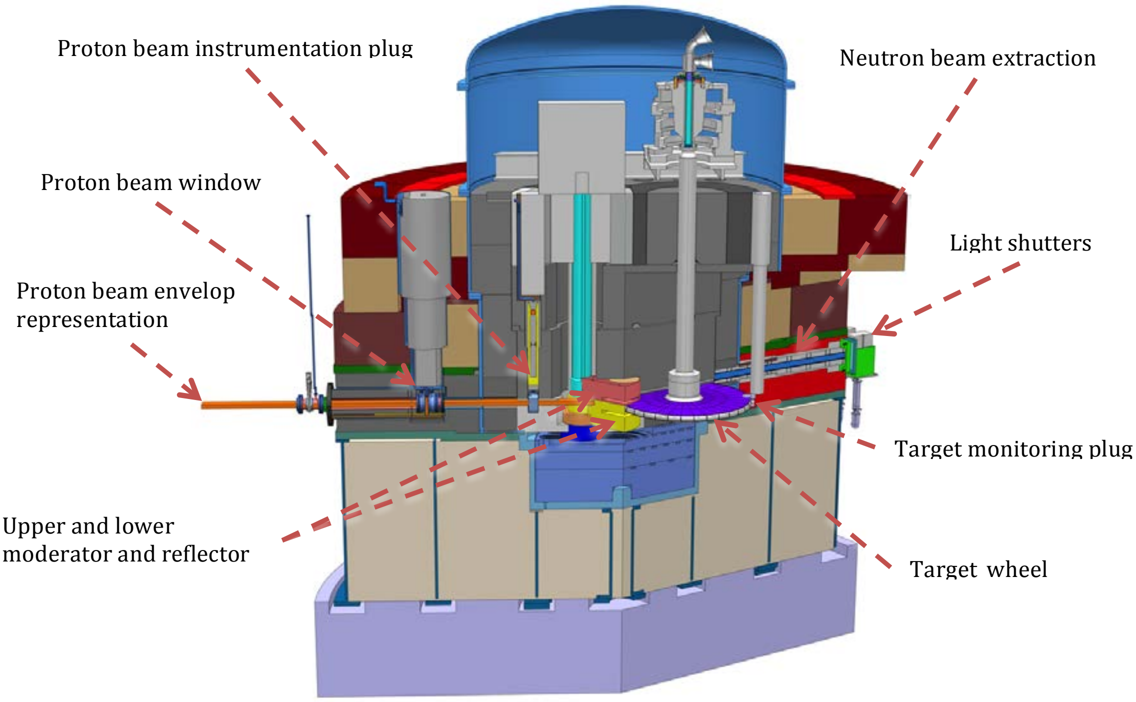

Figure 2. Status snapshot of the monolith layout during autumn of 2014.

2.1.3. *Development status for the monolith systems*. All changes and modifications of the monolith systems, gathered together, have resulted in a much simpler and robust design. It provides high flexibility and is more adapted for instance to the modified MR configuration, addressed later in this paper. A very big advantage and in fact a driver for some of the changes is that the presented monolith layout makes provisions for an installation sequence that will be as independent as possible on the concrete construction works. As a whole the modifications, especially the relaxation of requirements on permanent bulk shielding parts, are in fact part of the strategy to mitigate risks related steel cost variation.

2.2. Important changes to the target systems

The target systems at ESS comprises two main parts. The first part is the target wheel unit which is a rotating disc containing tungsten as spallation material, a long shaft, a motor drive and bearings. Secondly the target primary cooling system that circulates helium for removal of the heat deposited in the wheel unit by the impinging proton beam.

The design of the target systems have not been significantly modified compared to the TDR [1] description of the technical concept, but the target wheel unit as well as the target primary cooling system has been taken to the next level of details. In the beginning of the autumn of 2014 the cooling system passed the preliminary design review tollgate. Likewise, the preliminary design review for the target wheel unit was planned for late 2014. This means that both systems were taken to detailed design by the end of 2014.

The main change for the target systems was the decision to increase the pressure of the helium coolant from 0.35 MPa to 1.0 MPa. The advantages and drawbacks are described below and as a conclusion the benefits of the change of the pressure that has been taken credit for are summarized.

2.2.1. *Advantages of an increased helium coolant pressure*. The most significant advantages with a higher gas pressure is that the power consumption of the helium circulator will be reduced. It also means that the volume flow of helium becomes lower which can be taken credit for either as lower fluid velocities, i.e. lower pressure loss, in the piping system and components or as smaller dimensions of the pipes and components.

2.2.2. *Drawbacks of an increased helium coolant pressure*. The main disadvantages of an increased gas pressure that the static primary stresses of the target vessel will be higher which puts higher demands on the design of the target wheel unit. Also leakage rates in shaft seals, flanges and joints will increase. A minor drawback is that the helium inventory will be larger.

2.2.3. *Credited benefits of increased helium coolant pressure*. The current technical solutions for the target wheel unit as well as for the target primary cooling system, i.e. the solution that have passed the preliminary design review, are effectuating the following advantages of increasing the operating pressure from 0.35 MPa to 1.0 MPa. The circulator will consume considerably less power and the size and cost of the circulator will be significantly smaller. It actually means that there will be more possible suppliers of the circulator since a more conventional product can be chosen.

Also smaller pipes, fittings and other components will be used in the system, keeping the total pressure loss at the same level as for the previous system layout for a lower pressure.

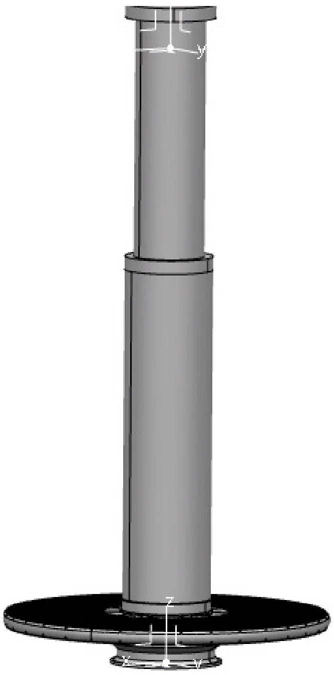

Figure 3. Picture showing the previous size of the target shaft as presented in the TDR [1], April 2013. Total mass of the component was approximately 17 tons.

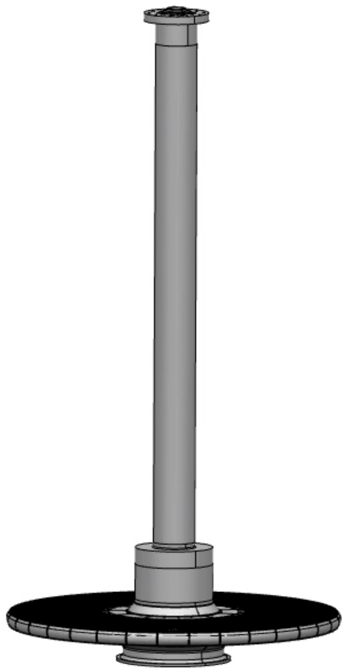

Figure 4. Picture of the current design of the target wheel featuring a smaller size shaft, decreasing the total mass to 11 tons.

The effect on the target wheel unit is, as mentioned, that the design of the pressure sustaining parts like the vessel and connection flanges will have higher design requirements. However, the increased pressure also makes provisions for making the long shaft much slimmer as can be seen in figures 3 and 4. This means that the mass of this component, meaning the entire target wheel unit, can be decreased from 17 to 11 tons which is a big advantage for handling and disposal of a spent target wheel.

For more information on the design changes for the target systems, see [2].

2.3. Evolution of the moderator and reflector systems

Original design and configuration of the ESS moderators and reflectors. The previous MR configuration had two identical "volume" moderators in one single plug. For neutronic performance reasons the viewing angles of each of the two sets of moderators were limited to two opposite 60° sectors. A picture of the original TDR [1] design of the MR plug is shown in figure 5. Figure 6 indicates its position inside the monolith relative to the target wheel. The total mass of the complete MR plug was as high as 24 tons.

Extraction of a double MR plug from its operational position, for replacement, included a horizontal shift of about 1 m followed by a vertical lift. Especially the horizontal shift was considered being a risky step in the handling procedure.

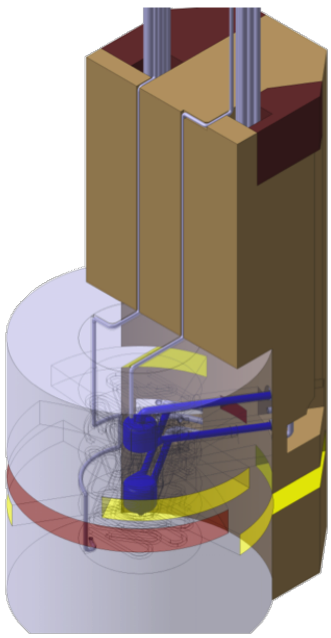

Figure 5. Double MR unit with two integrated identical volume type moderators as presented in the TDR [1], April 2013.

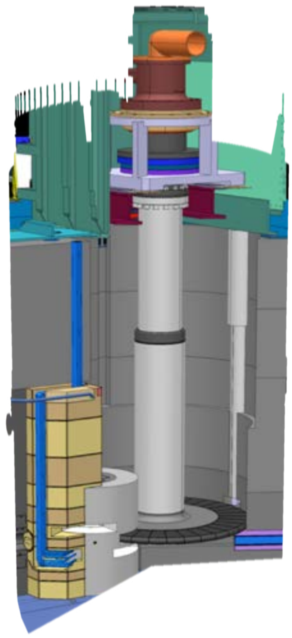

Figure 6. Location of the double MR unit and its configuration with the target wheel inside the monolith.

2.3.1. *The flat moderator concept*. During the neutronic optimization phase of the project following the release of the TDR a concept with a flat moderator was studied and concluded to be worth pursuing for use at ESS. Such a flat type moderator can serve a much larger sector than a volume type moderator. Thus it became an option to either use only one moderator for all instruments or to employ two different types of moderators above and below the target wheel. In any case it was concluded to be beneficial to structurally separate the upper and the lower MR assemblies.

During the spring of 2014 the design team for the ESS target station focused on developing a good engineering solution for a flat moderator. These efforts have resulted in a preliminary design proposal that is depicted in figure 7.

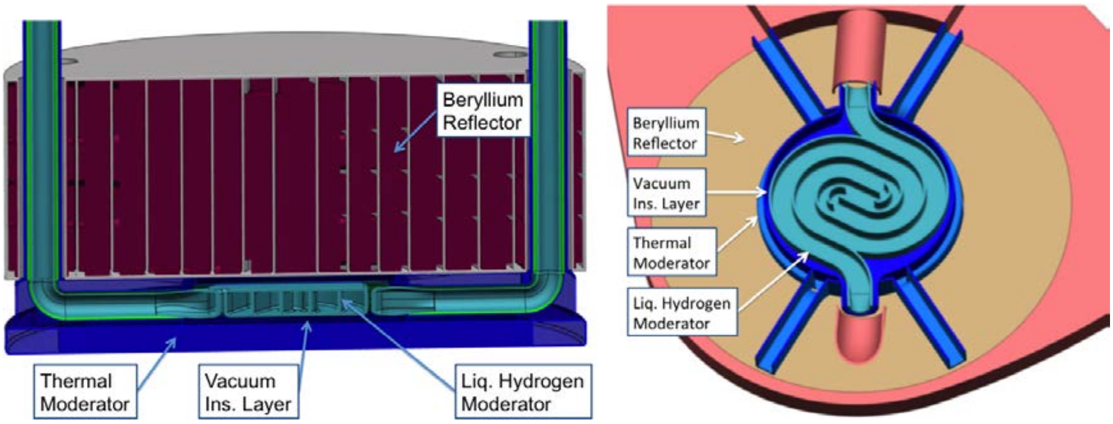

Figure 7. Final preliminary design proposal for a flat moderator, with a central cylindrical cold hydrogen moderator and thermal water moderator wings.

2.3.2. *Flat moderator impact on the MR plug configuration and design*. As indicated above, the decision to change one of the MR assemblies to a flat type moderator led to the need of redesigning the MR plug(s) to be structurally decoupled and possible to handle and replace independently. In fact, it was concluded to be practically impossible to open up as large openings in the reflector structure of the previous double MR plug.

A handful of configuration and design alternatives with separate upper and lower MR plugs/assemblies were studied during the summer of 2014. Several of these studied solution candidates included a simpler, only vertically handled (lifted), upper MR plug together with a lower MR plug with different access path and handling concept. Some of the alternatives that was finally discarded assumed horizontal insertion from one of the experimental halls, inclined insertion from an upstream basement room, vertical insertion to a position upstream the target wheel but offset the spallation hot spot and a wheel like structure that enabled the lower moderator to be rotated from its operational position to a replacement position.

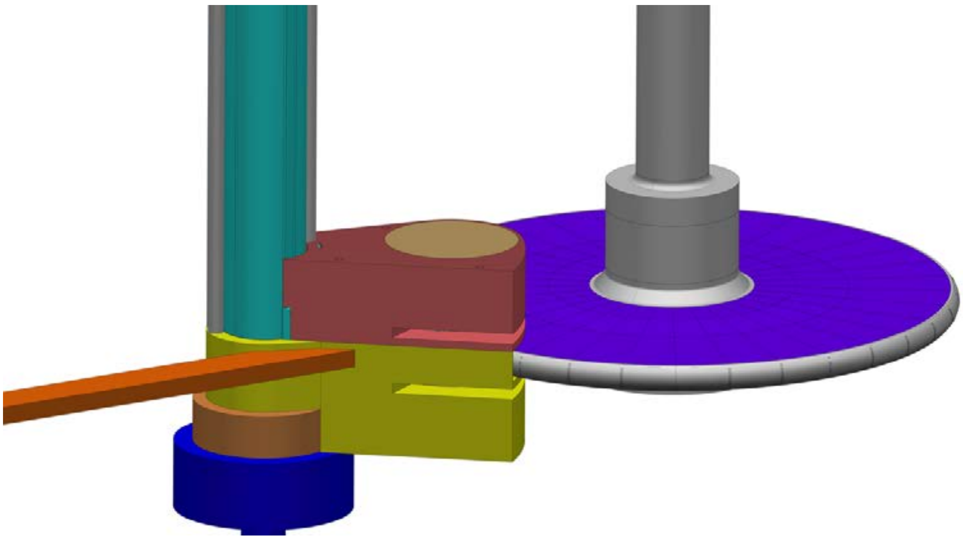

Figure 8. The chosen configuration and design concept for moderators and reflectors, designated with the working name "the double twister".

Figure 8 shows the configuration and design concept for the separated MR plugs that was finally chosen and decided. It features the same replacement and handling scheme for both the upper and the lower MR assemblies with a rotation around a common stationary axis followed by a vertical lift. The upper MR unit (magenta) is connected to the outer annular shaft (turquoise) while the lower MR unit (yellow) is attached to the inner annular shaft (brown).

Further details on the preliminary design for the MR plugs and the handling concept can be found in [3].

References

[1] S Peggs, "ESS Technical Design Report", ISBN 978-91-980173-2-8.
[2] R Linander, U Odén, "Status update on the ESS Target systems development", ICANS XXI paper, TM-P04
[3] D Lyngh, R Linander, "Engineering developments of the ESS Moderator and Reflector systems" ICANS XXI paper, TM-P12