ESS Proton Beam Window Design Update

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Abstract.

ESS target station is devised inside a large vessel that serves as confinement for the atmosphere surrounding main components of the neutron source. Such an environment cannot be in contact with the accelerator one, where ultra high vacuum is needed to guarantee a good transporting media for the 2.0 GeV protons.

The Proton Beam Window (hereon PBW) of the European Spallation source is an intricate component that behaves as a physical separator between the accelerator atmosphere and the target one; permitting to work with both environments and thus selecting the optimal vacuum level at each side.

As the proton beam has to cross the window, scattering interactions will take place inside, releasing a considerable amount of energy of around 6 kW, and distorting the protons’ path. A thin and robust model has been designed while having to accomplish the crucial requirement founded on the desire to intrude the beam in the lowest way possible; besides a cooling system is conceived to evacuate all the power deposited.

Recent discoveries on materials analyzed in other facilities have motivated a design change from the former beam wind model, together with the aim of improving the design and enhance the cooling capabilities to handle the power deposited. Therefore, the former helium-based cooling system has been replaced by light water, providing larger cooling rates and reducing the high design pressure in the old model. The new water-cooled PBW has a thinner cooling channel, as water can lead to undesired beam distortion, what results in a double cylindrical plate shape of 1 mm each, that leaves another 2 mm cooling channel inside. Solution presented includes the thermo-fluid and mechanical analysis of the PBW that led to the above design.

Prototype manufacturing has started, and progress is presented.

Together, the sealing system that will be mounted on to guarantee the requested leak rates has been design ad-hoc for this component, with a robust pneumatic system to actuate remotely and inflatable belows to bring the desired vacuum levels at both sides. Sealing system has also allowed for beam measuring instrumentation to control the beam parameters, and the mounting device and its cabling have been introduced in a modular way to facilitate the operation inside such aforementioned vacuum requirements.

Moreover, a shielding analysis has been also performed to arrive to the final model, which includes neutron streaming evaluation through the cooling pipes, and thermal and mechanical analyses to assess whether an active or passive cooling should be implemented.
1. General description

More than 500 m long of accelerator tube will lead 2 GeV protons to a tungsten target, depositing up to 5 MW of energy in a rotating helium cooled wheel.

UHV is needed inside the accelerator tube to avoid any interaction between protons and gases. The target wheel and surrounding components will be confined into a big vessel, and under-pressurized to avoid any undesired leakages.

To separate both atmospheres, a double plate PBW design, inside cooled by water, is presented.

Protons will enter this atmosphere through the PBW, which aims to preserve beam shape and features by reducing scattering. Such a purpose results in two plates of 1.0 mm thickness in aluminum.

As a result of a 5 MW proton beam crossing the material, around 0.1% of its power is deposited there. In such small piece of aluminum, the challenge is to evacuate all that power, while ensuring a resistant structure to the many loads present in the system.

Several systems will be arranged together not only to guarantee proper cooling, but also to ensure that high level sealing, extremely precise alignment, and complete shielding to avoid neutron streaming, are perfectly gathered in a robust and compact plug that follows RCC-MRx nuclear code regulation rules. A thorough description of this system is presented within this document.

1.1. The PBW system

A vessel is designed to wrap the shielding and pipes, and makes connection with a port block place below. Rough vacuum is made inside the vessel to reduce leakages at the seal.

![Figure 1. General overview of the PBW assembly inside the port block and vessel.](image)

1.2. The PBW and its cooling structural frame

The PBW consists in 2 thin plates separated by a 2mm cooling channel. This plates are 1.25mm and 1.00mm each. It is located at 3.750 m from the target. Cooling channels are machined in a structural Al6061-T6 block, hereon the “frame”, and the PBW is welded to this frame. This system is split into this two components to ease manufacturing procedures.

A 0.3 kg/s water flow rate at 20° is circulated from the pipes above inside the cooling channel, and guided to the PBW plates.
Side supports are made in 1.00 mm thickness to permit deformations and allocate stresses. The outer part of the PBW will be welded to the frame.

![Figure 2. PBW detailed](image)

2. CFD and FEM analyses

MCNPX© nuclear code has been used determine the nuclear deposition in materials, and that power source has been implemented in Computer Fluid Dynamics (CFD) programs. CFD analyses have been performed in water flow, to guarantee that a small 2 mm cooling volume can remove all the heat deposited. Ansys Fluent© with $\kappa - \omega$ turbulence models have been selected to evaluate the fluid behavior.

Once obtained thermal conditions, and ensured the cooling capability, FEM analyses have guaranteed that mechanical stresses are under material limits, the structure won’t suffer from buckling or fatigue, and deformations are acceptable.

2.1. Thermal analyses

Operating conditions of the beam are quite demanding: 14 Hz, 2.857 ms, 67.5 mA peak eventuating in 5 MW power released. Al6061-T6 will be irradiated, unable to accommodate more than 2100 appm of He due to nuclear gas generation; therefore, no more than 60ºC are allowed, to minimize diffusion and prevent from swelling. Every six months of full power operation, the PBW will be removed and completely changed. Coolant pressure needs to be raised up to 5 bar.

![Figure 3. Integrated thermal analyses performed.](image)
2.2. Mechanical analyses

Maximum stresses and deformations are calculated by coupling CFD results to mechanical FEM analysis. RCC-MRx methodology for Class 3 (N3Rx) is applied to the analysis. Model is developed to be resistant to type P, type S and buckling damages.

Mechanical and thermal buckling are studied, and modal analysis are also carried out. Results prove that with such geometry and dimensions, safety factor of more than 3 is achieved in the system, what makes it possible to pass all nuclear regulations while pushing the design to its physical limits.

3. Seal design

Different facilities as J-PARC [1], KEK [2] and PSI have been studied as reference for the sealing design. They make use of a pillow seal to guarantee proper contact between surfaces.

An adapted design for ESS has been developed together with spanish company AWGE© [3].

The seal system consists of a grooved cylindrical surface (Figure 5(a)), with membranes between the grooves. Two inner and outer belows (Figures 5(b) and 5(c)) are inflated to expand the system and approach the sealing faces to their counterparts. Besides, different levels of vacuum are applied to the grooves to generate a vacuum resistance for the flow to pass through. Membranes are inflated with same belows’ pressure, enhancing the contact between surfaces.

Leak rates are expected to be less than $2 \cdot 10^{-5}$ mbar$^{-1}$, considering a UHV atmosphere at the accelerator side, and rough vacuum at the target one.

The full system is mounted as shown in Figure 5(d). Two large flanges will cover the distance between the PBW and the seal, while allocating instrumentation for the proton beam. An aperture monitor will be fed by a vacuum feedthrough from above, cabling the signal up through the 4 m height vessel.

![Figure 4. Complete mechanical analyses.](image-url)
Gaseous nitrogen or helium will be used to inflate the belows, with capability to move the sealing surface \( \pm 3 \) mm in beam direction, and hence permitting to seal by totally remote operations. To remove it, some pressure can be applied to the grooves, as long as a slight vacuum is applied to the belows, retracting them.

The alignment of the system will rely in several guides placed along the PBW frame.

**Figure 5.** Design of the seal for the PBW.

4. **Nuclear shielding, activation and decay heat analyses**

Protons are partially scattered in the PBW, releasing around 0.1% of the beam energy. These interactions produce secondary particles, including neutrons and photons, that escalate dose rates above the system, and have to be properly shielded. Planned removal and replacing operations every six months for the PBW force to unplug and plug the cooling media and auxiliary systems placed above the vessel, where hands-on maintenance is envisaged for such operations. Decay dose rates need to be assessed to guarantee integral safety for workers.

Together, heat deposition analyses are performed to check the needs of active cooling in the seal system.

Isotopic composition is of vital importance for the hot cell storage and segregation operations. Activation has been calculated by ACAB\( ^{\circledR} \) code, and time dependent isotopic contribution to activity is evaluated. Volume independent values permit direct evaluation of future changes in component shapes and geometry.

**Figure 6.** Time dependent isotopic activity in one of the seals.

5. **Prototyping**

Manufacturing of two thin plates for PBW design is a challenge that entails precise operations. High requirements imposed by ESS force to find a high quality manufacturing process which
guarantees every thickness described in the design drawings.

Alongside, a prototype for the seal is envisaged in order to learn from experimental values the most suitable vacuum levels and pressures that will have to be applied to make the leak rates dwindle to lower values possible.

5.1. PBW prototype
A bulk of Al6061-T651 is used for the starting operation. Electrical Discharge Machining (EDM) is used to perform a thin and 200 mm length hole in the place where cooling channel will be machined. Afterwards, Wire EDM (WEDM) is sequentially employed to achieve the final 2 mm thickness and channel shape.

External milling is therefore applied in next step, giving the rounded surface needed without the use of any welds.

Measurement techniques while machining, as 3D probes and ultrasonic measurements, are utilized to control thickness down to 10 microns [4].

![Final prototype 1](image1)
![Final prototype 2](image2)

Figure 7. WEDM operations and final manufactured prototype.

WEDM operations and manufactured prototype are presented in Figure 7. Final geometry has been achieved avoiding any welds, and removing any weak point in the structure, as it eases RCC-MRx regulation.

6. References
[1] Meigo S and Teraoku T 2015 Proton Beam Window Assembly Tech. rep. J-PARC
[2] 2015 New milestone at MUSE Tech. rep. KEK, MUON Science Lab
[3] Mirapeix F, Guerra D, Pérez N et al. 2017 Vacuum Seal design for the PBW Tech. rep. AWGE
[4] Rey A 2017 PBW Manufacturing preliminary proposal Tech. rep. Leading