3.3.1

Thermal Hydraulic and Thermo-Mechanical Design of the Proton Beam Window for ESS

J Wolters[1, 4], M Butzek[1], B Laatsch[1], Y Beßler[1], G Natour[1], P Nilsson[2] and P Sabbagh[3]
[1] Forschungszentrum Juelich GmbH, 52425 Juelich, Germany
[2] European Spallation Source ESS, Lund, Sweden
[3] DAES Development of Advanced Engineering Solutions, Geneva, Switzerland

E-mail: j.wolters@fz-juelich.de

Abstract. The proton beam window for the European Spallation Source ESS will separate the 1 bar monolith helium atmosphere and the accelerator vacuum. In medium power spallation sources like ISIS, SINQ or the SNS source in Oak Ridge, cylindrical or spherical double walled water cooled windows are used, but during the design of the beam window for the spallation source SNS it became obvious, that this concept is already pushed to its limits at a beam power of 1.4 MW. A novel design concept called pan-pipe design was proposed for the ESS-PBW, which is optimized for high coolant pressures – as helium is the designated coolant for the PBW at ESS - and the typical pressure difference of 1 bar over the window. In the present study the detailed thermo-mechanical design of the PBW made of aluminium is shown. The main focus of the investigations was set on fatigue loading due to mechanical and cyclic thermal loads and on an optimized flexible interface between the PBW and its massive frame.

1. Introduction

The ESS proton beam window will separate the 1 bar monolith helium atmosphere and the accelerator vacuum. In 2003 a novel design concept called pan-pipe design was proposed for the PBW for higher beam powers [1]. This design was optimized for high coolant pressures and the typical pressure difference of 1 bar over the window. Due to the interim stop of the ESS-project in 2003 only very rough investigations were shown in [1], which were now adapted to the current ESS conditions – e.g. helium as designated coolant medium and new proton beam parameters - and further particularized for this report.

This report concentrates on thermo-mechanical stresses and fatigue due to normal operation conditions. Off-normal loads were only considered with respect to the thermal layout so far (cp. chapter 3). In a next step all possible load cases - including faulty conditions - and their impact on the life-time of the PBW have to be investigated in detail.

---

[4] To whom any correspondence should be addressed.

2. Pan Pipe Design

The pan-pipe design is shown in Figure 1. Basic drivers for the design of the beam window are

- cooling: window material is subjected to volumetric energy deposition by the proton beam and by scattered neutrons from the surroundings and the target
- mechanical strength: mechanical loads imposed on the window material are the coolant pressure and the pressure difference between the helium atmosphere and the accelerator vacuum
- radiation damage: basically driving the life time and thus the handling frequency
- defocusing: proton beam will be scattered by the window material

Al6061-T6 [2] was chosen as the preferred material for the window because of its low density, which guaranties a good transmissibility for protons and a moderate heat deposition, and its good mechanical properties. On the other hand this choice limits the maximum temperature to approximately 100 °C, because at higher temperatures (>130 °C) the material will lose its tempered state in a long term and consequently its strength.

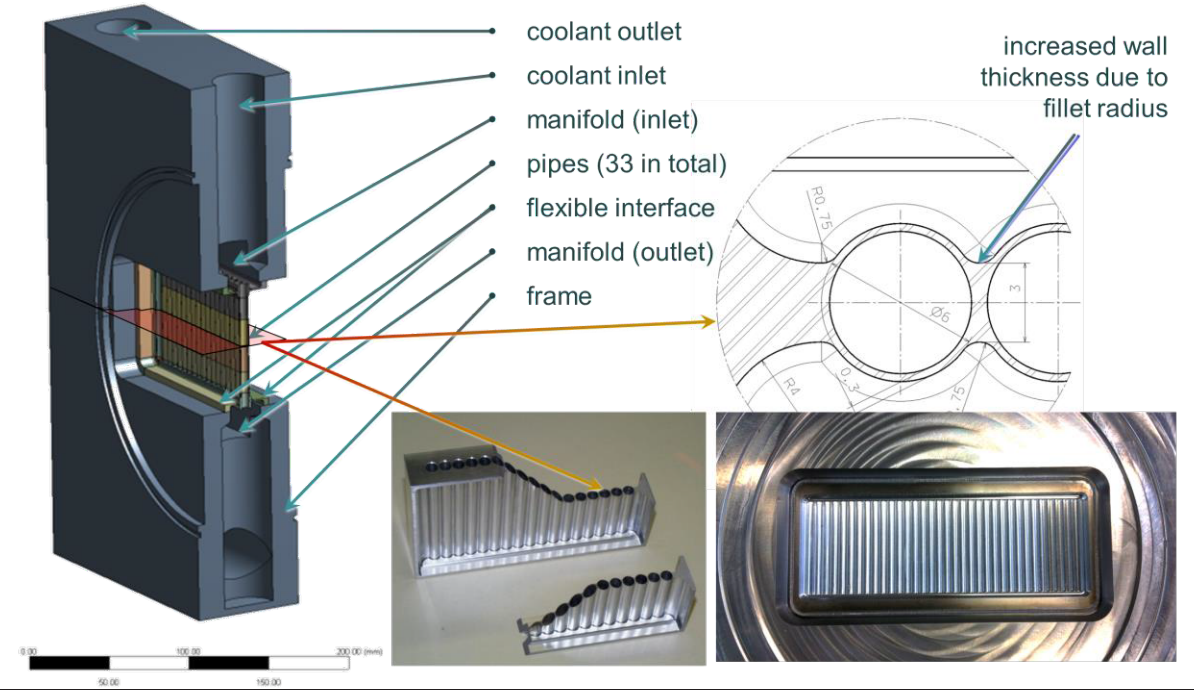


Figure 1. Pan-pipe design: The window itself consists of 33 pipes, each 6mm in diameter, and a flexible interface to the massive aluminium frame. At present manufacturing and welding tests are carried out at Forschungszentrum Jülich GmbH, ZEA-1 (bottom right figures)

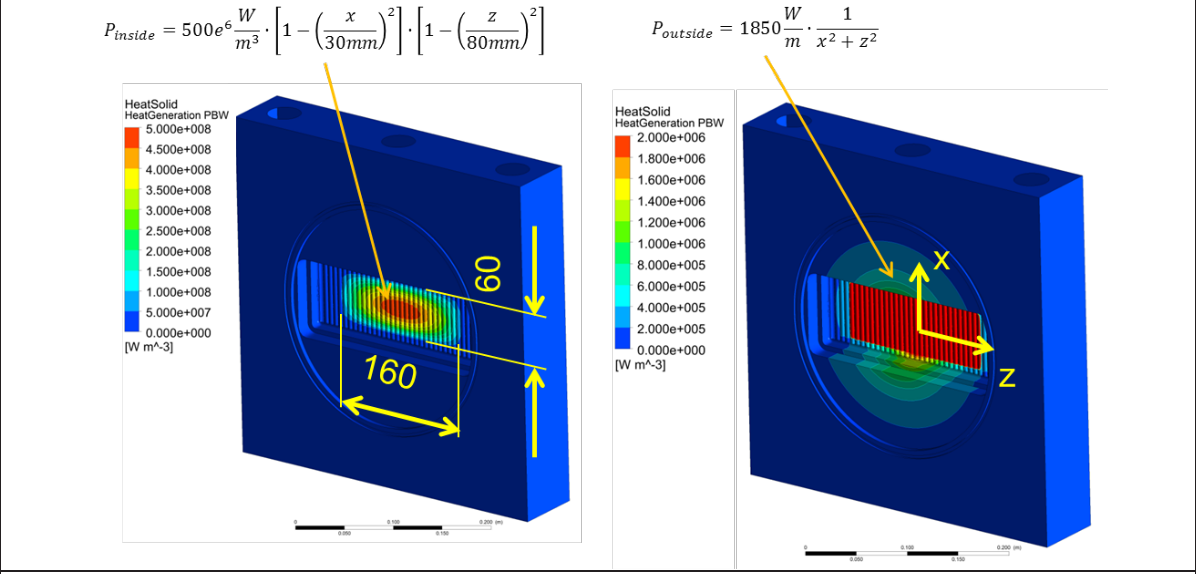
The current design focuses on minimizing the wall thickness to be cooled by using an array of small pipes – 33 in total - connected to each other. The single pipes with an outer diameter of 6 mm and a wall thickness of only 0.3 mm are suitable to resist the high coolant pressure of 10 bar, that will lead to circumference stress in the pipe walls, and the pressure difference of 1 bar between the monolith helium atmosphere and the accelerator vacuum, that will lead to bending stresses in the PBW. The clamping of the PBW in its massive frame is flexible in vertical direction to allow the pipes to thermally expand in longitudinal direction. Moreover the tilting effect at both ends of the pipes due to the deflection of the PBW is compensated by the flexible clamping. Thus the stresses in the PBW within the beam footprint could be reduced significantly and the zone of maximum thermo-mechanical stressing could be transferred to the flexible interface. This is important since radiation damage will degrade ductility and fatigue resistivity of the material within the beam– which is still a point that has to be investigated carefully in the near future.

The flexible interface of the PBW is built into a massive aluminum block containing the cooling connections (cp. Figure 1). The central borehole in the massive aluminum frame is the helium inlet and the helium will leave the configuration through the two boreholes on the side. In order to distribute the helium flow to all single pipes and to collect it again after having passed the window, manifolds are foreseen above and below the PBW.

Manufacturing of the window will be performed by machining the outer contour of the pipes from a solid block of aluminum, followed by drilling holes of a diameter of 5.4 mm leaving a wall thickness of 0.3 mm. Thus there is no need for using joining techniques like brazing or welding in the zone suffering most from proton beam radiation. Figure 1 shows a first proof-of-manufacturing window from the year 2003 to analyse to tolerances regarding the wall thickness and a current test weld of a prototypic window in its massive frame.

3. Thermal layout

In order to determine thermal stresses for the whole PBW configuration a detailed CFD (Computational Fluid Dynamics) model was set up in ANSYS CFX [3], which includes all relevant solid parts as well as the coolant passages of the configuration. The thermal-hydraulic calculations on the PBW were performed for the reference mass flow rate of 0.2 kg/s, a helium inlet temperature of 20 °C and a parabolic heat deposition profile (cp. Figure 2, left side). The peak value of the applied time-averaged heat deposition profile is 0.5 kW/cm³, which is a conservative value for the nominal beam. The half width of the beam footprint is 80 mm and the half height is 30 mm [4]. Outside the beam footprint a heat deposition distribution which decreases with the distance to the beam axis to the second power and which results in a maximum power density of about 1 W/cm³ in the massive frame of the PBW is considered (cp. Figure 2, right side). The power density during the pulse is determined by the time averaged values scaled by 1/f/tpulse = 1/14 s^{-1}/2.86 ms ≅ 25, while in between the pulses no thermal load is considered.



$$P_{inside} = 500e^{6}\frac{W}{m^{3}}\cdot\left[1-\left(\frac{x}{30mm}\right)^{2}\right]\cdot\left[1-\left(\frac{z}{80mm}\right)^{2}\right]$$

$$P_{outside} = 1850\frac{W}{m}\cdot\frac{1}{x^{2}+z^{2}}$$

Figure 2. Time averaged heat deposition profiles within (left) and outside of beam footprint (right)

Turbulence is modelled by using the kω-SST model [5]. For aluminum constant material properties according to [6] were used, while for helium pressure and temperature dependent values according to the formulas given in [7] and [8] were used.

The results of the thermal hydraulic calculation with respect to the coolant flow and the temperatures in the PBW are shown in Figure 3, left hand side. The maximum temperature after a pulse is about 65 °C for nominal loading conditions. The temperature increment in the centre of the beam window due to the pulsed operation is about 14 °C. For off-normal conditions, which are given by a slightly focused beam footprint of 140 mm x 50 mm and a maximum beam shift of 6 mm [4], the maximum temperature can go up to 80 °C (not shown in Figure 3).

In case of a beam trip it takes only about half a second till the structural material of the PBW is cooled down to coolant temperature again (cp. Figure 3, right hand side). Thus even for short beam trips (< 1 s) a full beam trip stress cycle has to be considered in the fatigue analysis.

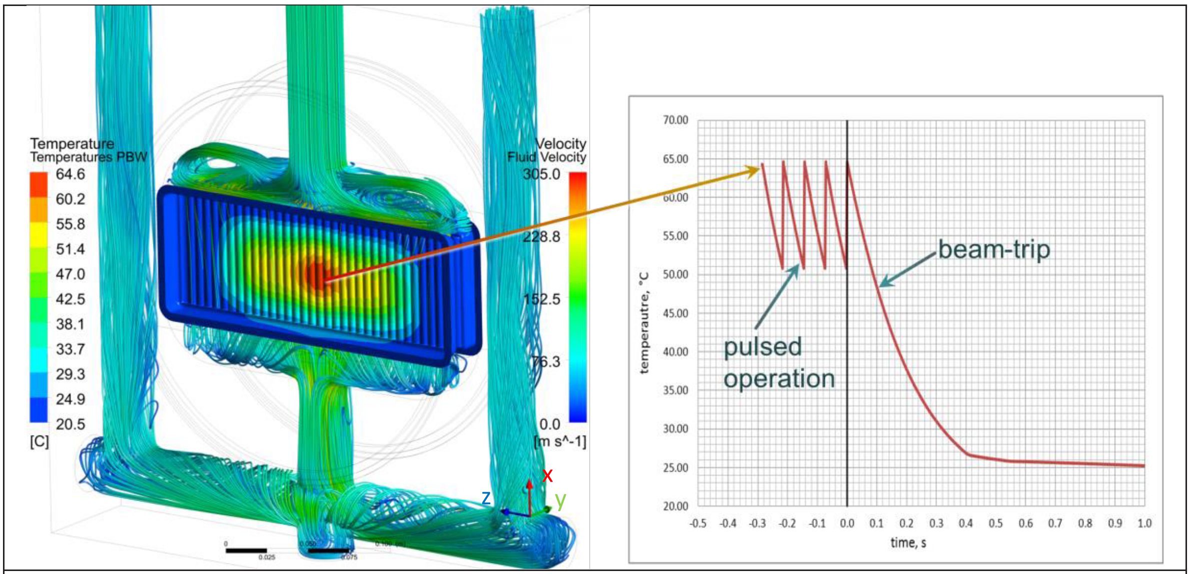


Figure 3. Results of thermal-hydraulic calculation

4. Thermo-mechanical layout

The thermo-mechanical simulations were performed with ANSYS Workbench [9], using the imported fluid pressure and temperature distribution from the CFD calculation. Moreover the pressure difference of 1 bar over the window was applied to the mechanical model.

The clamping of the massive frame of the PBW is considered by simplified boundary conditions. On the one hand the surfaces on the sides of the massive frame are fixed in x- and y-direction and are not allowed to rotate about the z-axis, while they can still deform. This is realized by so called ‘remote displacements’ with a ‘deformable’ behaviour. These boundary conditions simulate the lateral guidance of the frame. Moreover for both sealing grooves of the frame rotation about the x-axis was suppressed and a rigid behaviour was used for the corresponding ‘remote displacements’, in order to consider the stiffness of the connected flanges. More precise boundary conditions will be investigated later on, when the detailed design of the frame and its surrounding is fixed. Anyway, the expected impact on the results for the PWB is small.

With respect to the applied temperatures three different cases were investigated, which are necessary to assess the fatigue limit:

- thermal state prior to a pulse,
- thermal state after a pulse and
- uniform coolant temperature after a beam trip.

The single pipes of the PBW are well designed to withstand the coolant pressure of 10 bar and the bending due to the pressure difference of 1 bar between the helium atmosphere in the monolith and the accelerator vacuum, what can easily be shown by analytical formulas for bending and pressurized pipes. The main optimization task was to design the flexible interface between the single pipes and the stiff frame, which is on the one hand flexible enough to reduce local stresses due to the clamping of the pipes and to compensate the thermal expansion of the PBW and which is on the other hand stiff enough to bear the mechanical loads. Moreover the design mustn't be too complex in order to guarantee easy manufacturing. In Figure 4 deformations for the PBW and its flexible interface are shown just due to the pressure loads (left side) and due to the additional thermal expansion of the PBW after a pulse (right side). An amplification factor due to the short-time heating up of the PBW during the pulse is not considered and can be neglected since the period time of the first eigenmode at 3800 Hz is one order of magnitude shorter than the pulse time.

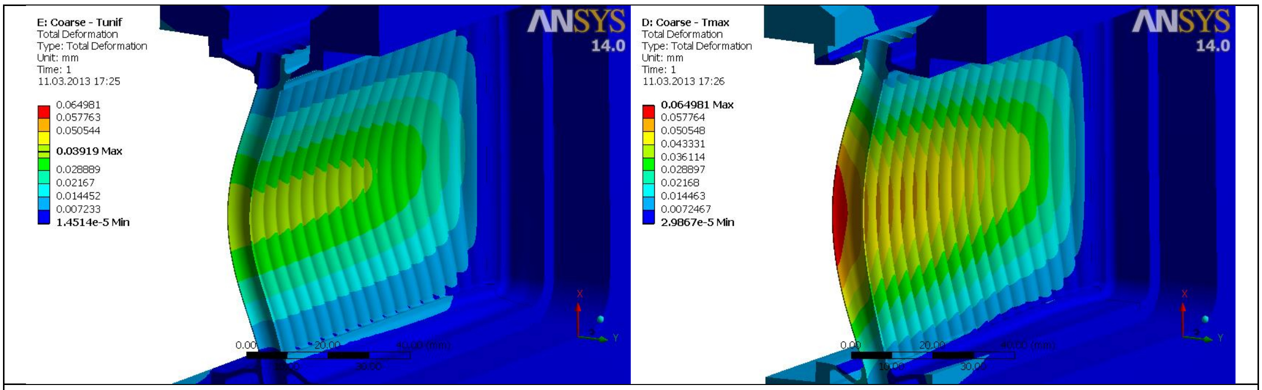


Figure 4. Deflection of the PBW; left side: just due to pressure loads; right side: due to thermal and pressure loads

In Figure 5 the stress distribution (equivalent stress) is shown for the global model – again just due to pressure loads (left side) and due to the additional thermal expansion of the PBW after a pulse (right side). It is obvious that within the single pipes of the PBW the primary stresses due to the pressure are far below the allowable stress of $S_m = 87$ MPa [10], while due to the thermal loads and the resulting lateral thermal expansion the single pipes will be additionally stresses by an ovalization. This will lead to stresses in the pipe walls of about 65 MPa (Figure 5, right side). But even this value is far below the allowable primary membrane and even more below the allowable membrane plus bending stress of $1.5\ S_m = 130.5$ MPa [10].

The maximum stress will occur in the flexible interface between the window and its massive frame. Here a refined sub-model was used to precisely resolve notch stresses for the following fatigue analysis. The maximum stress in the flexible interface arises if the maximum temperature after a pulse is applied. Again, the maximum value of 98 MPa in Point A (shown in Figure 6) is even below the allowable primary membrane plus bending stress. Without thermal loads Point B is highly stressed due to the deflection of the PBW and the resulting tilting in the flexible interface. Here the maximum stress is less than 86 MPa. It is also obvious that for those two points the stress state will change significantly with the thermal load. As a consequence these two points are of special interest for the fatigue analysis, particularly because the dominant stress component in y-direction is a tensile stress.

For point C of the flexible interface significant cyclic stresses will also occur for pulsed operation and beam trips, but here the dominant stress component is pressure which is less critical with respect to a complete failure due to crack initiation.

For point D the calculated equivalent stress is in the range of the maximum bending stress of the flexible interface, but here the stress state does not depend so much on the thermal load. Therefore this point is non-critical with respect to fatigue.

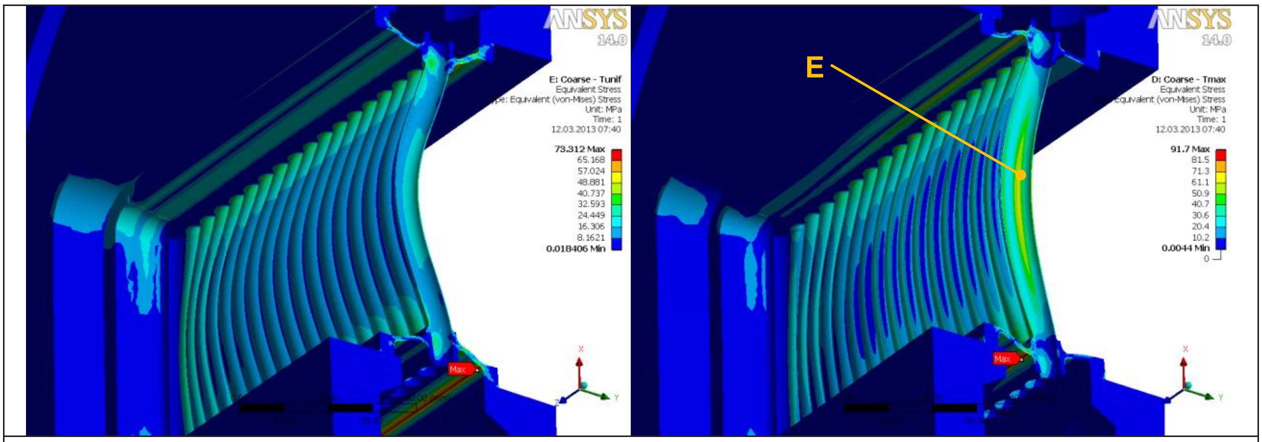


Figure 5. Stresses (equivalent) in the PBW; left side: just due to pressure loads; right side: due to thermal and pressure loads

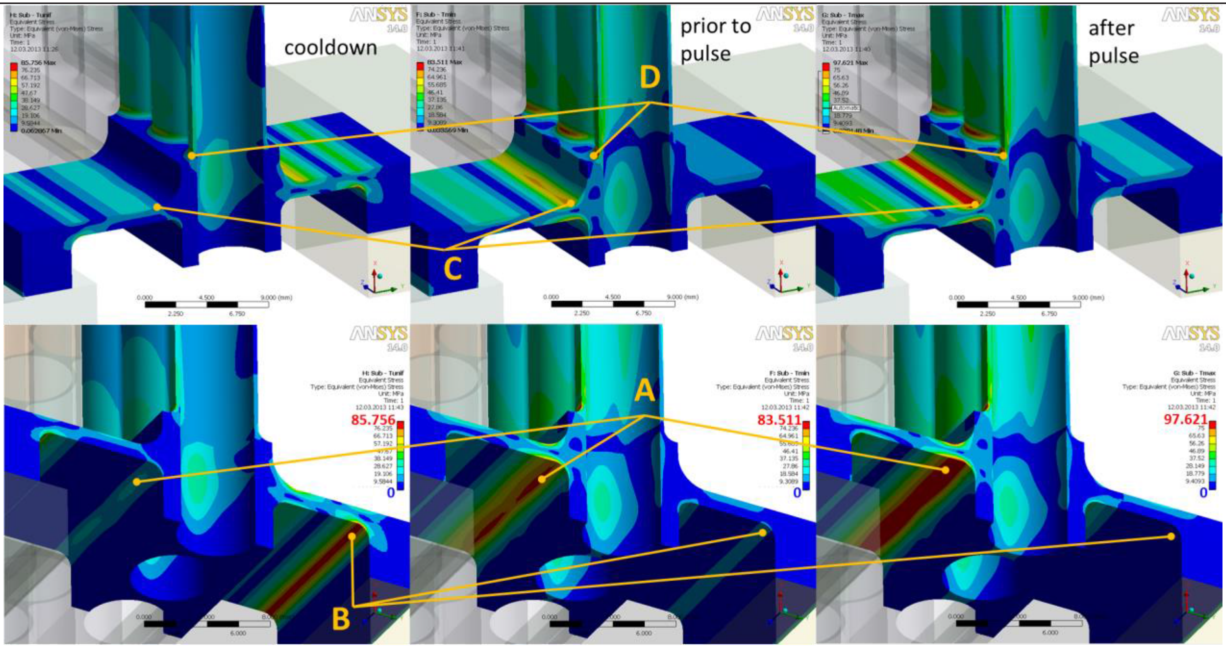


Figure 6. Local stresses (equivalent) for the refined sub-model

For the fatigue analysis two load cycles are considered. Regarding the pulsed operation the two stress states prior to a pulse and after a pulse are compared and corresponding mean stresses and stress amplitudes were determined. For beam trips the stress states after a pulse and after cool-down are compared.

With respect to the pulsed operation 242 days of operation per year have to be considered [11], which results in about $3 \cdot 10^8$ stress cycles if the PBW is replaced only once a year - according to [11] this is the final goal, while changing the PBW twice a year is the current specification. The number of expected beam trips per year is about 29000 according to [11].

The fatigue analysis is based on the FKM design rule [6] using a safety factor of 1.6 for the components endurance strength. The results are shown in Table 1. In general the degree of utilization for the flexible interface is larger for the considered 29000 beam trips than for the pulsed operation. The maximum degree of utilization occurs for point B (cp. Figure 6) and is 27.4 % due to the pulsed operation and 51.5 % due to beam trips. The sum of both values is well below 100 %.

For point E (cp. Figure 5) the resulting degree of utilization is 42.5% and therefore much lower than for the flexible interface. But one has to take into account, that this point is located within the beam footprint and is exposed to a higher radiation damage, which is up to now not considered in the analysis.

Table 1. Resulting degree of utilization with respect to fatigue according to the FKM design rules

	Point	A	B	C	D	E
degree of utilization [%]	pulsed operation	25.6	27.4	19.5	5.9	21.6
	beam trips	45.3	51.5	45.9	16.8	20.9
	total	70.9	78.9	65.4	22.7	42.5

5. Summary & Outlook

The ESS proton beam window was designed to withstand thermal loads due to a 5 MW proton beam and mechanical loads due to the necessary coolant pressure and the pressure difference over the window of 1 bar. In the present report it was shown, that the foreseen helium cooling at 10 bar pressure using a mass flow rate of 0.2 kg/s is sufficient to keep the aluminum temperature well below the maximum design temperature of 100 °C for normal and even for off-normal beam conditions.

The thermo-mechanical analyses have shown that the flexible interface between the PBW and its massive frame is well designed to compensate thermal strains in the thin-walled pipes of the PBW. Due to the flexible interface the maximum stress within the thin pipes of the PBW could be reduced to a maximum value of about 65 MPa for normal beam conditions. The stresses in the flexible interface are higher, but this region is not directly hit by the proton beam and moreover the wall thickness here is considerably higher than the thickness of the pipes of the PBW. All stresses are well below the allowable stresses.

With respect to fatigue the analysis were made according to the FKM design rules. The most relevant zones are located in the flexible interface. Here the maximum total degree of utilization is about 80 %, considering one year of operation. Less critical are the thin-walled pipes of the PBW. Here the total degree of utilization is about 43 %, not considering a possible radiation induced decrease of the endurance strength here.

At present manufacturing and welding tests are carried out for the PBW and its frame at the Central Institute for Engineering, Electronics and Analytics in Jülich. In these tests welding parameters are optimized to get a vacuum-tight connection between the PBW and its massive frame and to improve the quality of this connection.

For the next step with respect to the PBW design a thin coating of the PBW, which will be used for beam-diagnostics, has to be specified and considered in the calculations. Moreover faulty conditions have to be investigated in order to assess measures that are needed to safely handle such conditions. Here the most important aspects are how quick faulty conditions have to be detected and how fast the beam has to be switched off to prevent the PBW from complete failure.

Once the design of the PBW and its frame is completed, the calculations have to be adapted and finally the fatigue analysis has to be carried out according to MCC-MR, considering radiation damage of the material.

6. References

[1] M. Butzek, T. Kulessa and J. Wolters, *Proton Beam Window for High Current Densities,* ESS-Report No. ESS 03-147-T, 2003.

[2] S. Peggs and R. Kreier, *ESS Technical Design Report, Release 1.0 (under active development),* November 28, 2012.

[3] ANSYS., Inc, *ANSYS CFX 14.0,* Southpointe, 275 Technology Drive, Canonsburg, PA 15317, November 2011.

[4] P. Nilsson, *Proton Beam Window Loads,* Lund: ESS AB, 2012.

[5] F. R. Menter, *Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications,* AIAA Journal, vol. 32, no 8., pp.1598-1605, August 1994.

[6] Forschungskuratorium Maschinenbau, *FKM-Richtlinie: Rechnerischer Festigkeitsnachweis für Maschinenbauteile,* Frankfurt am Main: VDMA Verlag GmbH, 1998.

[7] KTA, *Sicherheitstechnische Regel des KTA, KTA 3102.1, Auslegung der Reaktorkerne von gasgekühlten Hochtemperaturreaktoren, Teil 1: Berechnung der Helium-Stoffwerte,* BAnz., Juni 1978.

[8] Helge Petersen, Danish Atomic Energy Commission, Research Establishment Riso, *The Properties of Helium: Density, Specific Heats, Viscosity, and Thermal Conductivity at Pressures from 1 to 100 bar and from Room Temperature to about 1800 K,* Riso Report, September 1970.

[9] ANSYS Inc., *ANSYS Workbench 14.0,* November 2011.

[10] AFCEN, *RCC-MRx code (draft), Section III - Tome 1 - Subsection B: Class N1Rx Reactor Components, its Auxiliary Systems and Supports,* December 2010.

[11] P. Sabbagh, *Cycle assumptions for fatigue analysis,* Lund, Sweden: European Spallation Source ESS AB, EDMS ID Number 1225592, 2012.