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Workpackage 3

The X-ray Source

Front-End thermal analysis

D 3.3

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INTRODUCTION

Work package 3 "X-ray source" of the H2020 project BEATS deals with the choice of the optimal type of photon source and its design as well as with the design and the selection of the Front-End components needed for the beamline to be operated safely. Some of these components must be designed to dissipate the heat generated by the photon beam. The thermal characterisation of these components constitutes deliverable (D3.3) of the work package.

This document provides a general overview of the thermal models used to calculate, via finite element analysis (FEA), the *operando* temperature and stress distribution of the water-cooled components of the Front-End. These components (crotch absorber, fixed mask, photon shutter, primary slits and CVD window) allow to confine and/or stop the photon beam. They are designed following the state-of-the-art of nowadays Front-End concepts.

In what follows we report on the general principles of the thermal models used as well as approximations adopted for heat load and thermal transmission by conduction and convection. The thermal cases studied and reported in this document are based both on normal synchrotron operation conditions as well as assumptions for a worst case. All thermal modelling simulations were carried out using the ANSYS Workbench environment [2].

The most important and most challenging item in terms of heat dissipation is the crotch absorber, which has to absorb up to 4.5 kW, but also other devices are crucial. The results of the simulations presented here will be important input parameters for the preparation of the Front-End components' specifications.

The simulations presented here are carried out for the currently used initial design of the Front-End components and will then be refined once the final fabrication design of the aforementioned components is established during the procurement process.

A summary and explanation of the results of the analysis is also reported and commented.

DESCRIPTION OF THE ANALYSIS PROCEDURE AND FRAMEWORK

The design of the Front End

The Front-End represents the first part of the beamline and is confined in the storage ring tunnel.

It has a key role, as it absorbs undesired radiation (and its thermal load) emitted in the direction of the beamline during injection and operation, thus ensuring personnel safety during experiments. It provides the beam collimation, prevents the white x-ray beam from impinging on unprotected and uncooled surfaces; it allows to extract the useful part of the x-ray radiation, to shape it and to fully stop it, in case access to the beamline components downstream is required in full safety. Furthermore, the Front-End assures the integrity of the storage ring vacuum.

Figures 1 and 2 show the layout of the Front-End components for the BEATS beamline.

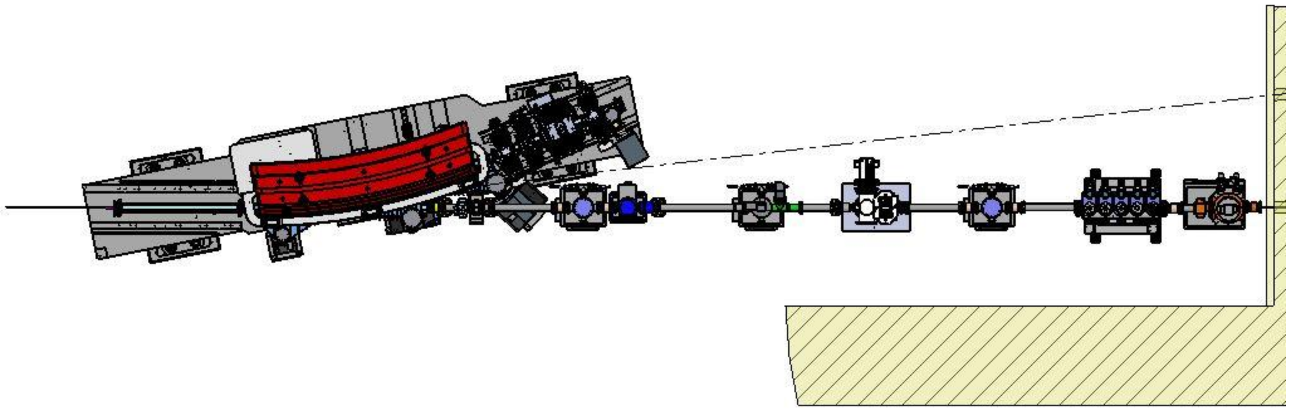

Figure1. Top view of the Front-End.

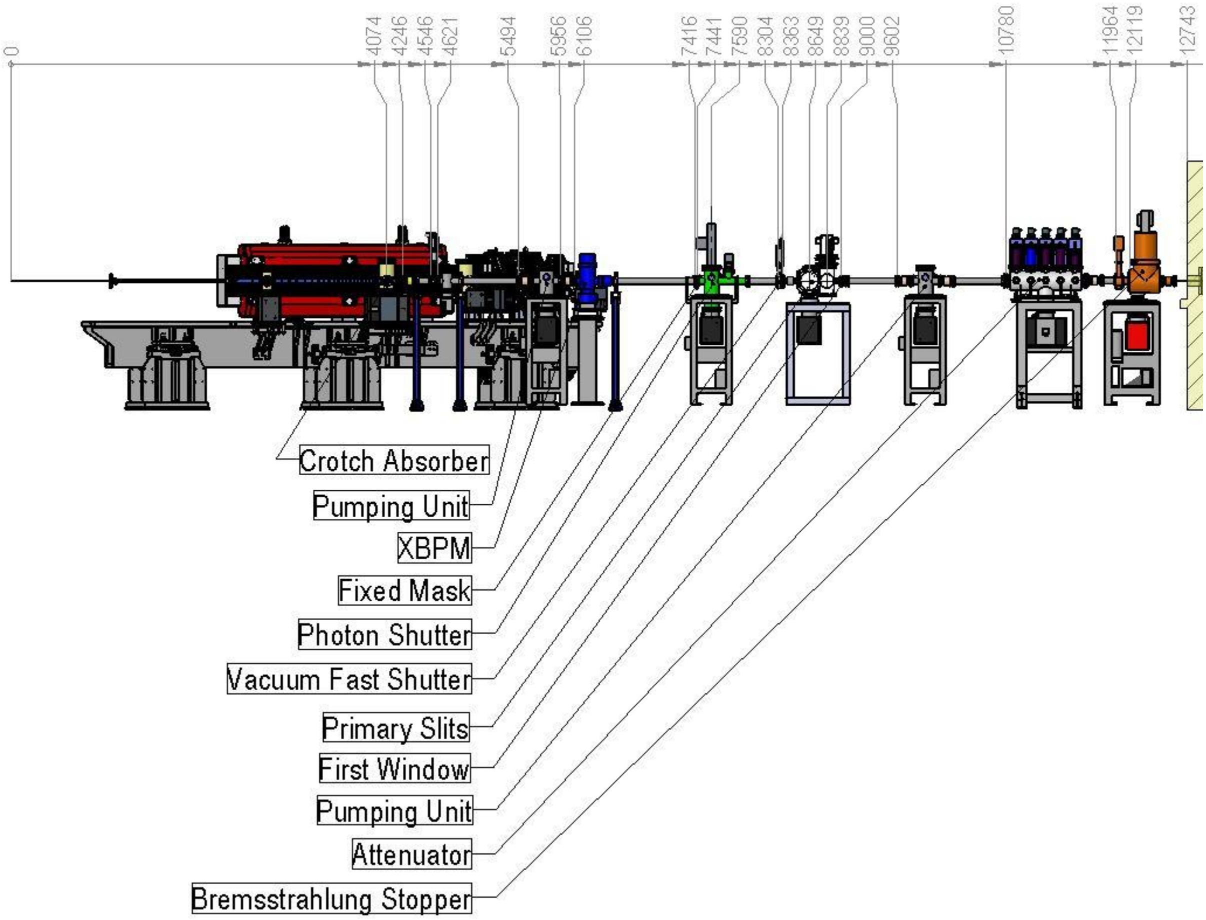

Figure 2. Side view of the Front-End.

The main components of the Front-End are the following:

- **Crotch Absorber**, is used to protect downstream UHV chambers and Front-End components from synchrotron radiation emitted by the 3-pole wiggler and the adjacent dipole magnets. It is made of glidcop and is water-cooled.
- **Pumping unit,** ensures to maintain a vacuum level down to $5x10^{-10}$ mbar within the Front-End by means of two ion pumps (75 l/s and 300 l/s).
- **X-ray Beam Position Monitor** to determine the vertical position of the center and the profile of the white x-ray beam.
- **Fixed Mask**, the first collimating element after the crotch absorber, which defines the beamline's aperture and reduces the downstream beamline components' heatload. The fixed mask is made of water-cooled copper.
- **Photon Shutter**, a cooled OFHC copper blade that is designed to intercept and absorb the complete white beam and to protect the downstram components, in particular the vacuum fast shutter.
- **Vacuum Fast Shutter**, which protects the storage ring vacuum integrity by separating the beamline from the storage ring in case of any vacuum indcident (for instance window failure or in case of leaks between the 1st window and the storage ring) occurring in the beamline.
- **Primary Slits**, they are needed both to block scattered radiation and allow to manipulate the horizontal and vertical dimension of the beam with high precision actuators. Furthermore, for certain operation modes of the beamline (coherence applications), they allow to generate a secondary source.
- **First Window**, which is necessary to permanently separate the storage ring vacuum from the Front-End / beamline vacuum.

- **Pumping unit**, to have a satisfactory vacuum level in the order of 10^{-8} mbar just downstream the window (300 l/s ion pump).
- **Attenuator**, a vacuum vessel equipped with several filter foils that can be inserted in the beam individually to manipulate beam intensity and spectrum according to the needs of the experiment.
- **Bremsstrahlung Stopper**, an uncooled collimating tungsten alloy block to further absorb Bremsstrahlung radiation.

Beam size, thermal load, and the goal to block, as much as geometrically possible, bremsstrahlung radiation, have been considered during the design of the Front-End to determine the position and aperture for each component.

Component	Distance from the source [m]	Beam size [mrad]		Acceptance [mrad]	
		Horizontal	Vertical	Horizontal	Vertical
Crotch absorber	4.074			3	1
Fix mask	6.548	3	1	2.2	0.3
Photon shutter	6.999	2.2	0.3		
Primary slits	7.603	2.2	0.3	1 (from 0 to 2.2)	0.3 (from 0 to 0.3)
CVD window	11.027	2.2	0.3		
Bremsstrahlung shutter unit	12.314	2.2	0.3		

Table 1. Main geometrical specifications of the Front-End water-cooled components.

The results of the thermal calculations presented in this report shall be used to further optimize geometry and cooling system design of the Front-End components and to verify that temperature increase and thermal stress within these components stay within acceptable limits during operation.

The design of all components follows some common rules:

- The active bodies are normally made of Oxygen-Free High Conductivity (OFHC) copper.
- Cooling channels are designed to remain as close as possible to the aperture to enhance the heat load dissipation.
- In order to prevent water leaks into the vacuum system all bonding connections of the cooling water channels are faced directly to atmosphere and not to vacuum.

Material Properties

Generally, all components subject to heating by radiation are made of solid blocks of OFHC copper. Only extremely critical components with respect to thermal stress will be made of Glidcop. AISI 316L is the material used for flanges and main structural components. Densimet is a tungsten alloy with high temperature tolerance used in the stoppers. The mechanical and thermal properties of these materials relevant for the thermal analysis are shown in Table 2.

Material properties	AISI 316L	OFHC COPPER	GLIDCOP AL-15	DENSIMET 185
Thermal conductivity (W/m°C)	15.6	391	341	90
Thermal expansion coefficient (µm/m/°C)	16.3	16.8	16.6	5.0
Young's modulus (GPa)	195	115	130	385
Poisson's ratio	0.28	0.343	0.33	0.2
Yield strength (MPa)	290	70	330	600
Ultimate tensile strength (MPa)	560	220	380	800
Melting temperature (°C)	1375	1083	1083	>3000

Table 2. Material properties used in the simulations.

The parameters of the X-ray source

Generally, the power absorbed by the Front-End components is mainly determined by the storage ring operation parameters. The following table shows the values we used for the heat load calculation.

Storage ring parameter	
Electron Energy [GeV]	2.5
Beam current [mA]	400
Circumference [m]	133.2
Horizontal beam size [µm], σx	820.8
Vertical beam size [µm], σy	14.2
Horizontal beam divergence [µrad], σx'	24.65
Vertical beam divergence [µrad], σy'	0.246
Max TPW Magnetic field [T], B	3.05
3 pole wiggler total power emitted [W]	986
Adjacent dipole Magnetic field [T], B	1.455
Adjacent dipole Total power emitted [kW]	17.75

Table 3. Parameters for the storage ring, adjacent dipole magnets and 3-pole wiggler used for the thermal calculations.

Calculating the temperature effects induced by the absorbed power

To conduct the thermal analysis according to the parameters listed in table 3, the total power and the spatial power distribution of the photon beam were calculated using the XOP software suite [1].

To simulate the effect of the heat load on Front-End components, the full power has been used as input parameter for the finite elements' calculations, considering that all the heat is absorbed in the surface that faces the photon beam.

In a conservative approach, energy loss caused by X-ray scattering in the heated surface is ignored and all power is assumed to be absorbed at the illuminated surface, neglecting the effect of X-rays penetrating the components material.

In an approximation, instead of the non-uniform power density, uniform equivalent loads were applied on the surface of a component directly via the widely used commercial "ANSYS" software package [2].

The temperature of every Front-End component's external temperature was assumed to be the ambient temperature (25 °C).

The process of water-cooling has been modelled applying a film coefficient in the water-cooling channel walls, calculated according to the formula

$$h = \frac{k\,Nu}{D_h}$$

where:

h is the convection film coefficient,

k the material thermal conductivity,

Nu is the Nusselt Number (A dimensionless number defining the ratio of convective to conductive heat transfer at a boundary in a fluid),

D_h is the reference diameter used for thermal exchange equations and is defined as

$D_h = (4\,A)/p$ (A is the cross-sectional area and p is the wetted perimeter of the cross section).

The Nusselt number for turbulent flow of liquids in tubes according to the Dittus Boelter [3] formula is

$$Nu = 0.023\,Re^{0.8}\,Pr^{0.3}$$

The Prandtl number (Pr) is a dimensionless number defined as the ratio of momentum diffusivity to thermal diffusivity. It's a thermophysical property of the coolant.

The Reynolds number (Re) is a dimensionless value that measures the ratio of inertial forces to viscous forces and describes the degree of laminar or turbulent flow of the cooling liquid.

The water thermal properties have been calculated for a water temperature of 25 °C. [4]

Failure criteria

The criteria for establishing the maximum thermal load acceptable for X-ray beam-intercepting components was chosen to be conservative:

In order to prevent material creep, the maximum temperature on the OFHC copper components is limited to 150 °C and the von Mises stress to 210 MPa.

The maximum temperature for Glidcop components was limited to 300 °C, here the maximum von Mises stress is assumed to be 400 MPa.

The maximum temperature on the AISI 316L components should be below 400 °C and the maximum von Mises stress below 200 MPa.

In order to prevent the boiling of cooling water and to maintain single-phase heat transfer, the maximum temperature on the cooling wall should be less than the boiling temperature at channel pressure (generally 148°C at a typical pressure of 4.5 bar, calculated considering the inlet water pressure and the expected pressure losses).

For thermal simulations assuming heat load at standard operation conditions a safety margin of 10% was applied.

For the calculation of thermally induced stress we used values for both normal operation and for a worst case scenario. We find, that the results of the finite element analysis (maximum temperature of the body, cooling wall temperature and the maximum stress values) of the Front-End components confirm that the proposed initial design of the Front-End components is compliant and safe.

The Analysis procedure

As a first step, a thermal analysis of the steady state (thermal loading conditions settled down, no more time dependence) was carried out to determine the temperature distribution, thermal gradients, heat flow and similar thermal quantities.

The results of this thermal analysis were then used as input for a subsequent structural analysis, yielding the distribution of stress caused by the thermal gradients determined in the first step.

Calculating the worst case

In real applications and after a certain period of operation, the real parameters may differ from the assumptions made during the aforementioned model calculations, due to aging, brazing effects, gap conductance, etc.

Therefore, a further simulation addressing a worst-case scenario for the components fixed mask, shutter and slits was carried out in order to determine the safety margin. For this worst-case analysis, the approach is different and aims at finding the maximum heat load that the system can accept before reaching the failure limit. This calculation has an inverse approach: we iteratively increased the headload until failure criteria for the components were reached.

All material properties used in the thermal design have been taken from well-established and proven thermal databases [5] [6] [7], heritage from previous applications and technical papers.

RESULTS OF THE THERMAL AND STRUCTURAL ANALYSIS

The Crotch absorber

The crotch absorber is a component mounted on a side flange of the photon exit chamber. It is used to protect the downstream UHV vacuum chambers and Front-End components by intercepting the radiation emitted by the bending magnets and unwanted radiation from the 3-pole wiggler. It is machined from a solid Glidcop bar. Sloped absorbing teeth are made in the lower and upper cooling body of the absorber. Blind water channels are drilled horizontally inside the copper body, while a pipe is concentric with the hole for the water outlet.

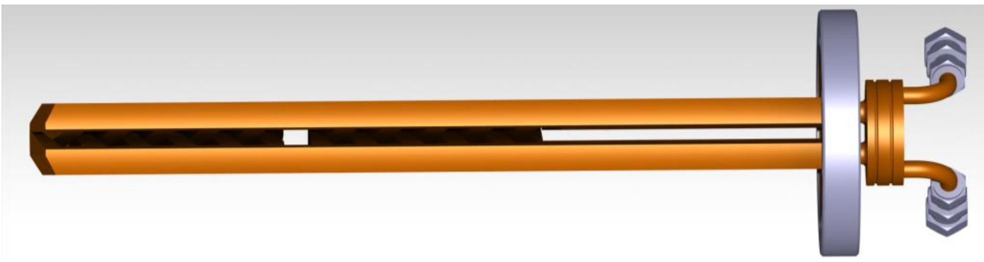

Figure 5a. 3D model of the crotch absorber.

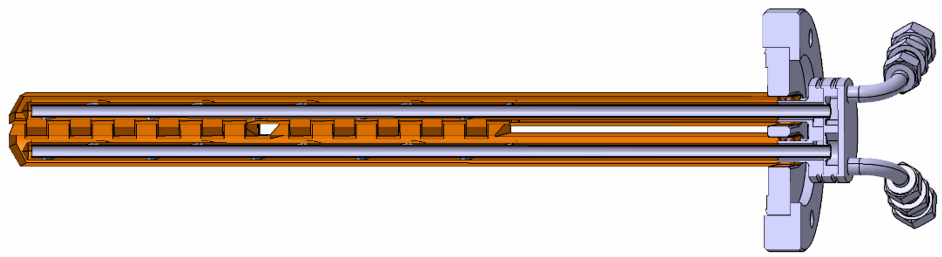

Figure 5b. Section view of the crotch absorber.

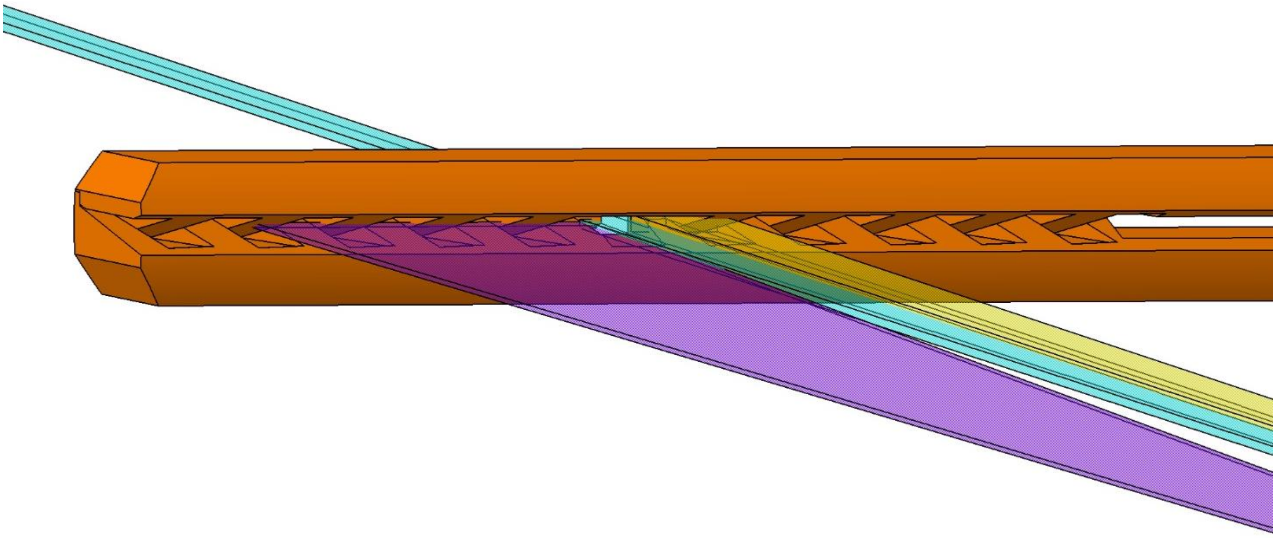

Figure 5c. Detailed view of the crotch absorber aperture and teeth absorbing system (Purple and yellow: undesired radiation from dipole magnet, light blue 3-pole wiggler radiation).

A thermal analysis for this component was carried out to assess its thermal and structural performance under radiation from the bending magnet and the 3-pole wiggler, in particular the stress inside the body.

Before carrying out the thermal and stress analysis, the model of the crotch absorber was simplified. Except for the thermally active parts, all the other parts such as flange, water connectors and stainless-steel welded pipes were neglected.

Total 3PW power heating the crotch absorber [W]	756
Total upstream BM power heating the absorber [W]	308
Total downstream BM power heating the absorber [W]	3417

Table 4. Power absorbed by the crotch absorber from the 3-pole wiggler and the adjacent dipole magnets.

The highest temperature on the crotch absorber is found in the tooth that receives both the radiation from the 3-pole wiggler and the downstream bending magnet. The maximum temperature on the copper body reaches 176.2 °C, the peak temperature of the cooling channels 64 °C. The maximum thermally induced von Mises stress is located near the corner and reaches a value of 126 MPa.

Due to the temperature and stress values reached in this component it must be made of Glidcop or CuCrZr [8]. With one of these materials, both the maximum temperature and the maximum stress are below the failure criteria mentioned above. Thus, the crotch absorber is considered safe under high-heat-load condition.

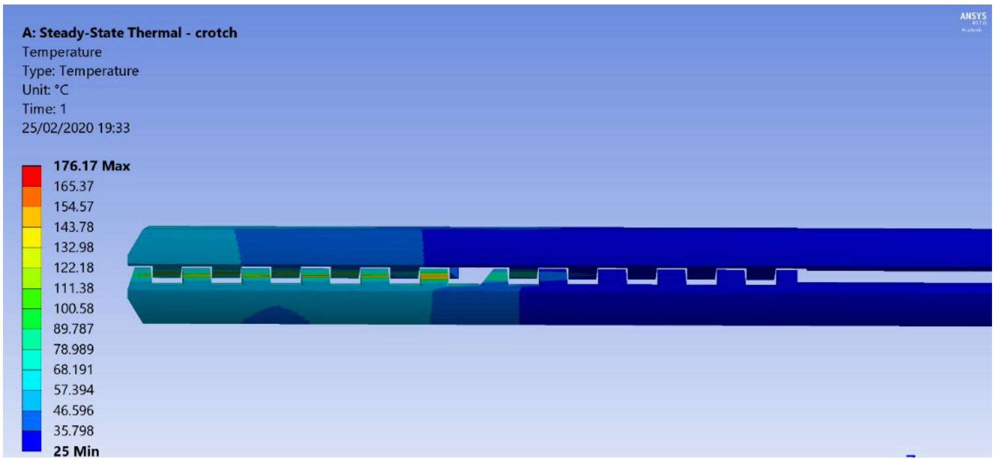

Figure 6a. Temperature distribution for the crotch absorber during normal operation of the storage ring

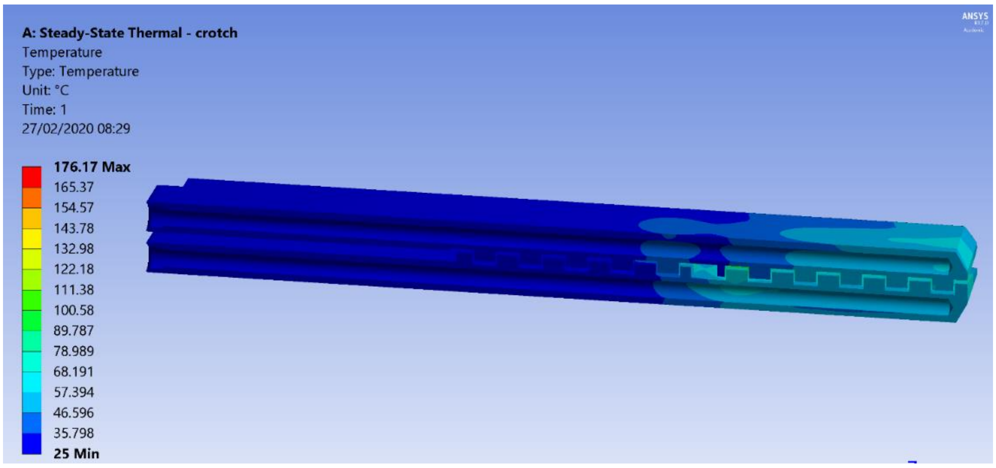

Figure 6b. Temperature distribution for the cooling channel wall inside the crotch absorber during normal operation.

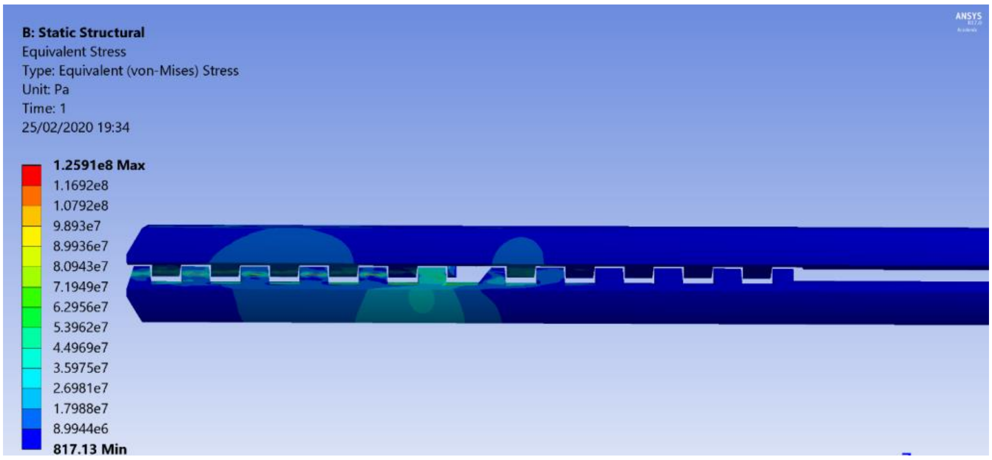

Figure 6c Stress distribution for the crotch absorber during normal operation.

The Fixed Mask

The fixed mask is the first mask closest to the storage ring. It is used to absorb undesired radiation from the bending magnet passing through the crotch absorber window and to limit the beam size from the 3-pole wiggler. It has a copper body placed inside a 63CF flange and is cooled via water channels. It is located at a distance of 6548 mm from the source.

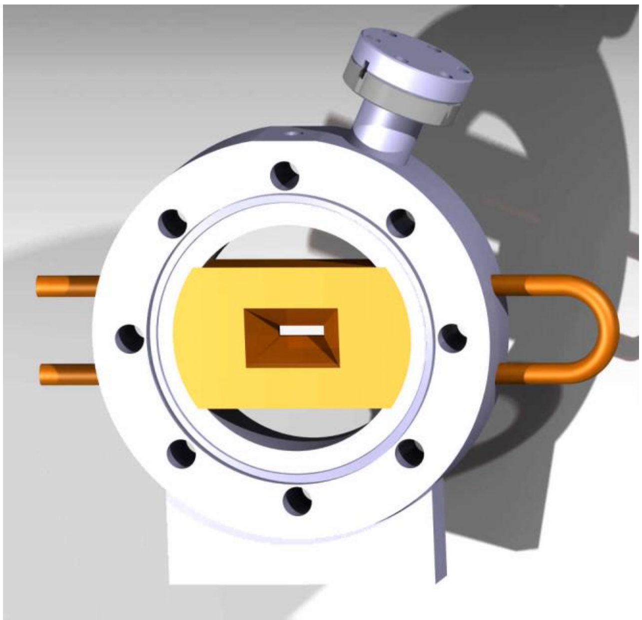

Figure 7. 3D model of the fix mask.

The fixed mask reduces the horizontal angular acceptance to 2.2 mrad, while the crotch absorber aperture accepts 3 mrad.

The model of the fixed mask is slightly simplified as the flange for the thermocouple feedthrough is neglected.

Considering a water velocity of 2.5 m/s, the convective coefficient is 11671 W/m^2°C.

The fixed mask receives up to 76 W of total thermal power, the maximum temperature will be 45.9 °C, the wall temperature of the channel rises to 32.1 °C. The maximum thermal-induced von Mises stress is 84 MPa.

To assess the safety margin, the maximum power that can impinge on the mask with an OFHC body was calculated. According to the failure criteria for copper the maximum heat load can increase up to 470 W.

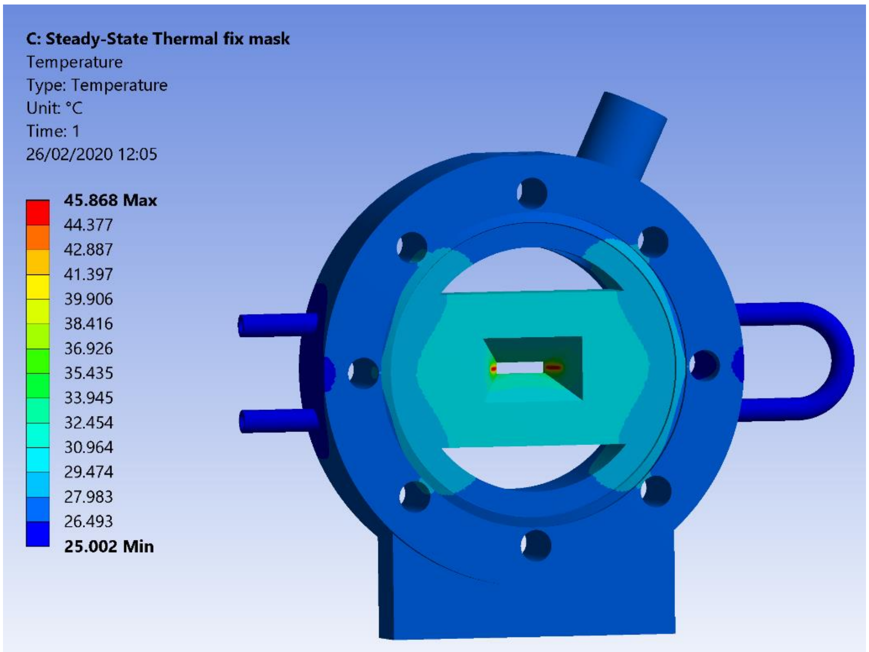

Figure 8a. Temperature distribution for the fixed mask during standard operation.

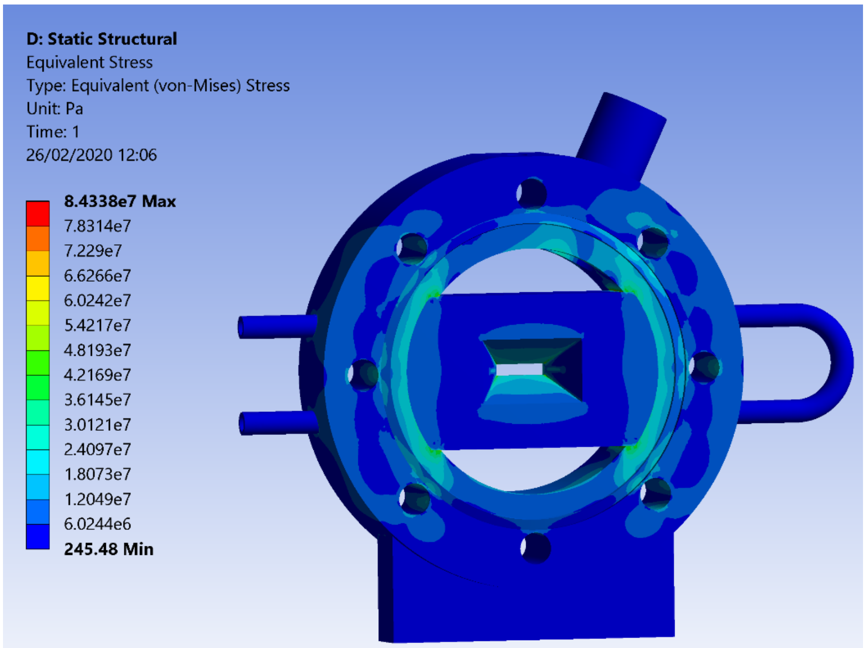

Figure 8b. Stress distribution for the fixed mask during standard operation.

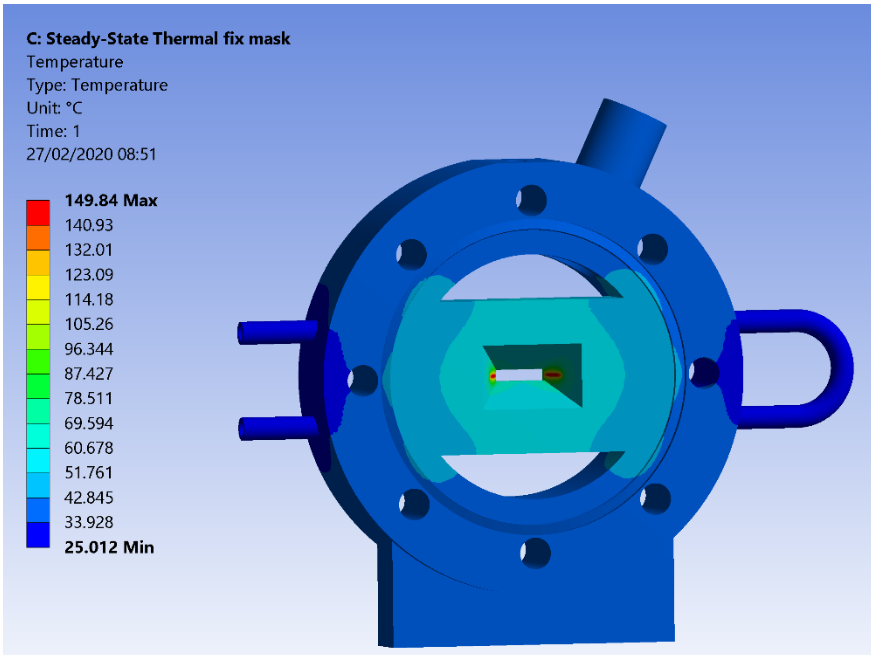

Figure 8c. Temperature distribution for the fixed mask with a maximum heat load of 470 W.

The Photon Shutter

This component is designed to completely intercept the x-ray photon beam and isolate the downstream components from the source. A fast-acting pneumatic mechanism assures a fast closing.

When the shutter is closed, the downstream components / hutches can be accessed safely.

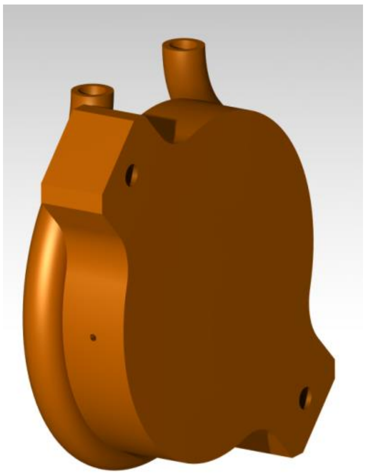

Figure 9. 3D model of the photon shutter.

In the model used for the finite element calculations, the actuating system and the holder are neglected. The total thermal power absorbed by the photon shutter is 155 W.

The finite element analysis results show the temperature rise contour as depicted in Figure 10a with a maximum temperature of 81°C, assuming in the model a film coefficient of 10500 W/m^2°C.

The maximum temperature on the cooling wall is far less than 40 °C and the maximum thermal stress is found to be 147 MPa (also considering mesh singularities in the constraint area), which is lower than the Copper's ultimate strength. Thus, the design is passively safe even when full power impinges on the component.

The shutter remains safe up to 405W heat load.

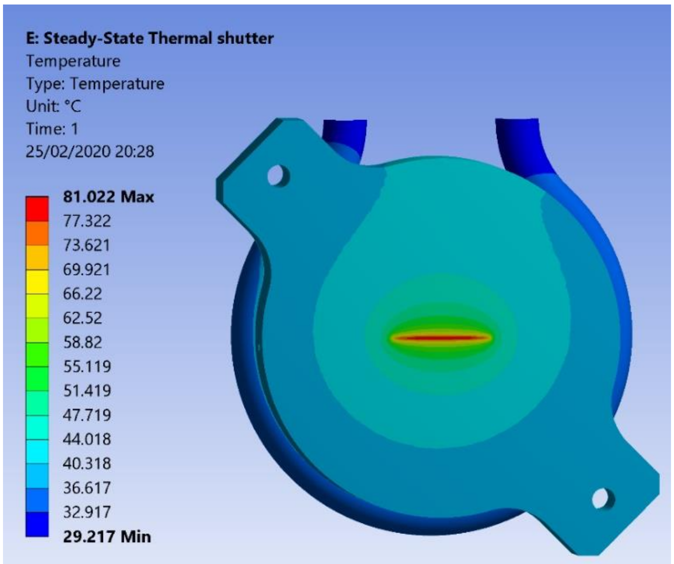

Figure 10a. Temperature distribution for the photon shutter during standard operation.

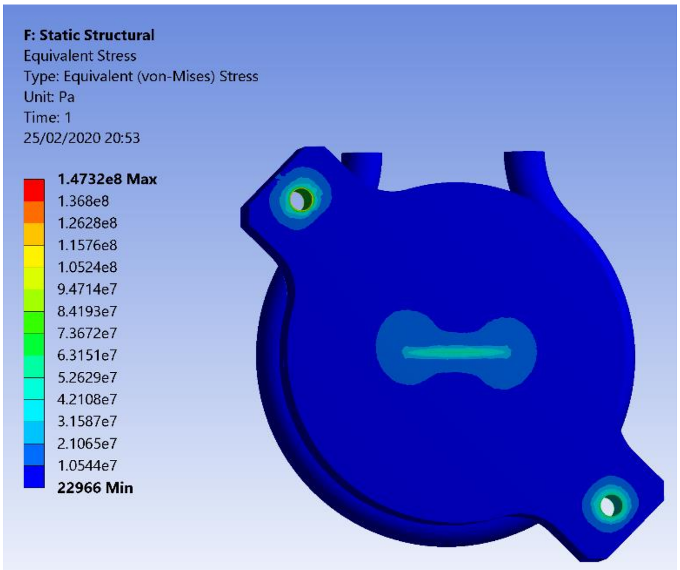

Figure 10b. Stress distribution for the photon shutter during standard operation.

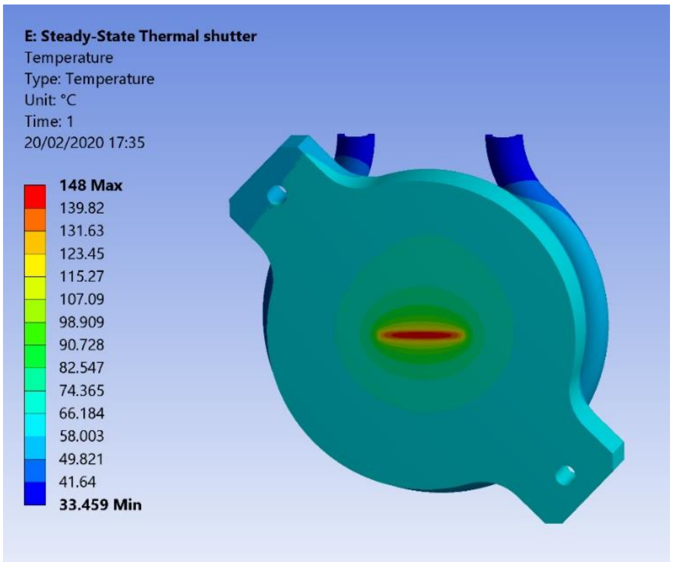

Figure 10c. Temperature distribution for the fix mask with a maximum heat load of 405 W.

The Primary Slits

The interaction of the beam with diagnostics and other components produces scattered radiation. This unwanted radiation, together with off-axis radiation, must be removed by a slit system. In addition, the slits can be closed in order to generate a secondary source that allows to adapt to certain experimental requirements.

Two horizontal and two vertical blades, moved by independent actuators, are made of tungsten alloy while the holders are made of copper, to dissipate the white-beam heat load.

A considerable safety margin concerning the heat load to be dissipated was taken into account to cover accidental exposure of each blade to the direct beam. The slits will be designed not only to remove stray scattering and cutting off-axis radiation but also to withstand the entire white-beam heat load.

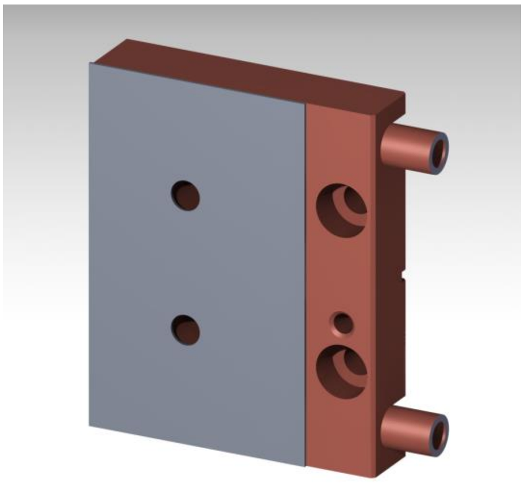

Figure 11. 3D model of the horizontal slits' blade.

The model of the slit system is extremely simplified as it consists only of a single copper holder and the tungsten blade.

In the simulation we assumed that a single horizontal blade (more critical than the vertical ones) absorbs, in normal operation, half the power of the beam, so the total thermal power absorbed by a single blade mask is up to about 77.5 W.

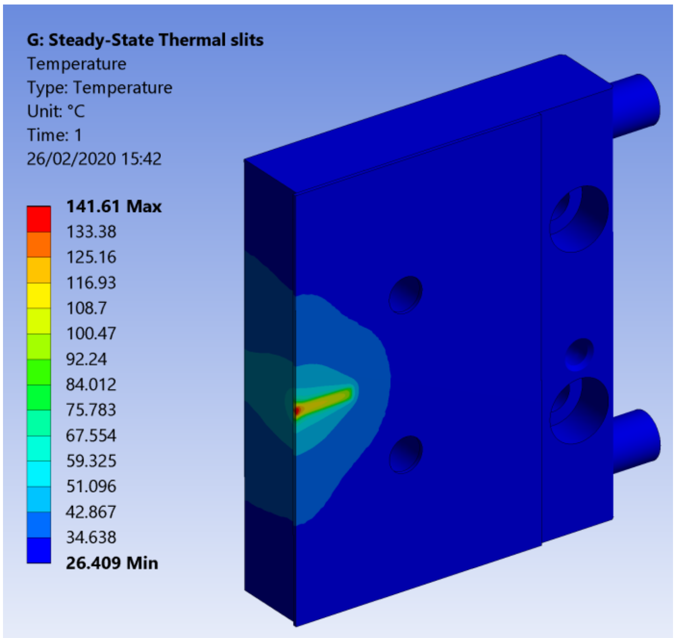

Figure 12a. Temperature distribution for a horizontal slit blade catching half the white beam during normal operation.

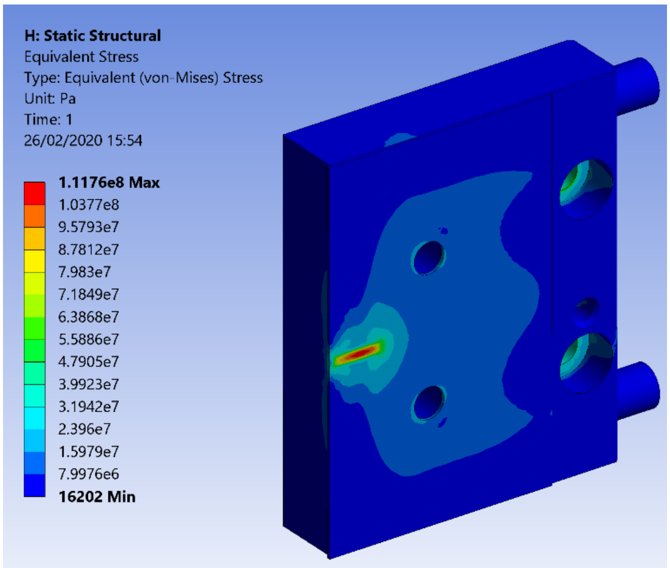

Figure 12b. Stress distribution for the slits blade catching half the white beam during normal operation.

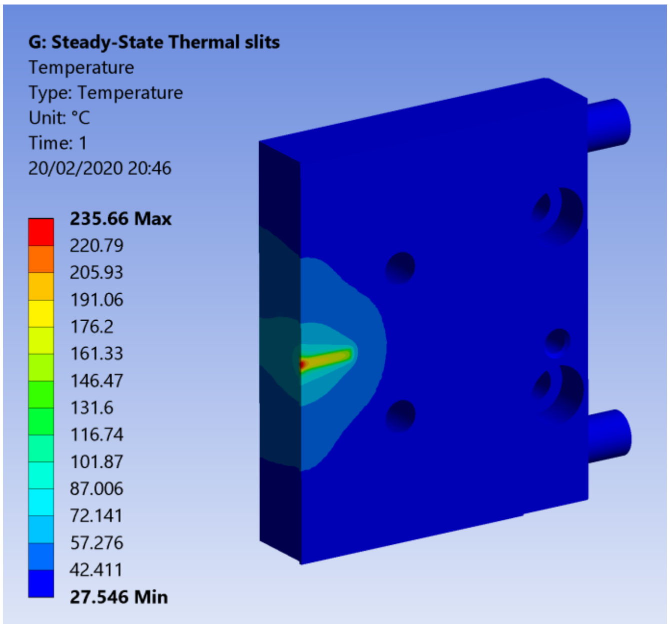

Figure 12c. Temperature distribution for the slits blade and a full power of 155 W.

Under these conditions, the maximum temperature, the maximum wall temperature and the von Mises stress values are clearly below any critical value.

In a further simulation it has been found, that even in case the heat load generated by the full beam is absorbed by a single blade, the maximum temperature on the tungsten alloy blade, the copper holder, the pipe walls as well as the von Mises stress are well below values leading to component failure.

The CVD window

This window is mandatory to separate the machine UHV-sector (10^{-10} mbar) from the beamline, where the vacuum is generally in the range between 10^{-8} and 10^{-9} mbar. For this purpose, a water-cooled CVD diamond window of 0.1 mm thickness is foreseen. This window, which is located 11027 mm from the source, has a full opening larger than 25(H) mm x 3(V) mm. The CVD window is cooled by means of a copper pipe on a copper body. The window absorbs an average power of 23.25 W. According to these parameters the simulations show a maximum temperature of 30.3 °C and a maximum von Mises stress of 84 MPa, due to both the thermal deformations and the differential pressure on the opposite sides.

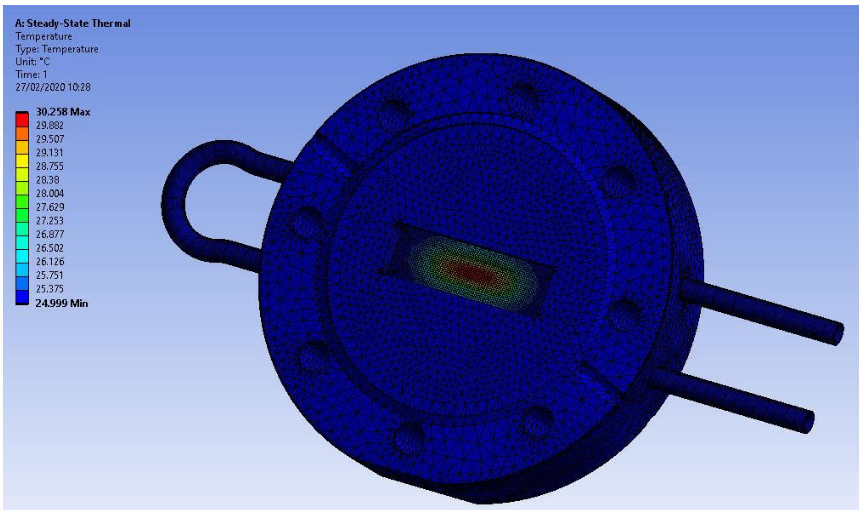

Figure 13a. Temperature distribution in the CVD window during normal operation.

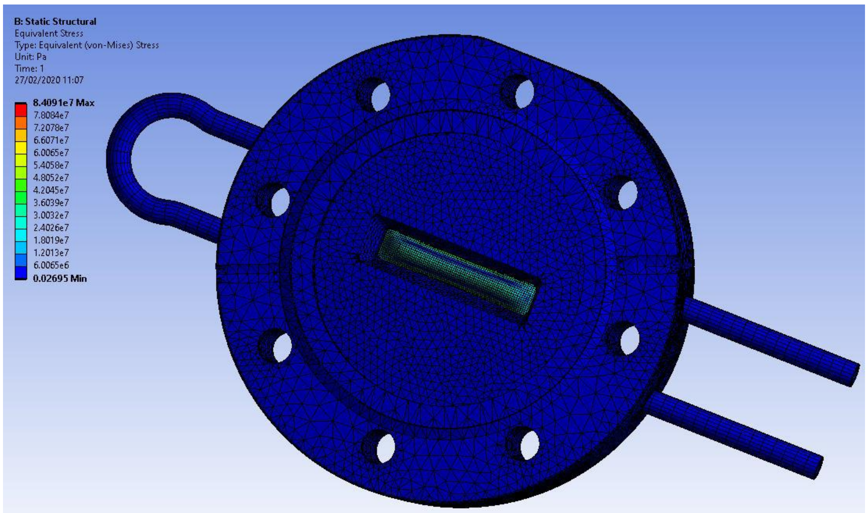

Figure 13b. Stress distribution for the CVD window during normal operation.

SUMMARY AND CONCLUSIONS

The results obtained from thermal and stress model calculations indicate that all Front-End components under normal operation as well as under extreme conditions have a reliable thermal design, compliant with the requirements and far from failure criteria including a largely sufficient level of safety margin.

Further thermal and stress analyses for all Front-End components will be (re-)conducted when the “as-built” drawings are established by the manufacturers, before the production phase.

REFERENCES

1. M. Sanchez del Rio and R. J. Dejus, “XOP: A Multiplatform Graphical User Interface for Synchrotron Radiation Spectral and Optics Calculations,” SPIE Proc., vol. 3152, 148-157, 1997.

2. ANSYS® Workbench, Release 17.0.

3. R.H.S. Winterton, “Where did the Dittus and Boelter equation come from?”, Int. J. Heat Mass Transfer, Vol.41, Nos 4-5, pp.809-810, 1998.

4. Drying Phenomena: Theory and Applications, First Edition. İbrahim Dinçer and Calin Zamfirescu, 2016 John Wiley & Sons, Ltd. Published 2016 by John Wiley & Sons, Ltd.

5. The NIST Standard Reference Data program (Available from http://www.nist.gov/srd/);

6. MatwebLLC. Material property database. (Available from: *www.matweb.com/*);

7. W. Rosenhow et. al., Handbook of heat transfer fundamentals, 1985 McGraw-Hill.

8. S. Sharma, “A Novel Design of High Power Masks and Slits”, Proc. of MEDSI2014, Australia (2014).