CERN

Thermal behavior of TAXN and TCDXM D2 collimator mask, Finite element studies

Summer student internship

Stepans Sklariks
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1. FINAL REPORT OF STEPANS SKLARIKS

The objective of this project was to perform thermal loading simulations of TCDXM (D2 collimator mask) (see Figure 1) and TAXN so as to allow the preliminary evaluation of the suitability of the given parts for the upcoming high luminosity upgrade that is to be performed in LHC in the nearest future. These parts are special purpose absorbers that are needed to protect superconducting magnets from the collision product radiation obtained within the experiment to prevent the superconducting magnets from quenching. The absorbers also localize the induced activation to the absorbers and surrounding shielding. The suitability of the current parts is evaluated in terms of maximum temperature generated due to the heat deposition, which in turn should not surpass the allowable critical temperature defined for the given structure. Depending on the results obtained, some recommendations for the design of cooling system are provided. For the current analysis CAE package ANSYS 16.1 was used. The analysis was performed using heat deposition data that was provided by the use of fully integrated particle physics Monte Carlo simulation software package Fluka.

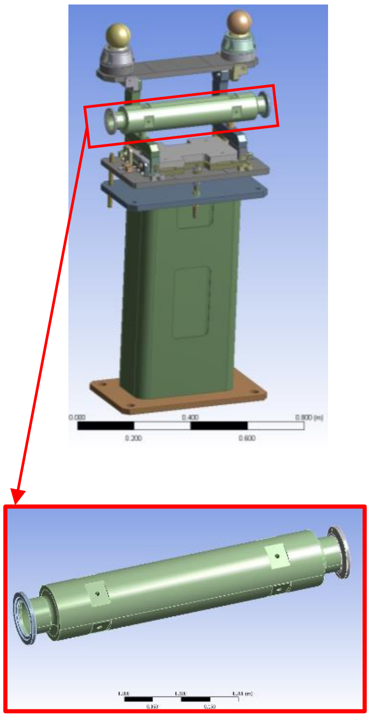

Figure 1: TCDXM D2 collimator mask geometry

1.1. TCDXM D2 COLLIMATOR MASK THERMAL ANALYSIS

For the TCDXM (D2 collimator mask) the analysis was performed in the following manner. For the objectives described a computational simulation model was generated (see Figure 3). Basic modelling parameters are as follows:

- The discretization is done by means of finite elements
- Volumetric parts are meshed by solid elements with tetragonal and quadratic shape functions;
- According to the design of TCDXM (D2 collimator mask) the material of the part is copper, thus an appropriate heat conductivity value of 401 W/(M*C) was chosen for further modelling

The applicable Mesh parameters are summarized in the Table 1. The density of the mesh can be seen in Figure 3.

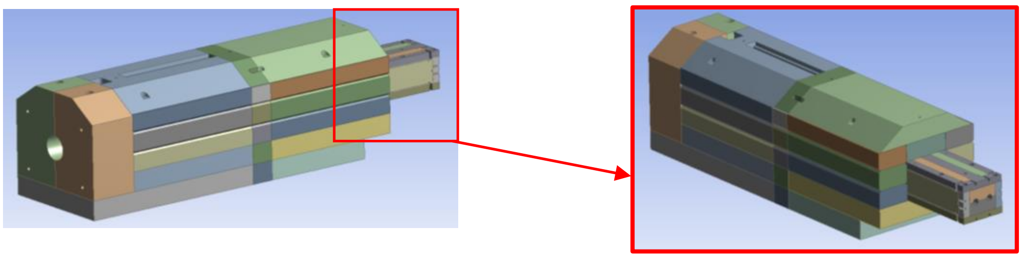

Figure 2 TAXN geometry

Table 1

Summary of mesh parameters applicable to thermal analysis performed on TCDXM D2 Collimator mask

Sizing	
Use Advanced Size Function	Off
Relevance Center	Coarse
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	3.4907e-004 m
Statistics	
Nodes	42196
Elements	25203
Mesh Metric	None

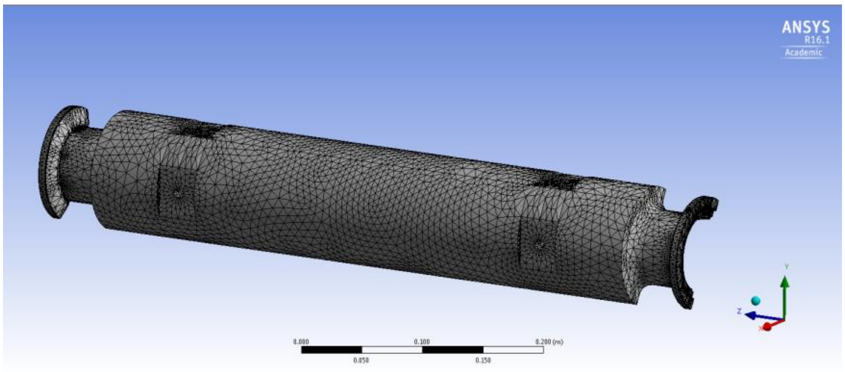

Figure 3: TCDXM D2 Mesh

Next, boundary conditions have been applied as follows:

- Heat deposited by the beam was modelled using Fluka data interpolated and defined as heat generation (see Figure 4). Heat generation data used in this scenario was taken from TAXS that was normalised at 5 L0 luminosity due to the absence of such data for the D2 collimator mask. The total power of the given part is much higher than it is required for the structure of the current study (~800 W for TAXS and 6.3 W for the collimator mask), thus the results obtained within the current study will illustrate a very pessimistic scenario and will have a very high safety margin.
- Convection was applied on the outer boundaries of the TCDXM D2 collimator mask as can be seen in Figure 5. The value for the convection used was 0.1 W/m^2. Such a value is appropriate according to the figure 4 in (Air Pressure Dependence of Natural-Convection, 2010) since the vacuum condition in the LHC is in the order of 10^{-6} mbar according to (CERN, 2015);
- Heat radiation was assumed and applied to the identical outer boundaries of TCDXM D2 mask as the ones that were chosen for convection (see Figure 6). According to the (Infrared services, 2000) emissivity value for commercial copper is 0.07, thus such a value was chosen and used for the current analysis.

Computational models in general contain simplifications and assumptions, which have to be considered for the interpretation of the results. Regarding the model of this particular project the following uncertainties apply:

- Material properties are fully isotropic;
- Contacts are perfect, fully bonded;
- Thermal expansion is not taken into account for contact surface calculation.

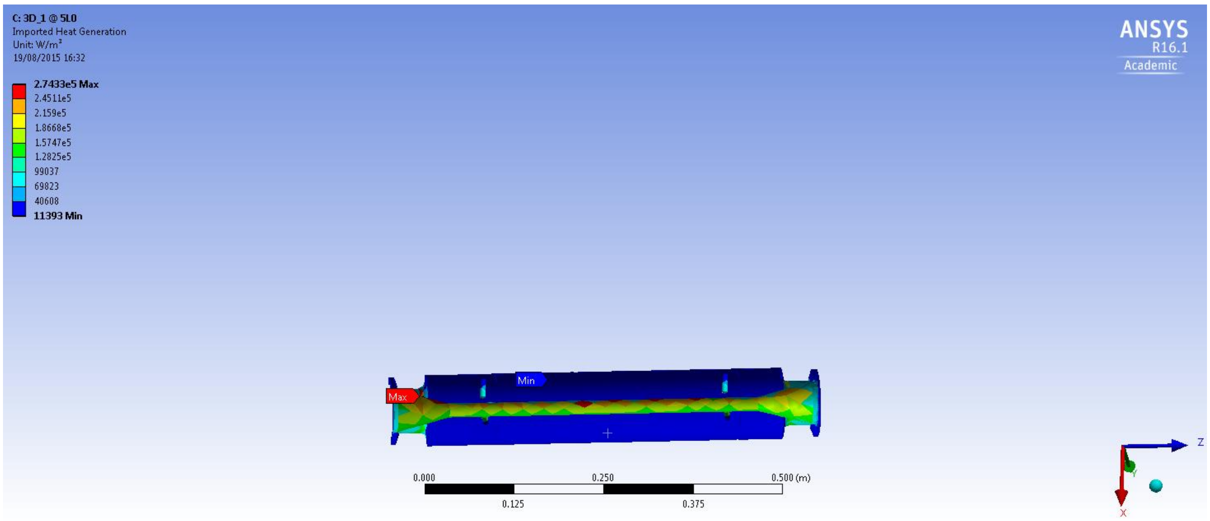

Figure 4 TAS heat deposition at 870 W applied for TCDXM D2 collimator mask

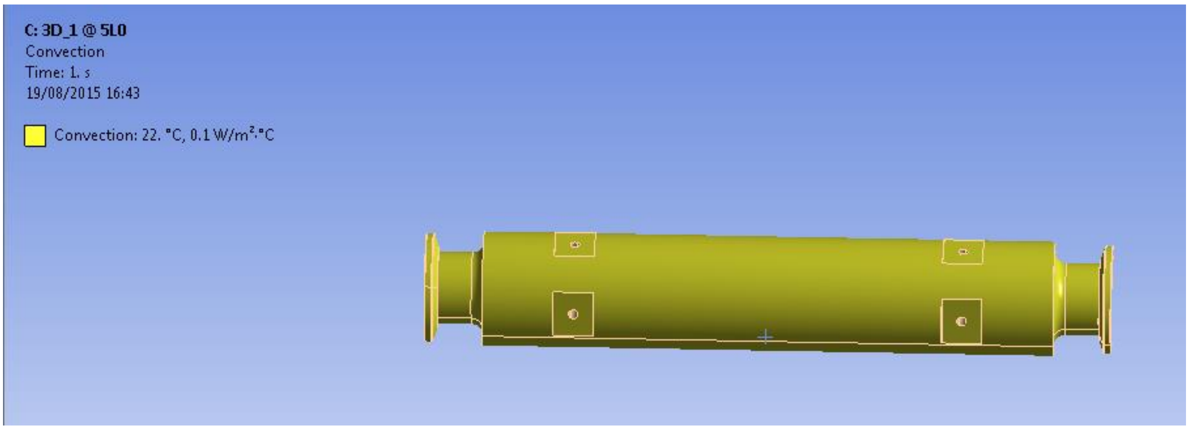

Figure 5 TCDXM D2 collimator mask outer convection.

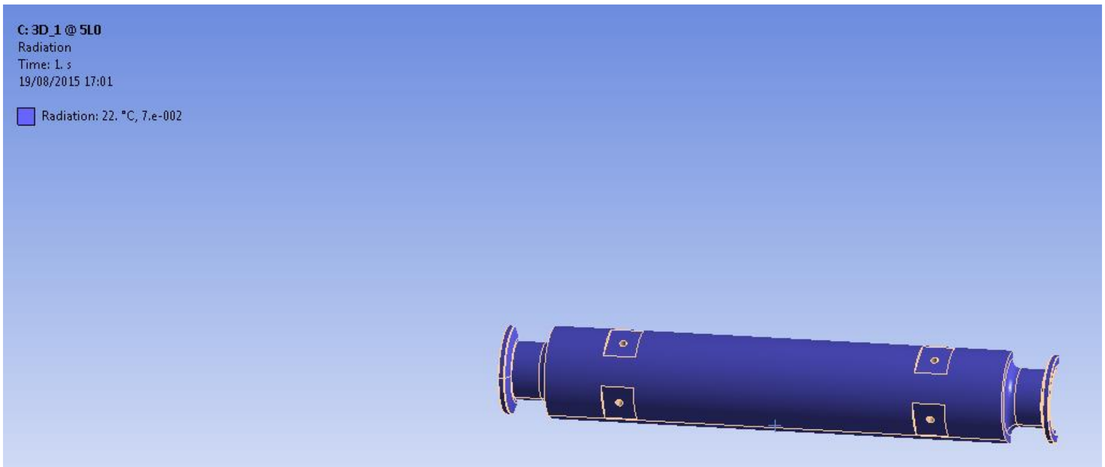

Figure 6 TCDXM D2 collimator mask emissivity faces

With the boundary conditions and assumptions described above the results that are illustrated in Figure 7 were obtained. For D2 collimator mask to conform to the applicable serviceability requirements, it was assumed that the maximum allowable temperature should not be higher than 100 °C. As it can be clearly seen form the results, the temperature variation within the structure is somewhat of ~470 °C till 472.2 °C. Such a level of heating of the structure is not acceptable, thus some possibilities of cooling were considered in the further steps of study.

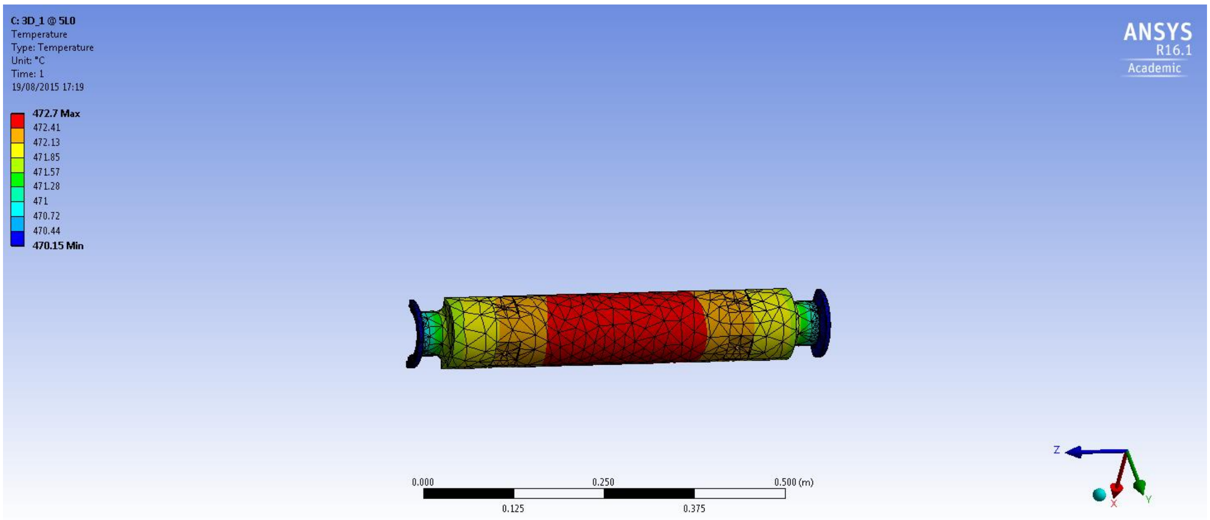

Figure 7 Temperature distribution within the structure of TCDXM D2 collimator mask

Firstly, a cooling collar with the variable width of 25…50 mm was assumed with the water channels going through the collar for the cooling purposes. The effect of the placement of such collar in the middle of the given structure was modelled with the convection value set to 300 w/m^2 on a specified region of the defined width that can be seen in Figure 8. All the other boundary conditions and assumptions are left identical as with the case of no cooling.

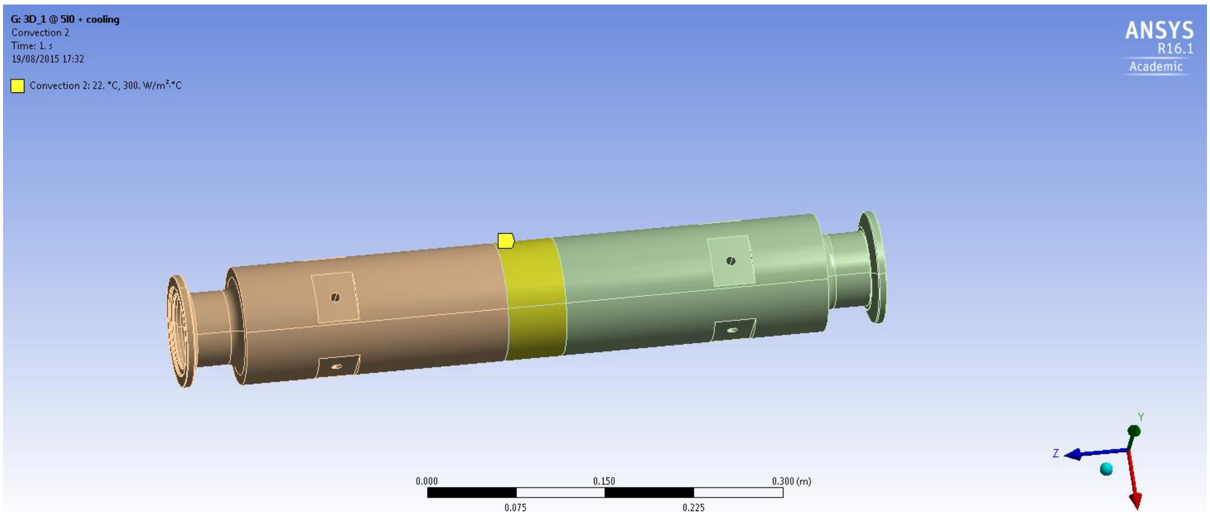

Figure 8 The definition of the defined width of convection region with the value of 300 w/m^2 for the purpose of imitating the effect of cooling collar

The graph of maximum temperature within the structure as a function of the width of the collar was obtained and can be viewed in Figure 9. The result for the width of collar set to 50 mm can be seen in Figure 10. Given that such a temperature still does not conform to the requirement of not exceeding the 100 °C with the maximum width of collar possible, a 2 collar cooling system was considered (the configuration of such cooling system can be seen in Figure 11). The results of such simulation are given in Figure 12. From these results it can be stated that a system with effective placement of much smaller cooling collars is much more effective than a single collar cooling system, and that 2 collar cooling system can provide the necessary cooling conditions for the total structure to conform to the requirement of not exceeding the 100 °C boundary.

The total Ansys interface simulation tree for the D2 collimator mask is schematically illustrated in Figure 13.

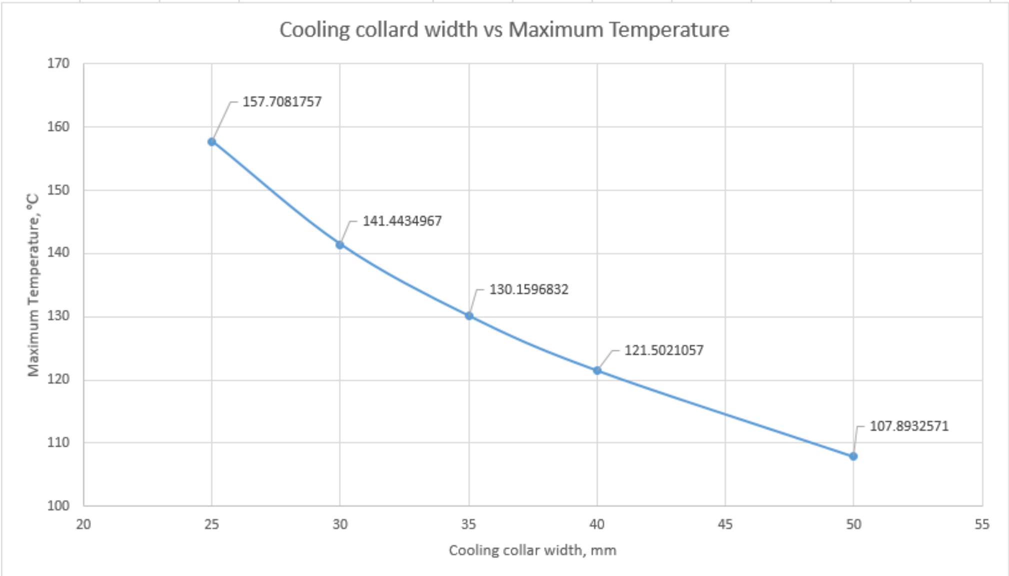

Figure 9 A graph illustrating maximum structure temperature variation with different single collar width values

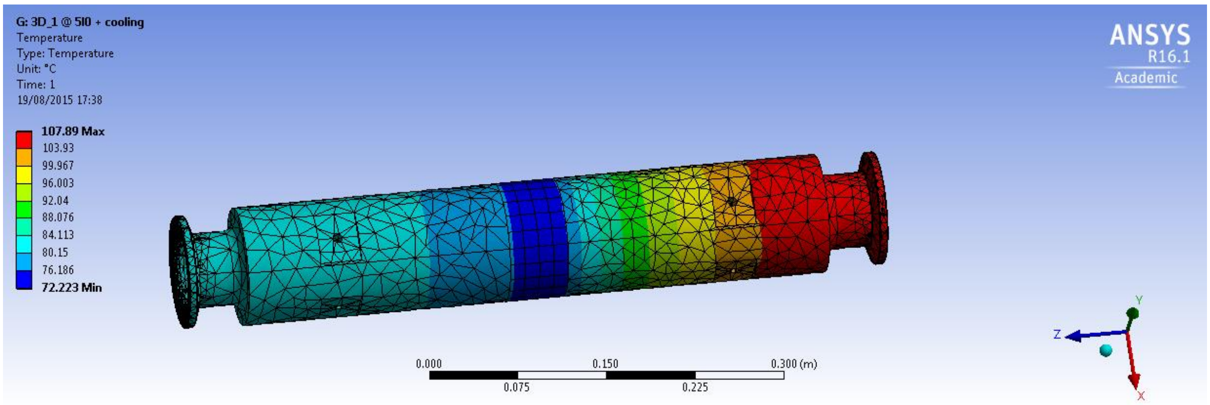

Figure 10 Temperature distribution within the structure of TCDXM D2 collimator mask with the imitated 50 mm wide cooling collar

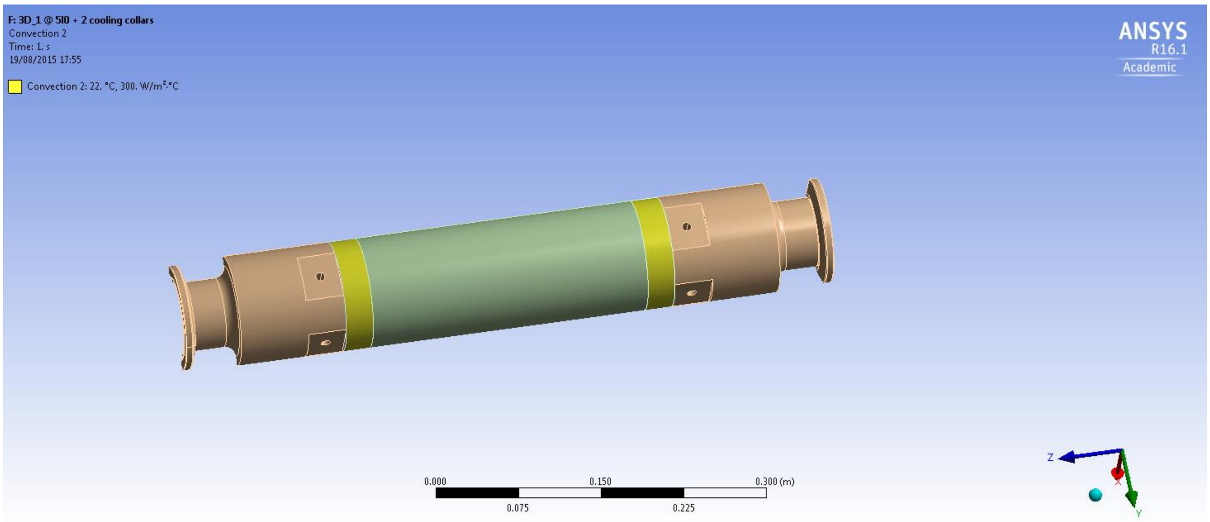

Figure 11 Two 10 mm collar cooling system definition of convection

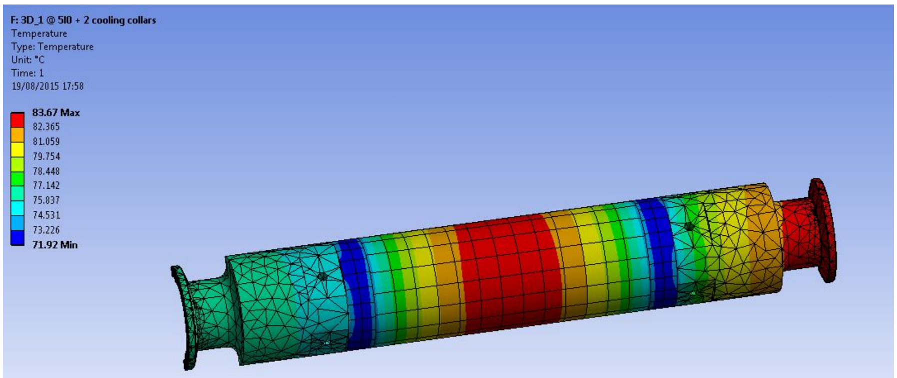

Figure 12 Temperature distribution within the structure of TCDXM D2 collimator mask with the imitated two 10 mm wide collars

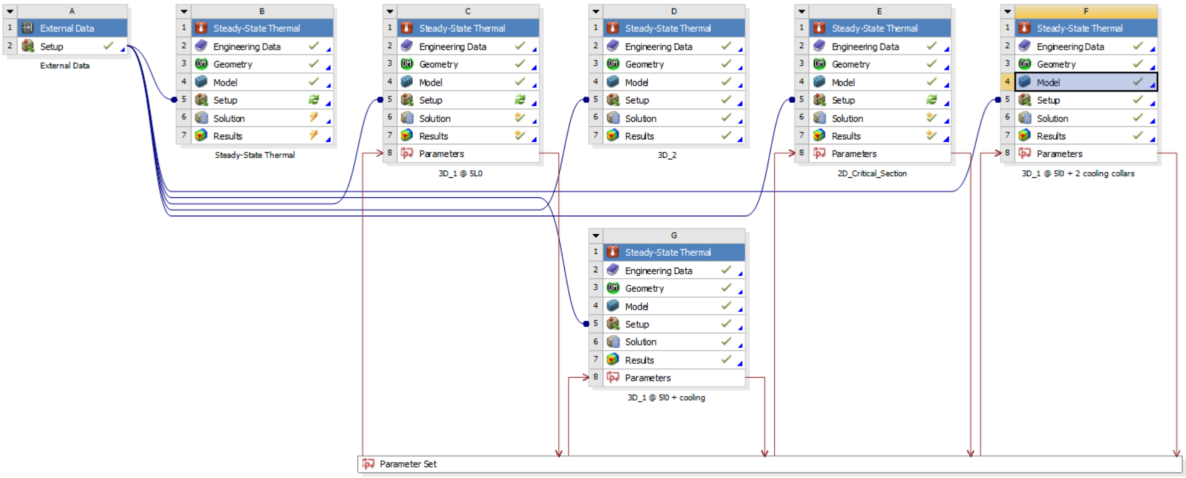

Figure 13 ANSYS interface simulation tree of the performed simulations for the TCDXM D2 collimator mask study

1.2. TAXN THERMAL ANALYSIS

For the first and simplified set of studies a geometry with no shielding was considered (see Figure 14).

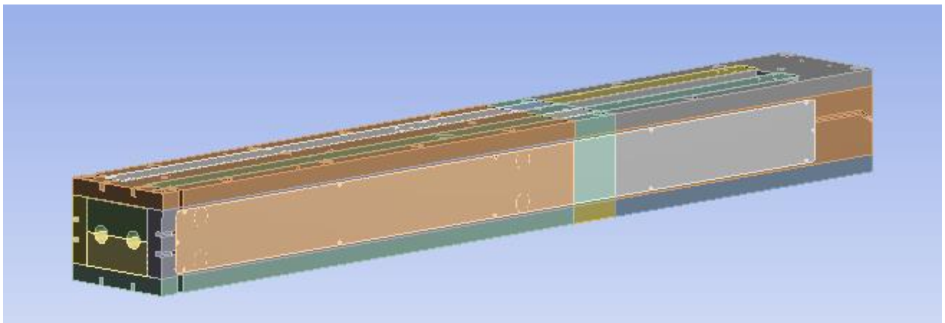

Figure 14 Simplified geometry of TAXN with no shielding

Heat deposition data source is the same as in previous study, but the data is provided only for the critical section of the particle beam. Critical section is the peak heat generation value of the longitudinal profile of the beam, which is illustrated in Figure 15. Such conditions require a following action to be made to successfully implement the given data for the study:

- A critical section must be constantly applied to a given width (given as X in Figure 15) of the structure within a certain interval of structure such that the total power corresponds to 1.8 kW.

The X can be found by applying a random value of heat generation width to the starting point of the critical section and evaluating the total power value as an output.

To initiate the execution of studies the following model parameters were chosen:

- Discretization is done by means of finite elements

- Volumetric parts are meshed by solid elements with tetragonal and quadratic shape functions;
- TAXN simulations are performed assuming the core to be either copper or tungsten alloy (Inermet 180) with the conductivity values being 401 and 174 W/(M*C) accordingly; the first layer of shielding to be made from stainless steel with 15.1 W/(M*C) and the second layer of shielding to be structural steel with the thermal conductivity value being 60.5 W/(M*C).

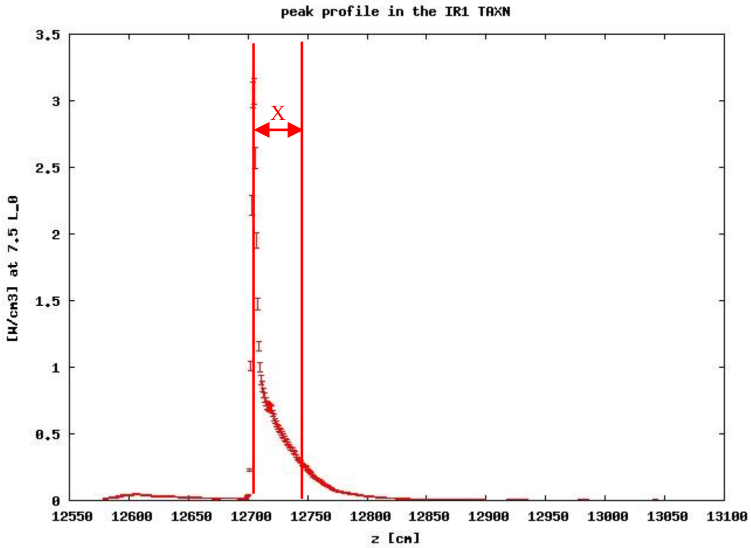

Figure 15 Peak profile of the TR1 TAXN

The applicable Mesh parameters are summarized in the Table 2. The density of the mesh can be seen in Figure 16.

Table 2

Summary of mesh parameters applicable to thermal analysis performed on TAXN

Defaults	
Physics Preference	Mechanical
Relevance	5
Sizing	
Use Advanced Size Function	Off
Relevance Center	Coarse
Element Size	1.e-002 m
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Medium
Minimum Edge Length	3.2623e-004 m
Statistics	
Nodes	1270449
Elements	710966
Mesh Metric	None

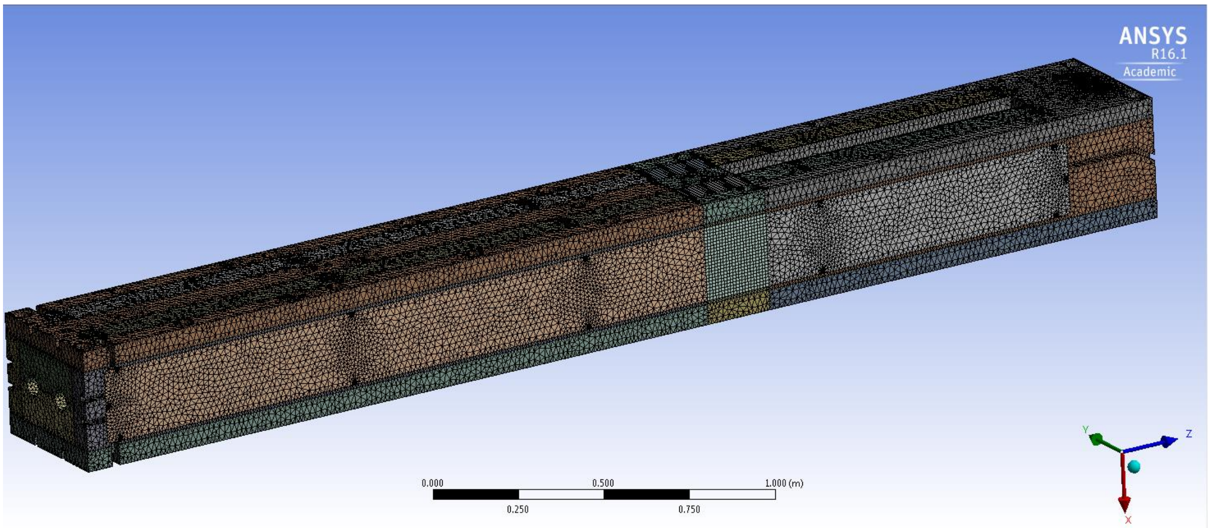

Figure 16 TAXN Mesh

Next, boundary conditions have been applied as follows:

- Due to a very highly complicated computational model within a given study, a parametrization of the heat deposition region width and total output power failed after several attempts of ANSYS software crashing and indicating that there is no available resources for calculations, a subsequent course of action was chosen to find the width (X in Figure 15). Firstly, the width is chosen randomly starting at 100 mm (see Figure 17). Depending on the output of total power the value of width is increased or decreased appropriately in the consequent steps of analysis.
- Basing upon the service conditions intended by the design of the structure, the whole outer boundary of part is surrounded by shielding, thus in a given situation, the only appropriate convection conditions are applied to the cooling channels of the TAXN (Figure 18). The convection value that was applied for the cooling channels was 500 W/m^2 which correspond to the water cooling flow through the given channels.

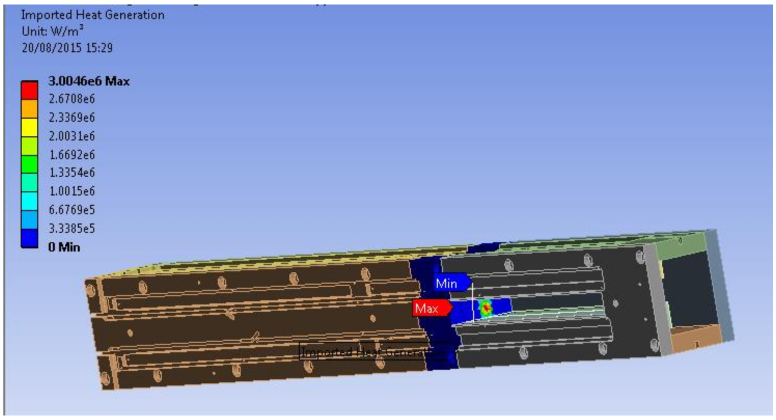

Figure 17 TAXN heat deposition applied to a region of 100 mm

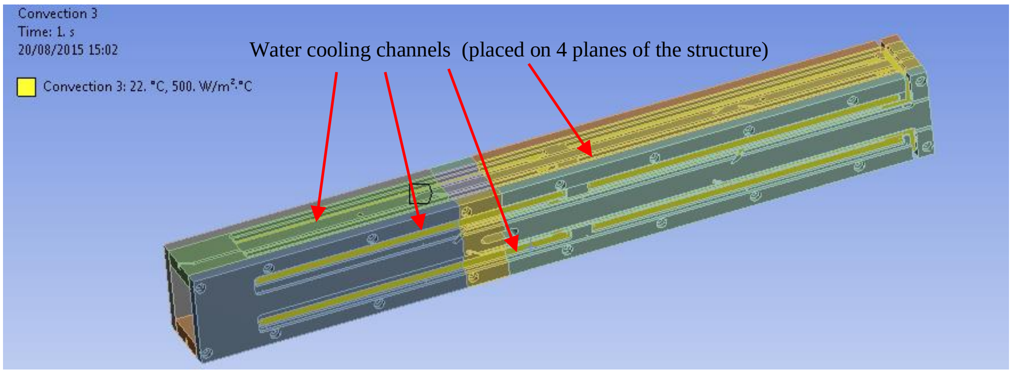

Figure 18 Water cooling convection definition within the cooling channels of TAXN

Regarding the model of this particular project the following uncertainties apply:

- Material properties are fully isotropic;
- Contacts are perfect, fully bonded;
- Thermal expansion is not taken into account for contact surface calculation.

The total power output that was obtained for the given study (heat deposition region being 100 mm wide) was ~ 800 W, whereas the true power output is ~ 1800 W, thus the results of such simulation do not reflect true in-service situation. Hence, power deposition region was increased and the total power output was verified again. These steps were repeated multiple times until the total power output of order ~ 1800 W was achieved. This amount of power was achieved with heat deposition region being 210 mm. The results for the 210 mm wide heat deposition region with all cooling channels actively performing cooling function from all 4 sides of the structure, while the structure core is made out of copper alloy and stainless steel shielding can be viewed in Figure 19.

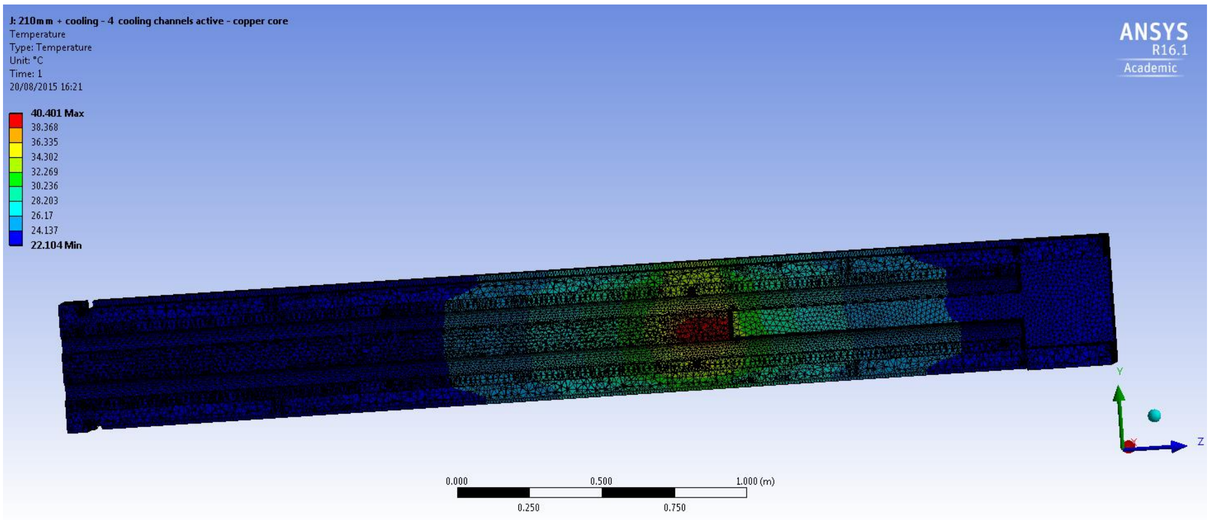

Figure 19 Temperature within TAXN with heat deposition region being 210 mm wide; all cooling channels active on all 4 planes copper alloy core and stainless steel shielding

Results of this simulation provide a clear justification of such cooling system, because the maximum temperature within the whole body of the structure does not exceed 100 ºC.

Next step of the simulation was to imitate some faults of the cooling system in terms of deactivation of the cooling in 1, 2 and even 3 planes of the structure. The results of these simulations can be viewed in Figure 20, Figure 21 and Figure 22 accordingly. These results illustrate how the heating is gradually spreading across the structure toward the 2 ends of the TAXN, and in the case of only 1 plane of channels being active the heating actually reaches one of the ends, but the overall temperature does not exceed 100 ºC (Max temp. 43, 48 ºC and 59 ºC the values of which correspond to the case of 1; 2 and 3 cooling channels being deactivated. Hence it can be stated that the copper core alloy is an acceptable choice for the given in service conditions.

The same calculation were performed for the tungsten alloy core of the given structure, and the only difference between such a material choice is a much broader temperature distribution field within the structure as well as much wider temperature interval (for the worst case scenario of having only 1 plane of active cooling channels the temperature values are within the interval of 23 – 79 ºC as illustrated in Figure 23). Obviously the 100 ºC limit is not exceeded thus the current cooling system is sufficiently efficient.

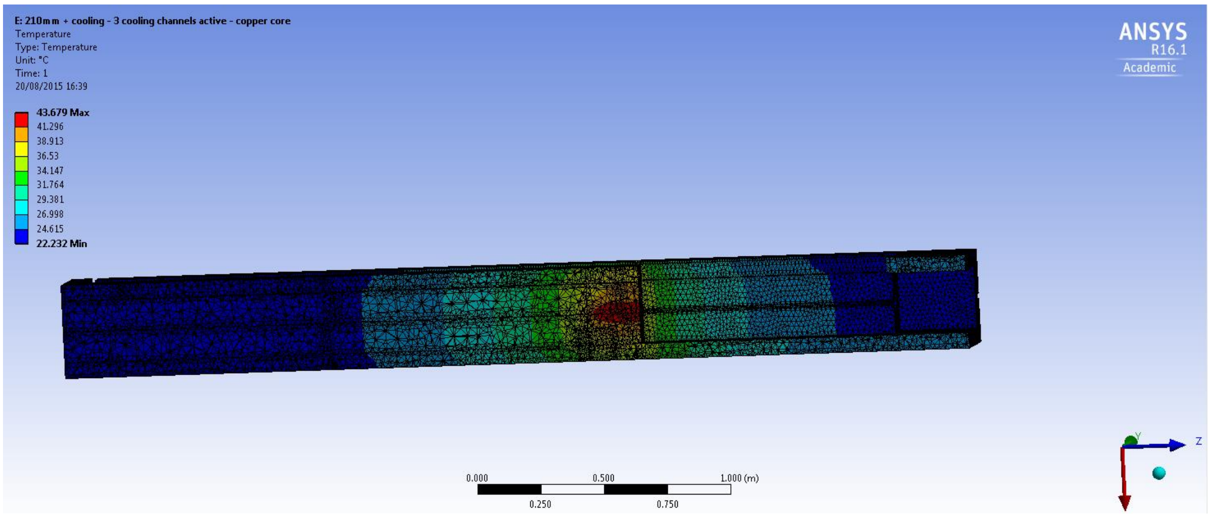

Figure 20 Temperature within the cross section of TAXN with heat deposition region being 210 mm wide; all cooling channels active on 3 planes; copper alloy core and stainless steel shielding

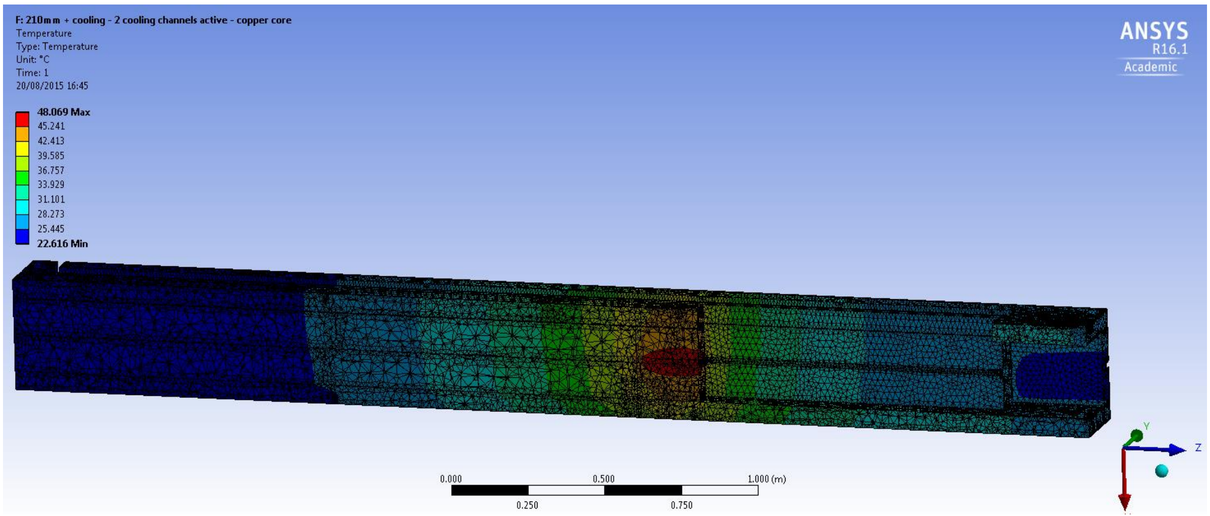

Figure 21 Temperature within the cross section of TAXN with heat deposition region being 210 mm wide; all cooling channels active on 2 planes; copper alloy core and stainless steel shielding

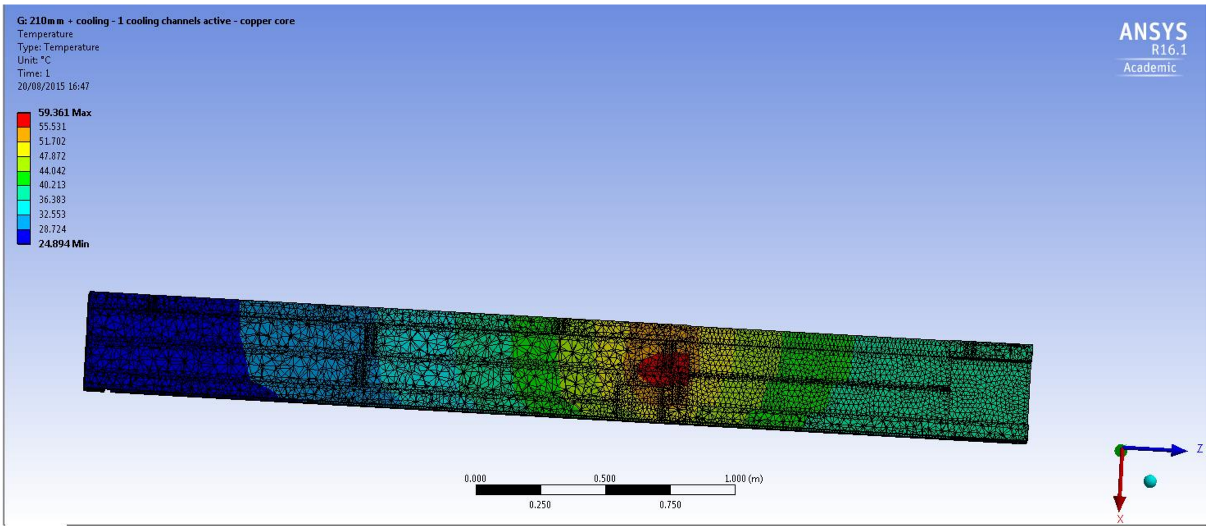

Figure 22 Temperature within the cross section of TAXN with heat deposition region being 210 mm wide; all cooling channels active on 1 plane; copper alloy core and stainless steel shielding

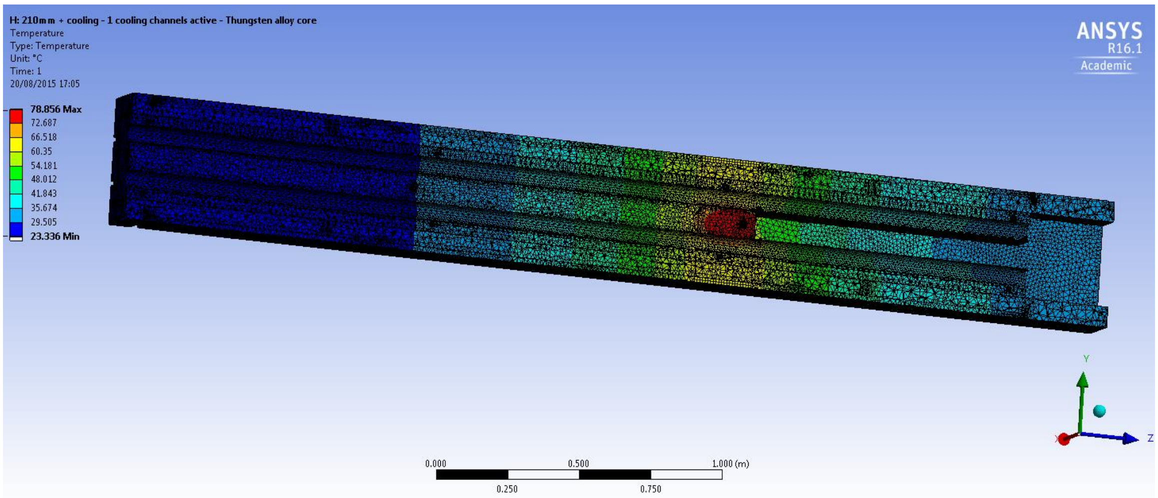

Figure 23 Temperature within the cross section of TAXN with heat deposition region being 210 mm wide; all cooling channels active on 1 plane; tungsten alloy core and stainless steel shielding

The next set of studies were performed on TAXN with all the surrounding shielding structures. Global mesh parameters are kept the same as in Table 2, but for the region of application of heat generation (see Figure 24) an additional body sizing option was used the parameters of which are summarized in Table 3. Mesh density of TAXN can be viewed in

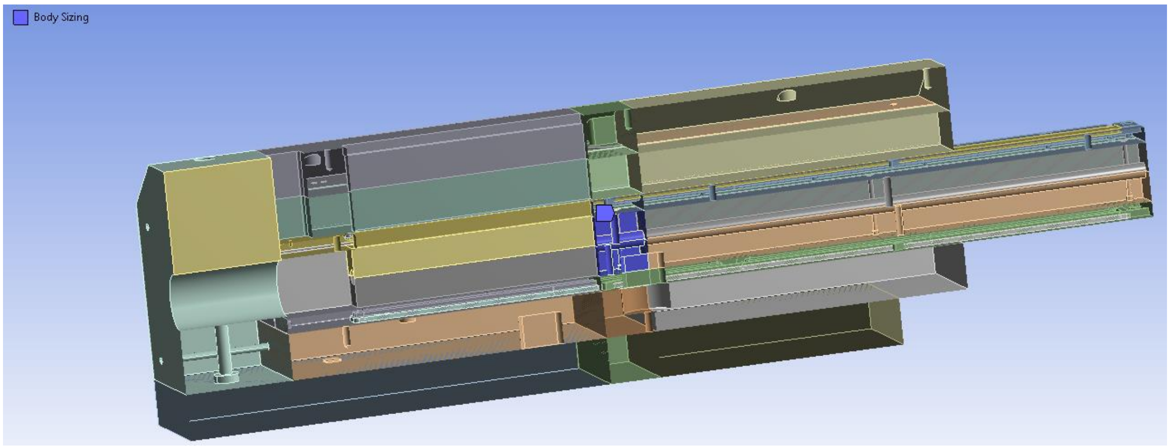

Figure 24 Body sizing function application region on the TAXN

Table 3

Summary of body sizing mesh function parameters used for the heat generation application region of TAXN

Object Name	*Body Sizing*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	2 Bodies
Definition	
Suppressed	No
Type	Element Size
Element Size	0.15 m
Behaviour	Soft

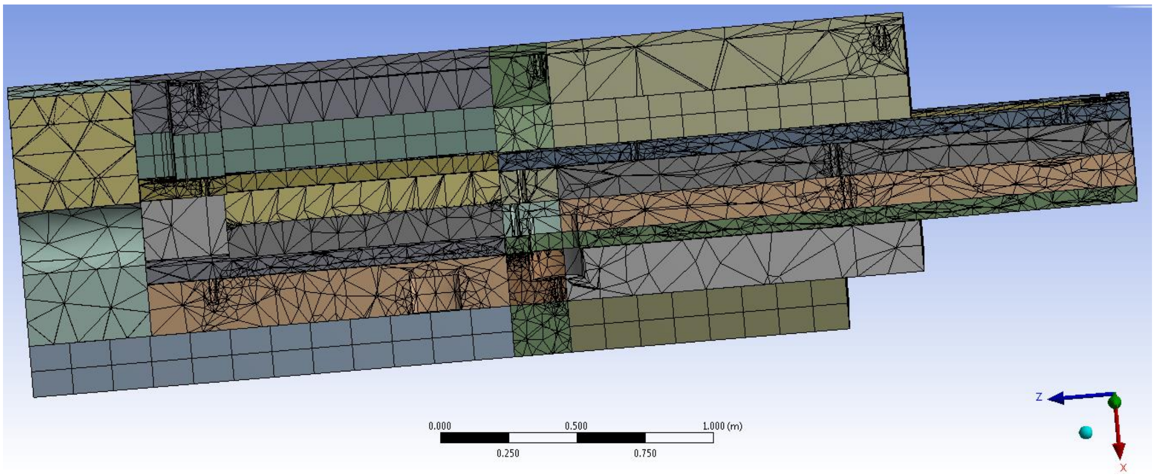

Figure 25 Shielded TAXN Mesh

Within the given case besides the convection values applied for the cooling channels as described in the previous studies, additional convection value was applied to the outer boundaries of the TAXN, with the value being 0.1 W/m^2 and radiation value of 0.07.

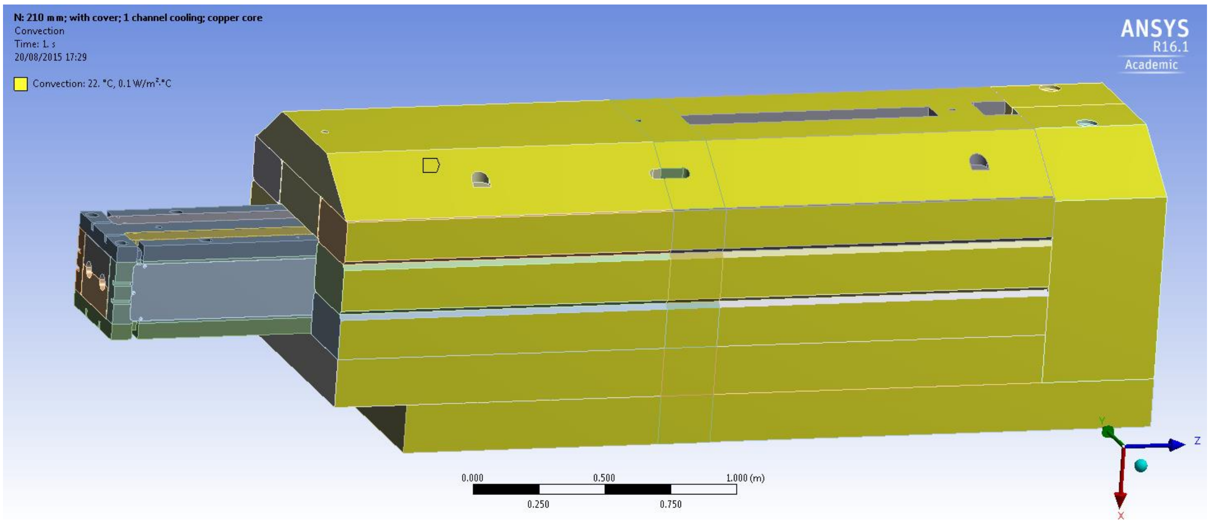

Figure 26 TAXN outer convection definition

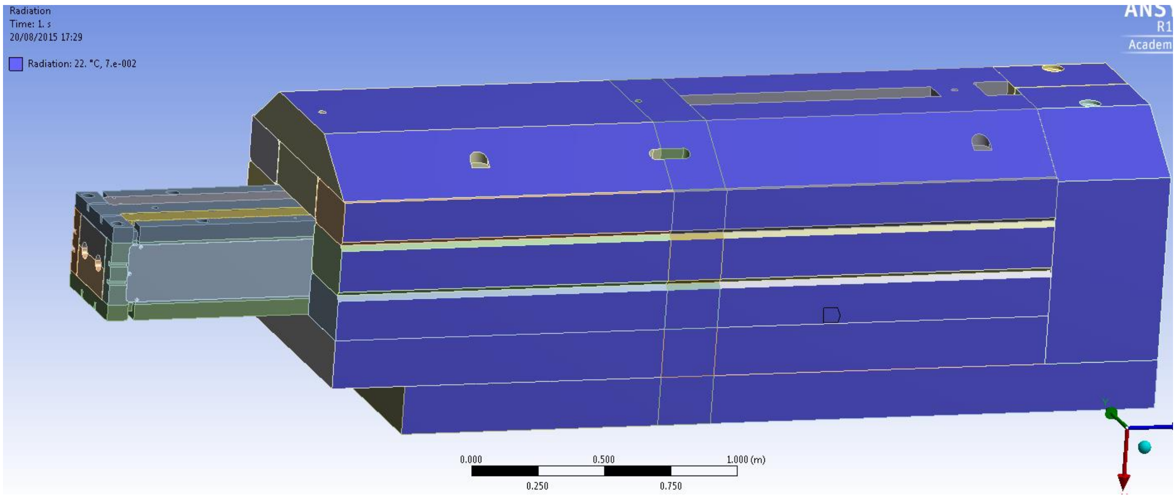

Figure 27 TAXN outer radiation definition

Different scenarios of cooling channel failures the variations of 2 different materials (copper alloy and tungsten alloy) were the main variables that defined the next simulations. Analogous studies were performed on the shielded TAXN as the on the ones that did not have any shielding. The results of these studies can be viewed in Figure 28, Figure 29, Figure 30 and Figure 31.

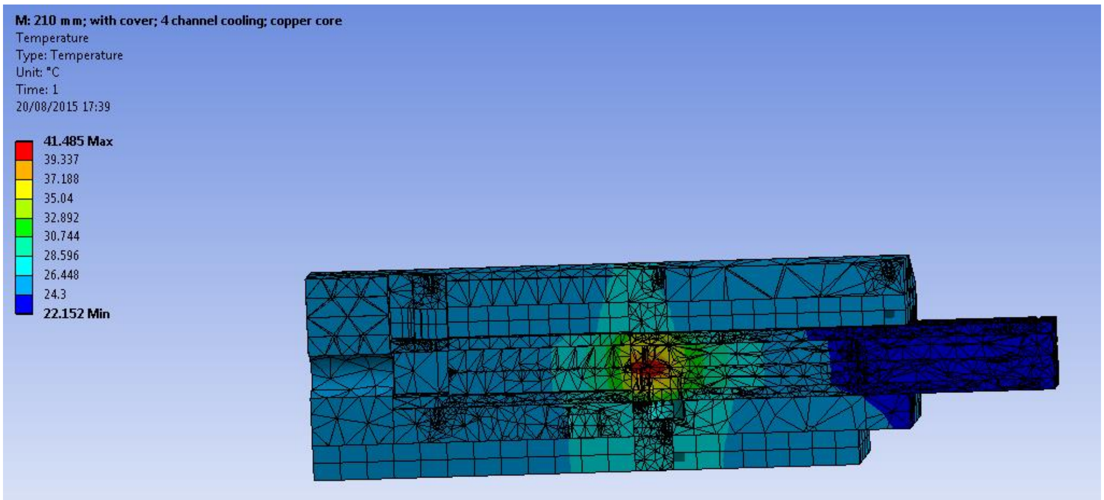

Figure 28 Temperature within the cross section of TAXN with heat deposition region being 210 mm wide; all cooling channels active on all 4 planes of core structure; copper alloy core, stainless steel and structural steel shielding

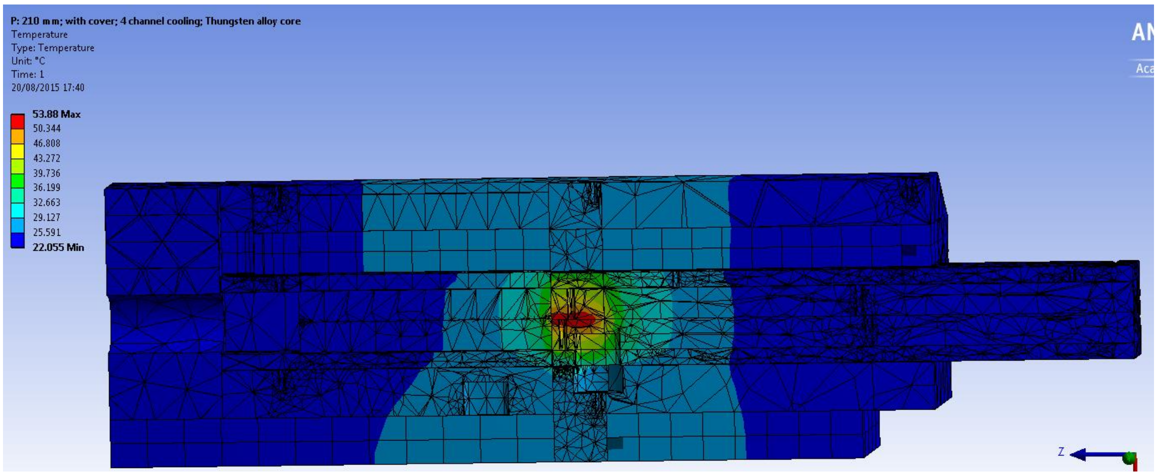

Figure 29 Temperature within the cross section of TAXN with heat deposition region being 210 mm wide; all cooling channels active on all 4 planes of core structure; tungsten alloy core, stainless steel and structural steel shielding

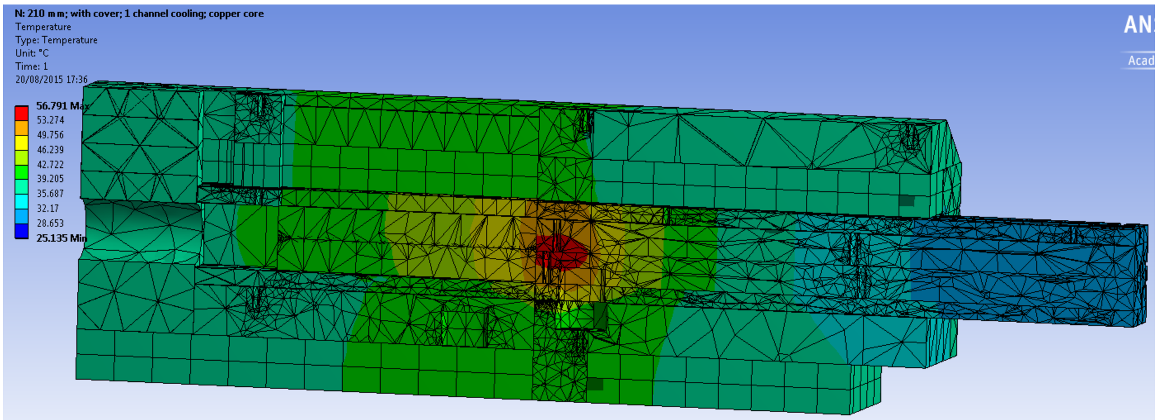

Figure 30 Temperature within the cross section of TAXN with heat deposition region being 210 mm wide; cooling channel active only on 1 plane of core structure; copper alloy core, stainless steel and structural steel shielding

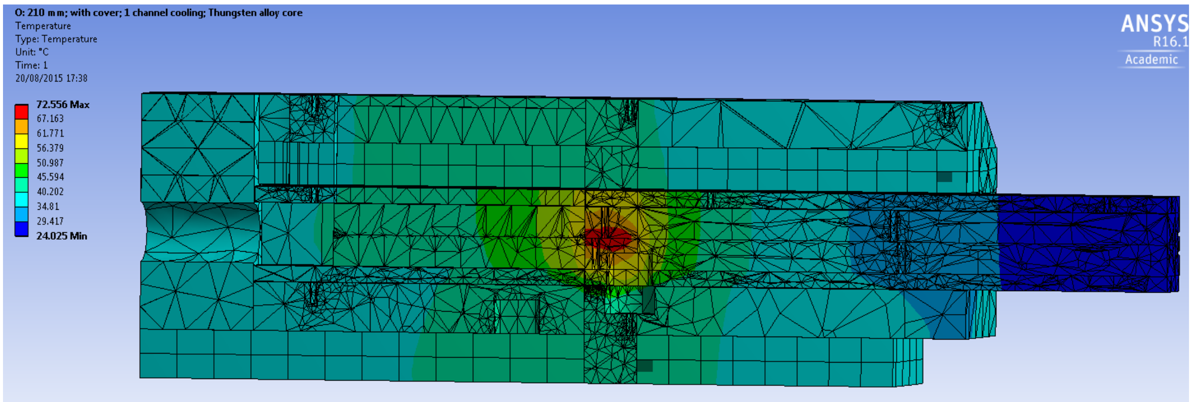

Figure 31 Temperature within the cross section of TAXN with heat deposition region being 210 mm wide; cooling channel active only on 1 plane of core structure; copper alloy core, stainless steel and structural steel shielding

Results obtained are similar to the ones generated previously, meaning that at no point of time the temperature is going to exceed a 100 ºC limit, and given that at least one plane the TAXN core structure will have active cooling. Obviously the implementation of the copper core provides much lower temperature (22 ºC – 41 ºC with all 4 planes of cooling channels being active and 25 ºC - 56 ºC with only 1 plane of cooling channels being active (see Figure 28 and Figure 30) comparing to the tungsten alloy core, where the according temperatures are 22 – 53 ºC and 25 ºC - 72 ºC (see Figure 29 and Figure 31). Additionally the geometric distribution of heat is much more even in the case of utilization of copper alloy comparing to tungsten alloy core.

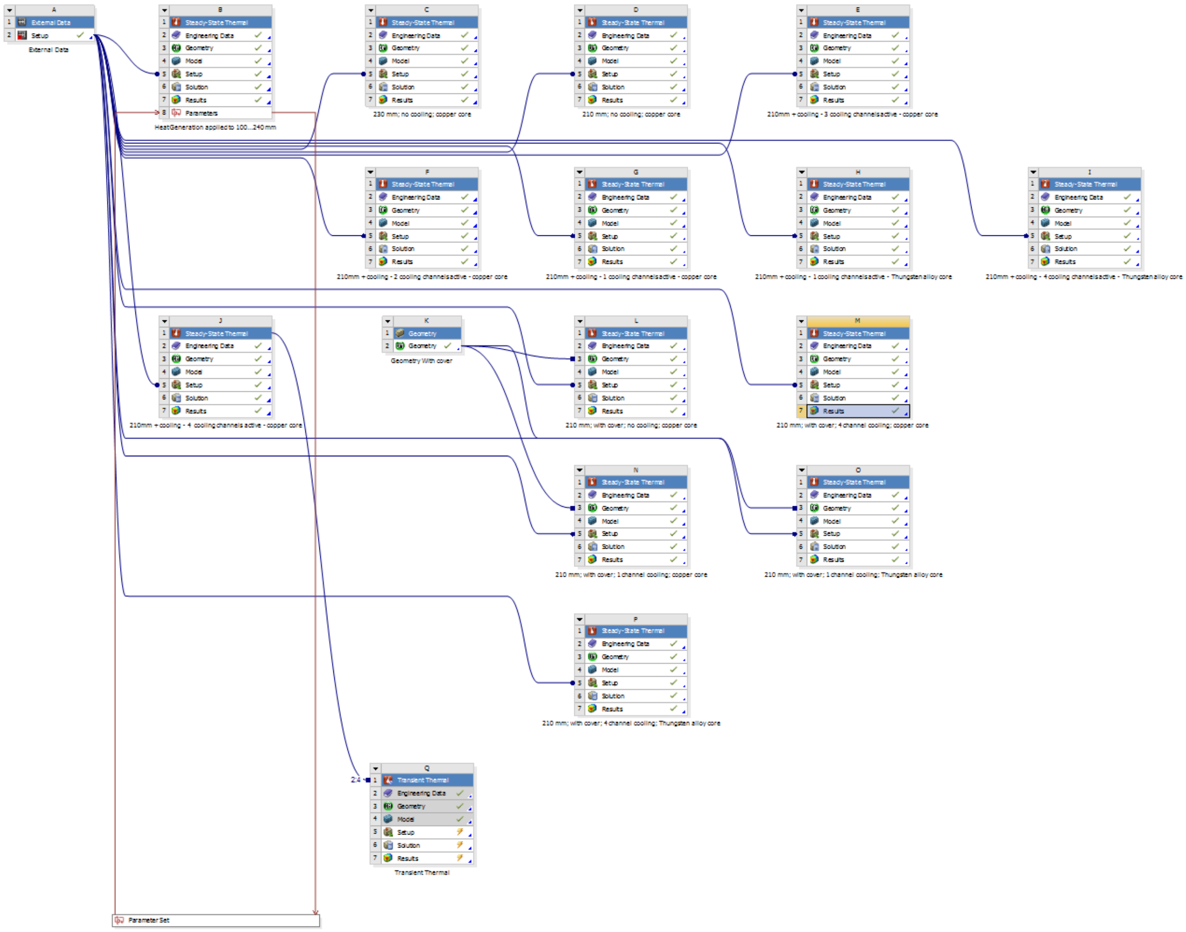

Figure 32 ANSYS interface simulation tree of the performed simulations for the TCDXM D2 collimator mask study

1.3. CONCLUSIONS

Finally it can be concluded that performing the simulation of a very pessimistic case of in-service thermal conditions for TCDXM D2 collimator mask, it can be stated that the given structure will withstand the heat impact applied, given that there is a very simple cooling system present consisting out of 2 small cooling collars placed in a configuration that is displayed in Figure 12. Nevertheless, more precise external data is necessary that would be applicable to the TCDXM D2 collimator mask so as to obtain results that would be more realistic. But given that the realistic heating conditions of TCDXM will be several magnitude lower, it can be stated with an appreciable amount of confidence that TCDXM D2 collimator mask will conform to all serviceability requirements even with no cooling system present.

Thermal analysis of TAXN clearly illustrated that the present concept of intended cooling system is more than sufficient to provide appropriate service life conditions for the given part. Some options of minimizing the amount of cooling system instalments may be considered for the future studies so as to minimize the economic issues concerning the development and maintenance.

Nevertheless, for the future studies a transient thermal analysis has to be done in order to evaluate all aspects of fatigue loading impact on the whole structure as well as local temperature peaks.

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