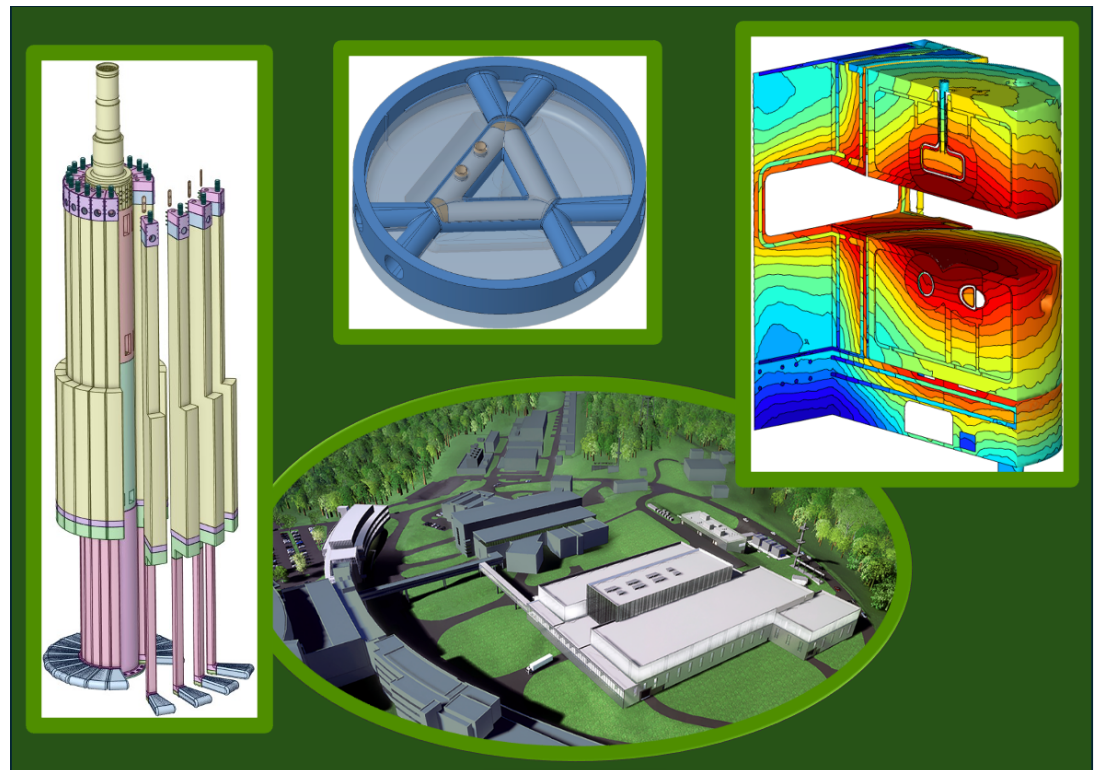


Neutronics Performance, Energy Deposition, and Radiation Damage in ORNL's Second Target Station Final Design of the Moderator Reflector Assembly (MRA)



Lukas Zavorka

March 2026

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Second Target Station Project

**NEUTRONICS PERFORMANCE, ENERGY DEPOSITION, AND RADIATION
DAMAGE IN ORNL'S SECOND TARGET STATION FINAL DESIGN OF THE
MODERATOR REFLECTOR ASSEMBLY (MRA)**

Lukas Zavorka

March 2026

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CONTENTS

CONTENTS	iii
LIST OF FIGURES	iv
LIST OF TABLES.....	vi
ABBREVIATIONS	vii
EXECUTIVE SUMMARY	viii
1. SCOPE.....	1
2. ACCEPTANCE CRITERIA	1
3. ASSUMPTIONS AND LIMITATIONS	1
4. METHODOLOGY AND MODELS.....	2
4.1 Models for the analysis.....	2
4.2 CAD to MCNP conversion.....	5
4.3 Materials, physics models, source	8
4.4 Energy deposition tally.....	9
4.5 Radiation damage and He production cross sections and tally.....	10
4.6 Neutronics point detector tally.....	12
5. RESULTS.....	13
5.1 Energy deposition	13
5.2 Radiation damage	14
5.3 Neutronics performance.....	16
5.3.1 Neutronics performance under nominal conditions.....	17
5.3.2 Sensitivity studies	24
5.3.3 MRA misalignment study.....	32
6. CONCLUSIONS	35
7. REFERENCES	36
Appendix A. COMPUTER HARDWARE AND SOFTWARE.....	A-3
Appendix B. LOCATION OF COMPUTATIONAL INPUT AND OUTPUT FILES	B-3
Appendix C. TECHNICAL REVIEW DOCUMENTATION.....	C-3
Technical Review Checklist	C-3

LIST OF FIGURES

Figure 1. 3D view (left) and elevation plot (right) of the MRA and backbone.	2
Figure 2. Elevation plot (left) and horizontal view (right) of the cylinder moderator.	3
Figure 3. Elevation plot (left) and horizontal view (right) of the tube moderator.	3
Figure 4. Geometry dimensions of the moderators.	4
Figure 5. UM model of the full MRA and backbone (left) with some shielding components hidden to show the water cooling and hydrogen supply and return pipes (right).	6
Figure 6. UM model of the reflector vessels (left) with water cooling and Be reflector (right).	7
Figure 7. UM model of the cylinder moderator (left) and the tube moderator (right).	7
Figure 8. Elevation plot of the central portion of the geometry, including the MRA, target segment, target shaft, and CV shielding, as displayed by the MCNP plotter.	7
Figure 9. UM models of the moderator and reflector vessels for the energy deposition and damage analyses.	10
Figure 10. Example of energy deposition on UM in the elevation cross section through the MRA.	10
Figure 11. Applied dpa cross sections for neutrons [16].	11
Figure 12. Applied dpa cross sections for protons [16].	11
Figure 13. Horizontal cross section through the CSG emission surfaces (thin black) inserted into the non-meshed vacuum gap between the moderator and reflector vessels of the tube (left) and cylinder (right) moderators.	12
Figure 14. Energy deposition and relative uncertainties in the MRA and backbone.	13
Figure 15. Detailed view of energy deposition in the MRA.	14
Figure 16. Elevation plot of the radiation damage as dpa/year in aluminum vessels of the MRA.	15
Figure 17. Horizontal view of the radiation damage as dpa/year in aluminum vessels of the MRA. Bottom of the cylinder reflector vessel is shown on the left and the top of the tube reflector vessel is on the right.	15
Figure 18. Elevation plot of the radiation damage as dpa/year in the steel backbone.	16
Figure 19. Calculated time emission spectra at 5 Å.	17
Figure 20. Calculated time emission spectra at 10 Å.	18
Figure 21. Calculated time emission spectra at 8 Å.	18
Figure 22. Calculated time emission spectra at 4 Å.	19
Figure 23. Calculated time emission spectra at 3 Å.	19
Figure 24. Calculated time emission spectra at 2 Å.	20
Figure 25. Calculated peak brightness, shown on a logarithmic y-scale.	21
Figure 26. Calculated peak brightness, shown on a linear y-scale.	21
Figure 27. Calculated time-integrated brightness, shown on a logarithmic y-scale.	22
Figure 28. Calculated time-integrated brightness, shown on a linear y-scale.	22
Figure 29. Calculated time resolution at one half of maximum.	23
Figure 30. Calculated time resolution at one tenth of maximum.	23
Figure 31. Calculated root mean square.	24
Figure 32. Calculated peak brightness of the cylinder moderator as a function of para-hydrogen fraction.	25
Figure 33. Calculated time-integrated brightness of the cylinder moderator as a function of para- hydrogen fraction.	25
Figure 34. Calculated peak brightness of the tube moderator as a function of para-hydrogen fraction.	26
Figure 35. Calculated time-integrated brightness of the tube moderator as a function of para- hydrogen fraction.	26
Figure 36. Calculated time-emission spectra 5 Å of the cylinder moderator as a function of hydrogen density.	27

Figure 37. Calculated peak brightness of the cylinder moderator as a function of hydrogen density.....	27
Figure 38. Calculated time-emission spectra at 5 Å of the tube moderator as a function of hydrogen density.....	28
Figure 39. Calculated peak brightness of the tube moderator as a function of hydrogen density.....	28
Figure 40. Calculated peak brightness of the tube moderator as a function of hydrogen density.....	29
Figure 41. Calculated time-emission spectra at 5 Å of the cylinder moderator as a function of hydrogen temperature.	30
Figure 42. Calculated peak brightness of the cylinder moderator as a function of hydrogen temperature.	30
Figure 43. Calculated time-emission spectra at 5 Å of the tube moderator as a function of hydrogen temperature.	31
Figure 44. Calculated peak brightness of the tube moderator as a function of hydrogen temperature.	31
Figure 45. Illustrations supporting the maximum misalignment study. Shown are misalignment rotation axes for the cylinder (top left) and tube (top right) moderators, as well as the elevation cross sections of the misaligned cylinder (bottom left) and tube (bottom right) moderators overlaid on aligned vessels.	32
Figure 46. Time-integrated brightness of the maximally misaligned cylinder moderator.	33
Figure 47. Time-integrated brightness of the maximally misaligned tube moderator.	33
Figure 48. Time emission spectra at 5 Å of the maximally misaligned MRA.	34

LIST OF TABLES

Table 1. Geometry dimensions of the moderators.....	4
Table 2. Most important Attila4MC meshing parameters for the neutronics performance analysis.....	5
Table 3. Most important Attila4MC meshing parameters for the energy deposition and radiation damage analysis	6
Table 4. Supercritical para-hydrogen at 20 K. Density 0.073 g/cm ³ and 0.072 g/cm ³ for cylinder and tube moderators, respectively.	8
Table 5. Ambient light water. Density 1.0 g/cm ³ . STS neutronics mat #9, ENDF/B-VII.1 library	8
Table 6. Aluminum Al-6061. Density 2.7 g/cm ³ . STS neutronics mat #7 and #8, ENDF/B-VII.1 library.....	8
Table 7. Beryllium. Density 1.82922 g/cm ³ . STS neutronics mat #11, ENDF/B-VII.1 library	8
Table 8. Stainless steel 316 composition. Density 8.0 g/cm ³ . STS neutronics mat #252, ENDF/B- VII.1 library	9
Table 9. Invar. Density 8.05 g/cm ³ . STS neutronics mat #238, ENDF/B-VII.1 library	9
Table 10. Total heating in the MRA and backbone in individual materials.....	14

ABBREVIATIONS

CAD	Computer Aided Design
cc	Cubic centimeter or cm ³
CPU	Central Processing Unit
CSG	Constructive Solid Geometry
CV	Core Vessel
dpa	Displacement per atom
FTS	First Target Station at SNS
FW-CADIS	Forward-Weighted Consistent Adjoint Driven Importance Sampling
KPP	Key Performance Parameter
LH2	Liquid hydrogen
MRA	Moderator Reflector Assembly
ORNL	Oak Ridge National Laboratory
PBW	Proton Beam Window
SNS	Spallation Neutron Source
STS	Second Target Station at SNS
TVP	Target Viewing Periscope
UM	Unstructured Mesh
VR	Variance Reduction
ZAID	Proton and neutron isotopic identification number

EXECUTIVE SUMMARY

This report discusses the simulations of the neutronics performance, energy deposition, and radiation damage in ORNL's Second Target Station (STS) Moderator Reflector Assembly (MRA) based on the MRA final-design geometry from February 2025. The simulations were performed with the radiation transport code MCNP6.2 [1] and they used the Unstructured Mesh (UM) geometry models of the target and the MRA. The UM models were converted from the original solid Computer Aided Design (CAD) models with Attila4MC [2]. The use of the detailed UM models is a key factor in ensuring that the neutronics performance is calculated with the most accurate geometry representation of the final-design model. The UM models also provide results of energy deposition and radiation damage in the MRA with high spatial resolution, which is especially important for the subsequent structural stress and thermo-mechanical engineering analyses.

This report shows that the calculated neutronics performance of the final-design geometry of the MRA exceeds the peak brightness of $2 \cdot 10^{14}$ n/cm²/sr/Å/s at 5 Å, which is a key performance parameter (KPP) to be measured as an objective of the STS project. This report also shows that the MRA Material Lifetime Requirement [3], defined as "The MRA materials shall allow for a lifetime of at least 5 years of operation", has been met.

1. SCOPE

This report documents MCNP radiation transport (neutronics) calculations of the neutronics performance, energy deposition, and radiation damage in the final design geometry of the Second Target Station (STS) Moderator Reflector Assembly (MRA). Neutronics performance is a key indicator of success of the STS project. This report shows that the calculated neutronics performance exceeds the peak brightness of $2 \cdot 10^{14}$ n/cm²/sr/Å/s at 5 Å, which is an objective within the list of the STS Key Performance Parameters (KPP) and needs to be verified experimentally after the commissioning.

The energy deposition in the MRA and the backbone was calculated as input for the subsequent structural stress and thermo-mechanical engineering analyses to ensure that the final design is robust enough for the MRA to operate reliably during the minimal service lifetime of 5 years. The lifetime is evaluated by the MCNP calculations of radiation-induced effects, namely the helium (He) gas and silicon (Si) production in aluminum vessels of the MRA and radiation damage in the MRA and backbone, quantified as displacements per atom (dpa).

This MCNP analysis uses highly detailed unstructured mesh (UM) models of the MRA to ensure that the neutronics performance is calculated with the most accurate representation of the original solid models and that the energy deposition results are delivered with high spatial resolution.

2. ACCEPTANCE CRITERIA

This report shows that the calculated neutronics performance of the final-design geometry of the MRA exceeds the peak brightness of $2 \cdot 10^{14}$ n/cm²/sr/Å/s at 5 Å, which is a KPP to be measured as an objective of the STS project. This report also shows that the MRA Material Requirement on a lifetime of at least 5 years of operation has been met.

3. ASSUMPTIONS AND LIMITATIONS

This analysis was performed with a solid CAD model “mra_am_001update.asm” for the MRA and backbone from February 4, 2025, known at that point to represent the STS final-design geometry. This model does not include engineering details such as weld details, fasteners, fit up gaps, and other fabrication details that have practically no impact on the neutronics performance. The results do not capture any subsequent design developments or modifications.

4. METHODOLOGY AND MODELS

4.1 MODELS FOR THE ANALYSIS

This analysis uses a solid CAD model “mra_am_001update.asm” for the MRA and backbone from February 4, 2025. The MRA is complemented with the target, target shaft, core vessel (CV), core vessel shielding, target viewing periscope (TVP), and proton beam window (PBW). The final-design model of the target discussed in [4] was used. More distant STS components, such as the target crown in the target drive room, accelerator components, neutron beamline components and very distant shielding components are not included in the MCNP model for this analysis, because they have negligible impact on the results and their incorporation would significantly slow down MCNP calculations. The used solid model of the MRA and the backbone is shown in Figure 1.

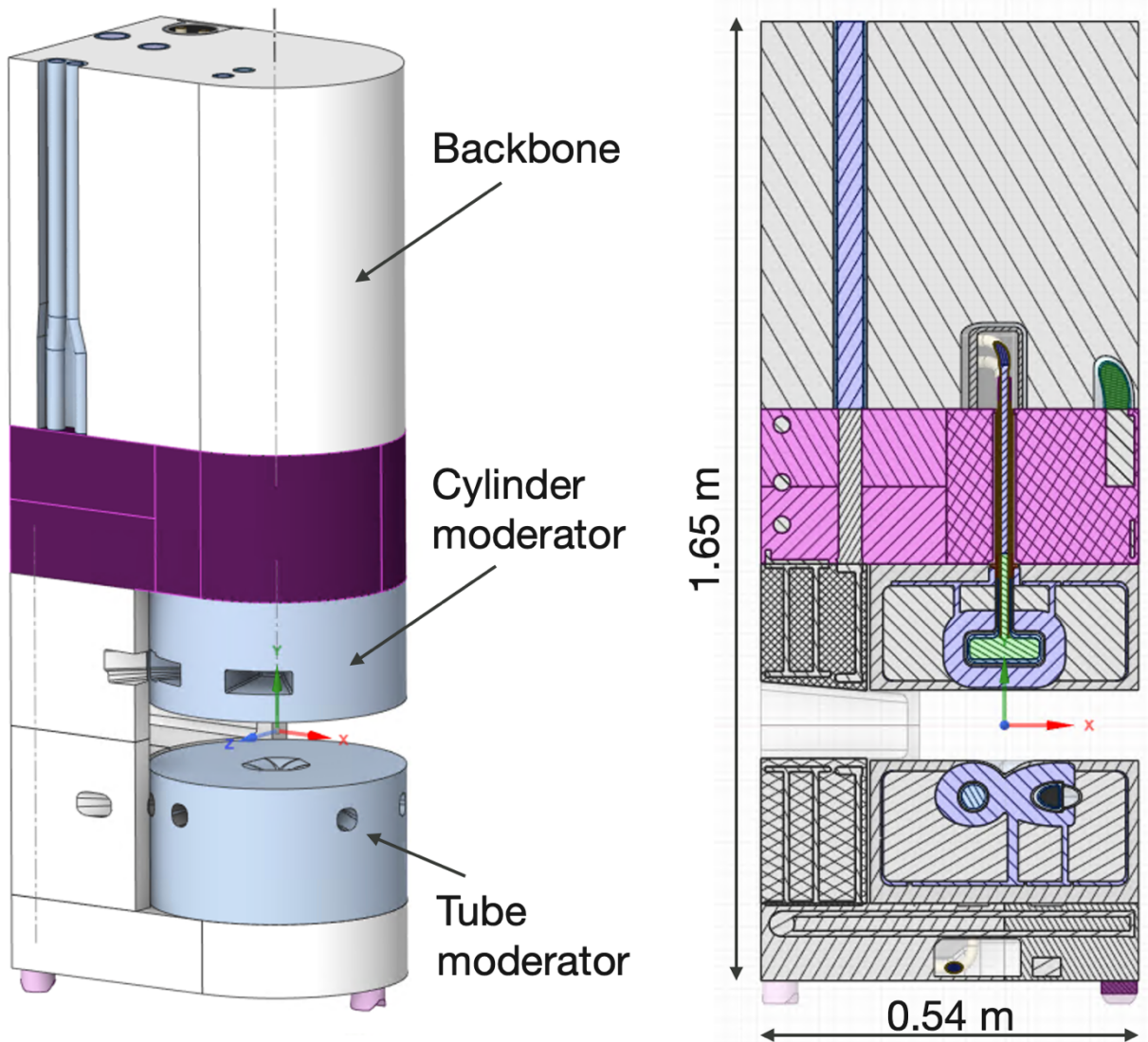


Figure 1. 3D view (left) and elevation plot (right) of the MRA and backbone.

The MRA consists of two low dimensional (flat) [5-9] pure parahydrogen moderators at 20 K designed to deliver high peak neutron brightness. The moderators are surrounded with a light water pre-moderator at room temperature and a beryllium reflector, and they are encased in the water-cooled aluminum vessels. The cylinder moderator is located above the spallation target, it has four $3 \times 3 \text{ cm}^2$ fields of view, and it can serve up to 12 neutron beamlines. The tube moderator is located below the target, it has three fields of view with a diameter of 3 cm, and it can serve up to six neutron beamlines. Detailed views of the cylinder and tube moderators are shown in Figure 2 and Figure 3, respectively.

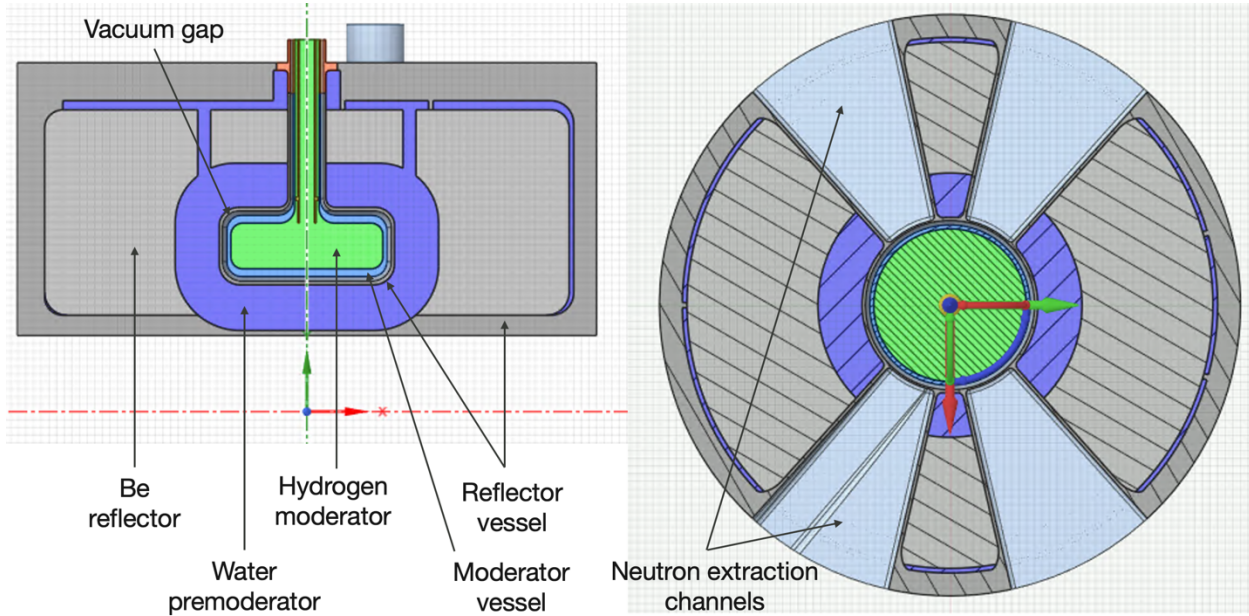


Figure 2. Elevation plot (left) and horizontal view (right) of the cylinder moderator.

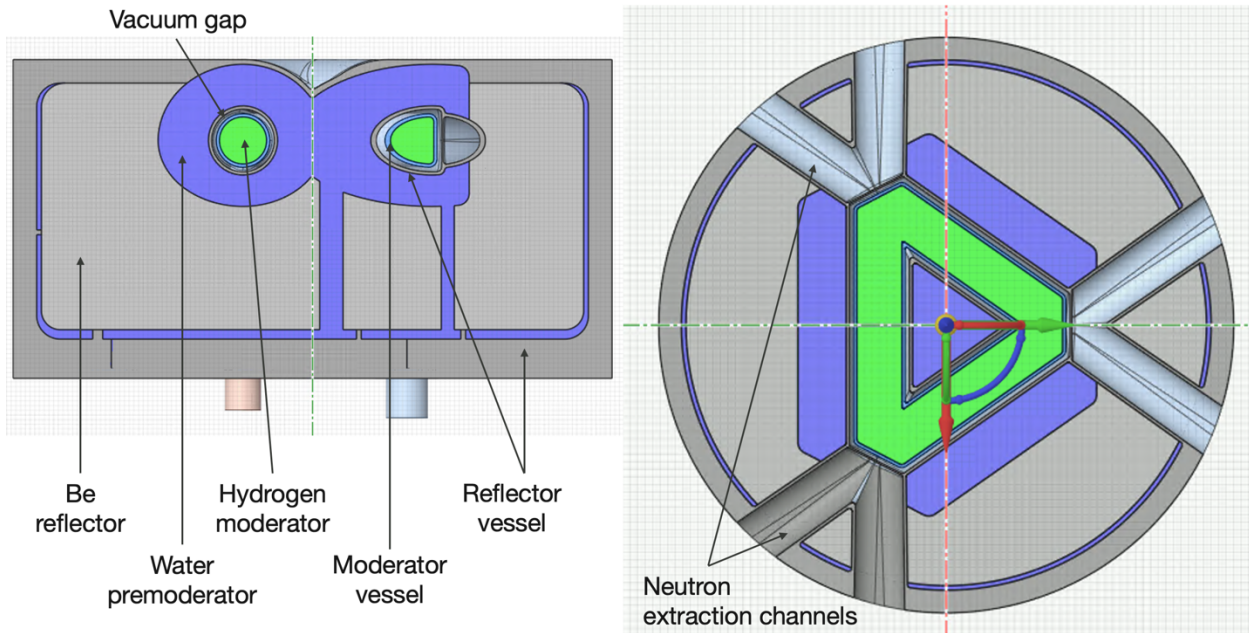


Figure 3. Elevation plot (left) and horizontal view (right) of the tube moderator.

The dimensions of the moderators were determined in a comprehensive optimization study [10-13] that simultaneously combined the optimization of the moderators, spallation target, and proton beam profile. The fully automated optimization pioneered the use of the parametrized solid CAD models of the target and moderators automatically converted into the unstructured mesh (UM) models. The optimization workflow generated the results of the neutronics performance and optionally the results of energy deposition in the target, thus enabling the coupled neutronics–structural stress optimization of the STS. The final optimized geometry dimensions of the moderators are marked in Figure 4 and listed in Table 1.

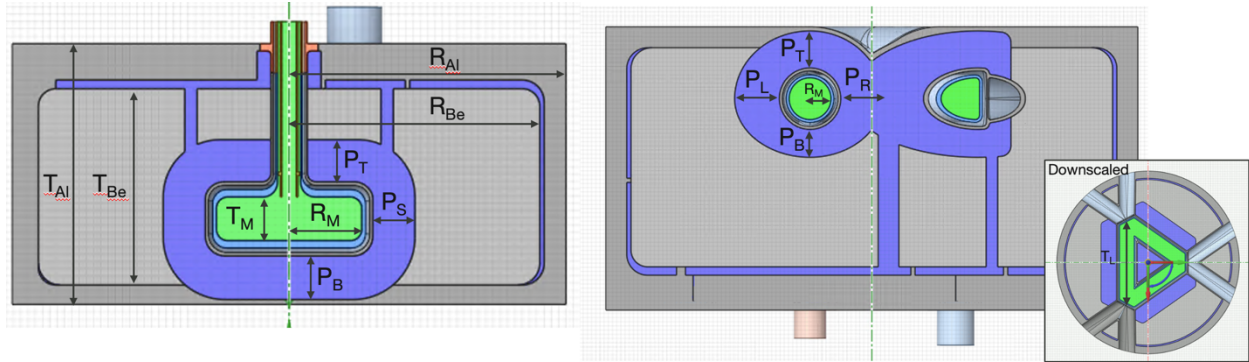


Figure 4. Geometry dimensions of the moderators.

Table 1. Geometry dimensions of the moderators.

Dimension	Cylinder (mm)	Tube (mm)
T_{Al} (Thickness of the Al vessel)	179.3	203
R_{Al} (Radius of the Al vessel)	190.5	190.5
T_{Be} (Thickness of the Be reflector)	135	157
R_{Be} (Radius of the Be reflector)	172.5	172.5
R_M (Radius of the moderator)	50	15
T_M (Thickness of the moderator)	30	
P_S (Side thickness of the premoderator)	29	
P_B (Bottom thickness of the premoderator)	30	20
P_T (Top thickness of the premoderator)	29	26.5
P_L (Left thickness of the premoderator)		32
P_R (Right thickness of the premoderator)		30
T_L (Tube length)		170

4.2 CAD TO MCNP CONVERSION

The solid CAD model of the final-design MRA was converted into the UM model for the neutronics calculations with Attila4MC's tetrahedral mesh generator in the non-manifold non-imprint mode, which generates contiguous mesh with no overlaps of the neighboring objects. Such a mode is extremely important to use for accurate neutronics performance and energy deposition calculations in comparison with the default part-by-part mesher that can generate discontinuous mesh with possible mesh overlaps, resulting in potentially incorrect results in mesh elements on adjacent objects boundaries.

For the neutronics performance analysis, the mesh generation parameters are summarized in Table 2 for the MRA, including the backbone. For the energy deposition analysis, the mesh generation parameters are summarized in Table 3. This selection of meshing parameters results in good compromise between the high-fidelity of the UM model, as required by the subsequent analyses, and efficiency or speed of the MCNP calculations and limits of the hardware. In general, the finer the UM model and the higher the number of mesh elements, the more MCNP computing time and CPU memory is necessary to reach the results with good statistical uncertainty. A reasonable computing time that is available – given by the existing STS neutronics hardware and the need to complete a range of other analyses within the STS project – is maximally about a week to 10 days occupying one half of the nodes available on Kryo cluster, which provides 448 computer processors (CPUs) with almost full memory usage.

For the neutronics performance analysis, the settings of the mesh generation parameters from Table 2 resulted in the MRA UM model that is composed of 3,800,000 mesh elements. The total number of mesh elements in the entire MCNP model, including the target, PBW, and shielding is approximately 5,000,000. A separate model was generated for energy deposition and radiation damage analysis. Due to memory constraints and more extensive format of energy deposition tallies, slightly coarser mesh generation parameters from Table 3 resulted in the UM model composed of 3,000,000 mesh elements.

Figures 5-8 show the UM models of the MRA and the backbone for the neutronics performance analysis. Figure 5 shows the full MRA model with several components intentionally hidden to reveal the complexity of the water cooling and hydrogen supply and return pipes. Figure 6 shows only the reflector vessels and their cooling with the backbone not displayed. Figure 7 shows only the meshed volumes of the moderators. Figure 8 shows the integration of the MRA UM models with the model of the target and surrounding shielding, as displayed by the MCNP plotter.

Table 2. Most important Attila4MC meshing parameters for the neutronics performance analysis

Meshing parameter type	Meshing parameter value
General max allowable edge length	0.025 m
Max allowable edge length for components other than backbone	0.008 m
Max allowable edge length for hydrogen and hydrogen vessel in the cylinder moderator	0.0025 m
Max allowable edge length for hydrogen and hydrogen vessel in the tube moderator	0.003 m
Size transition factor	0.4
Maximum d/h ratio	0.01
Minimum edge length	0.01
Anisotropic refinement	yes

Table 3. Most important Attila4MC meshing parameters for the energy deposition and radiation damage analysis

Meshing parameter type	Meshing parameter value
General max allowable edge length	0.1 m
Max allowable edge length for components other than backbone	0.01 m
Max allowable edge length for hydrogen and hydrogen vessel in the cylinder moderator	0.005 m
Max allowable edge length for hydrogen and hydrogen vessel in the tube moderator	0.005 m
Size transition factor	0.4
Maximum d/h ratio	0.01
Minimum edge length	0.01
Anisotropic refinement	yes

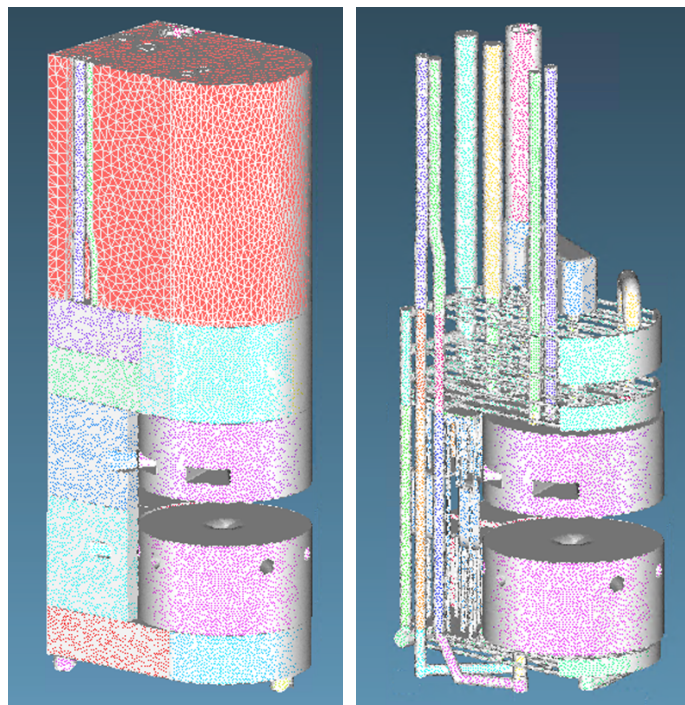


Figure 5. UM model of the full MRA and backbone (left) with some shielding components hidden to show the water cooling and hydrogen supply and return pipes (right).

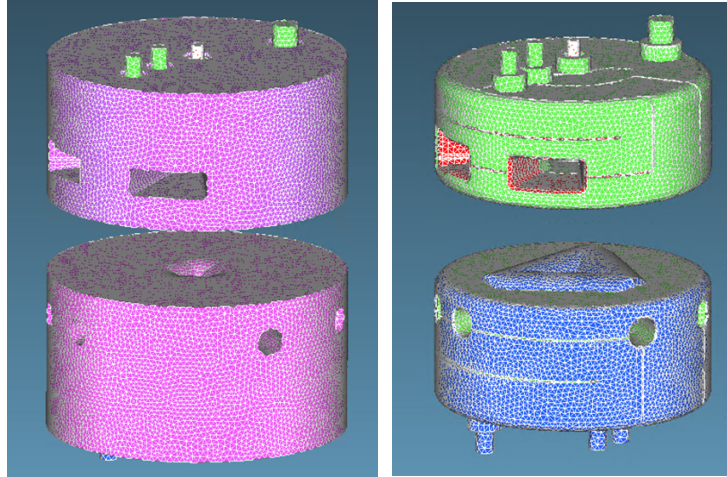


Figure 6. UM model of the reflector vessels (left) with water cooling and Be reflector (right).

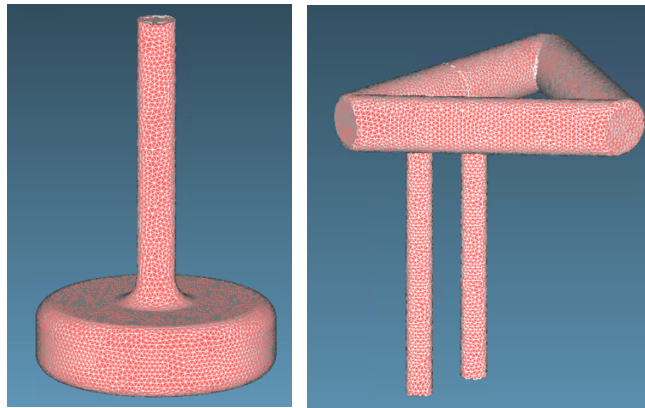


Figure 7. UM model of the cylinder moderator (left) and the tube moderator (right).

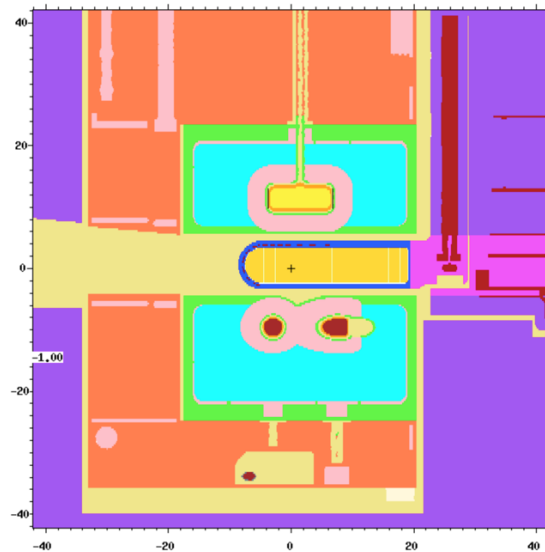


Figure 8. Elevation plot of the central portion of the geometry, including the MRA, target segment, target shaft, and CV shielding, as displayed by the MCNP plotter.

4.3 MATERIALS, PHYSICS MODELS, SOURCE

The material composition of the most important materials (hydrogen, water, aluminum, beryllium, stainless steel 316, and invar) used in the MCNP analysis is summarized in Tables 4-9. Z Aid is the proton-neutron identification number used by MCNP. By default, the nuclear data library ENDF/B-VII.1 is used for neutron interactions below 20 MeV. For the low-energy neutron interactions, scattering kernels S_{AB} are also used from the ENDF/B-VII.1 library at temperatures either 20 K (hydrogen, hydrogen vessel) or 294 K. Above 20 MeV and for all high-energy charged particle interactions, this analysis uses the CEM03.03 physics model with the default setting of the model physics cards.

Standard densities are used for all materials. Hydrogen density in the cylinder moderator is 0.073 g/cm³, and the density is 0.072 g/cm³ in the tube moderator. Supercritical para-hydrogen fraction is 99.9% in both moderators, as defined by the Cryogenic Moderator System (CMS)-MRA Interface Sheet [14].

As an MCNP particle source, this analysis uses a nominal 60-cm² proton beam starting at a distance of 3 m from the target, upstream of the proton beam window (PBW) to realistically simulate the scattering of protons as they pass through the PBW.

Table 4. Supercritical para-hydrogen at 20 K. Density 0.073 g/cm³ and 0.072 g/cm³ for cylinder and tube moderators, respectively.

ZAID	Atomic fraction	ZAID	Atomic fraction
1004	0.999	1001	0.001

Table 5. Ambient light water. Density 1.0 g/cm³. STS neutronics mat #9, ENDF/B-VII.1 library

ZAID	Atomic fraction	ZAID	Atomic fraction	ZAID	Atomic fraction
1001	1.99977	1002	2.3E-4	8016	0.99962
8017	3.8E-4				

Table 6. Aluminum Al-6061. Density 2.7 g/cm³. STS neutronics mat #7 and #8, ENDF/B-VII.1 library

ZAID	Atomic fraction	ZAID	Atomic fraction	ZAID	Atomic fraction
12024	5.309692002E-4	12025	6.721980000E-5	12026	7.400899980E-5
13027	5.92923E-02	14028	3.218859369E-4	14029	1.635205550E-5
14030	1.079200760E-5	24050	2.730510970E-6	24052	5.265518611E-5
24053	5.970675426E-6	24054	1.486227490E-6	29063	4.978039350E-5
29065	2.220860650E-5				

Table 7. Beryllium. Density 1.82922 g/cm³. STS neutronics mat #11, ENDF/B-VII.1 library

ZAID	Atomic fraction	ZAID	Atomic fraction	ZAID	Atomic fraction
4009	1.20829E-01	6000	1.37569E-04	8016	4.31511E-04
8017	1.73019E-07	12000	3.62579E-05	13027	4.08266E-05
14000	2.35331E-05	26054	1.49241E-06	26056	2.35401E-05
26057	5.38499E-07	26058	7.17997E-08		

Table 8. Stainless steel 316 composition. Density 8.0 g/cm³. STS neutronics mat #252, ENDF/B-VII.1 library

ZAID	Weight fraction	ZAID	Weight fraction	ZAID	Weight fraction
6000	4.099949E-4	14028	0.004657923	14029	0.000244800
14030	0.000167194	15031	0.000229818	16032	0.000141906
16033	1.1551E-06	16034	6.6798E-06	16036	3.3601E-08
24050	0.007102731	24052	0.142276576	24053	0.016441745
24054	0.004179124	25055	0.010140357	26054	0.037801314
26056	0.614798022	26057	0.014459771	26058	0.001943253
28058	0.080641263	28060	0.032127494	28061	0.001420162
28062	0.004596109	28064	0.001215537	42092	0.003553938
42094	0.002263389	42095	0.003936990	42096	0.004168349
42097	0.002411473	42098	0.006155910	42100	0.002506990

Table 9. Invar. Density 8.05 g/cm³. STS neutronics mat #238, ENDF/B-VII.1 library

ZAID	Weight fraction	ZAID	Weight fraction	ZAID	Weight fraction
6000	0.0002000065	14028	0.001837511	14029	9.6572E-05
14030	6.5956E-05	25055	0.003500082	26054	0.035718546
26056	0.580924026	26057	0.013663070	26058	0.001836184
28058	0.243372874	28060	0.096959799	28061	0.004286004
28062	0.013870916	28064	0.003668452		

4.4 ENERGY DEPOSITION TALLY

This analysis uses a set of embedded elemental edits control cards EMBEE type 6 to individually tally energy deposition as contributions from neutrons, photons (and electrons), protons, deuterons, tritons, alpha particles, and charged pions. These contributions are summed together and exported in the .csv format for individual materials. The .csv files serve as an input for the subsequent engineering analyses.

Figure 9 shows the UM model of the cylinder and tube moderators and their reflector vessels. This model also serves as energy deposition tally, and every single mesh element represents a data point in the output .csv file. Figure 10 then shows the elevation cross section through the moderators, as well as an example of energy deposition tallied on the UM model.

In the early stages of the STS project and elsewhere [13,15], a significant amount of time was spent on validating the energy deposition on UM in the spallation environment. Comparisons between EMBEE type 6 cards and traditional MCNP energy deposition tallies type +F6 and type 3 TMESH mesh tallies resulted in consistent agreement on both UM and traditional MCNP constructive solid geometries (CSG).

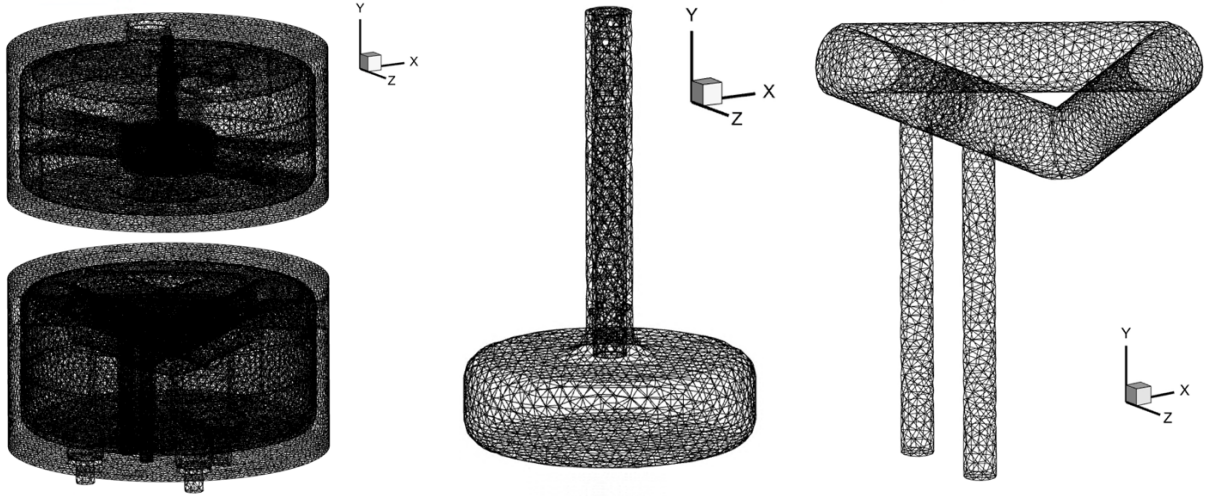


Figure 9. UM models of the moderator and reflector vessels for the energy deposition and damage analyses.

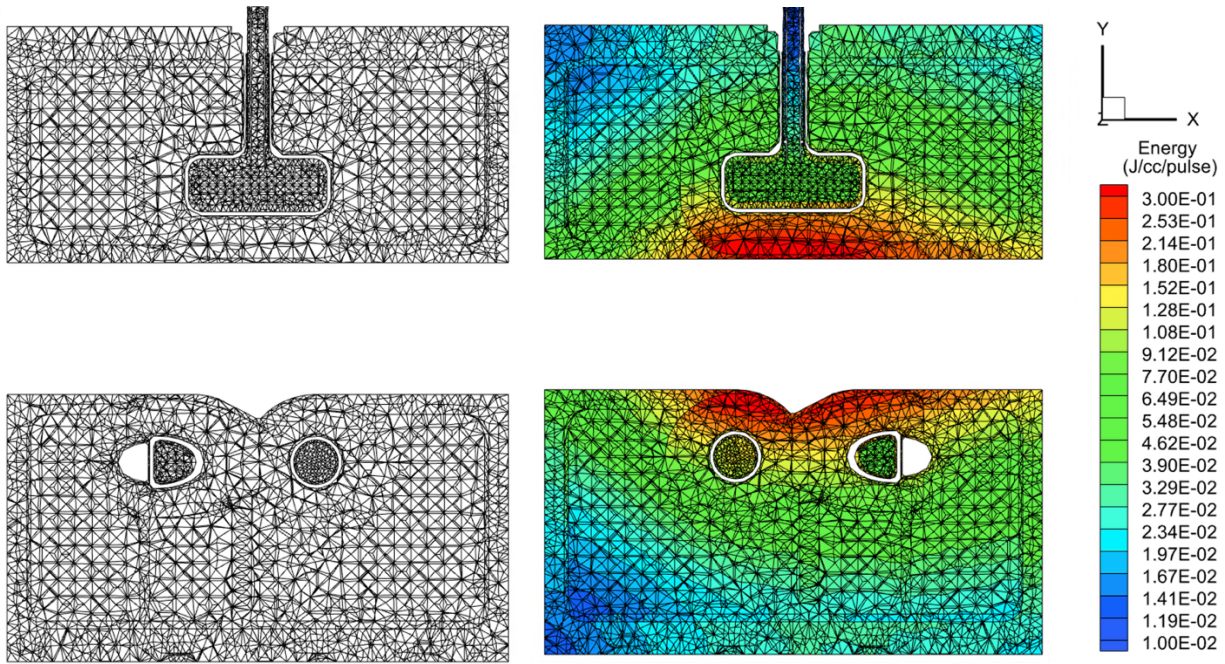


Figure 10. Example of energy deposition on UM in the elevation cross section through the MRA.

4.5 RADIATION DAMAGE AND HE PRODUCTION CROSS SECTIONS AND TALLY

This analysis uses radiation damage cross sections and He gas production cross sections developed at SNS' First Target Station (FTS) by Wei Lu [16] that extends up to 3.2 GeV for both neutrons and protons. Displacement per atom (dpa) is calculated individually for aluminum and stainless steel 316. Dpa cross sections are shown for neutrons and protons in Figure 11 and Figure 12, respectively.

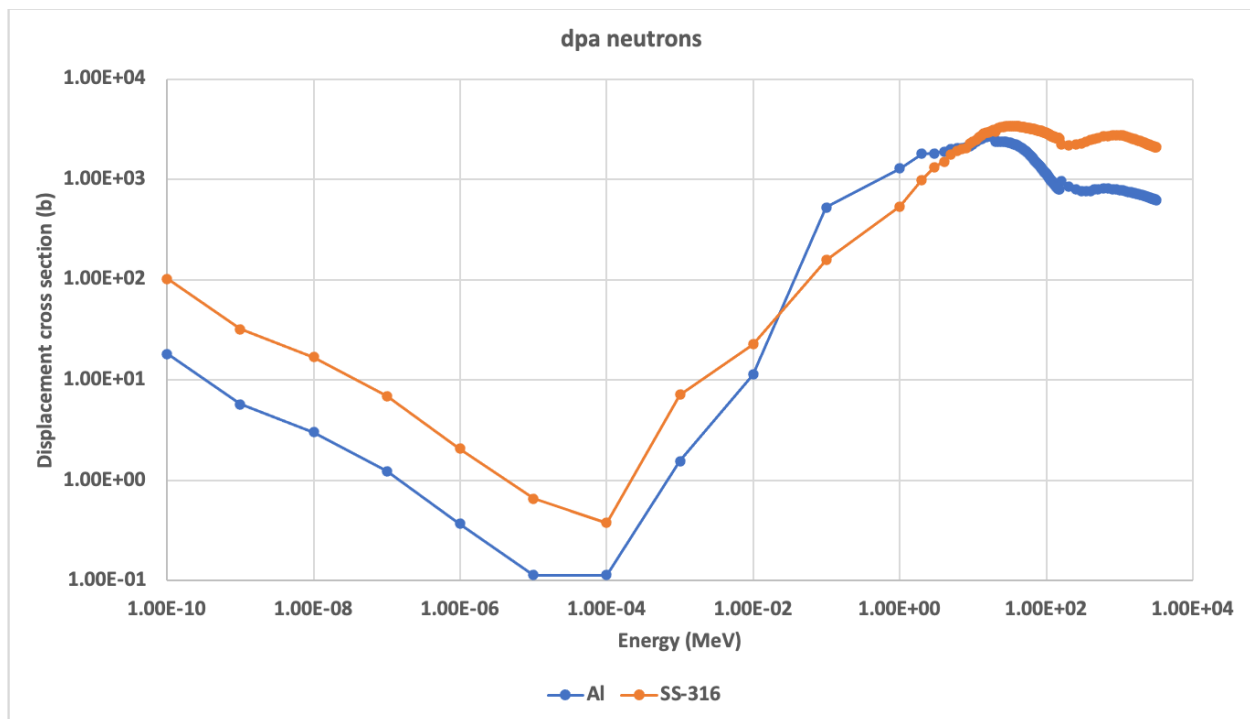


Figure 11. Applied dpa cross sections for neutrons [16].

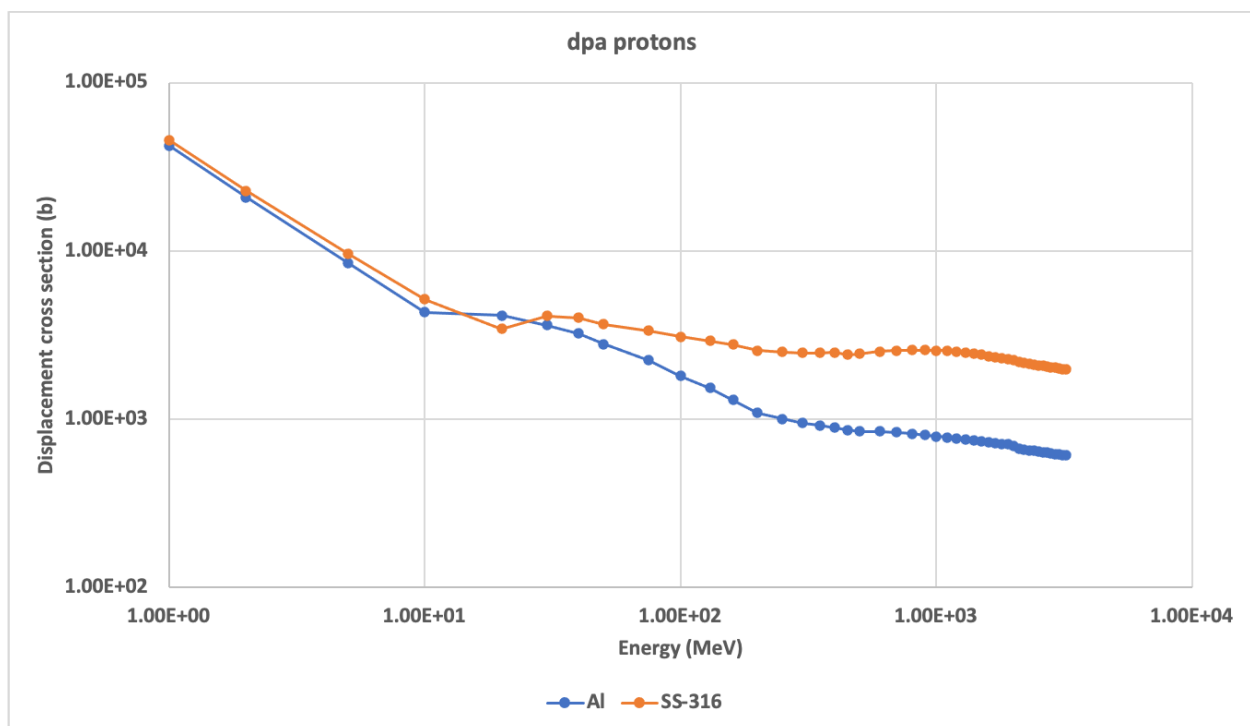


Figure 12. Applied dpa cross sections for protons [16].

Dpa and He production cross sections enter the MCNP calculations on the embedded elemental edit dose energy-bin multipliers cards EMBDF and energy-bin boundaries cards EMBDE as a portion of the elemental edits control cards EMBEE type 4. Neutron and proton displacement cross sections are located on separate cards and the results from both cards are summed together for each material. Results can be reported as dpa per one proton pulse (dpa/pulse), which is 2.24×10^{14} protons per pulse. To report the maximum radiation damage as dpa per one year of operation (dpa/year), which is 5,000 hours at 15 proton pulses per second (at 1.3 GeV proton energy and 700 kW beam power), the results are multiplied appropriately. The results can eventually be compared with the lifetime limits of the components defined in the STS Materials Handbook [17].

4.6 NEUTRONICS POINT DETECTOR TALLY

The neutronics performance of the moderators is tallied with a point detector, an MCNP tally type F5, at a distance of 10 m from the moderator emission surface. The emission surfaces are made of traditional MCNP CSG surfaces inserted into the non-meshed 2-mm thick vacuum gap between the moderator and reflector vessels, as shown in Figure 13. Half-way between the emission surface and the point detector is located an impenetrable wall with zero importance for neutrons except for the $1.5 \times 1.5 \text{ cm}^2$ and 1.5-cm diameter openings for the cylinder and tube moderator, respectively. These openings define the $3 \times 3 \text{ cm}^2$ and 3-cm diameter fields of view for the cylinder and tube moderators, respectively. Neutronics performance is tallied at beam line ST08 at 48.75° for the cylinder and at ST05 at 90° for the tube moderator, respectively. With a user-defined TALLYX subroutine, the tallied neutron time emission spectra at 10 m are corrected back to the moderator emission surface. Such a method of tallying the energy-dependent time emission spectra with MCNP is standardly used at other spallation neutron time-of-flight facilities, including FTS at SNS and LANSCE at Los Alamos National Laboratory.

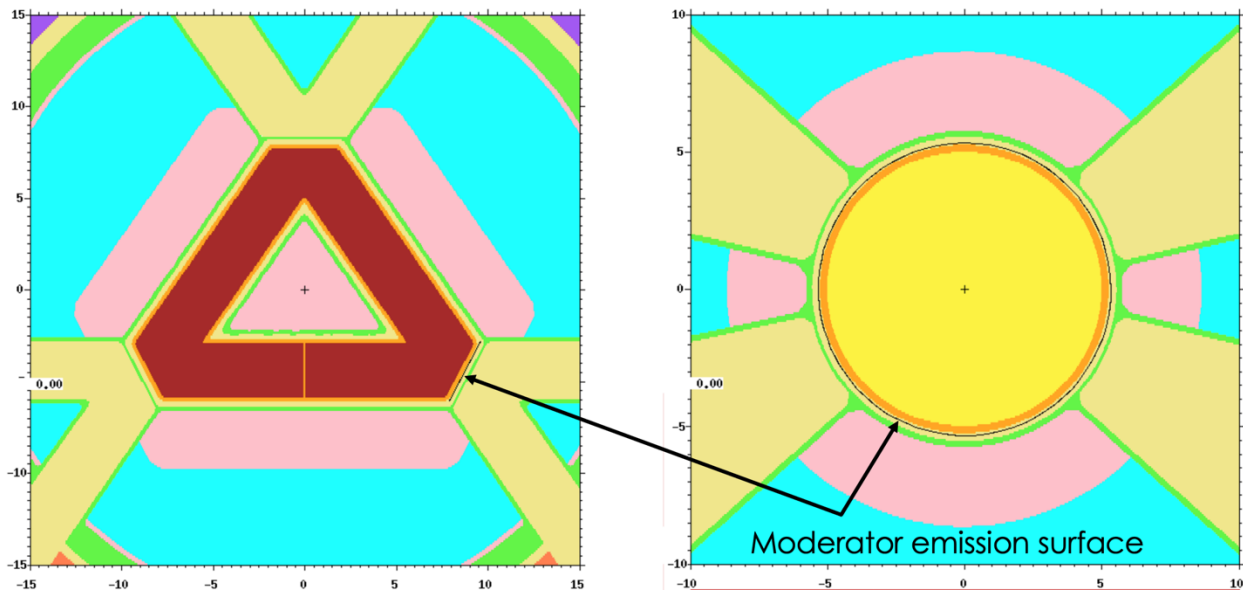


Figure 13. Horizontal cross section through the CSG emission surfaces (thin black) inserted into the non-meshed vacuum gap between the moderator and reflector vessels of the tube (left) and cylinder (right) moderators.

5. RESULTS

5.1 ENERGY DEPOSITION

Energy deposition was calculated in the MRA and backbone using the nominal 60-cm² proton beam profile, assuming 1.3 GeV protons at 15 Hz pulses and beam power of 700kW. Figure 14 illustrates the energy deposition in the entire assembly and Figure 15 shows the detailed energy deposition exclusively in the MRA. Relative statistical uncertainties stay mostly below 2% except for the upper end of the backbone. However, in that geometry region, the deposited energy is orders of magnitude below its maximum values in the MRA next to the spallation target and thus the increased uncertainties do not pose any significant concern. No MCNP/deterministic variance reduction methods were used for this analysis.

The peak energy deposition is at the bottom of the cylinder reflector vessel and is 0.35 J/cm³/pulse. Total heating in the MRA is 31.2 kW and total heating in the backbone is 26.2 kW deposited by the 700 kW proton beam. Total heating in the individual MRA materials is summarized in Table 10.

The total heating in aluminum also includes a contribution from the $^{27}\text{Al}(n,\gamma)^{28}\text{Al}$ reaction, which within a short halftime of 2.2 minutes deposits an average energy of 1.247 MeV per one β^- decay. The reaction rate was calculated on a separate elemental edits control card EMBEE type 4. This additional energy deposition from the neutron capture represents 3.2% and 17.5% of the total heating in the reflector and hydrogen vessels, respectively.

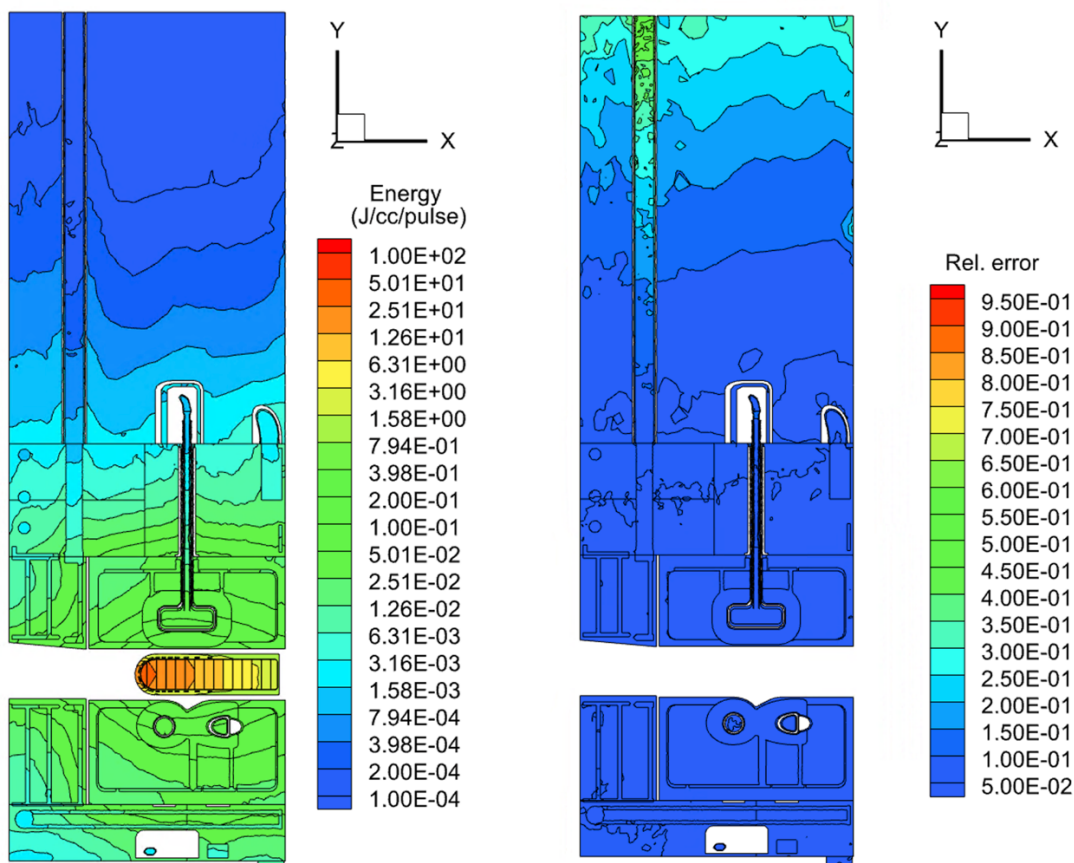


Figure 14. Energy deposition and relative uncertainties in the MRA and backbone.

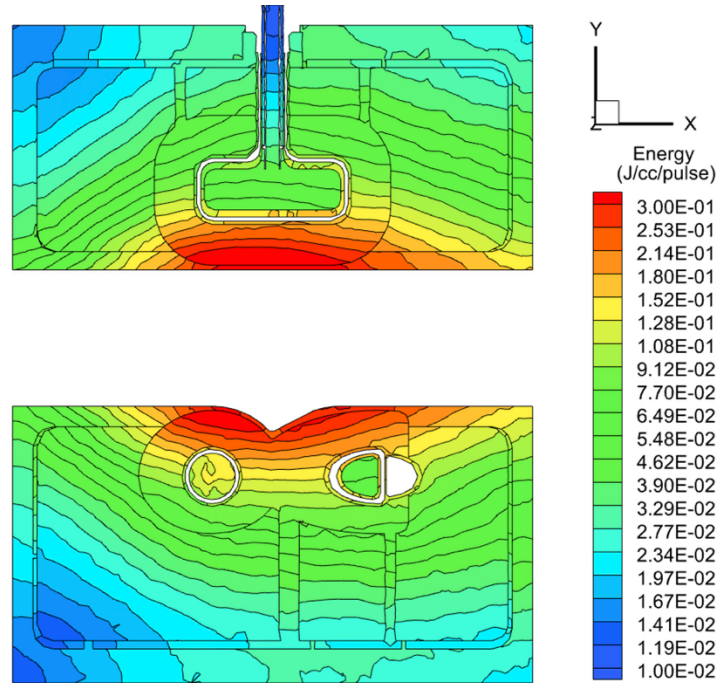


Figure 15. Detailed view of energy deposition in the MRA.

Table 10. Total heating in the MRA and backbone in individual materials.

Material	Heating (kW)
Hydrogen (cylinder)	0.17
Hydrogen (tube)	0.24
Aluminum (hydrogen vessels)	0.41
Aluminum (reflector vessels)	8.97
Beryllium	12.34
Water	9.04
SS316	26.24
Invar	0.07
Total MRA	31.2
Total backbone	26.2
Total	57.4

5.2 RADIATION DAMAGE

Radiation damage expressed as a number of displacements per atom was calculated in the aluminum vessels of the MRA and in steel backbone using the nominal proton beam. Figure 16 shows the elevation profile of dpa per one year of operation in the MRA. The highest radiation damage is at the bottom of the cylinder reflector vessel and on the top of the tube reflector vessel. The horizontal dpa profiles at these elevations are shown in Figure 17. The maximum value of 6.2 ± 0.1 dpa/year is at the bottom of the cylinder reflector vessel, which also determines the lifetime of the entire MRA assembly. Given the dpa limit for aluminum as 40 dpa [17], the MRA lifetime due to radiation damage is predicted as 6.5 years, well above the minimally required lifetime of 5 years.

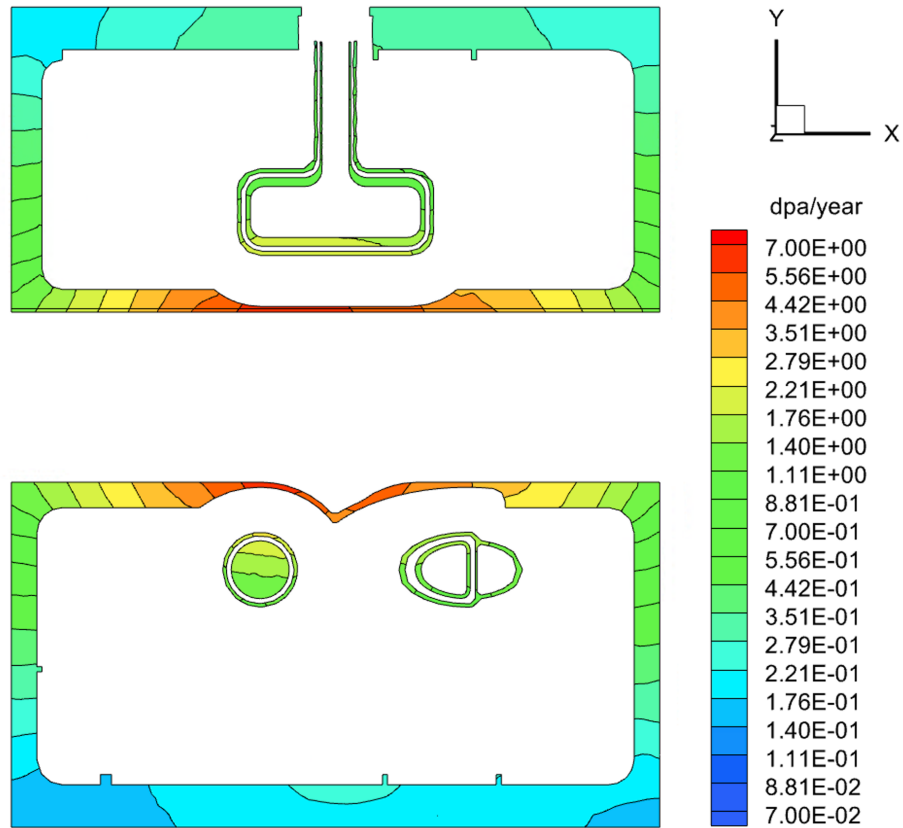


Figure 16. Elevation plot of the radiation damage as dpa/year in aluminum vessels of the MRA.

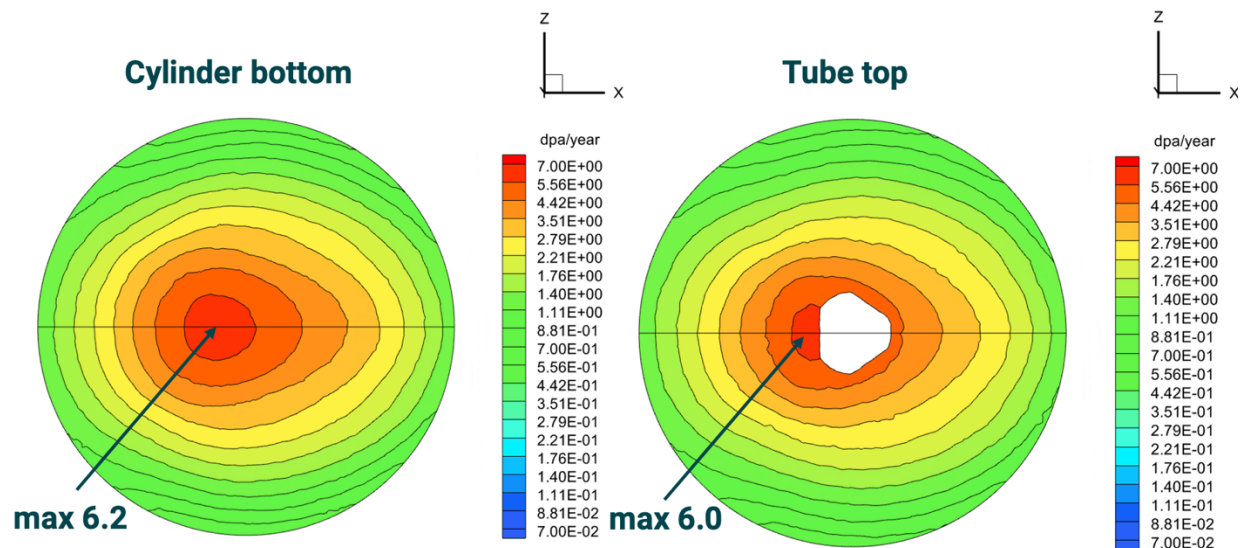


Figure 17. Horizontal view of the radiation damage as dpa/year in aluminum vessels of the MRA. Bottom of the cylinder reflector vessel is shown on the left and the top of the tube reflector vessel is on the right.

Radiation damage in the steel backbone is shown in Figure 18. With the maximum value of 0.65 dpa/year and the 60-dpa limit for SS316 and beam non intercepting components [17], the predicted lifetime of the backbone is 92 years, well above the MRA lifetime due to dpa in aluminum.

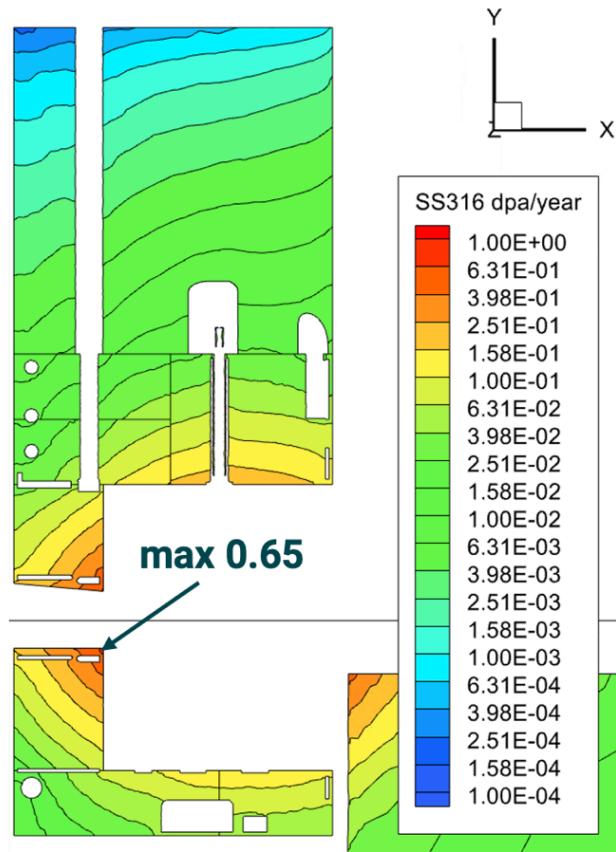


Figure 18. Elevation plot of the radiation damage as dpa/year in the steel backbone.

Other two possible modes of radiation-induced effects in the MRA are the silicon and helium production in the aluminum vessels. Silicon is produced mainly via the thermal neutron ($E < 0.414$ eV) capture in aluminum, $^{27}\text{Al}(n,\gamma)^{28}\text{Al}$, which decays via β^- into ^{28}Si . As calculated on a separate elemental edits control card EMBEE type 4, the maximum thermal neutron flux in aluminum is $5.75\text{E}+21$ n/cm²/year. Given the maximum dose limit for ^{28}Si as $6.9\text{E}+22$ n/cm²/year [17], the MRA lifetime due to the silicon production is 12 years, well above the predicted lifetime due to dpa in aluminum. Similarly, the lifetime due to He gas production in aluminum via spallation and other reactions is predicted as 25 years, well above the predicted lifetime due to dpa.

5.3 NEUTRONICS PERFORMANCE

This section first discusses the neutronics performance of the MRA calculated with the nominal 60-cm² proton beam and default materials and temperature properties, and its relation to the key performance parameters (KPP). The section then discusses a range of sensitivity studies, particularly the dependence of the neutronics performance on the ortho/para hydrogen fraction, hydrogen density, and hydrogen temperature. It also discusses the effect of maximally expected MRA misalignment.

5.3.1 Neutronics performance under nominal conditions

To fulfill the STS project's KPP, the measured peak neutron brightness at 5 Å must exceed the value of $2 \cdot 10^{14}$ n/cm²/sr/Å/s. As shown in Figure 19, the calculated peak brightness at 5 Å exceeds the KPP by 24% and 50% for cylinder and tube moderators, respectively.

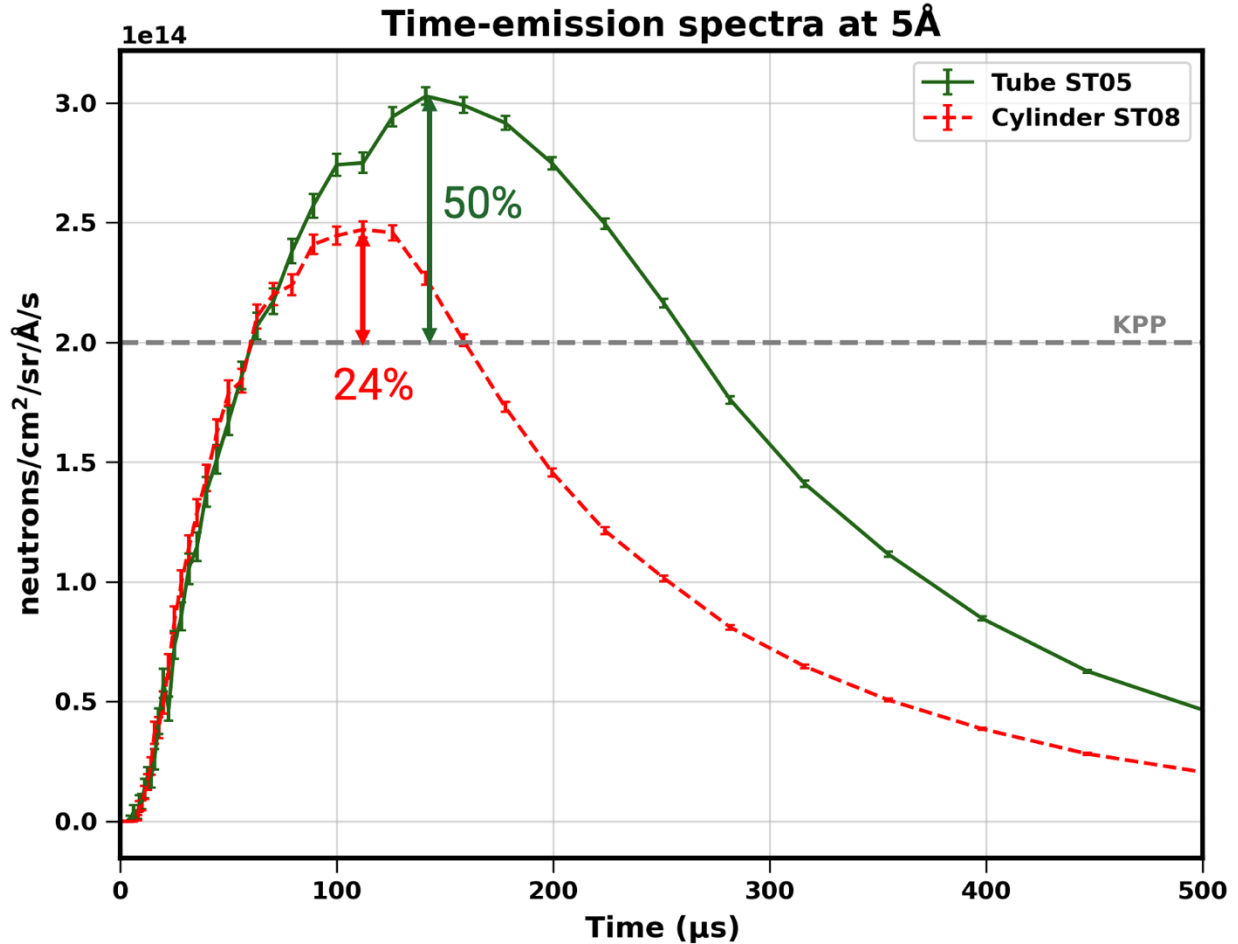


Figure 19. Calculated time emission spectra at 5 Å.

The following Figures 20-31 describe the calculated neutronics performance in more details. Specifically, Figures 20-24 show the neutron time emission spectra at 10, 8, 4, 3, and 2 Å. Peak neutron brightness across the full energy range is shown in Figures 25 and 26 on logarithmic and linear y-scale, respectively. Figures 27 and 28 show the time-integrated brightness on logarithmic and linear y-scale, respectively. Time resolution in terms of full width at one half of maximum and full width at one tenth of maximum is shown in Figures 29 and 30, respectively. Eventually, Figure 31 shows the root mean square (RMS) as a function of neutron energy.

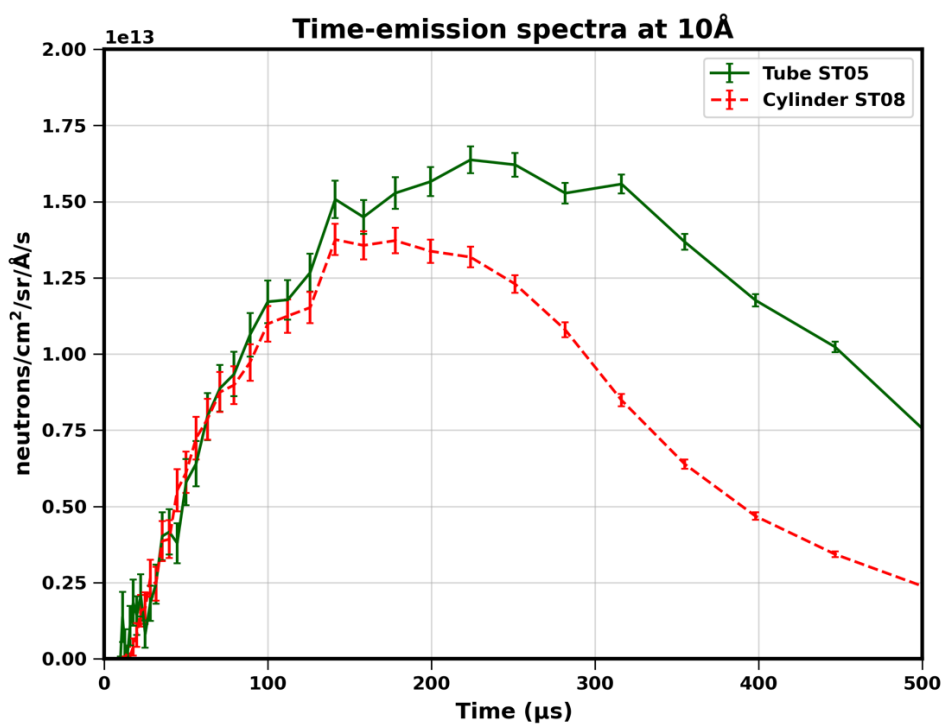


Figure 20. Calculated time emission spectra at 10 Å.

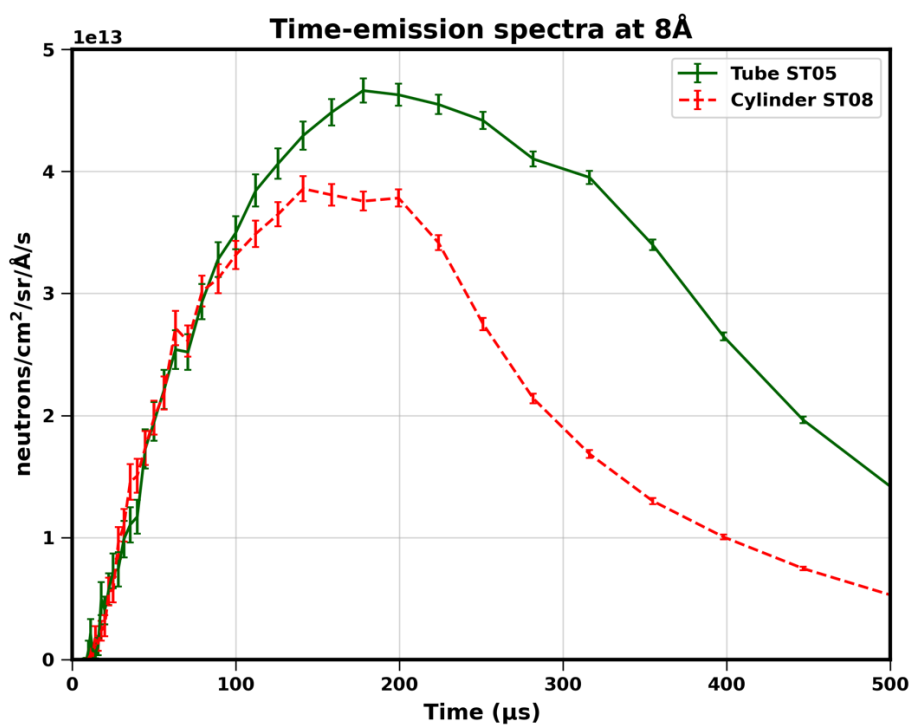


Figure 21. Calculated time emission spectra at 8 Å.

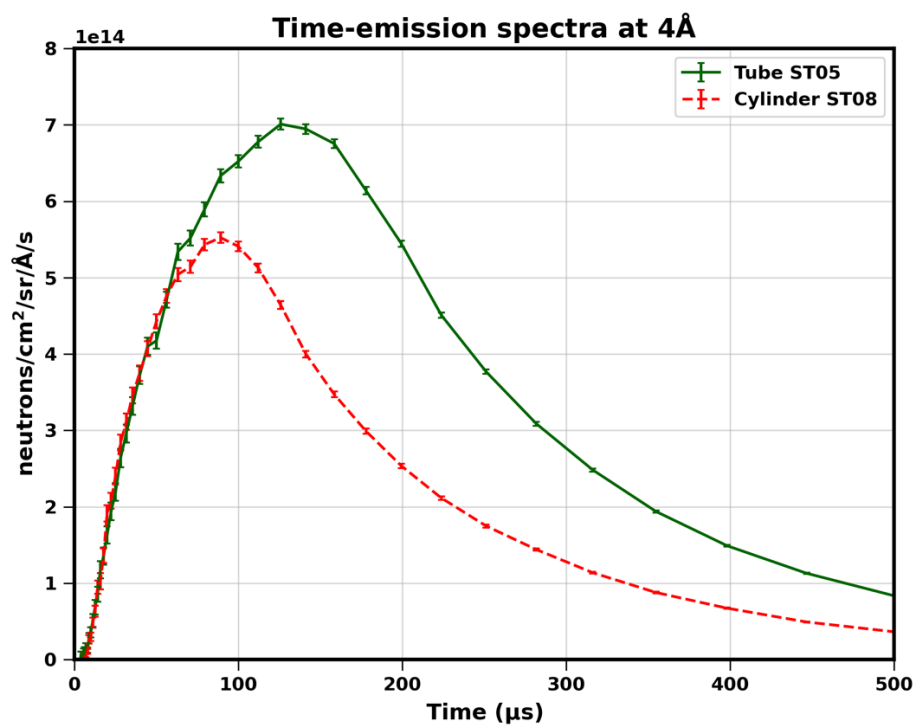


Figure 22. Calculated time emission spectra at 4 Å.

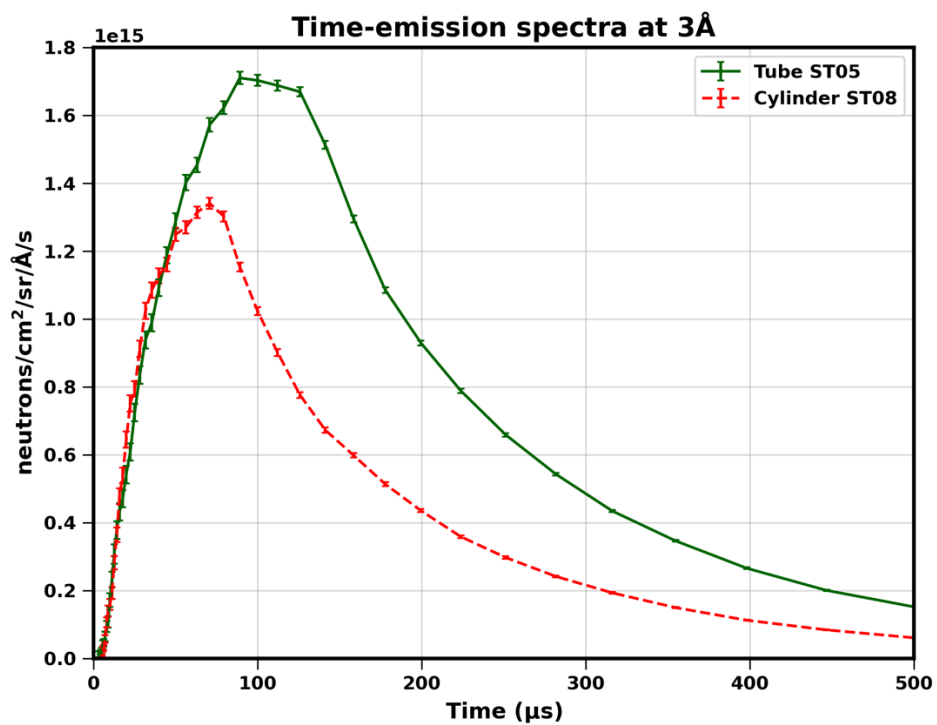


Figure 23. Calculated time emission spectra at 3 Å.

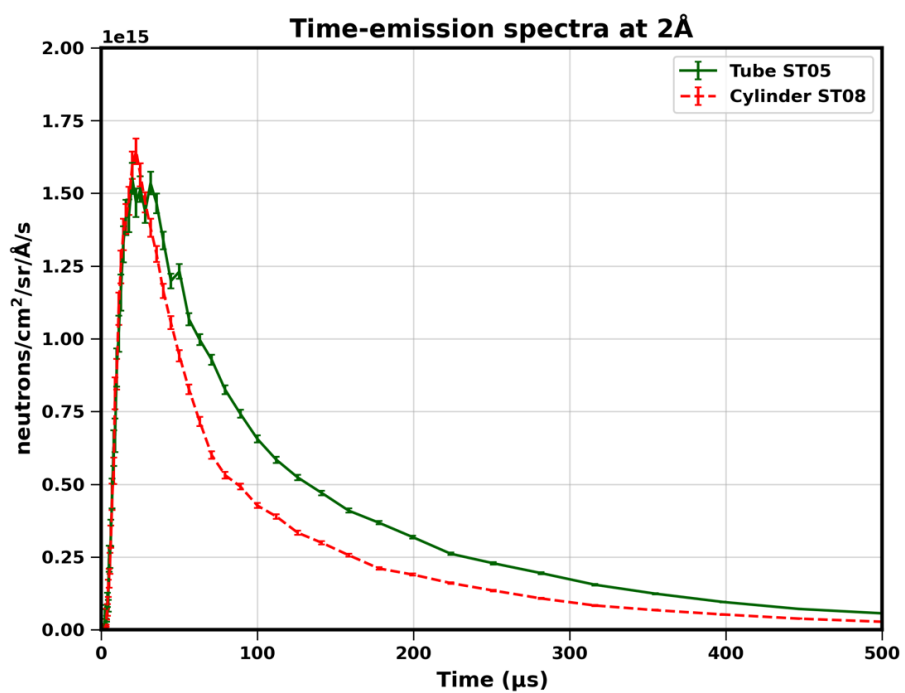


Figure 24. Calculated time emission spectra at 2 Å.

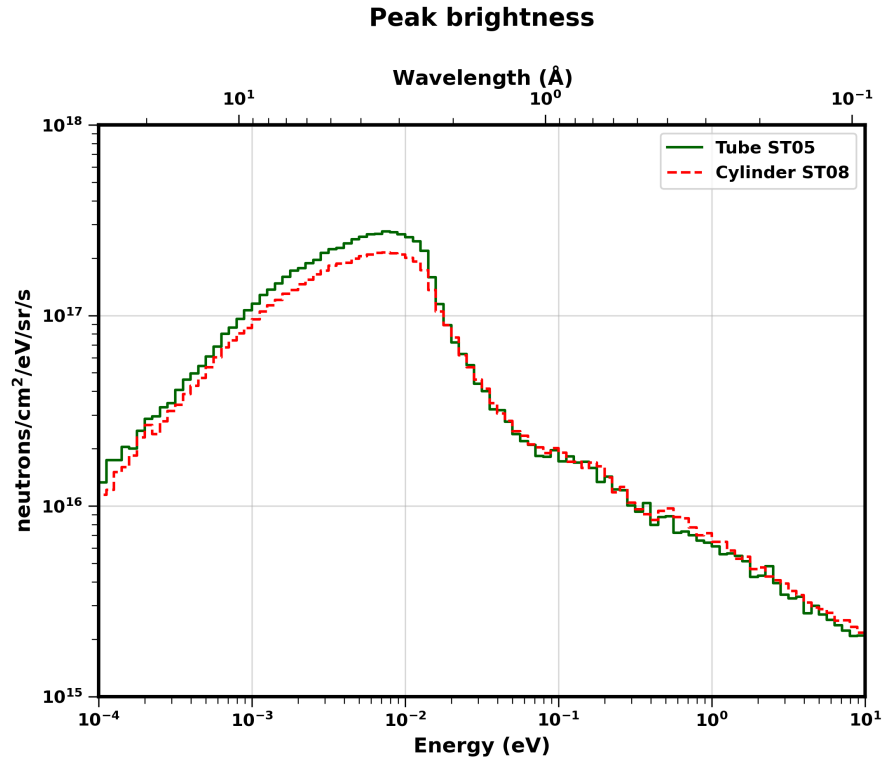


Figure 25. Calculated peak brightness, shown on a logarithmic y-scale.

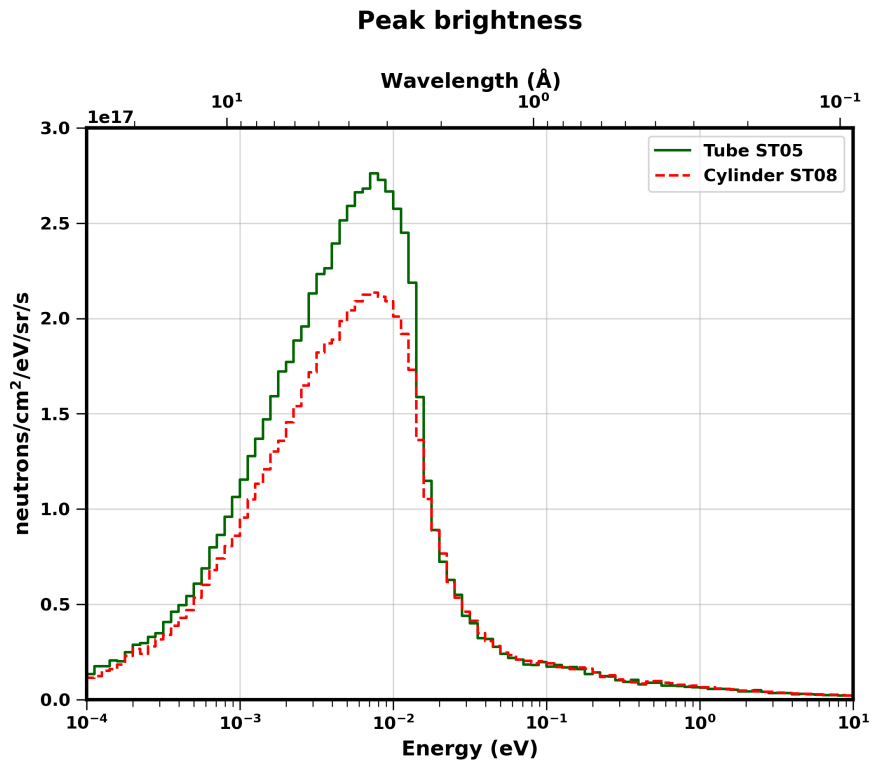


Figure 26. Calculated peak brightness, shown on a linear y-scale.

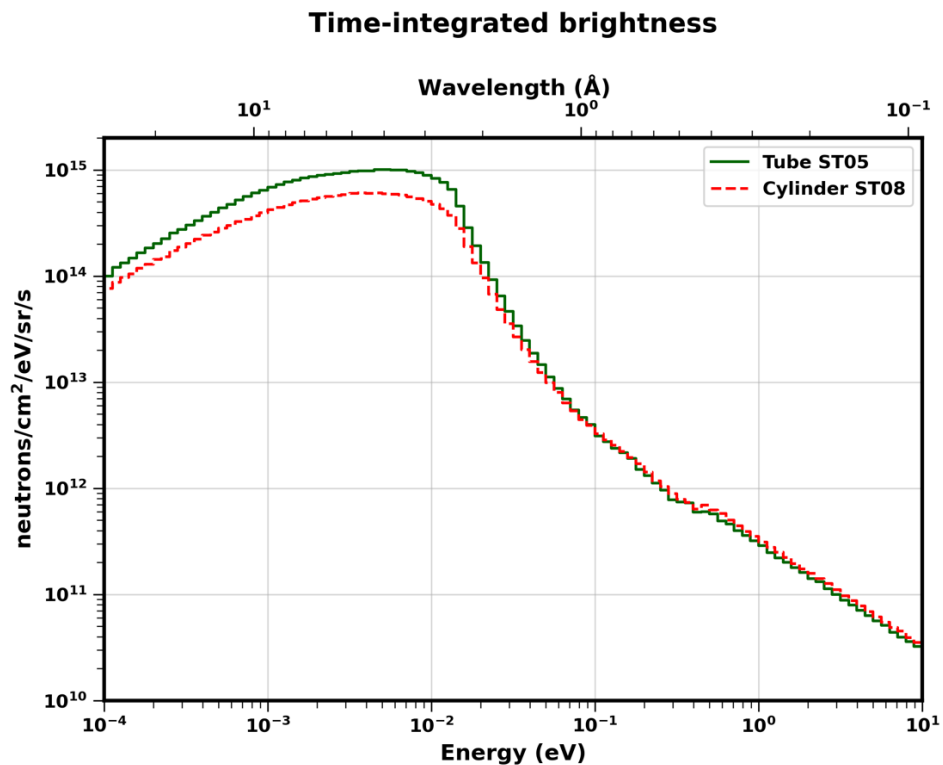


Figure 27. Calculated time-integrated brightness, shown on a logarithmic y-scale.

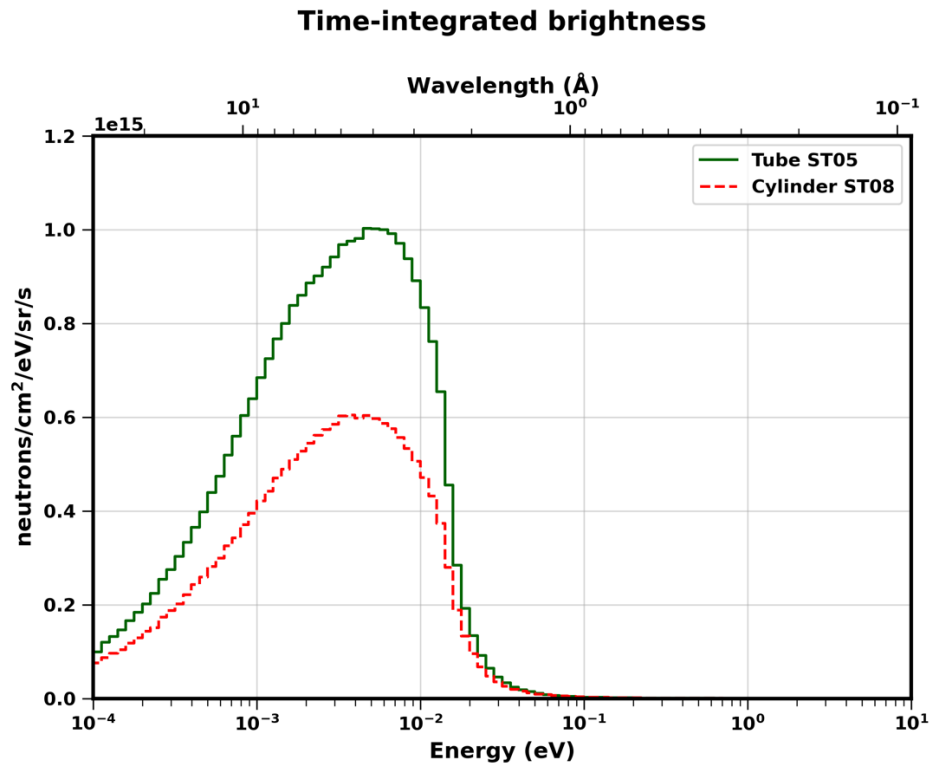


Figure 28. Calculated time-integrated brightness, shown on a linear y-scale.

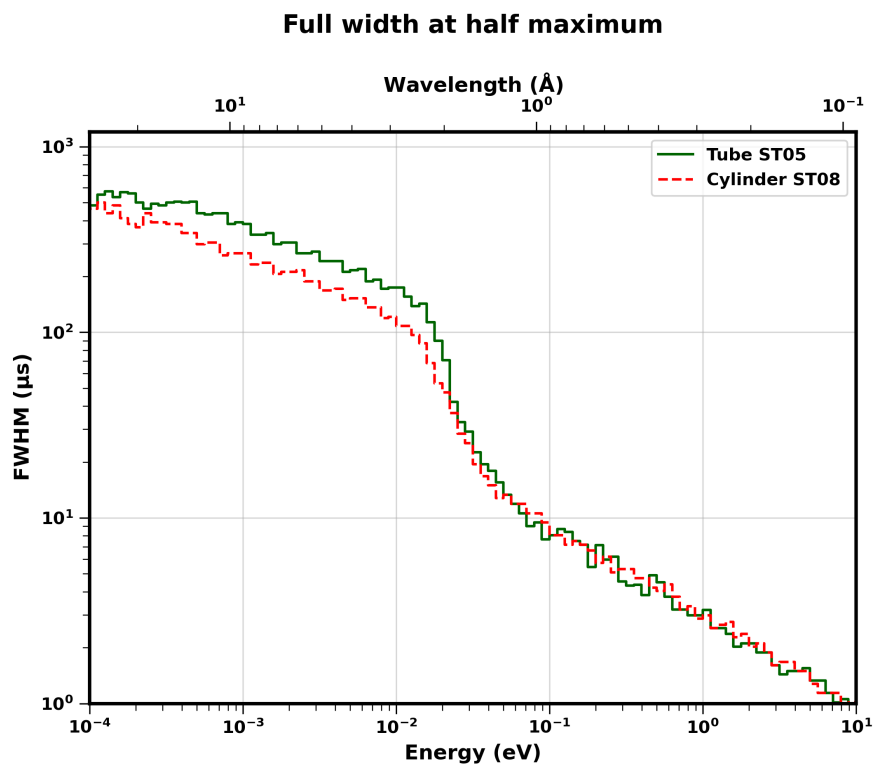


Figure 29. Calculated time resolution at one half of maximum.

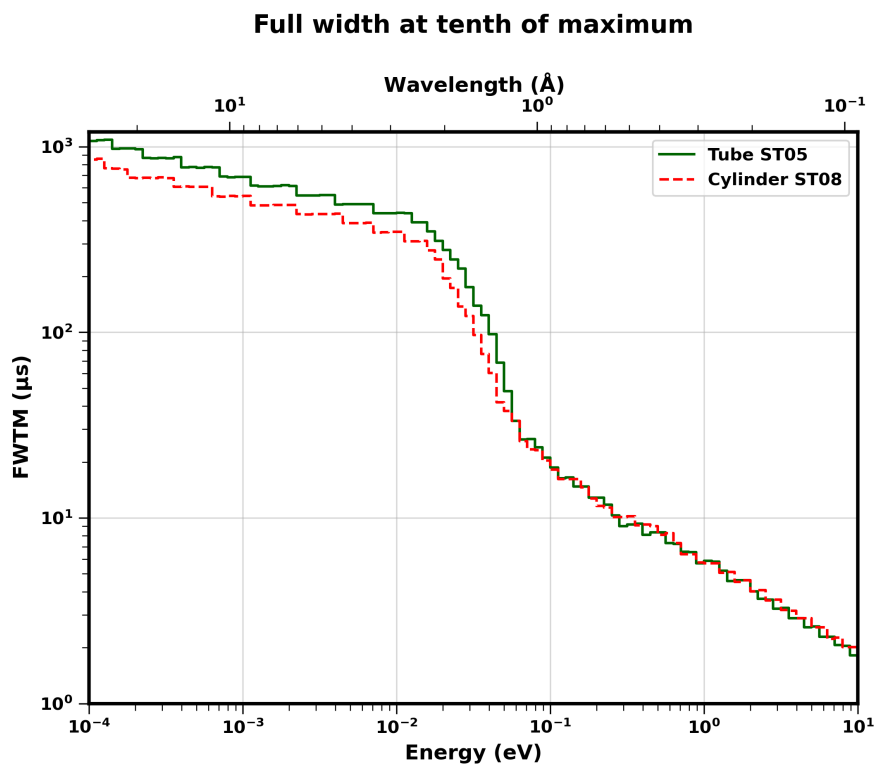


Figure 30. Calculated time resolution at one tenth of maximum.

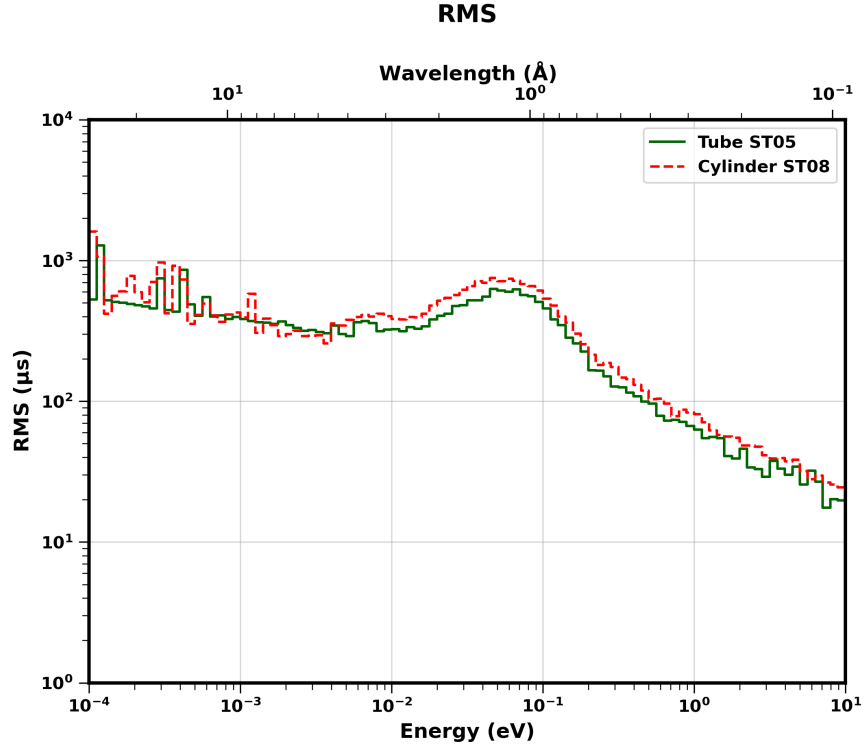


Figure 31. Calculated root mean square.

Figures 20-31 illustrate that the tube moderator delivers higher peak and time-integrated brightness and that the cylinder moderator delivers cold neutrons with better time resolution.

5.3.2 Sensitivity studies

A sensitivity study was performed to calculate the neutronics performance as a function of ortho/para hydrogen fraction, hydrogen density, and hydrogen temperature. To increase calculation efficiency, this study was performed with a simplified geometry model of the target and other surrounding objects, and therefore the amplitude of the performance might not match exactly the neutronics performance shown in the previous section, which was calculated with a comprehensive geometry model.

The default fraction of para-hydrogen in both moderators is 99.9%. A sensitivity study was performed within the para-hydrogen fraction from 95% to 100%. Figures 32 and 33 show the impact of changing ortho/para hydrogen fraction on peak and time-integrated brightness, respectively, for the cylinder moderator. Figures 34 and 35 show the same dependence for the tube moderator. A relatively small change within a few % points of performance can be seen for 0.1% changes in the ortho/para fraction, with significant drops in performance as the para-hydrogen fraction decreases only to 95%.

The expected variation in temperature and density during the STS operation are smaller than the 2 K change in temperature and 3% change in density. The default hydrogen density is 0.073 g/cm³ for the cylinder moderator, and it is 0.072 g/cm³ for the tube moderator. A sensitivity study was performed for the hydrogen densities in the range of 0.068 - 0.074 g/cm³. Figures 36 and 37 show the effect of varying density on time-emission spectra at 5 Å and on peak brightness, respectively, of the cylinder moderator. Figures 38 and 39 show the same dependence for the tube moderator. Only small variations within ~1% are seen for every 0.002 g/cm³ change in density in the relevant region of wavelengths (2-10 Å).

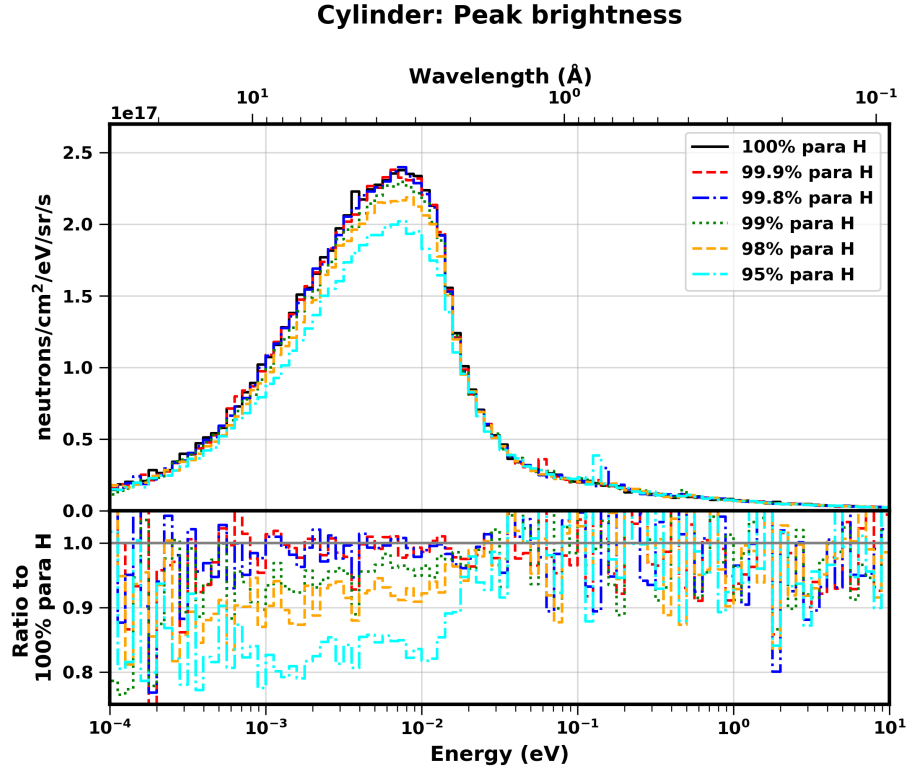


Figure 32. Calculated peak brightness of the cylinder moderator as a function of para-hydrogen fraction.

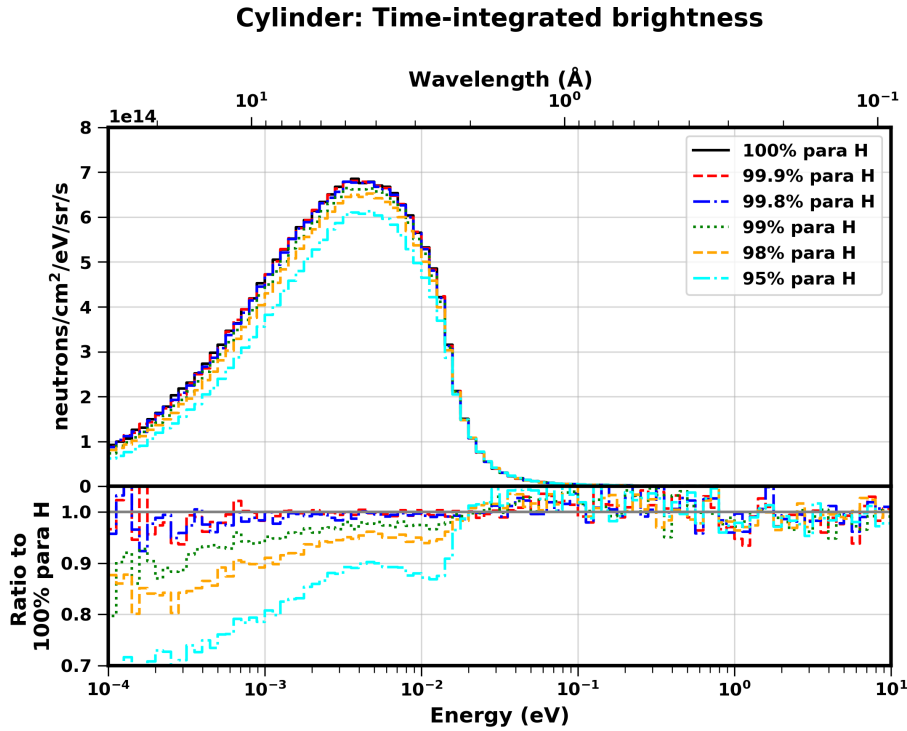


Figure 33. Calculated time-integrated brightness of the cylinder moderator as a function of para-hydrogen fraction.

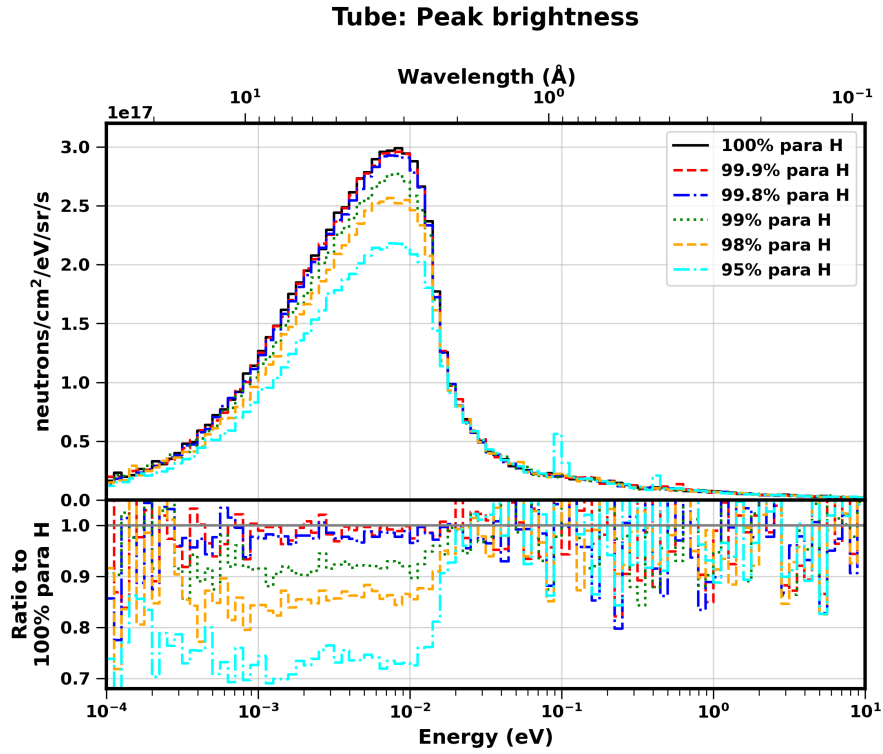


Figure 34. Calculated peak brightness of the tube moderator as a function of para-hydrogen fraction.

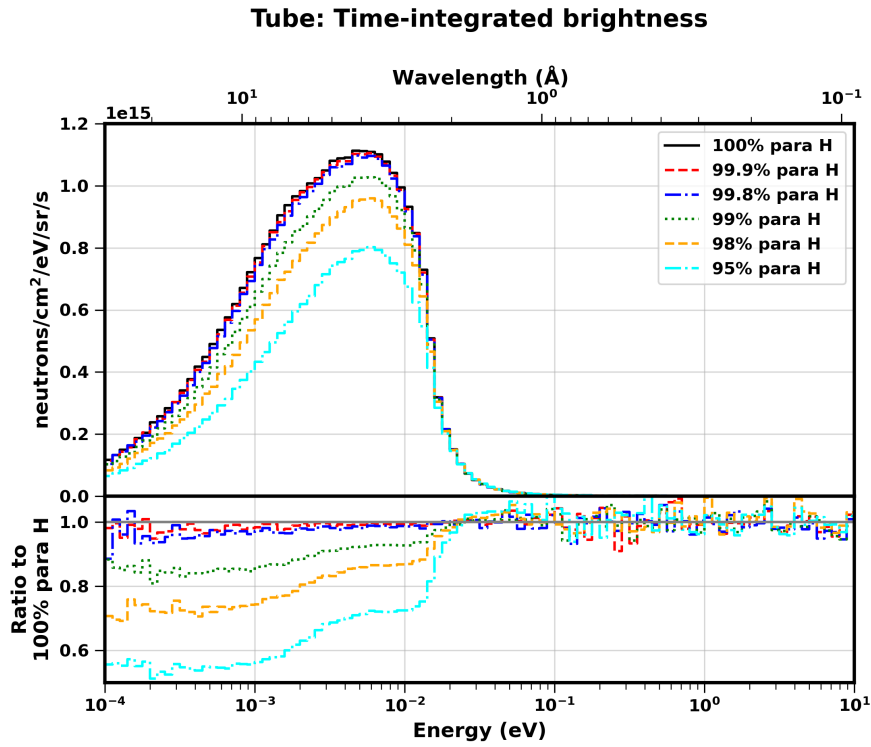


Figure 35. Calculated time-integrated brightness of the tube moderator as a function of para-hydrogen fraction.

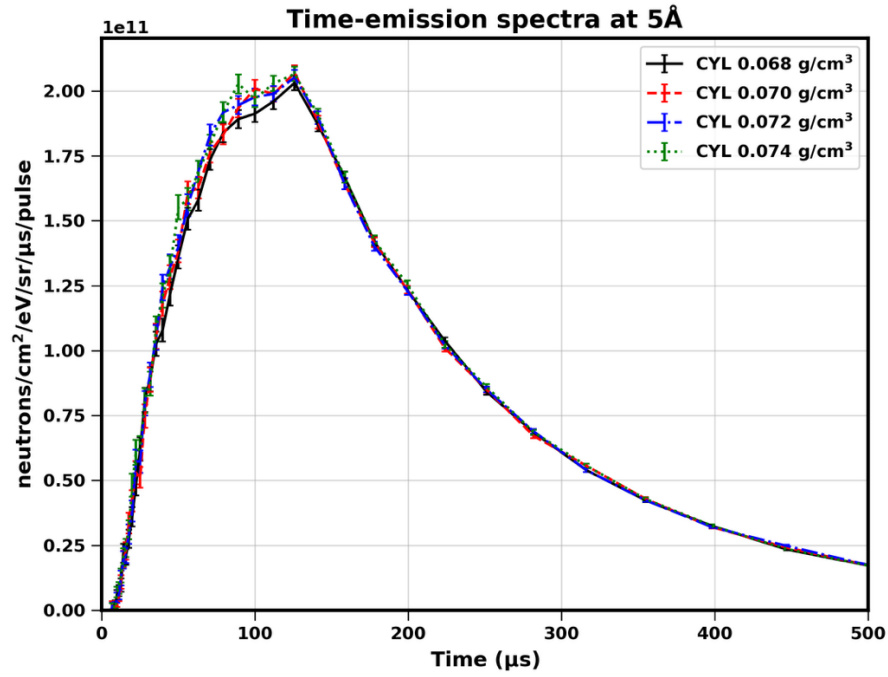


Figure 36. Calculated time-emission spectra 5 Å of the cylinder moderator as a function of hydrogen density.

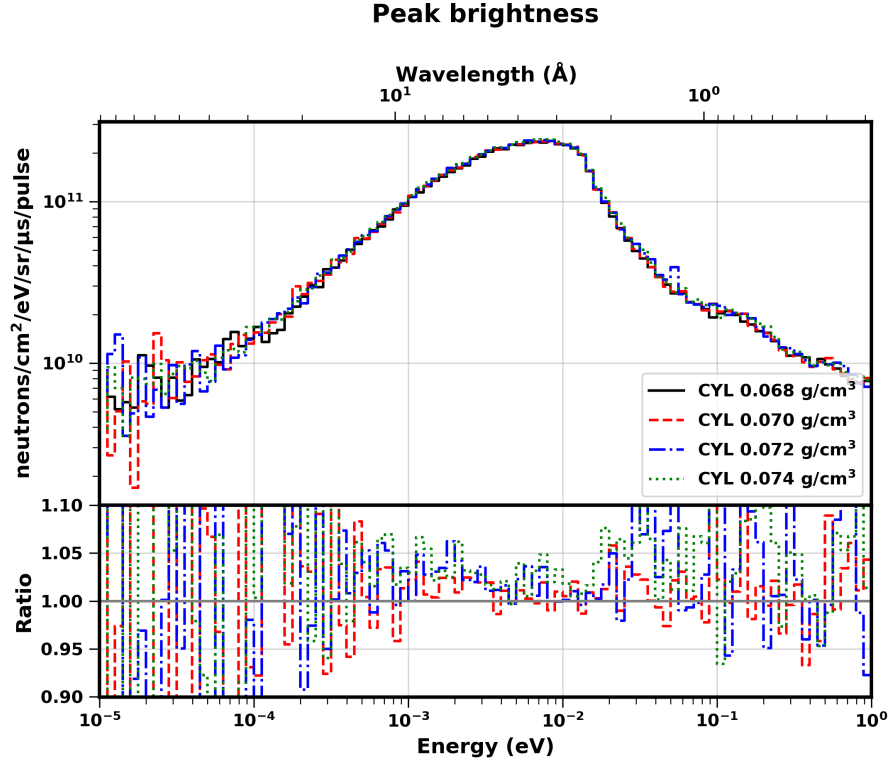


Figure 37. Calculated peak brightness of the cylinder moderator as a function of hydrogen density.

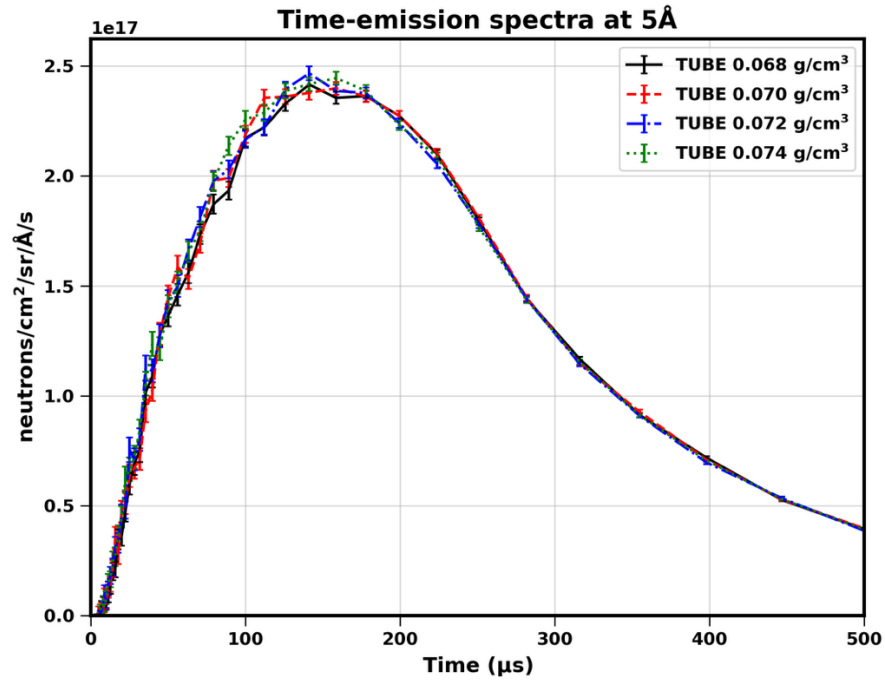


Figure 38. Calculated time-emission spectra at 5 Å of the tube moderator as a function of hydrogen density.

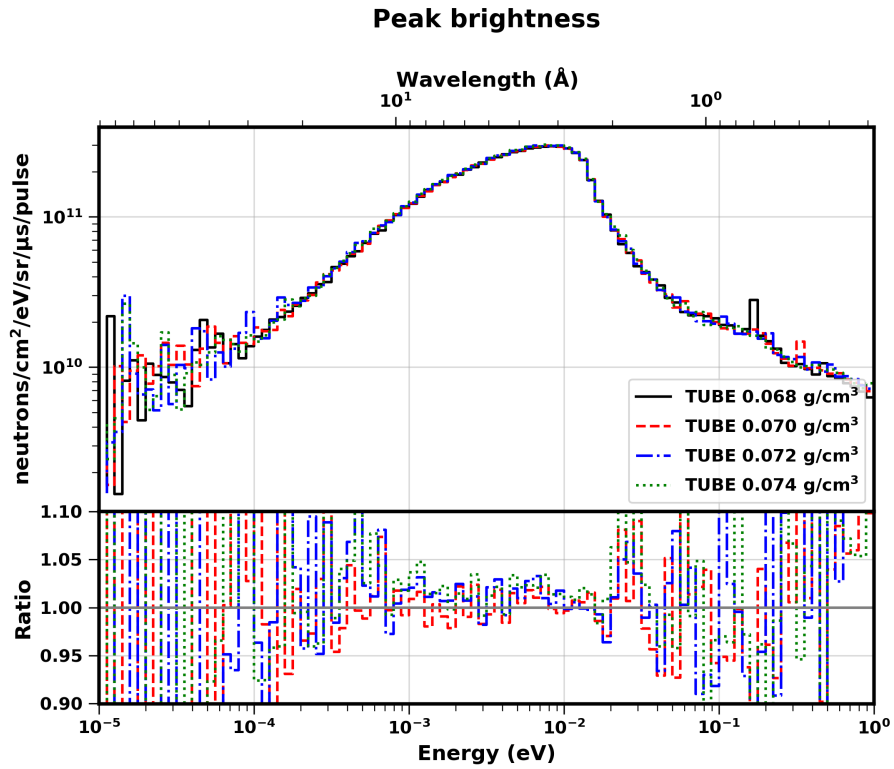


Figure 39. Calculated peak brightness of the tube moderator as a function of hydrogen density.

The default hydrogen temperature in the MRA is 20 K. A sensitivity study was performed to calculate the dependence of the neutronics performance on hydrogen temperature that changes between 18 K and 22 K. The evaluated data library JEFF 4.0 contains para-hydrogen scattering kernels for temperatures between 14 K and 19 K with the 1 K steps, as shown in Figure 40. A relative ratio between 18 K and 19 K datasets was used to modify scattering kernels ENDF/B-VII.1 used in this study that are available at 20 K. In this way, the supporting MCNP ACE files were produced for hydrogen temperatures of 18 K and 22 K from the original ENDF/B-VII.1 file at 20 K.

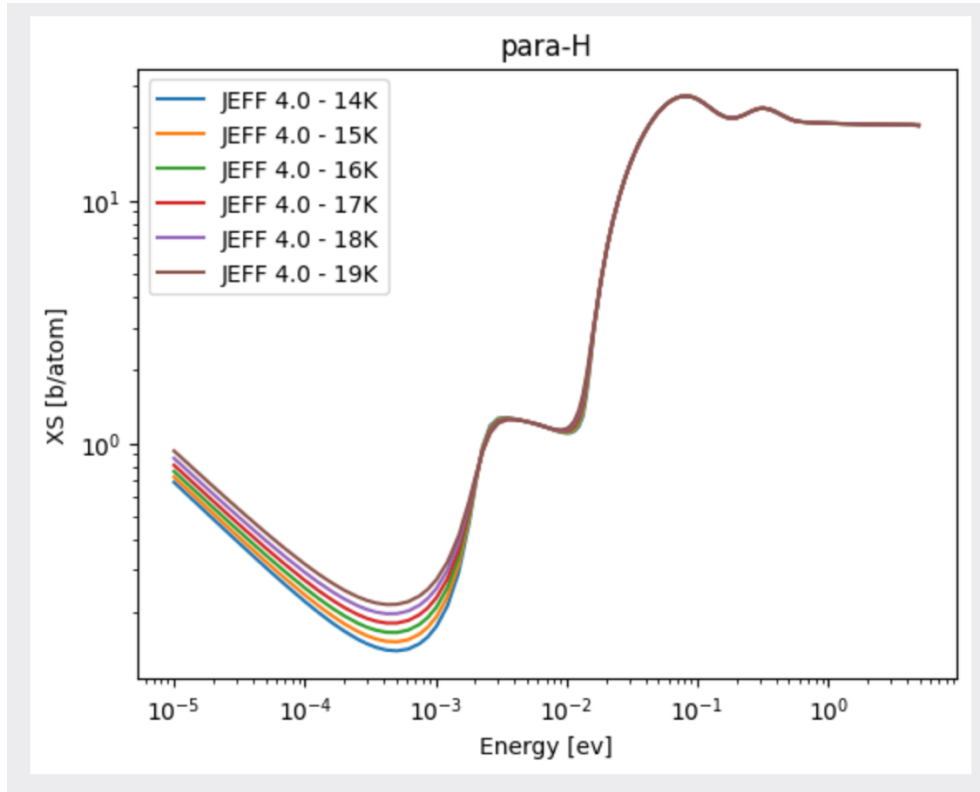


Figure 40. Calculated peak brightness of the tube moderator as a function of hydrogen density.

Figures 41 and 42 show the effect of changing hydrogen temperature on the time-emission spectra at 5 Å and on peak brightness, respectively, of the cylinder moderator. Figures 43 and 44 show the same dependence for the tube moderator. Only small variations in neutronics performance can be seen for every 2 K change in density in the relevant region of wavelengths (2-10 Å).

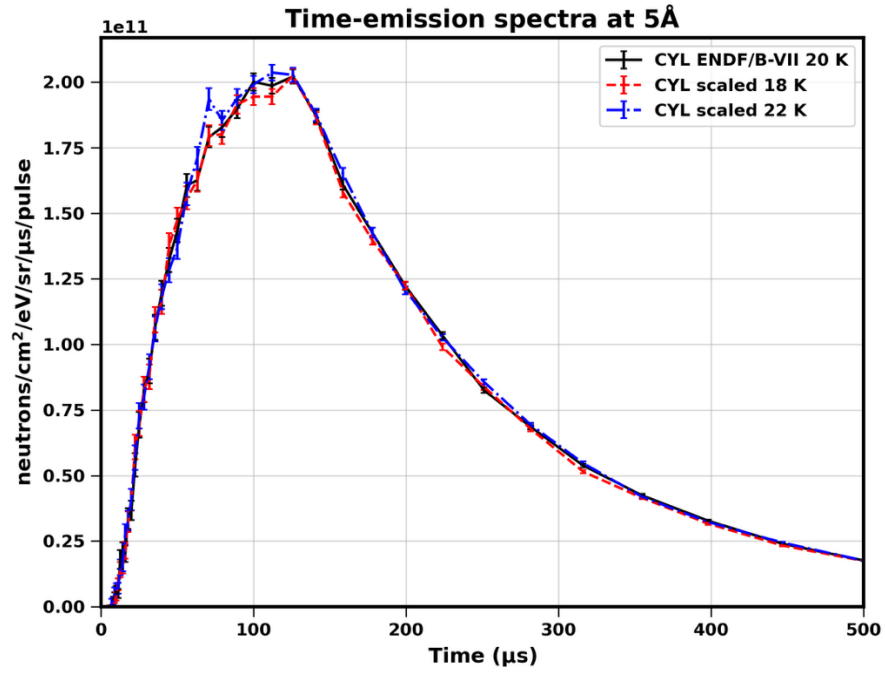


Figure 41. Calculated time-emission spectra at 5 Å of the cylinder moderator as a function of hydrogen temperature.

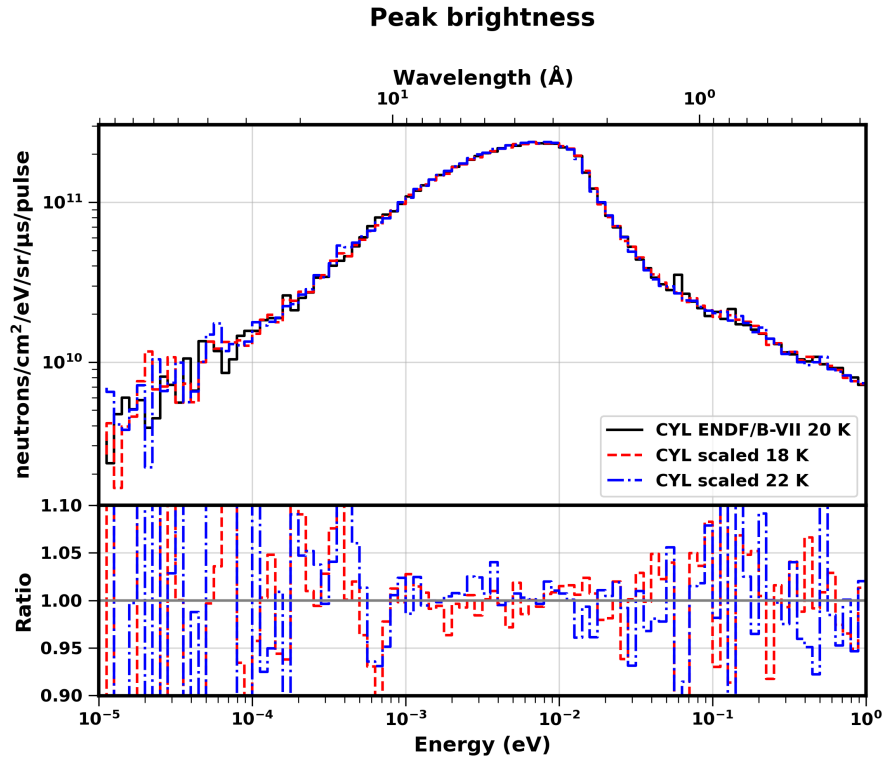


Figure 42. Calculated peak brightness of the cylinder moderator as a function of hydrogen temperature.

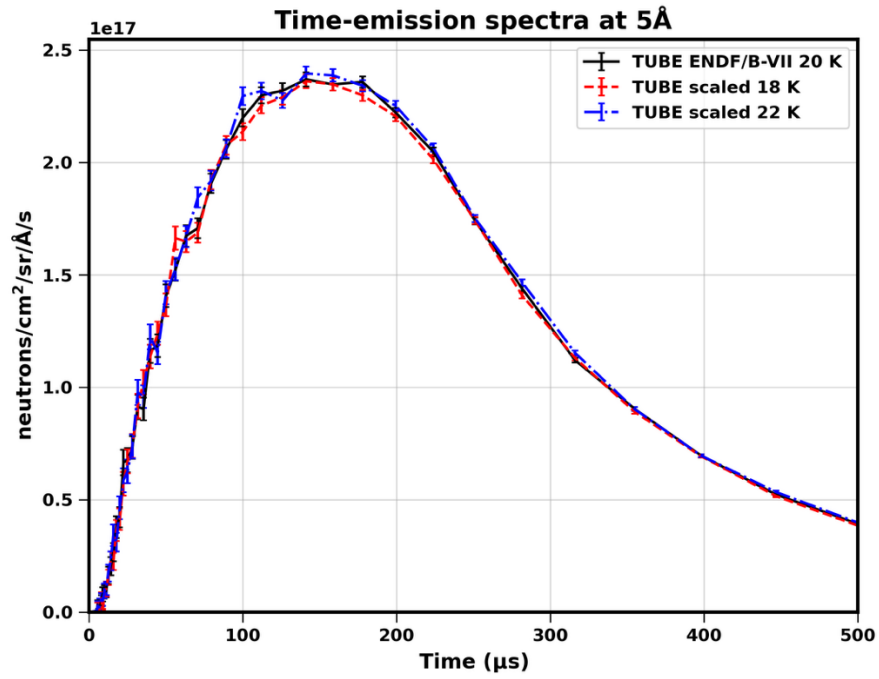


Figure 43. Calculated time-emission spectra at 5 Å of the tube moderator as a function of hydrogen temperature.

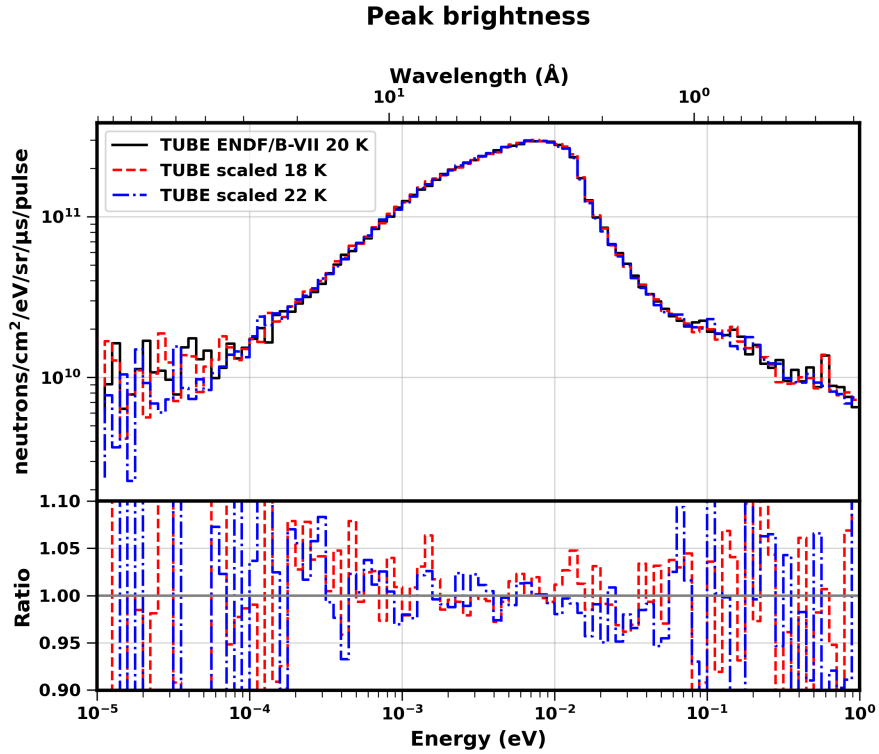


Figure 44. Calculated peak brightness of the tube moderator as a function of hydrogen temperature.

5.3.3 MRA misalignment study

The goal of the MRA misalignment study was to evaluate the decrease in the neutronics performance due to the maximum possible misalignment of the MRA. The maximum misalignment may occur due to the MRA installation tolerances and by the thermal distortion of the core vessel shield blocks. It was determined as 1.5 mm vertical shift and rotations of 1.2° and 0.75° for the cylinder and tube moderators, respectively, around the misalignment rotation axes shown in Figure 45.

This study was performed with the preliminary-design MRA geometry that is almost identical with the final-design geometry, and no substantial changes due to the geometry are expected. Figures 46 and 47 show the comparison of the time-integrated brightness for the maximally misaligned cylinder and tube moderators, respectively. Figure 48 shows the time-emission spectra at $5 \text{ \AA}$ of the maximally misaligned MRA. Results indicate that the performance decreases by $\sim 5\%$ for the tube moderator for wavelengths longer than $\sim 1.5 \text{ \AA}$. The performance decreases similarly for the cylinder moderator, with a drop of up to $\sim 10\%$ in a relatively narrow interval of wavelengths between $1\text{-}3 \text{ \AA}$.

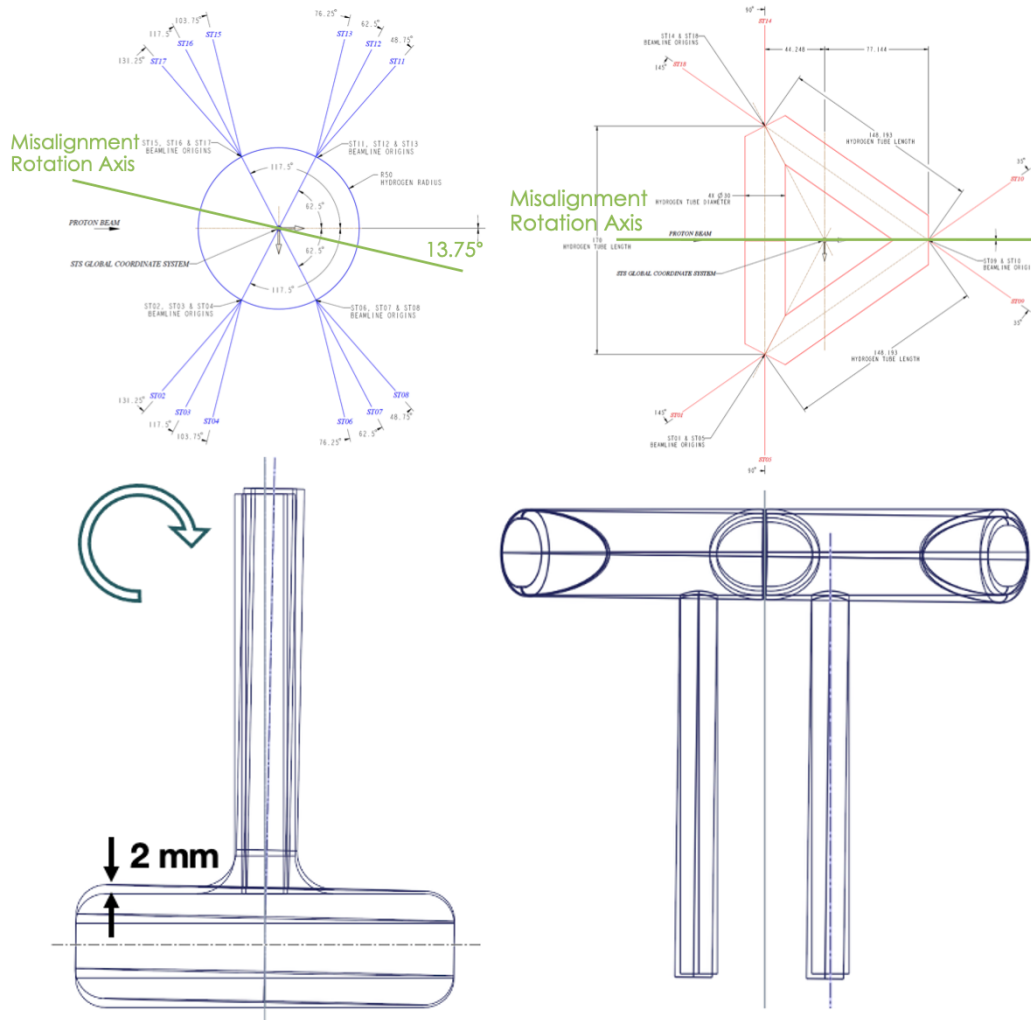


Figure 45. Illustrations supporting the maximum misalignment study. Shown are misalignment rotation axes for the cylinder (top left) and tube (top right) moderators, as well as the elevation cross sections of the misaligned cylinder (bottom left) and tube (bottom right) moderators overlaid on aligned vessels.

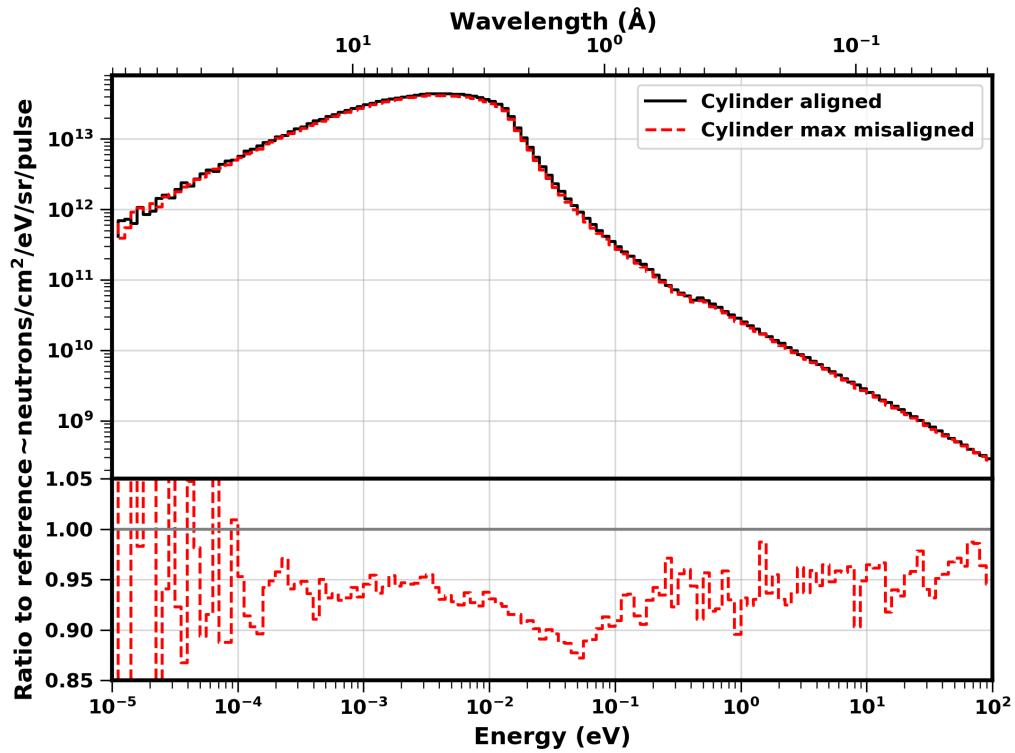


Figure 46. Time-integrated brightness of the maximally misaligned cylinder moderator.

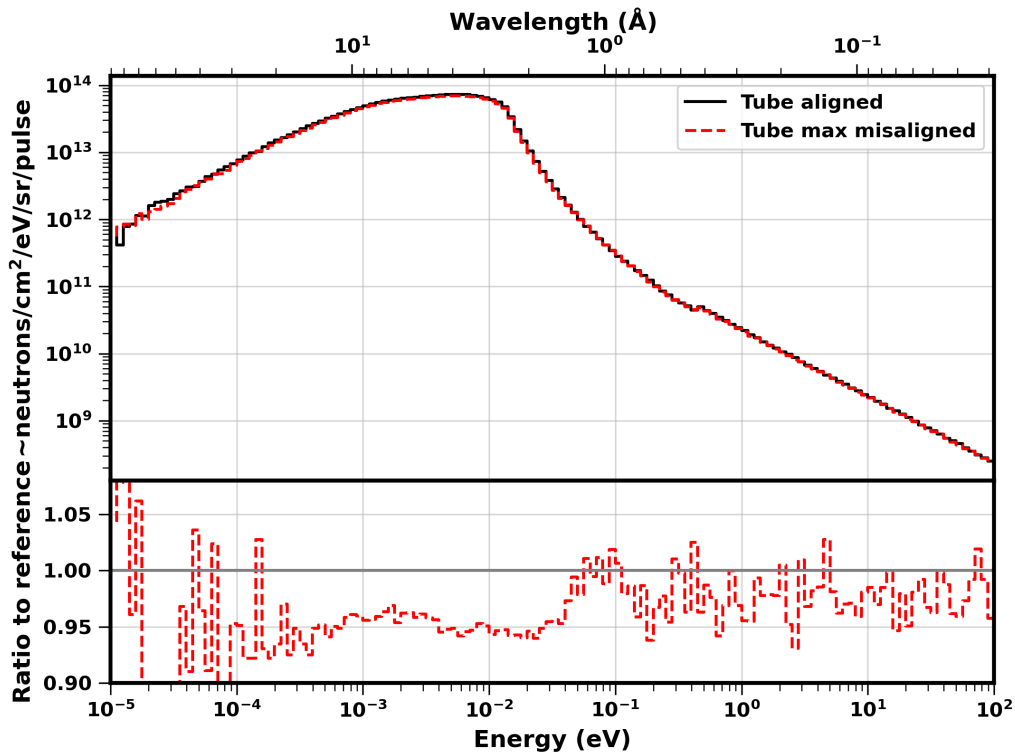


Figure 47. Time-integrated brightness of the maximally misaligned tube moderator.

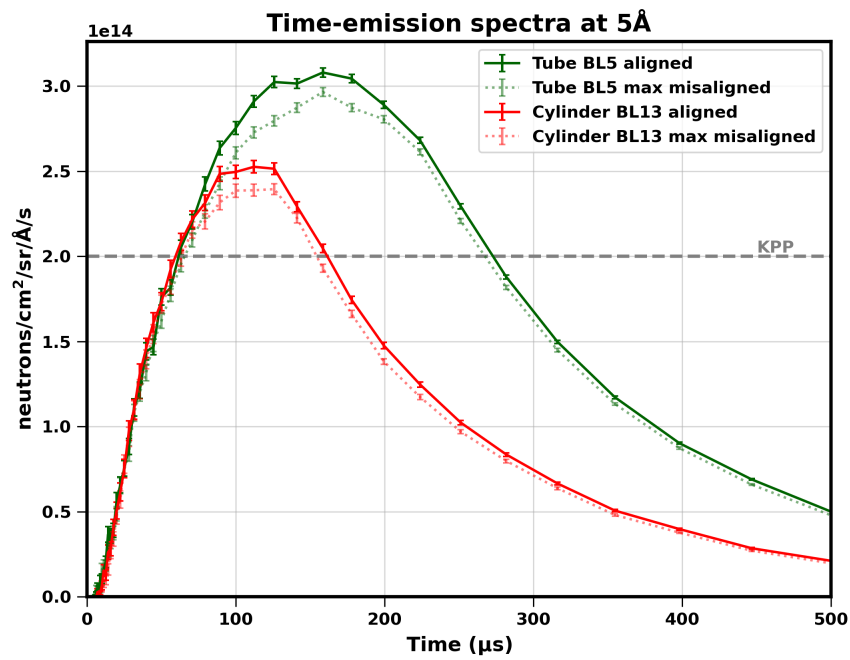


Figure 48. Time emission spectra at 5 Å of the maximally misaligned MRA.

Even with the maximally misaligned moderators, the neutronics performance stays well above the required KPP threshold at 5 Å.

6. CONCLUSIONS

Energy deposition, radiation damage, and neutronics performance were calculated with MCNP6.2 using the final-design geometry of the STS MRA, including the backbone.

Energy deposition in the MRA and backbone was calculated for the nominal proton beam scenario. The total heat deposited in the assembly is 57.4 kW delivered by the 700-kW proton beam. Results on unstructured mesh were filtered according to individual materials and they were exported as .csv files for the subsequent structural stress and thermo-mechanical engineering analyses. The results were archived in the repository on the STS Neutronics computational cluster Saturn.

Radiation damage was calculated in the form of displacements per atom in the aluminum vessels and in steel backbone and in the form of He gas and silicon production in aluminum vessels. Maximum dpa value at the bottom of the cylinder reflector vessel determines the lifetime of the MRA as 6.5 years under normal operating conditions, which is above the minimum lifetime requirement of 5 years.

Neutronics performance was calculated with the high-fidelity unstructured mesh model of the MRA. Results show that the final design exceeds the KPP requirements for the peak brightness at 5 Å by 24% and 50% for cylinder and tube moderators, respectively.

A range of neutronics sensitivity studies within the studied boundaries revealed that the highest impact on the performance has the decreasing fraction of para-hydrogen. It is therefore extremely important to keep the para-hydrogen fraction as close as possible to the nominal value of 99.9%. The MRA misalignment study informed that even the most severe predicted misalignment reduces the neutronics performance mostly by 5%, keeping the performance still above the KPP requirements.

7. REFERENCES

1. C. Werner (ed.), et al. “MCNP User’s Manual, Code Version 6.2,” LA-UR-17-29981, LANL (2017).
2. Attila4MC 10.3.0, “Release Notes, Silver Fir Software”, www.silverfirsoftware.com, (2024).
3. STS MRA Requirements document – S03040000-SR0001, ORNL, (2025).
4. L. Zavorka, “Energy Deposition and Radiation Damage in ORNL’s Second Target Station Final Design of the Target and Target Shaft”, S00000000-CAC10001, ORNL, STS, (2026).
5. F. Mezei, L. Zanini, A. Takibayev, K. Batkov, E. Klinkby, E. Pitcher, T. Schönfeldt, “Unperturbed moderator brightness in pulsed neutron sources”, J. Neutron Res. 17 (2014) 101–105, <http://dx.doi.org/10.3233/JNR-140013>.
6. K. Batkov, A. Takibayev, L. Zanini, F. Mezei, “Unperturbed moderator brightness in pulsed neutron sources”, Nuclear Instruments and Methods in Physics Research A 729 (2013) 500–505, <http://dx.doi.org/10.1016/j.nima.2013.07.031>.
7. L. Zanini, K. Andersen, K. Batkov, E. Klinkby, F. Mezei, T. Schönfeldt, A. Takibayev, “Design of the cold and thermal neutron moderators for the European Spallation Source”, Nuclear Instruments and Methods in Physics Research A 925 (2019) 33–52, <http://dx.doi.org/10.1016/j.nima.2019.01.003>.
8. J.K. Zhao, K.W. Herwig, J.L. Robertson, F.X. Gallmeier, B.W. Riemer, “Instrument performance study on the short and long pulse options of the second Spallation Neutron Source target station”, Review of Scientific Instruments 84 (10) (2013) 105104, <http://dx.doi.org/10.1063/1.4823778>.
9. F.X. Gallmeier, I. Remec, “A liquid hydrogen tube moderator arrangement for SNS second target station”, Review of Scientific Instruments 93 (8) (2022) 083301, <http://dx.doi.org/10.1063/5.0095900>.
10. K. Ghooos, L. Zavorka, I. Remec, “Moderator Optimization for the Second Target Station Final Design”, S03120100-TRT10020, ORNL/TM-2024/3450 (2024).
11. K. Ghooos, L. Zavorka, I. Remec, “Coupled Target-Beam-Moderator Optimization for the Second Target Station”, S03120100-TRT10014, ORNL/TM-2024/3339 (2024).
12. L. Zavorka, K. Ghooos, I. Remec, J. Risner, “An unstructured mesh based neutronics optimization workflow”, Nuclear Instruments and Methods in Physics Research A 1052 (2023) 168252.
13. K. Ghooos, L. Zavorka, J. Tipton, I. Remec, “Designing the Second Target Station with a Coupled Neutronics-Mechanical Optimization Workflow”, Nuclear Science and Engineering 199 (2025) S954-S965.
14. J. Janney, “CMS-MRA Interface Sheet”, S01020500-IST10148, STS, ORNL, (2025).
15. L. Zavorka, M.J. Mocko, and E.R. Olivas, “Hybrid unstructured mesh geometry model of the next-generation spallation neutron source at LANSCE”, Nuclear Instruments and Methods in Physics Research A 1040 (2022) 167210.

16. W. Lu, et al., “A reevaluation of radiation damage cross section”, Journal of Nuclear Materials 431, 33, (2012).
17. Y.J. Lee, “Materials Handbook: Second Target Station Project”, EDRM: S03010300-TDO10000, ORNL (2025).

APPENDIX A. COMPUTER HARDWARE AND SOFTWARE

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These simulations were performed on either Saturn or Kryo, which are the Linux clusters owned and maintained by the STS Neutronics Groups. The MCNP module used for this analysis is

mcnp/mcnp6.2mod_20230411

In addition to that, Attila4MC, version 10.2, installed on ORNL PC117963 was used.

Tecplot and custom python scripts were used to generate the plots and figures.

APPENDIX B. LOCATION OF COMPUTATIONAL INPUT AND OUTPUT FILES

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Geometry:

saturn.sns.gov

/home/vlz/calculations/mra/mra_am_001update.asm

Results:

Neutronics performance:

saturn.sns.gov

/home/vlz/calculations/mra/

i21bb and o21bb.m tally 15 for the tube moderator performance

i21d and o21d.m tally 5 for the cylinder moderator performance

Energy deposition:

saturn.sns.gov

/home/vlz/calculations/mra/

i20u and o20u_out.eeout is the instantaneous energy deposition for the MRA for all materials except i20z

i20z and o20z_out.eeout is the instantaneous energy deposition for the MRA for SS316,A36,Invar
and the respective .csv files

kryo.ornl.gov

/home/vlz/calculations/mra/

i20y3 and o20y3_out.eeout, o20y3_cyl_out.eeout, and o20y3_tube_out.eeout for the MRA

i20w3 and o20w3_cyl_out.eeout is the energy deposition from $^{27}\text{Al}(\text{n},\text{g})$ in cylinder

i20x3 and o20x3_tube_out.eeout is the energy deposition from $^{27}\text{Al}(\text{n},\text{g})$ in tube
and the respective .csv files

Radiation damage:

saturn.sns.gov

/home/vlz/calculations/mra/

i21f and o21f_out.eeout for dpa in Al

i21g and o21g_out.eeout for dpa in SS316

kryo.ornl.gov

/home/vlz/calculations/mra/

i20ug90 and o20ug90_out.eeout is the thermal flux for Si production in Al

Hydrogen density sensitivity study:

saturn.sns.gov

/home/vlz/calculations/opt/fdmra/sensitivity/optimal

mcnpi_60-74 and mcnp0_60-74.m

Para-hydrogen fraction sensitivity study:

kryo.ornl.gov

/home/vlz/calculations/opt/fdmra/sensitivity/optimal

mcnpi_*para and mcnp0_*para.m

Hydrogen temperature sensitivity study:

saturn.sns.gov

/home/vlz/calculations/opt/fdmra/sensitivity/optimal

mcnpi_18-22K and mcnp0_18-22K.m

Misalignment study:

saturn.sns.gov

/home/vlz/calculations/mra/

i10b and o10b.m

APPENDIX C. TECHNICAL REVIEW DOCUMENTATION

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TECHNICAL REVIEW CHECKLIST

	Yes	No	N/A
Is the calculation well organized, legible, and complete?			
If excerpts from other sources are included in the calculation package, are the excerpts legible and properly referenced?			
Do the calculations cover the expressed purpose?			
Are all necessary elements included?			
Is the method used appropriate considering the purpose and type of analysis and the use and acceptability of the results (i.e. margin to limits)?			
Is the method in accordance with codes, standards, and regulatory requirements?			
Has the method been employed similarly elsewhere in industry?			
Are assumptions necessary to perform the analysis adequately described, justified, and reasonable?			
Are there any Unverified Assumptions (UVAs)?			
Were UVAs justified?			
Are the inputs sufficiently documented considering the purpose of the analysis?			
Is all the software used identified correctly (name, version, manual reference, OS, and compilers are documented)?			
Are the computer codes suitable for the present analysis?			
Does the model adequately represent the physical systems?			
Is the magnitude of the result reasonable?			
Are the directions of trends reasonable?			

Additional comments:

Technical Reviewer

Date

