Neutronics Analysis for the STS MRA & TW Final Design Review

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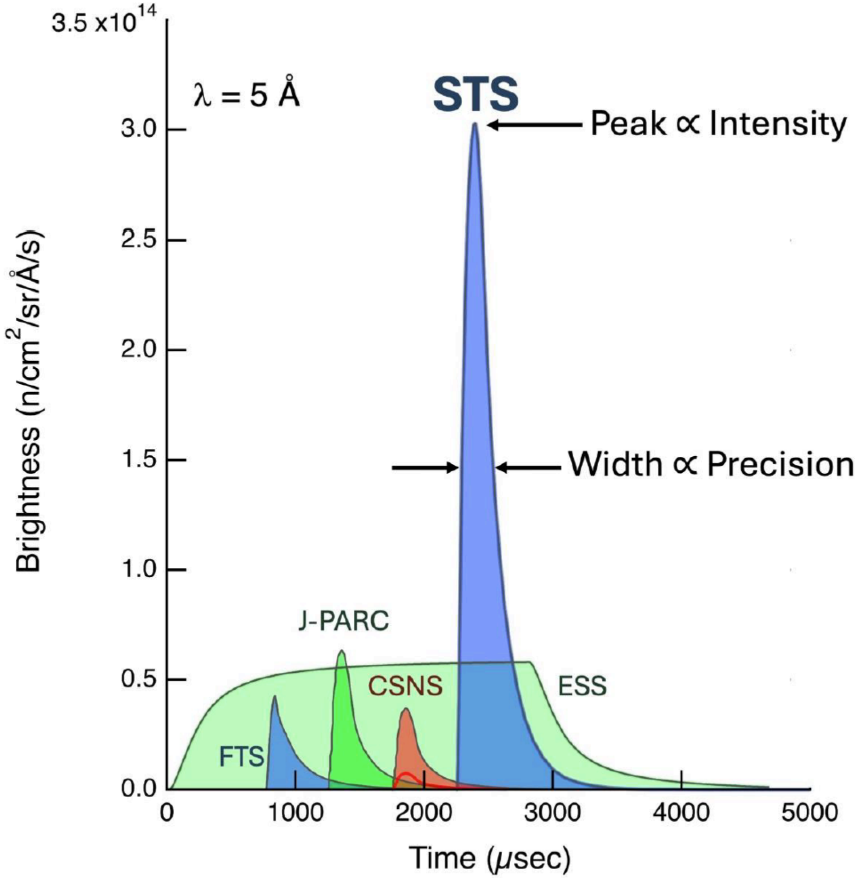
August 10-12, 2026, ORNL

STS Mission Need (approved 2009)

- The capacity for a STS to generate cold (long wave-length) neutrons has been included in the SNS project from the start
- Optimize STS for high peak brightness
  - Smaller samples under more extreme conditions
  - Advanced instruments with optics
  - High-quality experiments faster
- Enable new science capabilities
- Sustain US leadership in neutron sciences



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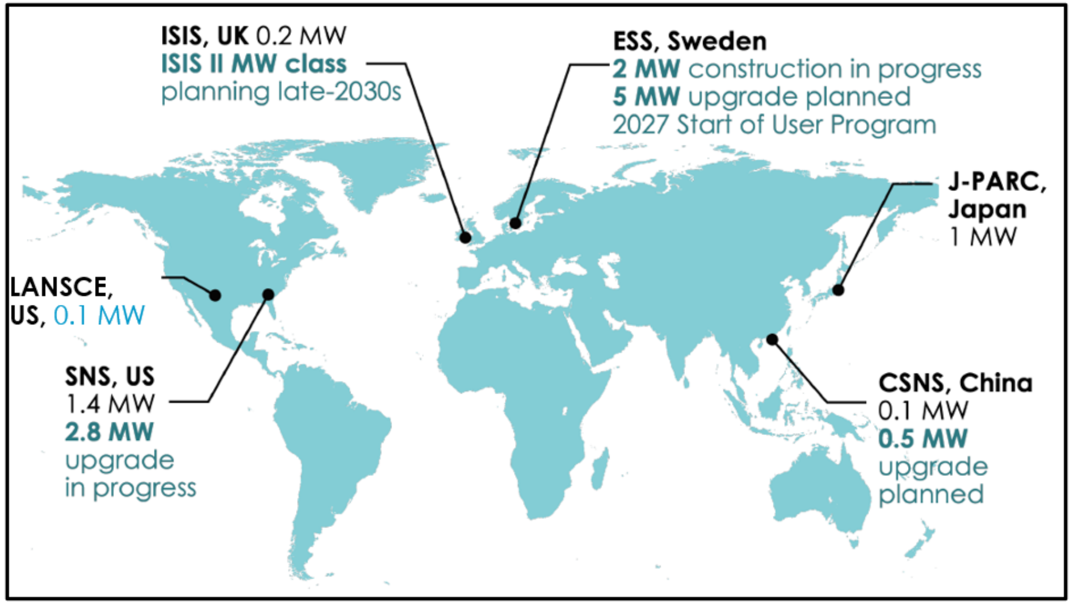
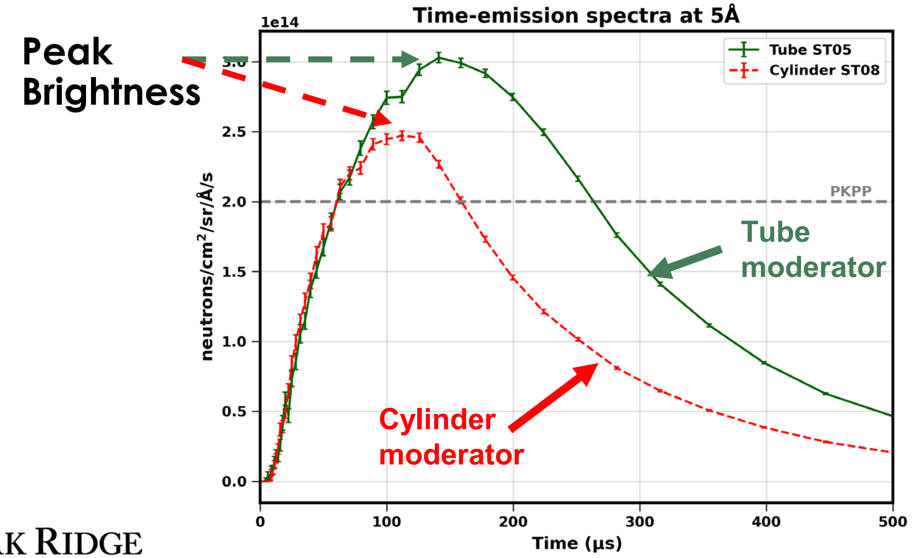
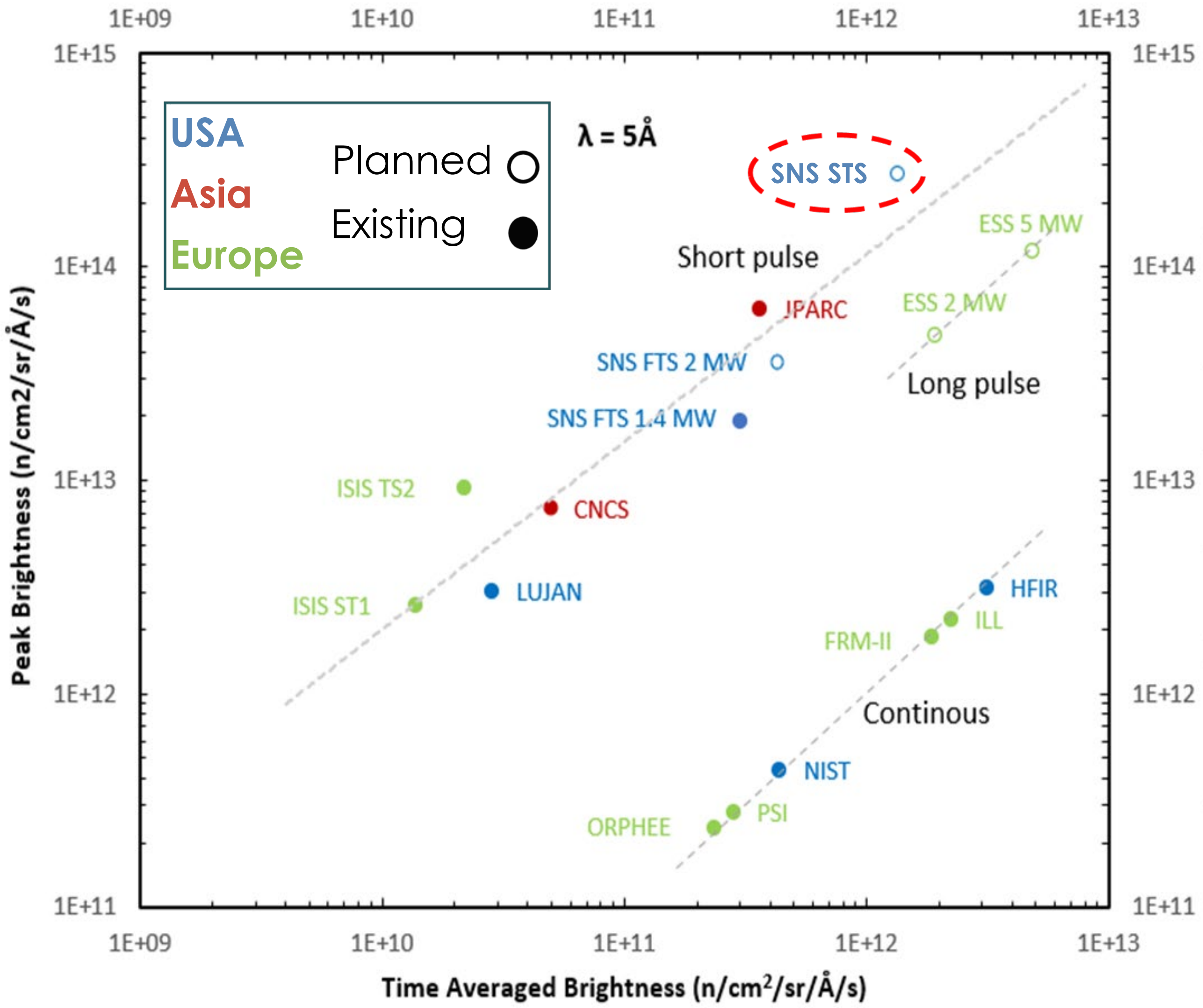
STS among other spallation neutron sources





The STS objective is to become the highest peak-brightness source of cold neutrons



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Key Performance Parameters (KPP)

ID	Key Performance Parameter	Thresholds (Performance Deliverable)	Objectives	Plan meets requirement
Subproject 1 – Facility and Infrastructure				
SP1-1	Demonstrate independent control of the proton beam on the two target stations	Operate beam to FTS at 45 pulses/s, with no beam to STS Operate beam to STS at 15 Hz, with no beam to FTS Operate with beam to both target stations 45 pulses/s at FTS and 15 Hz at STS		✓
SP1-2	Demonstrate proton beam power on STS at 15 Hz	100 kW beam power with FTS at 1.8 MW at 45 pulses/s	700 kW beam power with FTS at 2MW at 45 pulses/s	✓
SP1-3	Demonstrate STS neutron brightness	Peak brightness of 2 x 10^{13} n/cm^2/sr/Å/s at 5 Å	Peak brightness of 2 x 10^{14} n/cm^2/sr/Å/s at 5 Å	✓
Subproject 2 - Instruments				
SP2-1	Beamlines transitioned to operations	3 beamlines successfully passed the integrated functional testing per the IFP acceptance criteria	≥ 3 beamlines successfully passed the integrated functional testing per the IFP acceptance criteria	✓

Design Requirements (related to neutronics)

- Target Segment Displacements per Atom:
  - The materials in the segment shall not exceed DPA-NRT limits specified in the Second Target Station materials handbook

- MRA Material Lifetime:
  - The MRA materials shall allow for a lifetime of at least 5 years of operation

KPP and design requirements are met

Neutronics analysis for the FDR

- Methods
  - Codes, model conversion, unstructured mesh application
  - Innovation, validation
- Results in the target and target shaft
  - Energy deposition
  - Radiation damage
- Results in the Moderator-Reflector Assembly (MRA)
  - Neutronics performance
  - Energy deposition
  - Radiation damage
  - Sensitivity studies

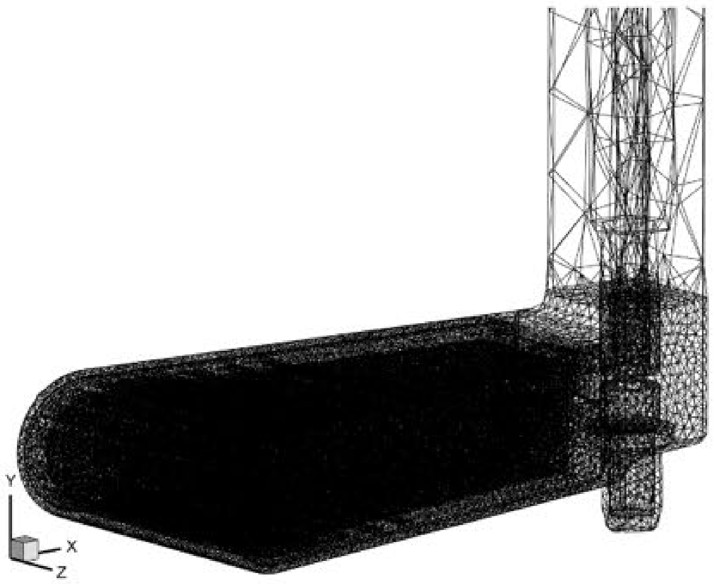
Dose rates analyzed and presented by T. McClanahan

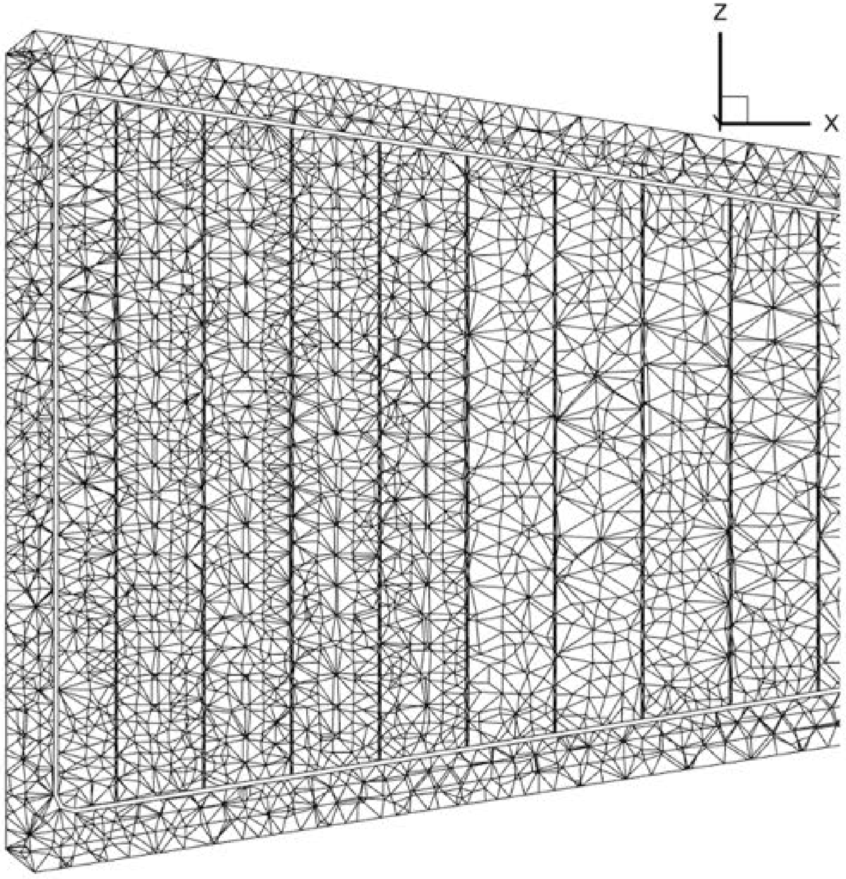
Methods

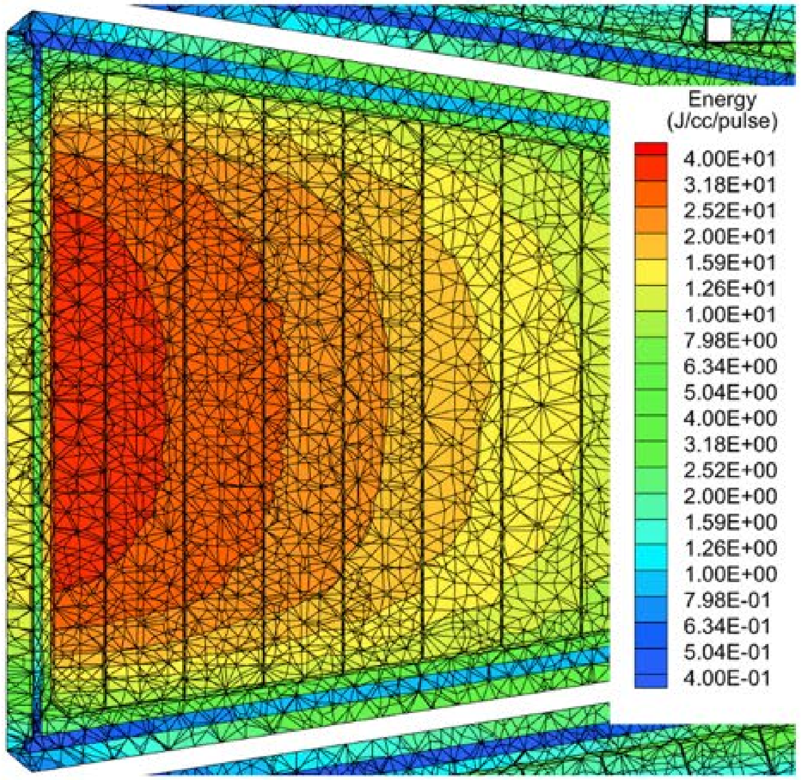
- Radiation transport with MCNP6.2
  - This and previous versions (MCNPX 2.7.0) used and validated during the design process at other spallation neutron sources, including ORNL FTS, LANL Lujan Center and WNR, ISIS, ESS, …
- Unstructured Mesh (UM)
  - Innovative approach that enables direct transfer of the neutronics results for subsequent engineering analyses
  - Now becoming standard at other facilities (LANL, CERN)
- CAD to MCNP UM model conversion with Attila4MC
  - Contiguous mesh with no overlaps
- Variance reduction (deterministic weight windows) with Attila4MC - Cottonwood

Extensive use of Unstructured Mesh (UM) at STS

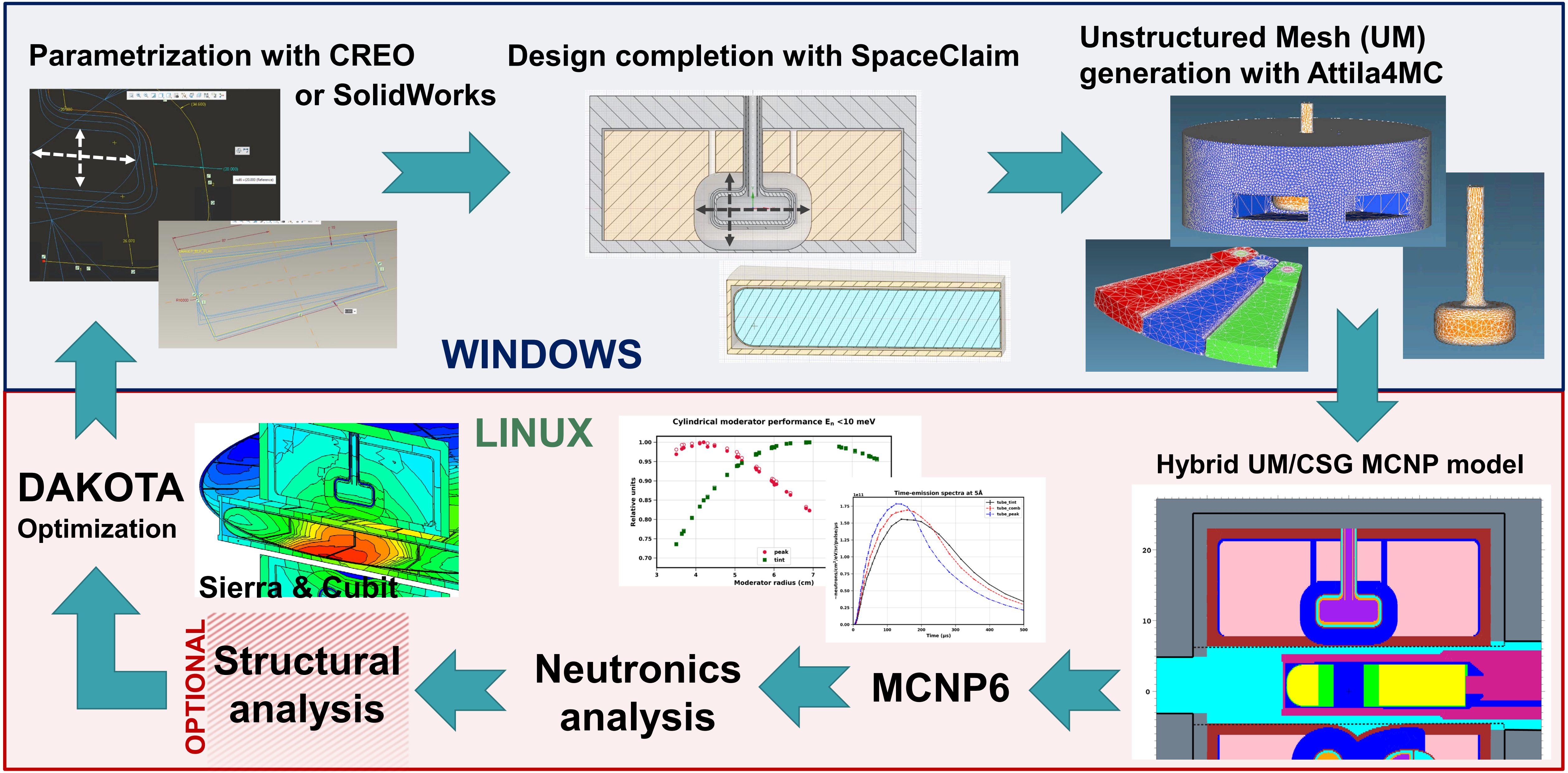
- Efficient CAD to MCNP model conversion with high level of fidelity
- Delivers high spatial-resolution data of energy deposition and dpa
- Direct import and mapping in ANSYS
- Enables advanced coupled multi-physics optimization





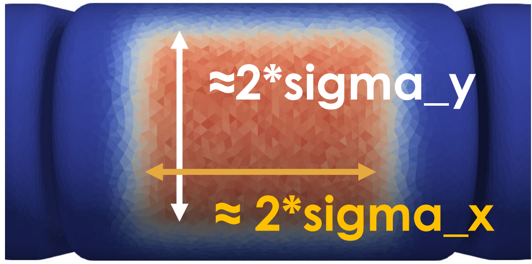


UM-based automatic multiphysics optimization workflow

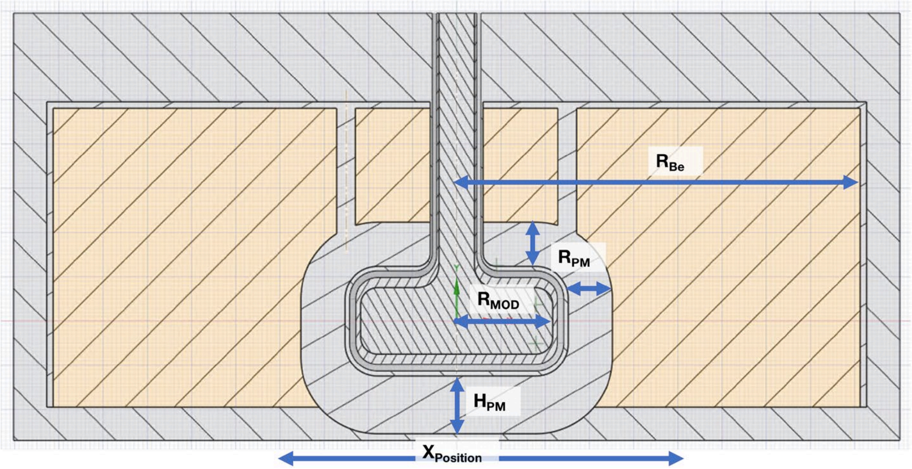


L. Zavorka et al., An unstructured mesh based neutronics optimization workflow, NIM A 1052 (2023) 168252.

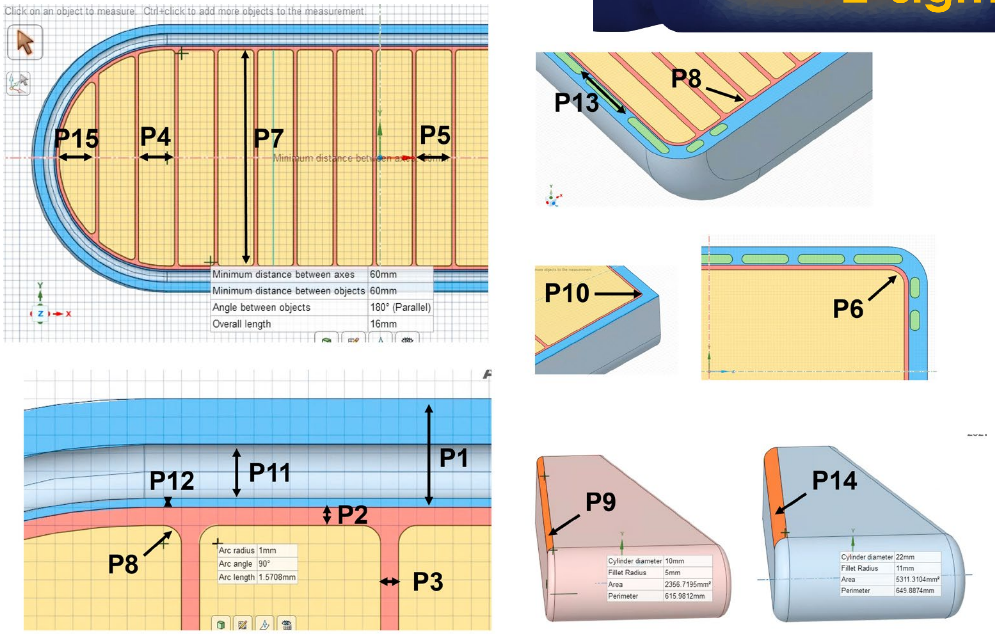
Coupled target-moderator-beam optimization



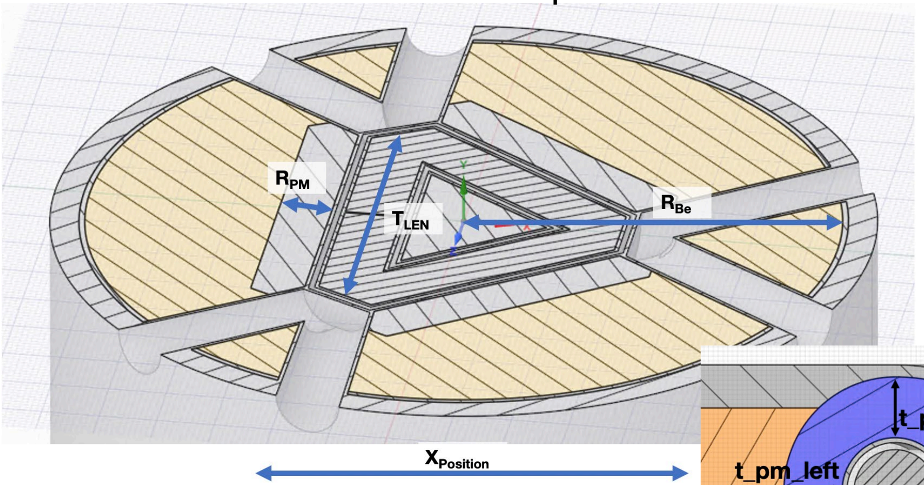
Cylindrical moderator: 6 parameters



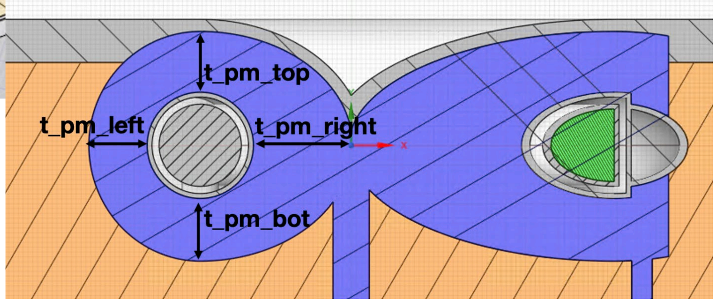
	min	max
Rh2 (mm)	35	80
t_pm_side (mm)	15	40
t_pm_bot (mm)	15	40
t_pm_top (mm)	10	40
r_be (mm)	175	200
x_shift (mm)	-20	20

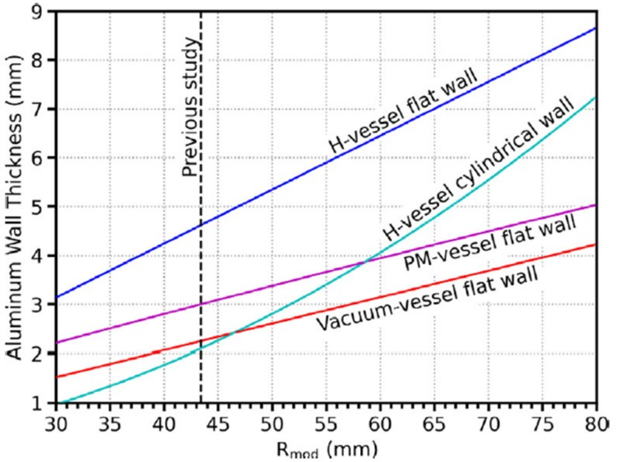


Tube moderator: 7 parameters



	min	max
T_len (mm)	120	240
t_pm_top (mm)	10	35
t_pm_right* (mm)	25	35
t_pm_bot (mm)	10	35
t_pm_left* (mm)	10	35
r_be_t (mm)	175	200
x_shift (mm)	-20	20





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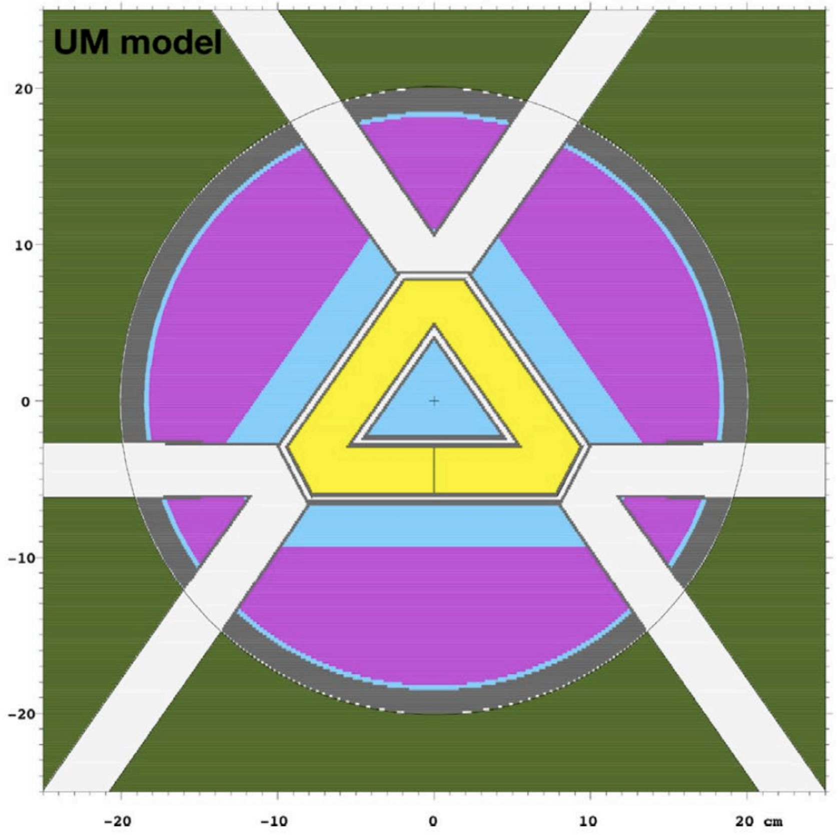
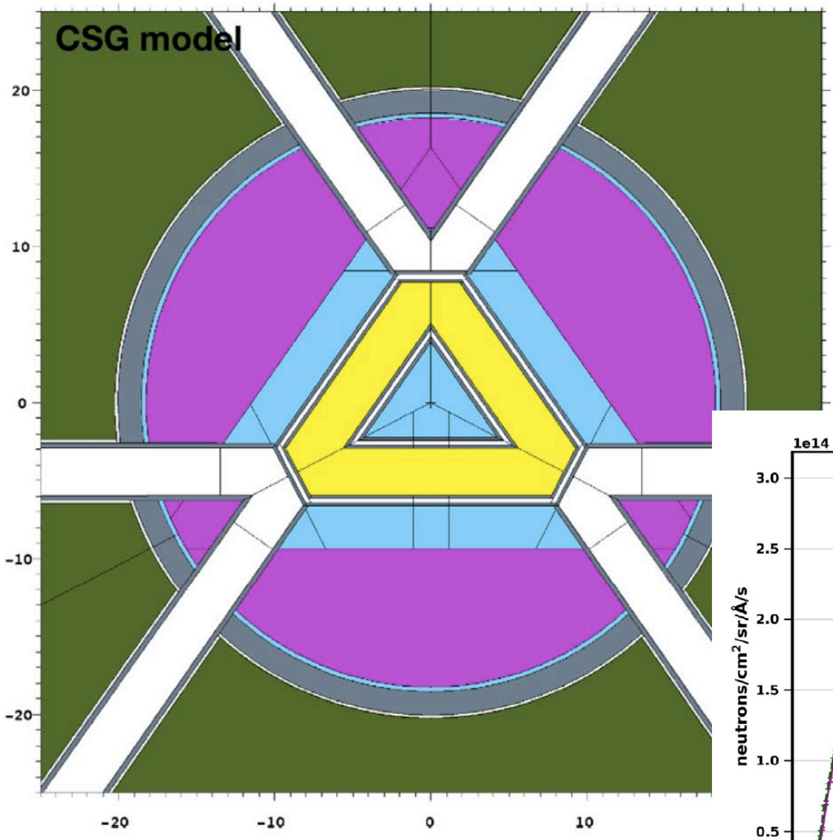
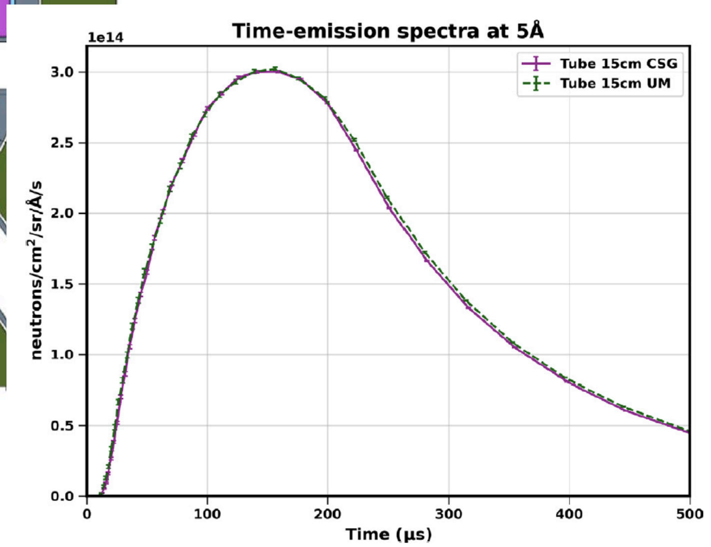
UM Validation

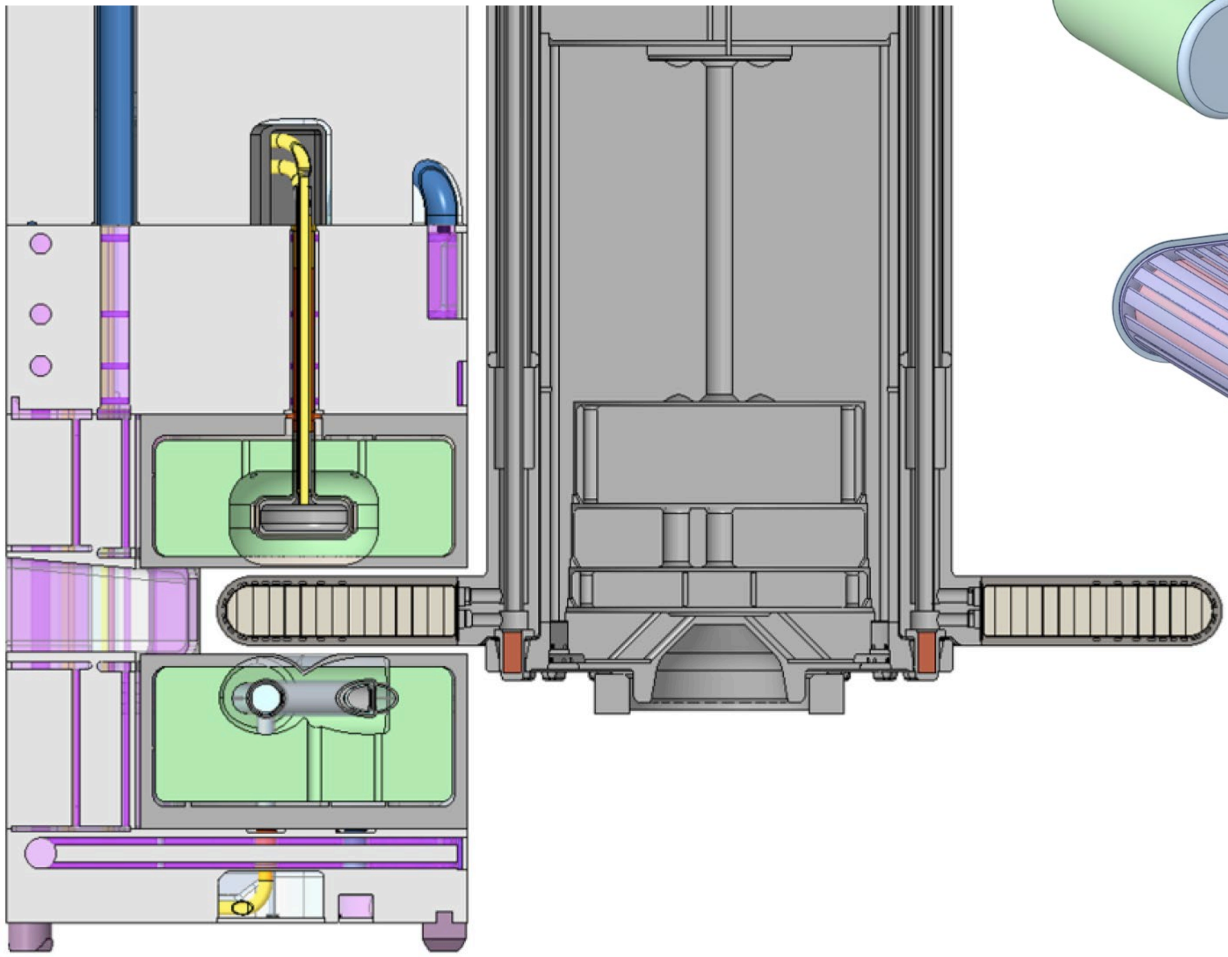
- Neutronics performance and energy deposition validated in MCNP against traditional models and (mesh)tallies

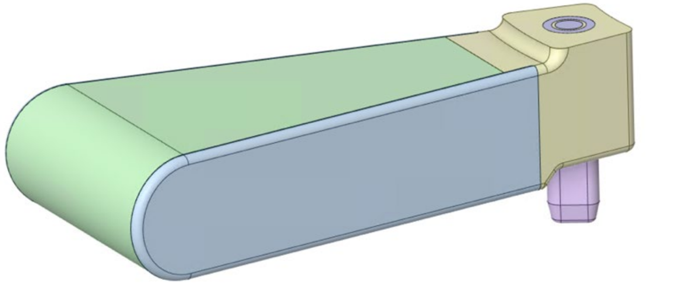


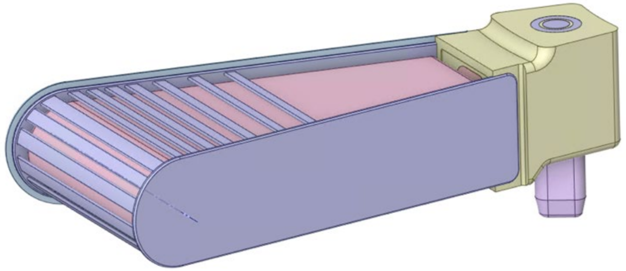


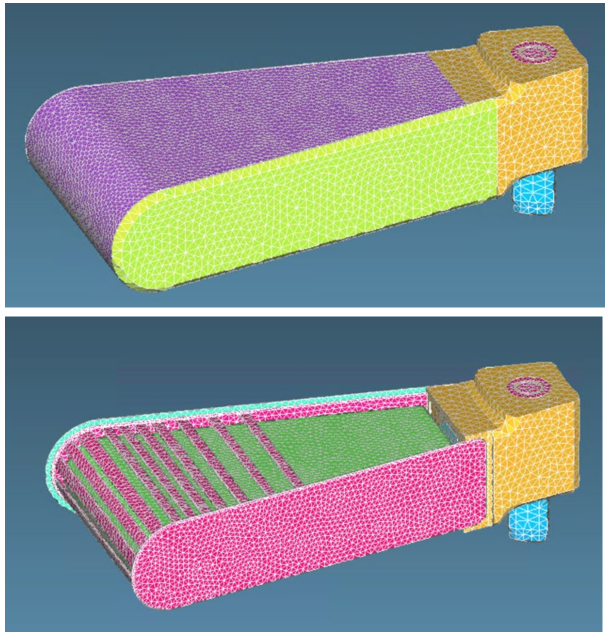


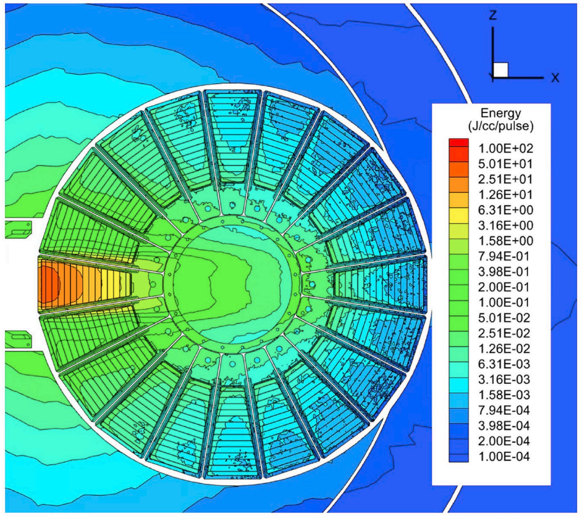
Results in the target and shaft

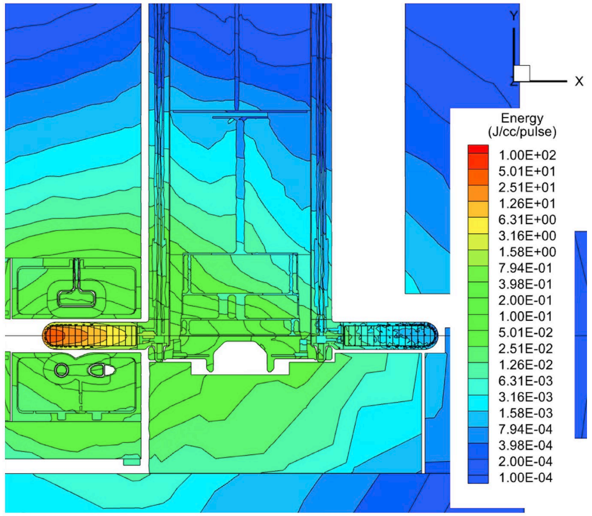




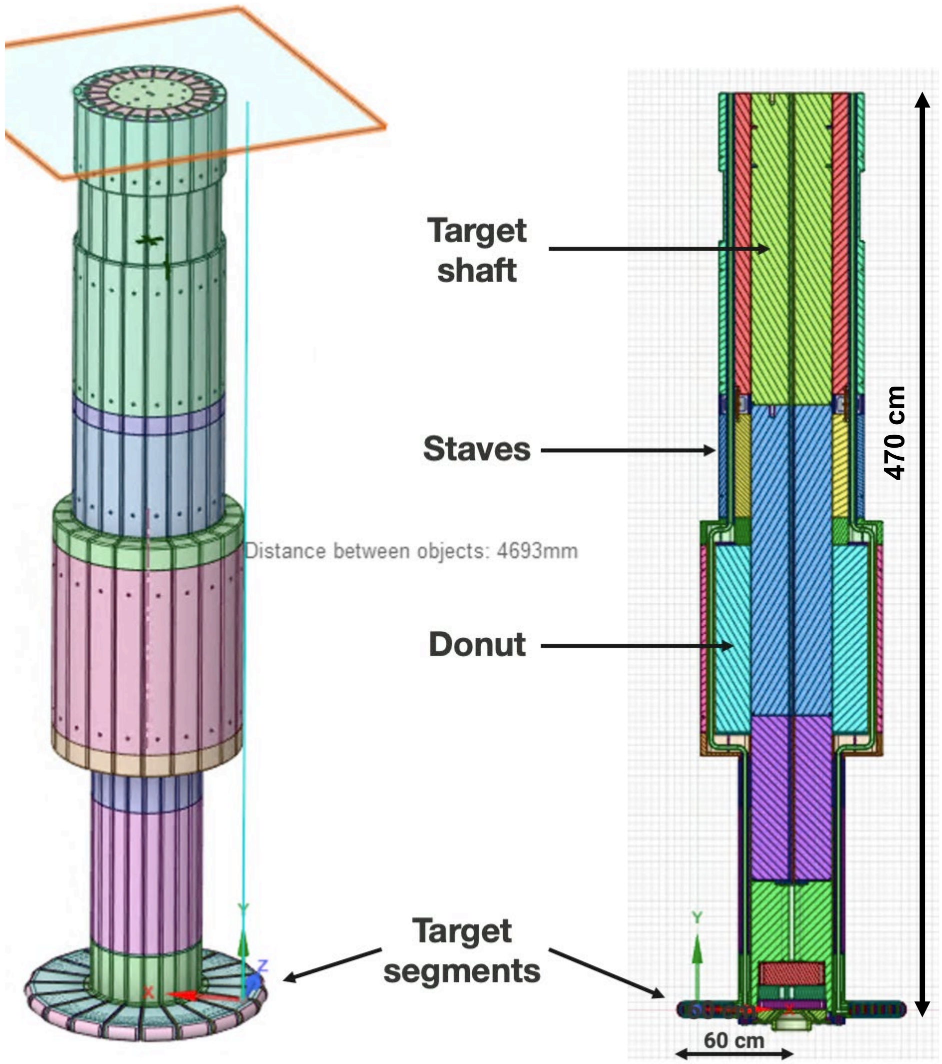




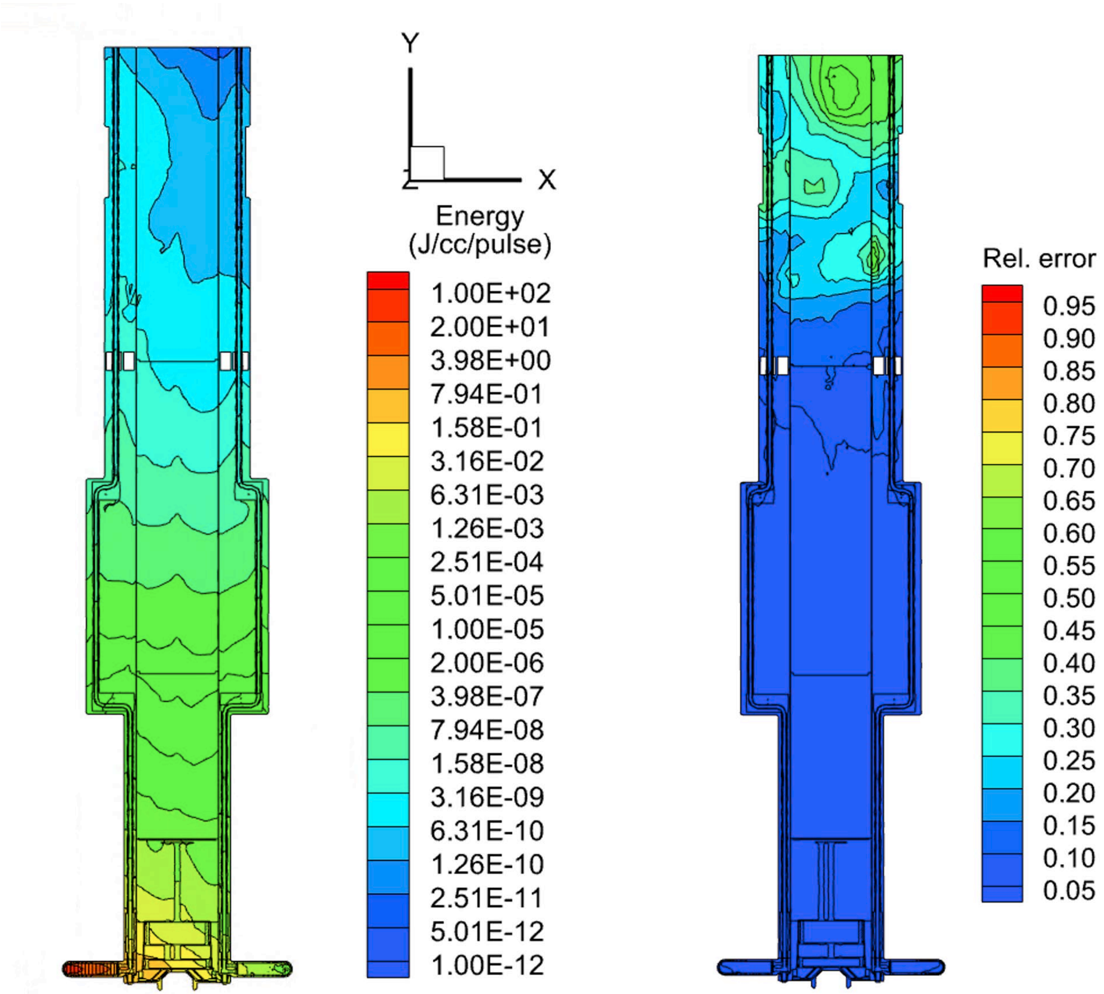




Results in the target and shaft



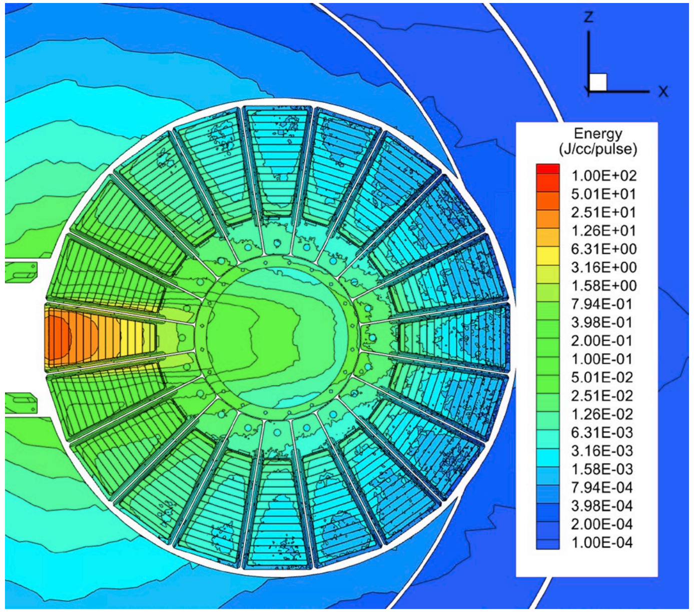
- Cottonwood deterministic solver with CADIS/FW-CADIS for variance reduction



Target heating for different proton beam conditions

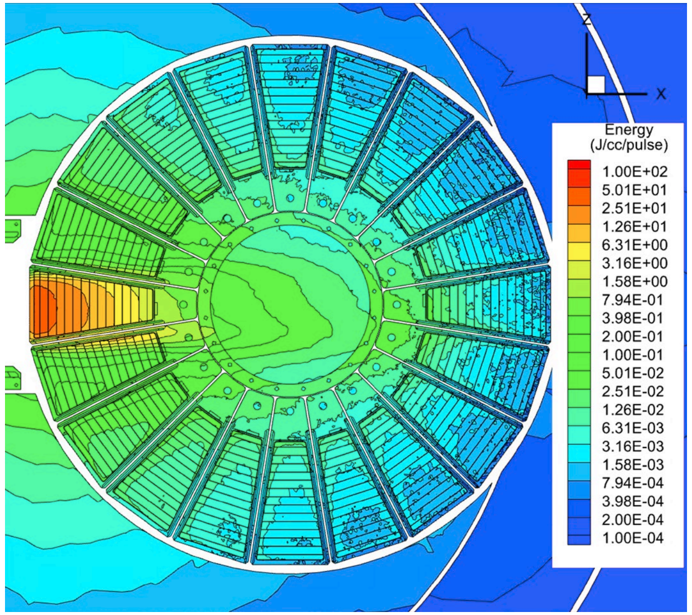
Nominal 60 cm^2

Total 378 kW
Tungsten 293 kW
Max 38.1 J/cc/pulse



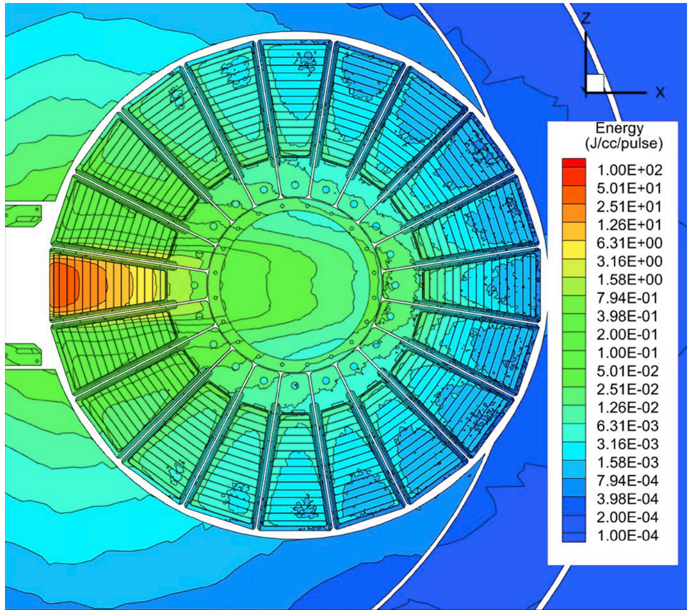
Nominal Corner

Total 370 kW
Tungsten 274 kW
Max 38.2 J/cc/pulse



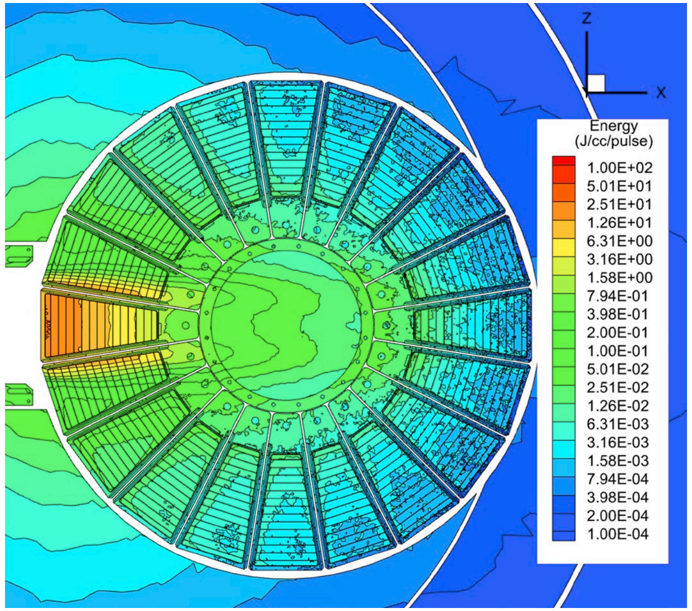
Overfocused 57 cm^2

Total 379 kW
Tungsten 296 kW
Max 40.0 J/cc/pulse



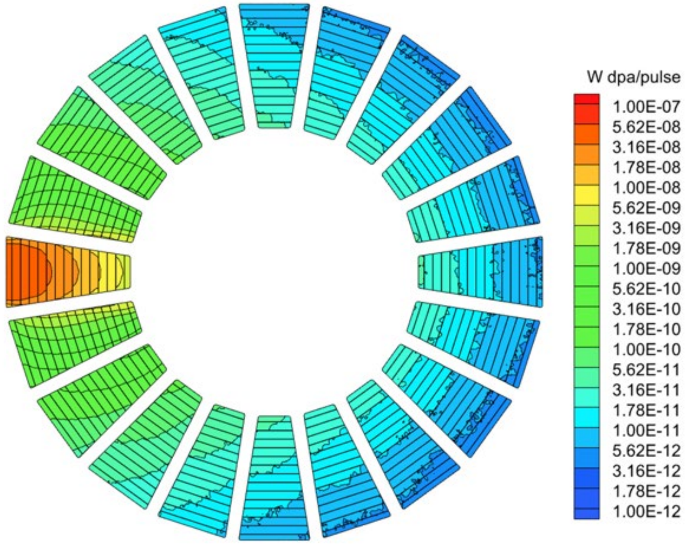
Diffused 94 cm^2

Total 371 kW
Tungsten 263 kW
Max 25.8 J/cc/pulse

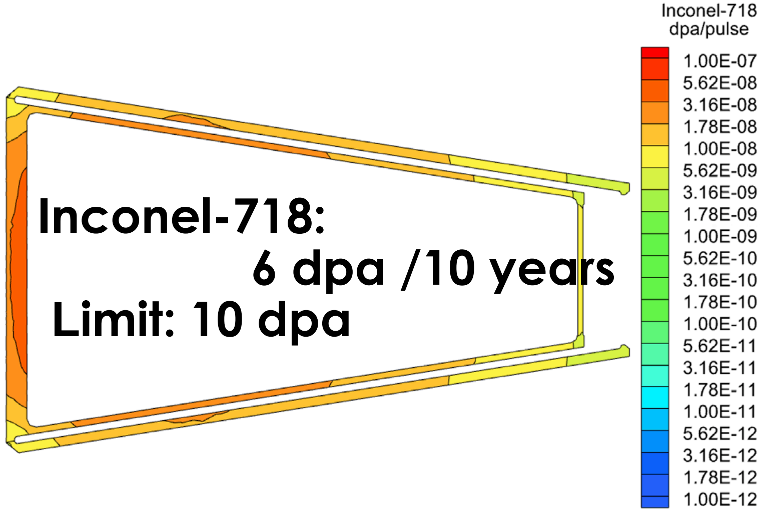


Radiation damage for the target and target shaft

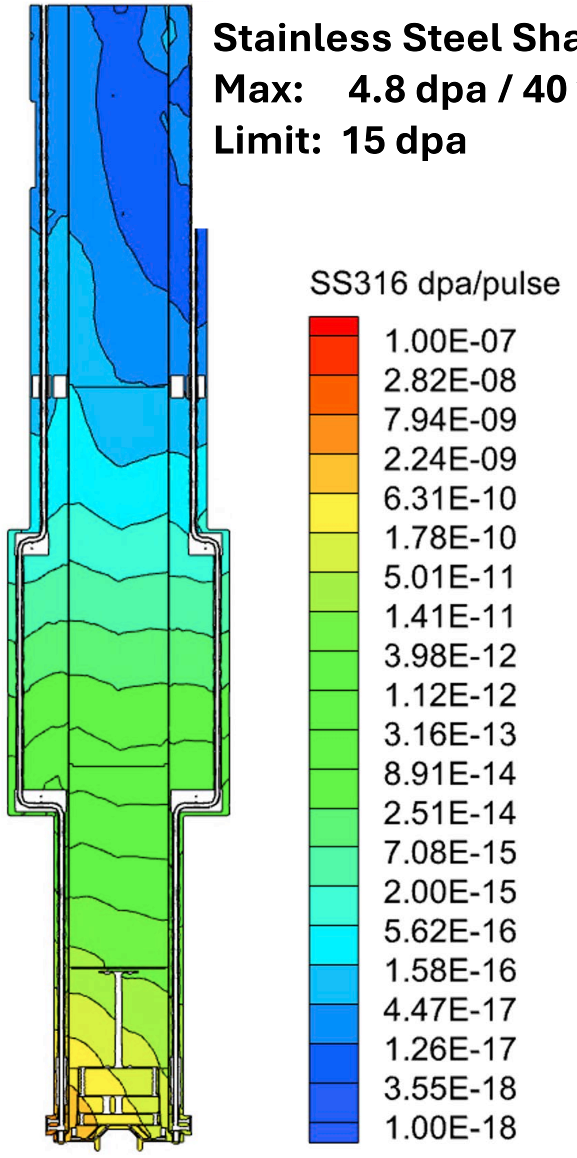
Tungsten: 8 dpa /10 years
Limit: -- (not structural)



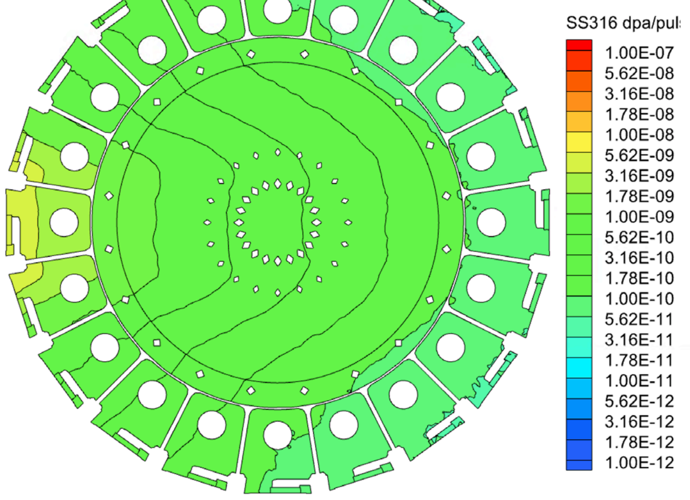
Inconel-718:
6 dpa /10 years
Limit: 10 dpa



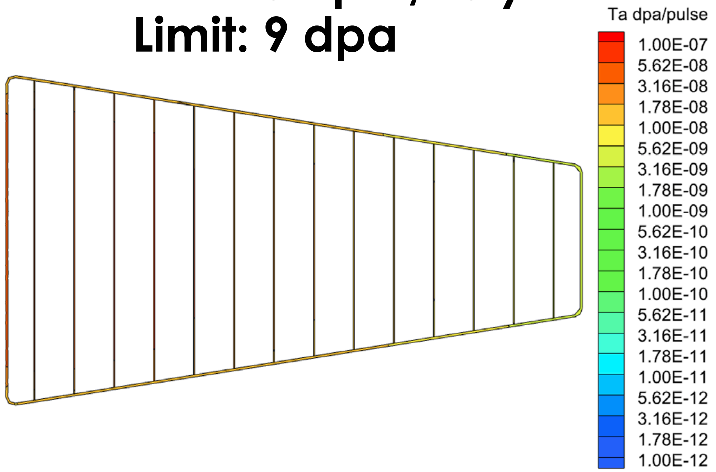
Stainless Steel Shaft
Max: 4.8 dpa / 40 years
Limit: 15 dpa



Stainless steel: 1.7 dpa /10 years
Limit: 15 dpa

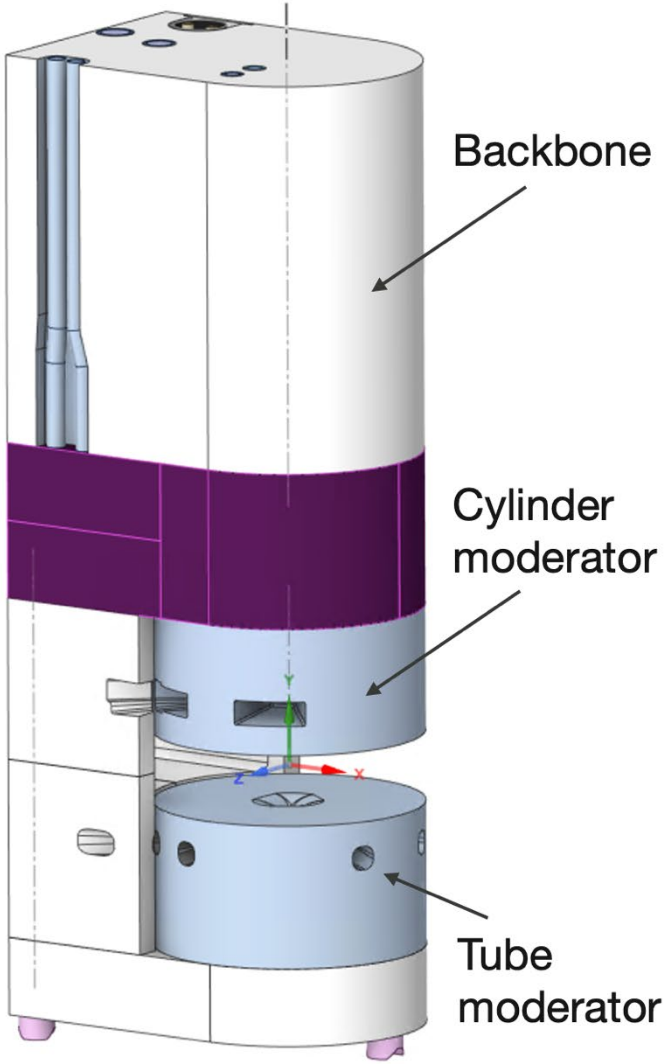


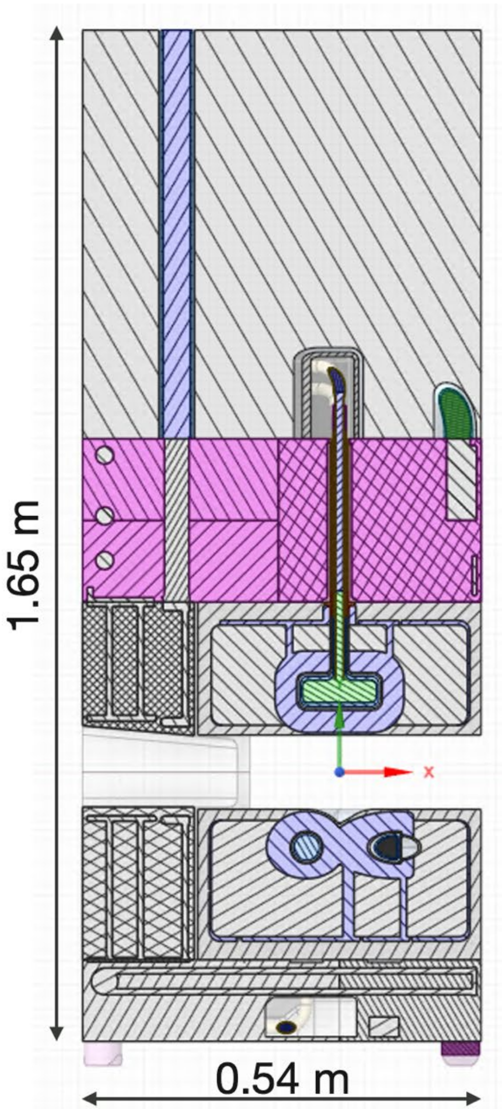
Tantalum: 8 dpa /10 years
Limit: 9 dpa

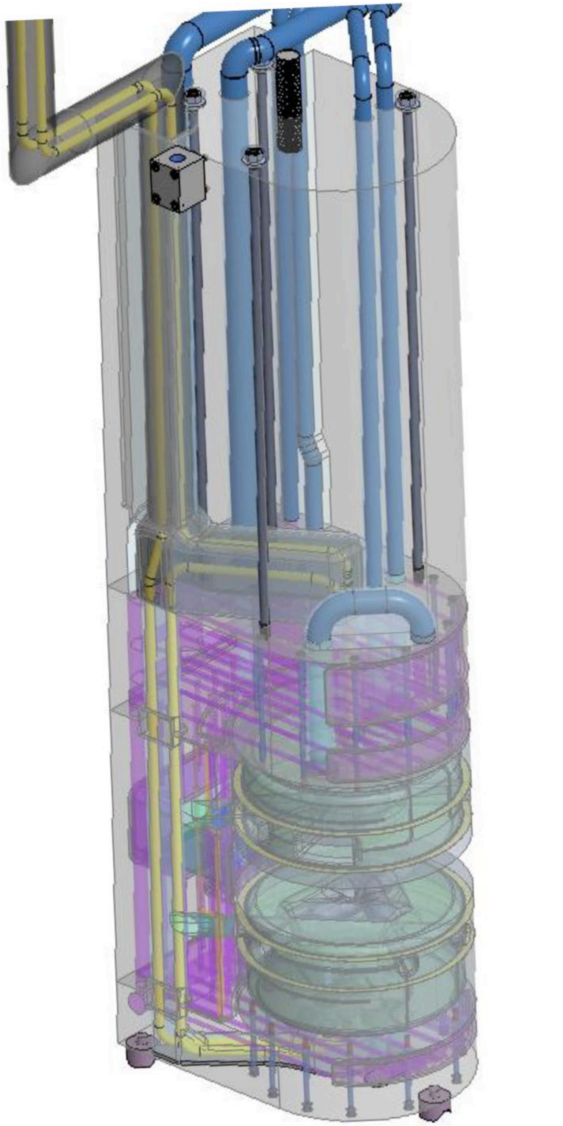


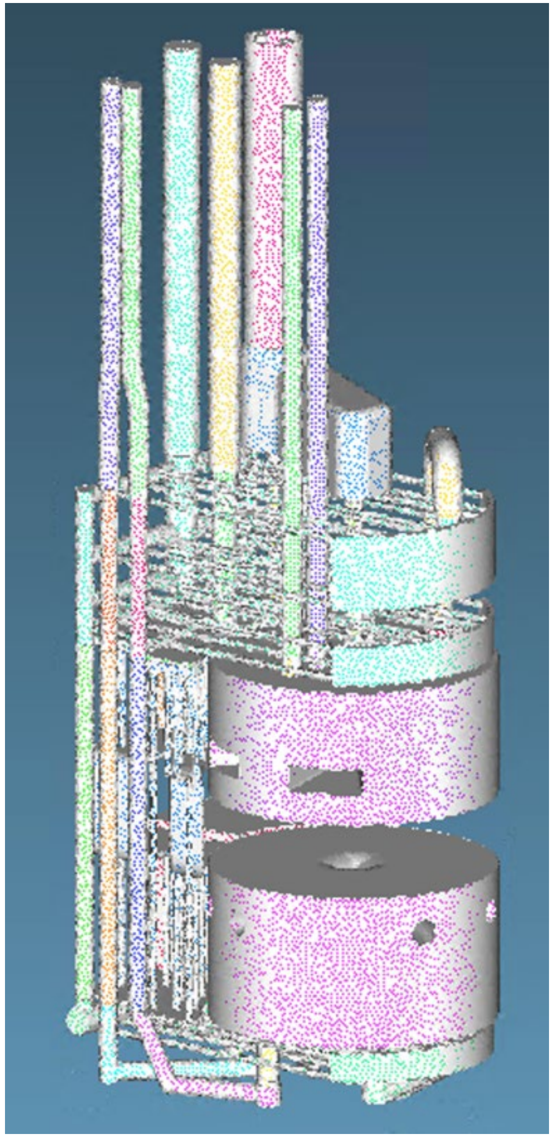
Design requirements are met

Results in the MRA



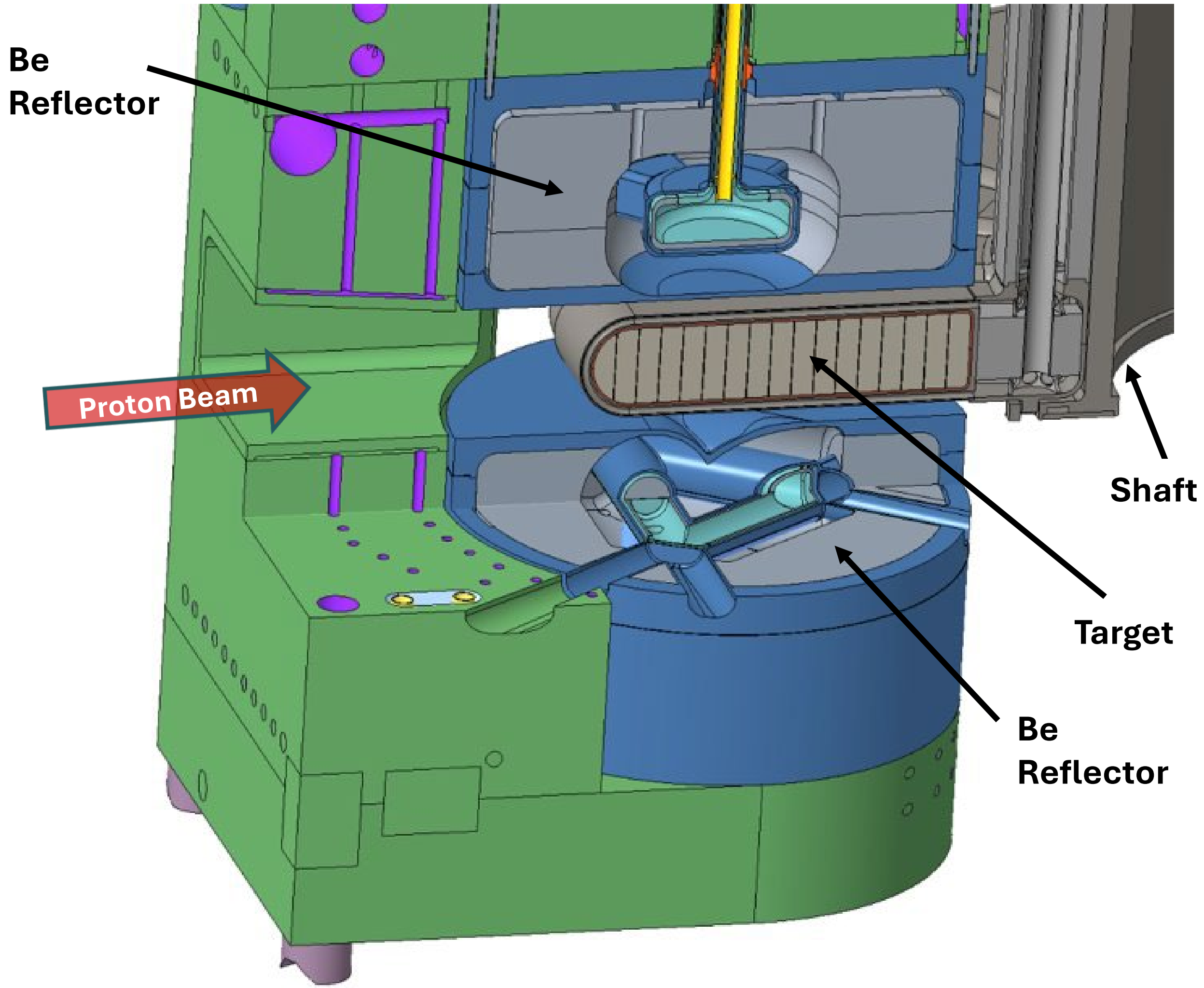






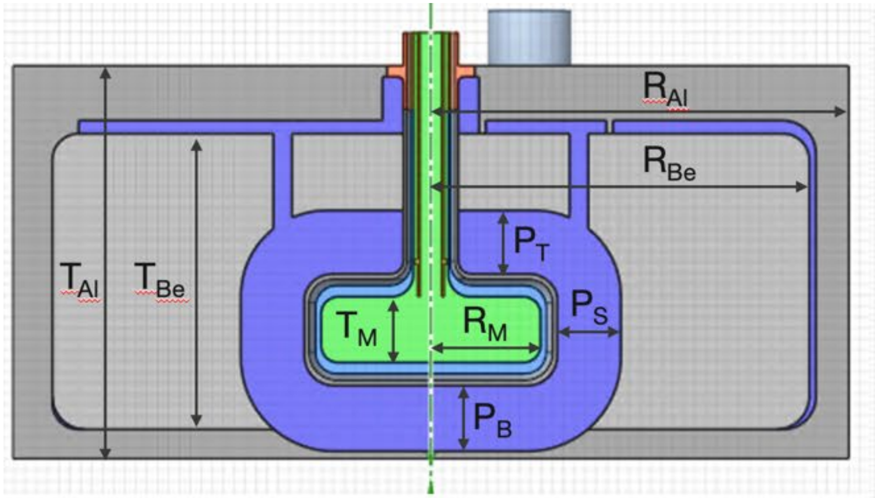
MRA final design

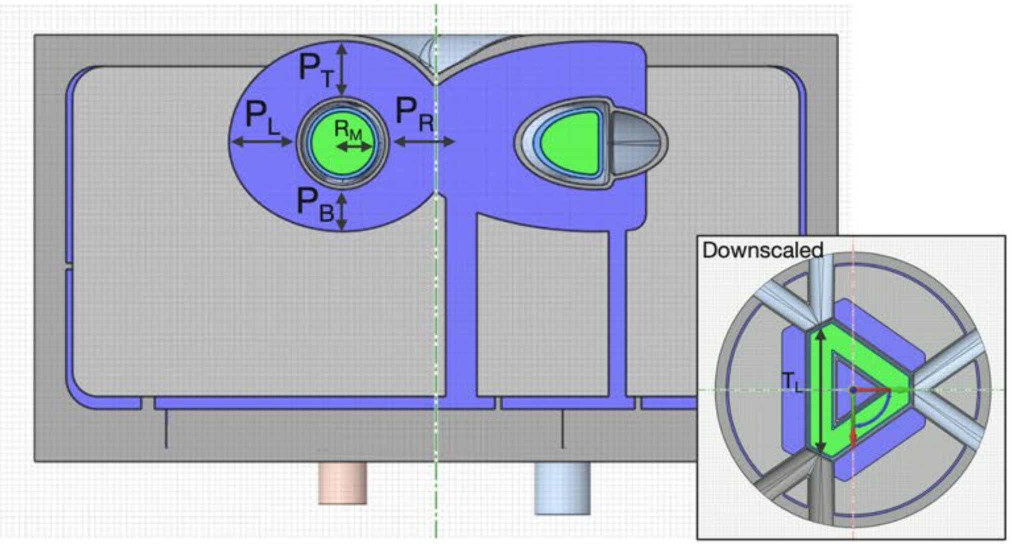
- Two moderators: cylinder and tube tightly coupled with the target (10 mm gap)
- Para-hydrogen at 20 K
- Water premoderator
- Beryllium reflector
- Aluminum vessels, steel backbone
- Low dimensional with 3 x 3 cm^2 and 3 cm diameter fields of view
- Serving up to 20 instruments
- Rigorous optimization



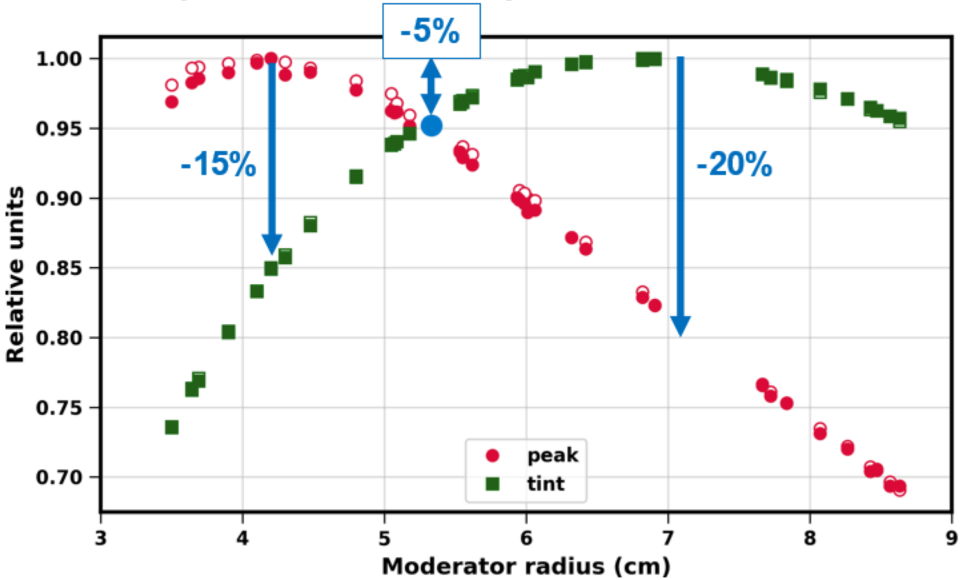
MRA optimization

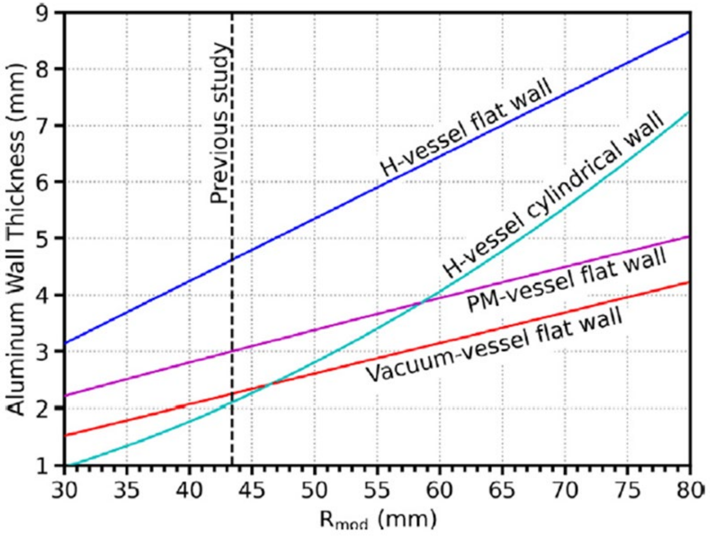
- MRA optimized for a sweet spot between peak and time-integrated brightness

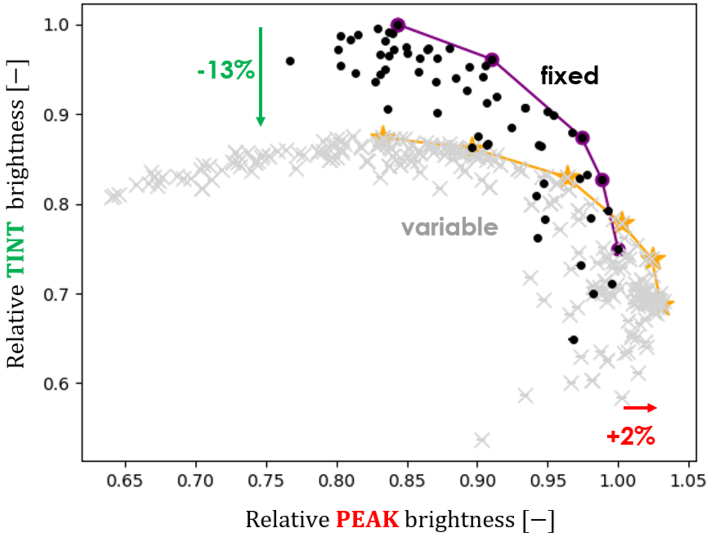




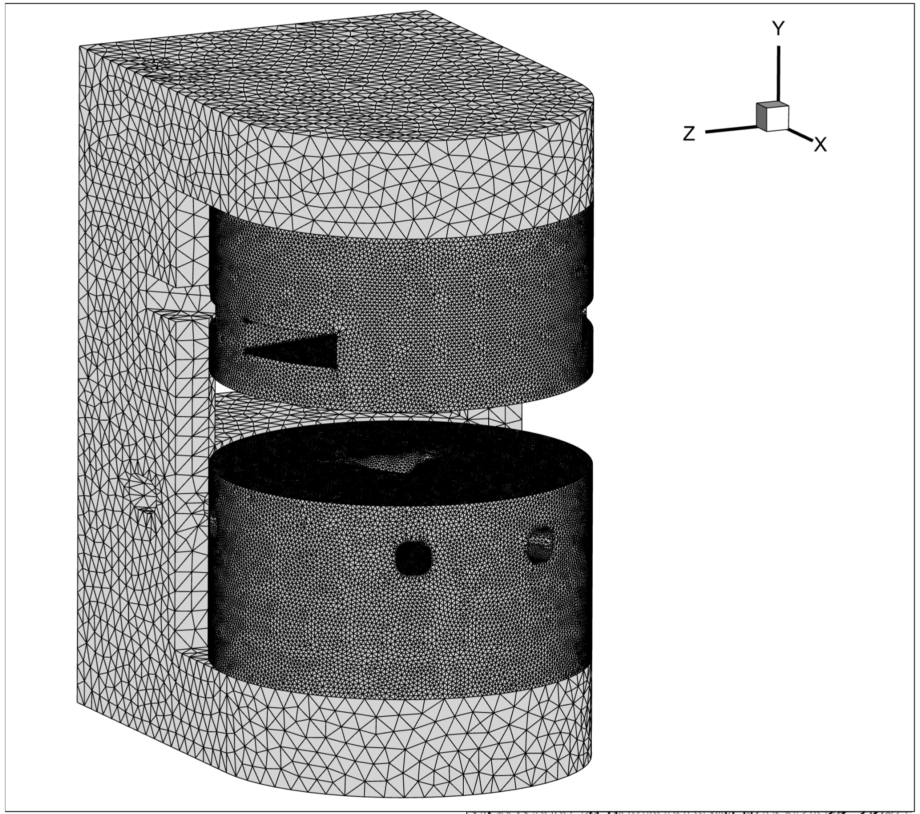
Cylindrical moderator performance E_n <10 meV

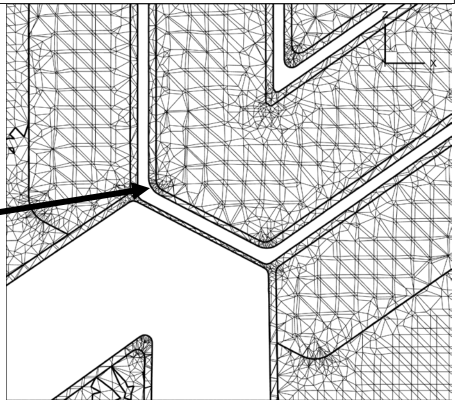




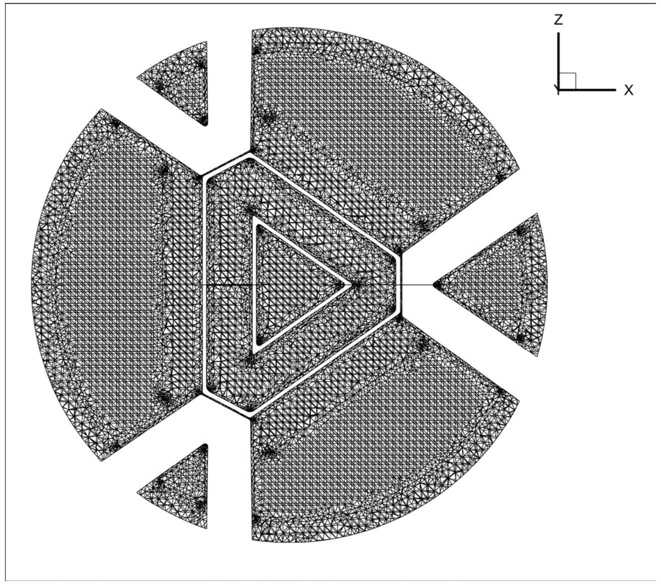


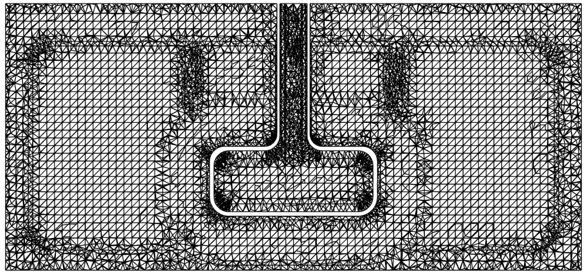
UM geometry

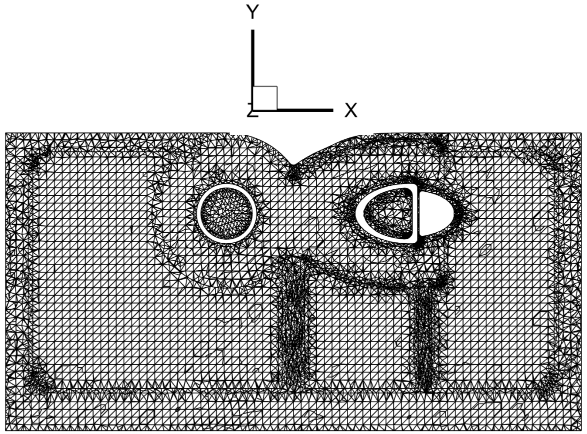




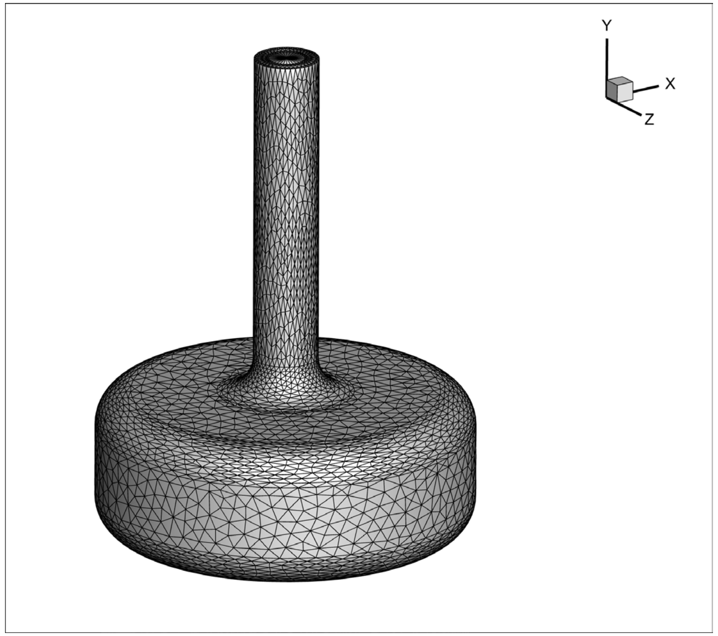
UM captures all fine curvatures (difficult to achieve with CSG)



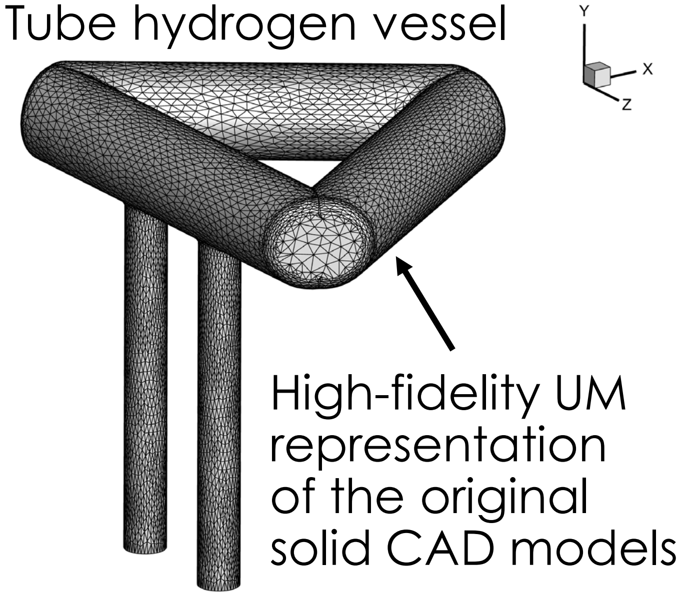




Cylinder hydrogen vessel



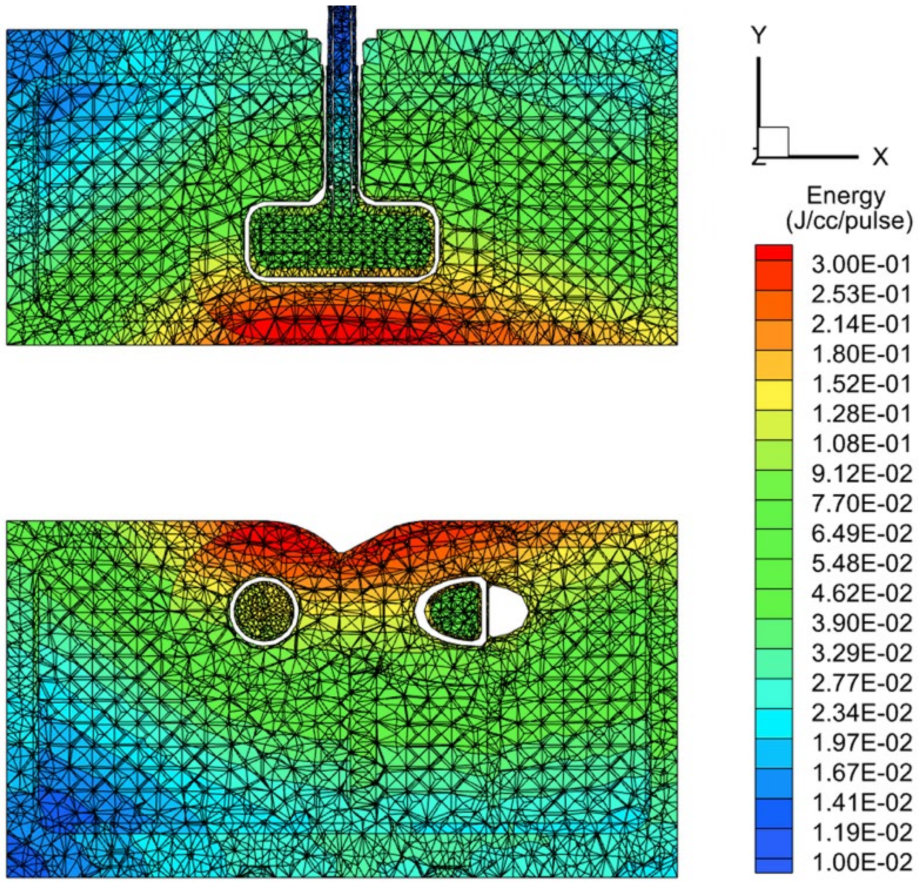
Tube hydrogen vessel

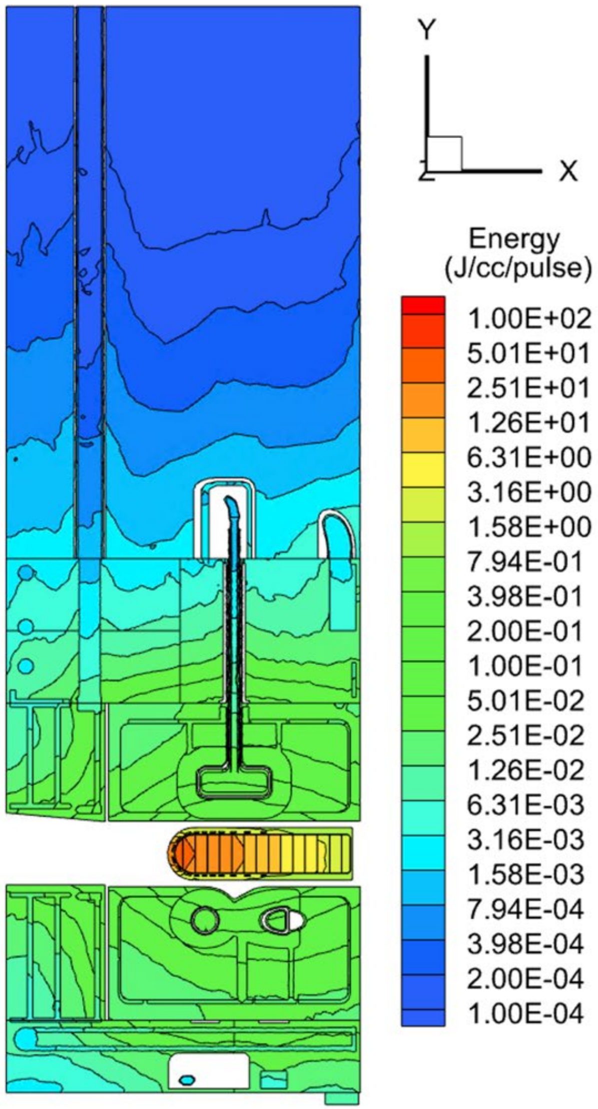


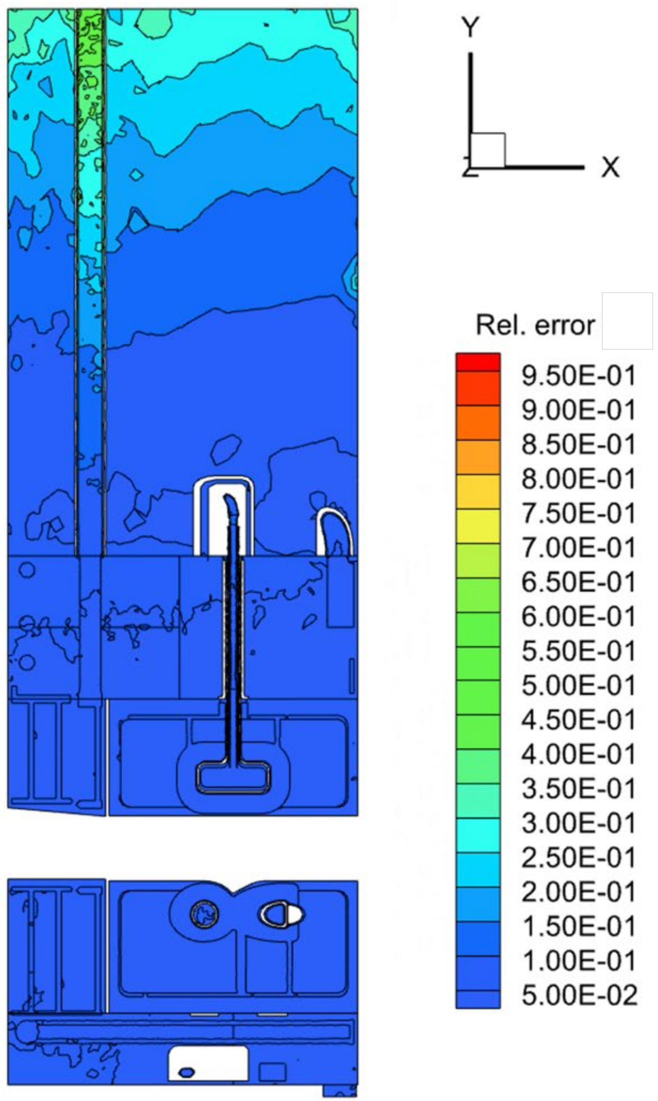
High-fidelity UM representation of the original solid CAD models

MRA energy deposition

- Total heating, including $^{27}Al(n,\gamma)$:
  - MRA: 31.2 kW
  - Backbone: 27.2 kW

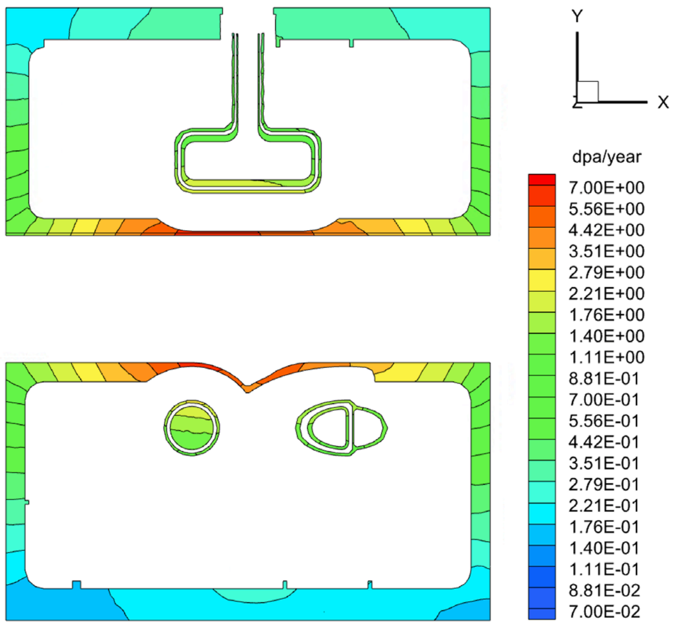




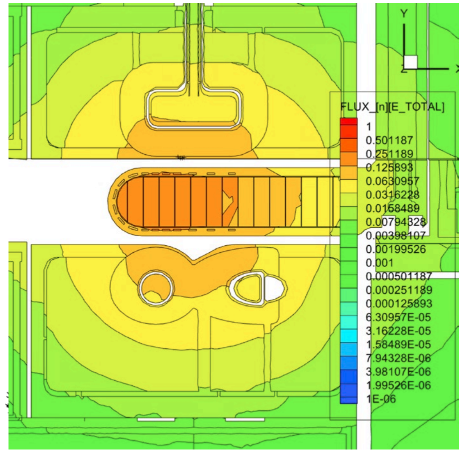


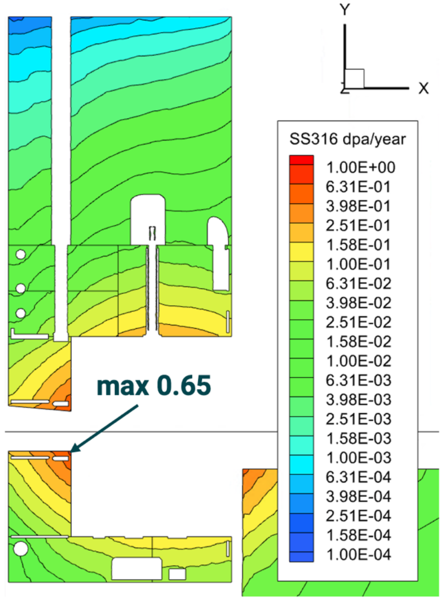
MRA radiation damage meets the design requirement of 5 years

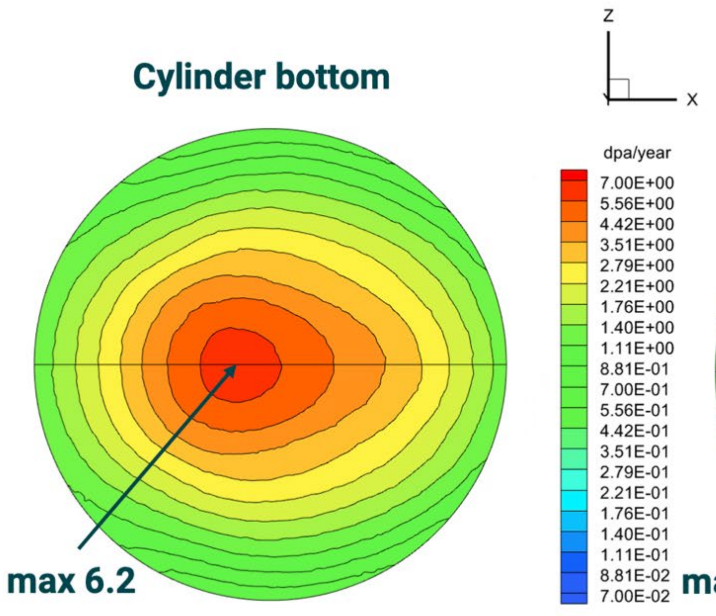
- Lifetime 6.5 years due to dpa in Al
  - Assuming 40 dpa limit
  - Maximum 6.2 dpa/year
  - He production not limiting (25 years)
  - Si production not limiting (12 years)
  - dpa in backbone not limiting (92 years)

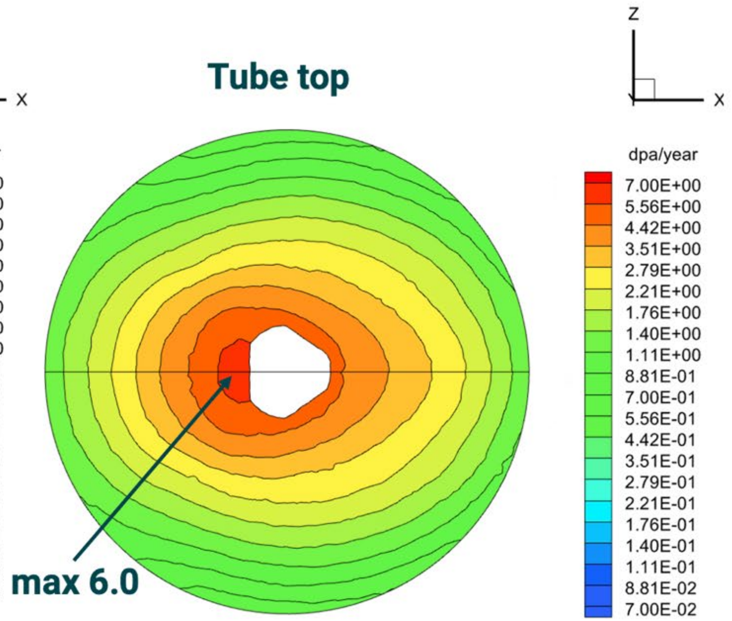


Si production (thermal flux)



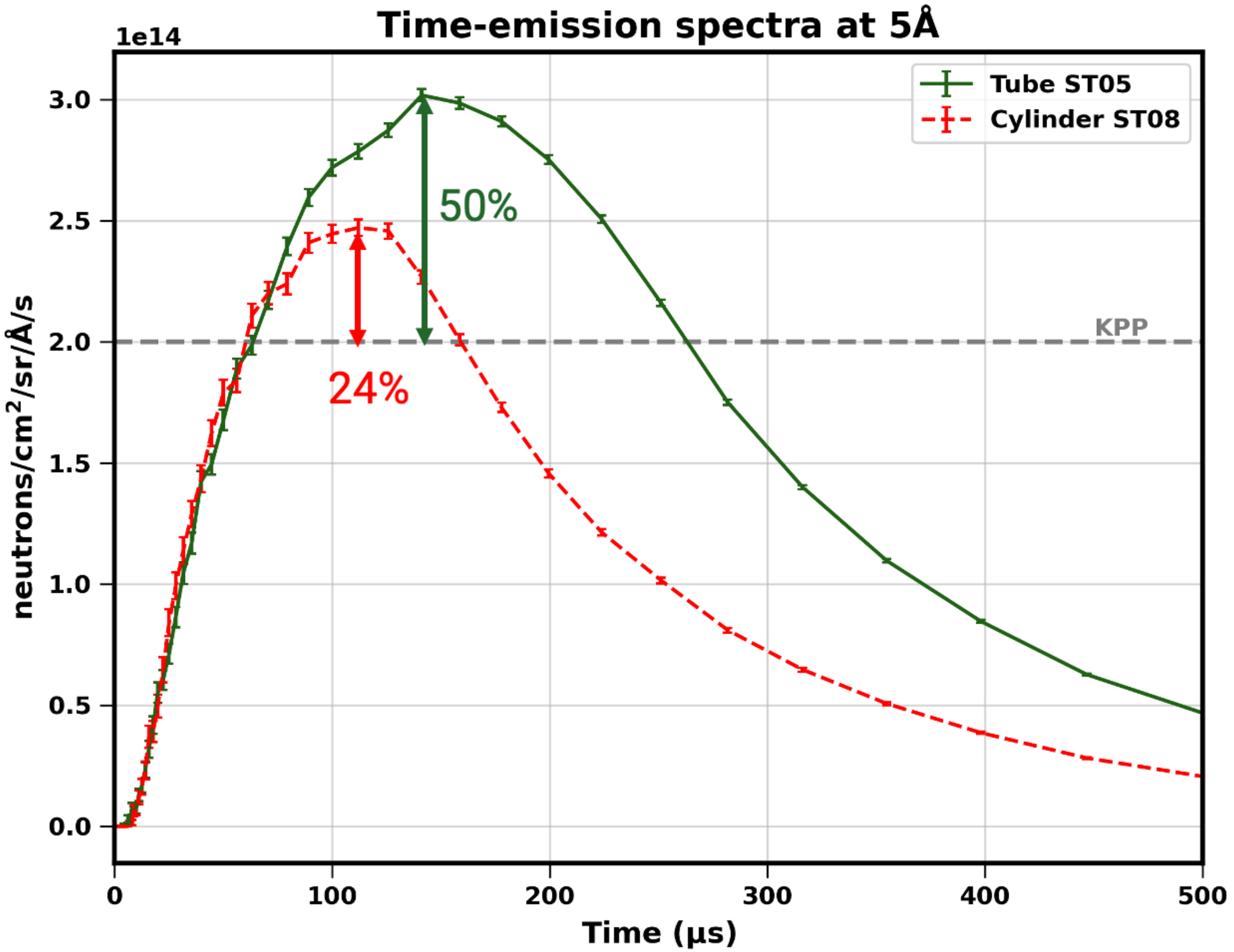






Neutronics performance – KPP threshold & objective met

2 x 10^{13} & 2 x 10^{14} n/cm²/sr/Å/s at 5 Å



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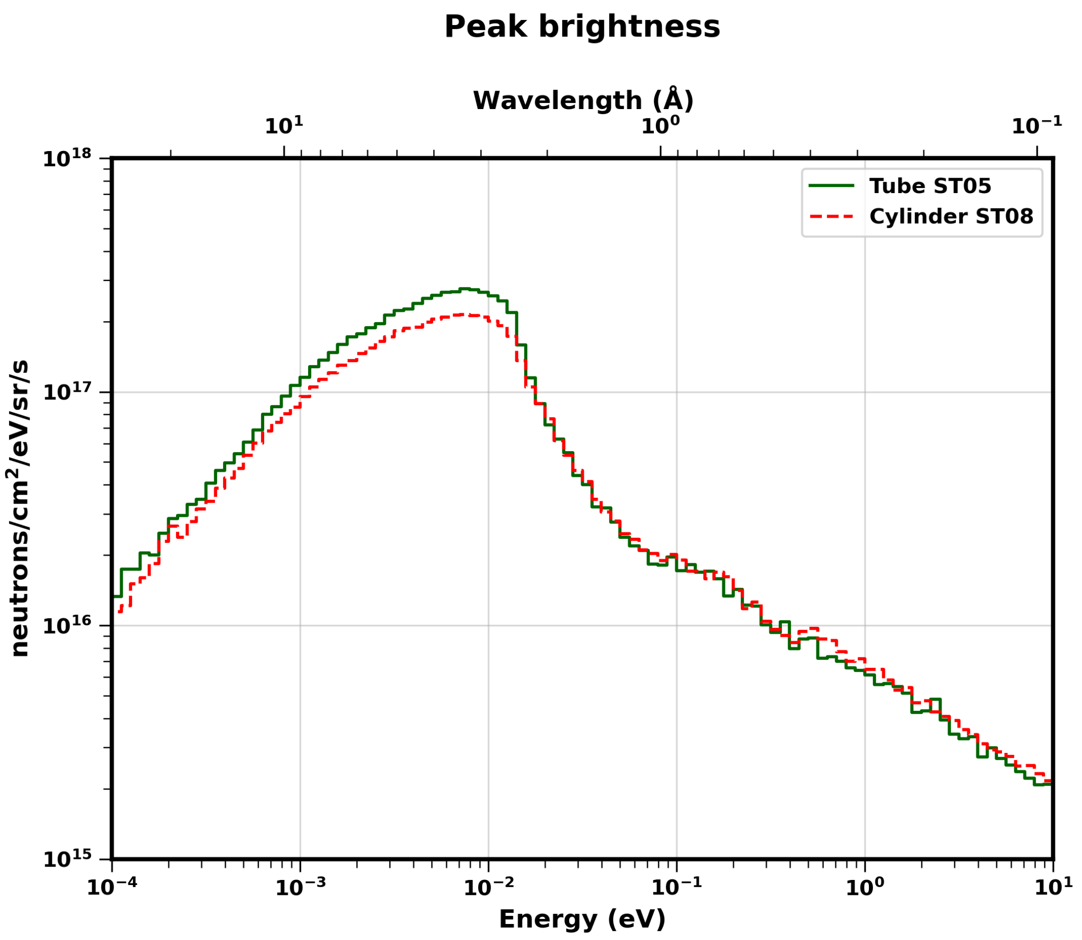
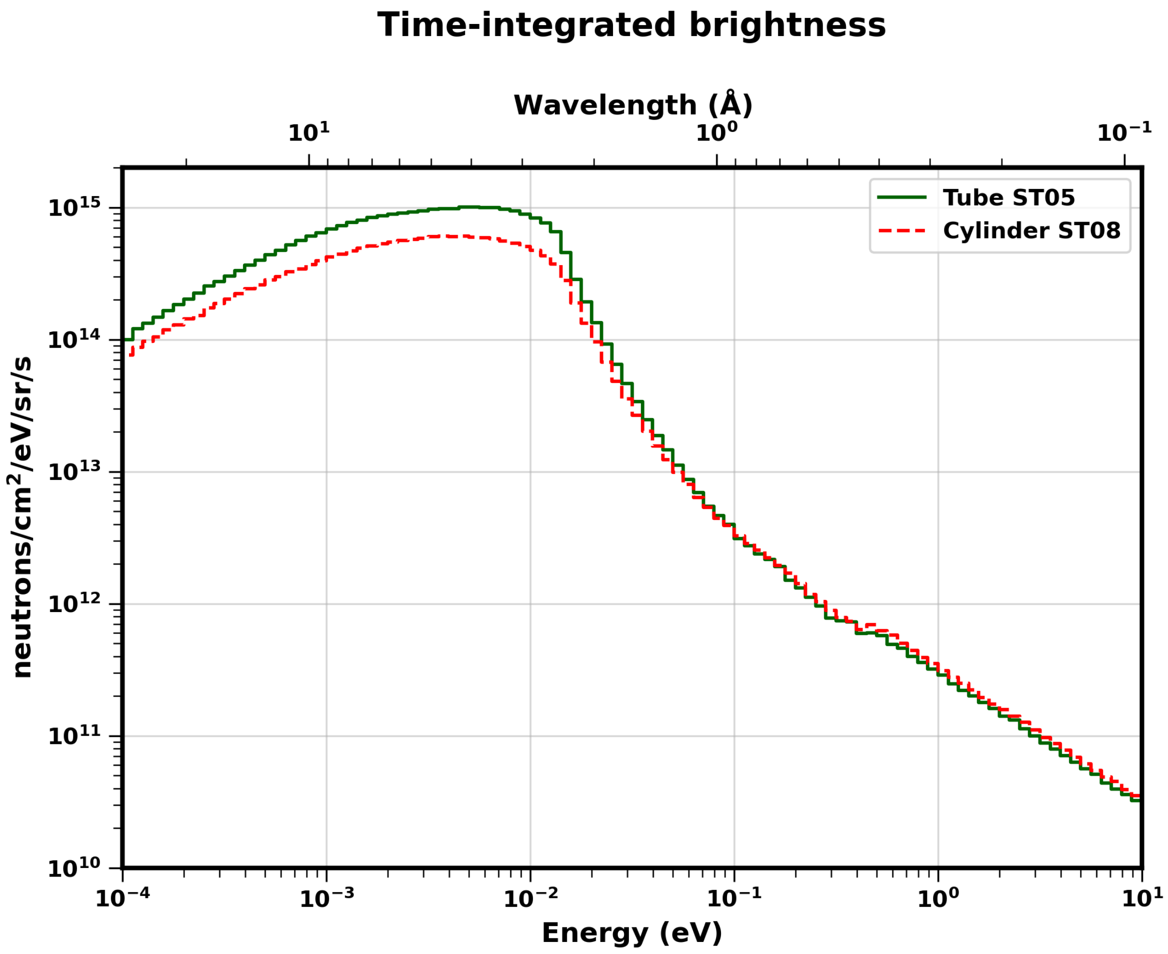
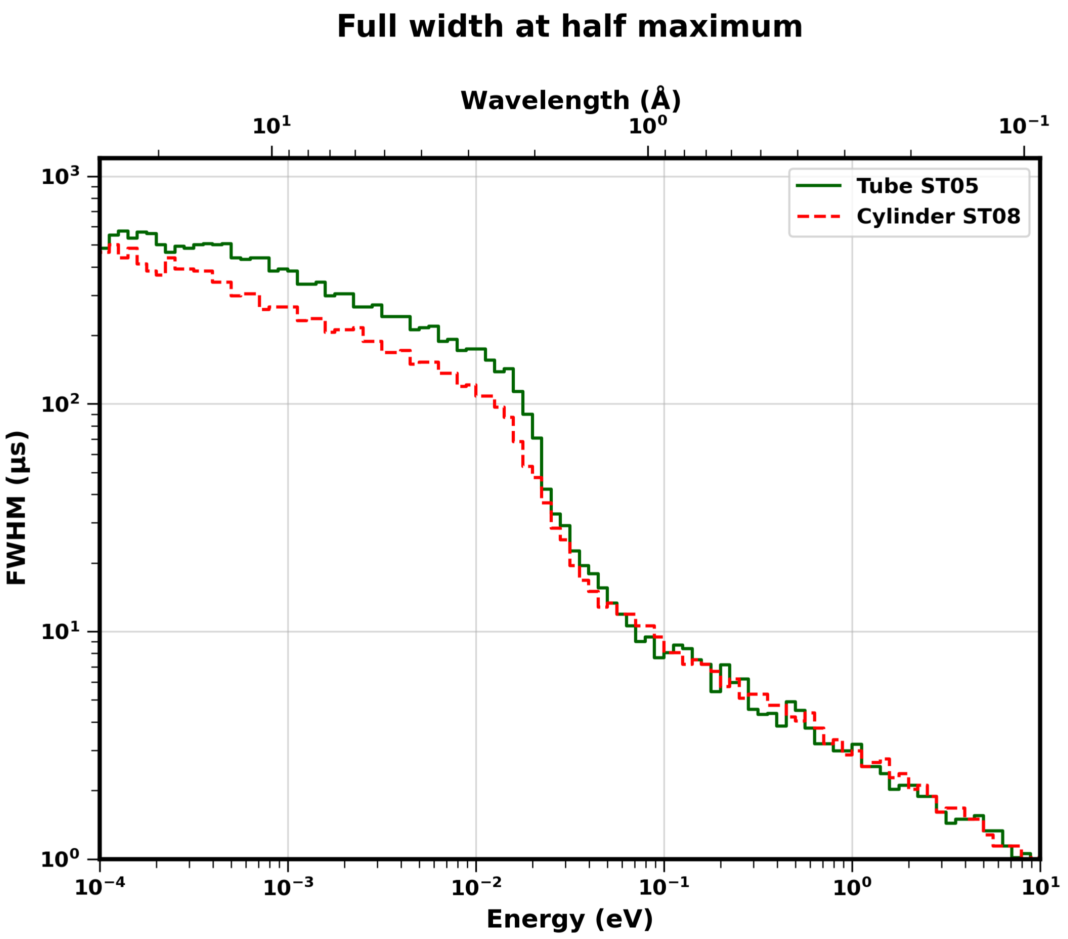
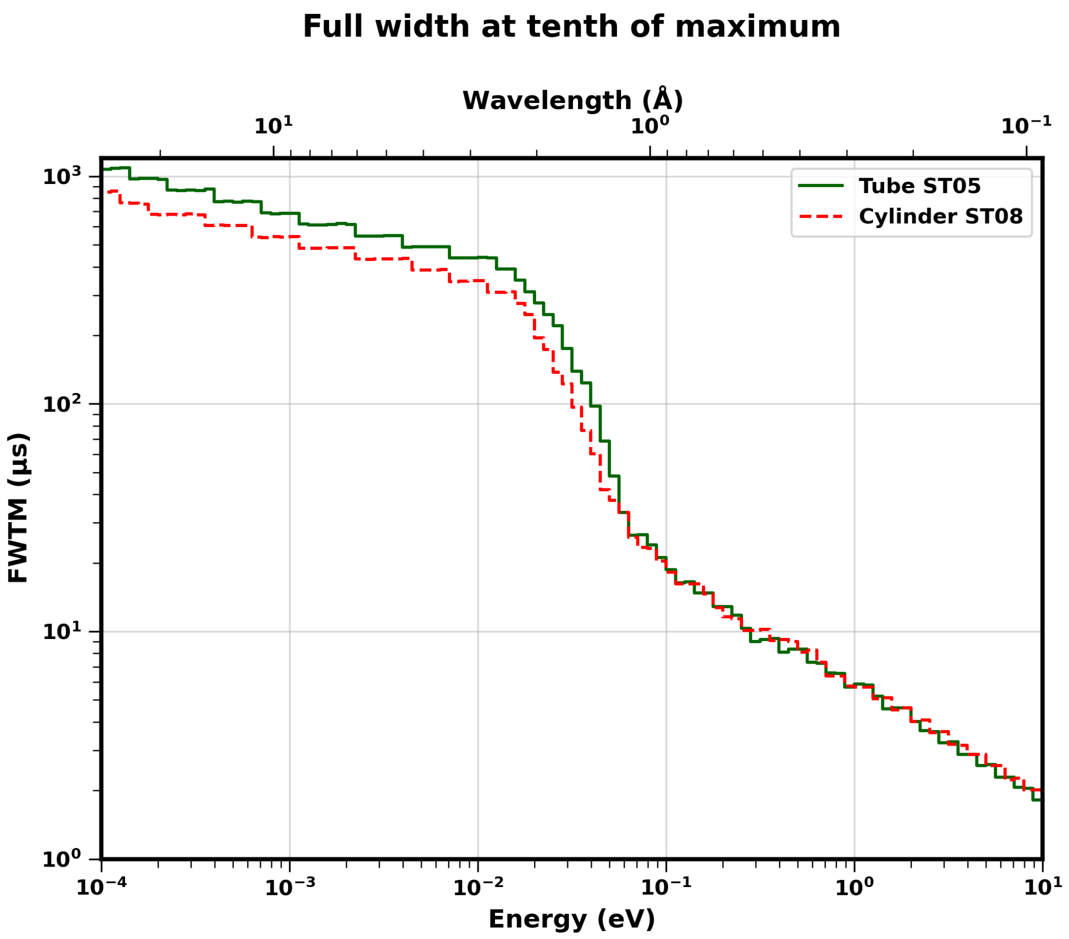
Neutronics performance





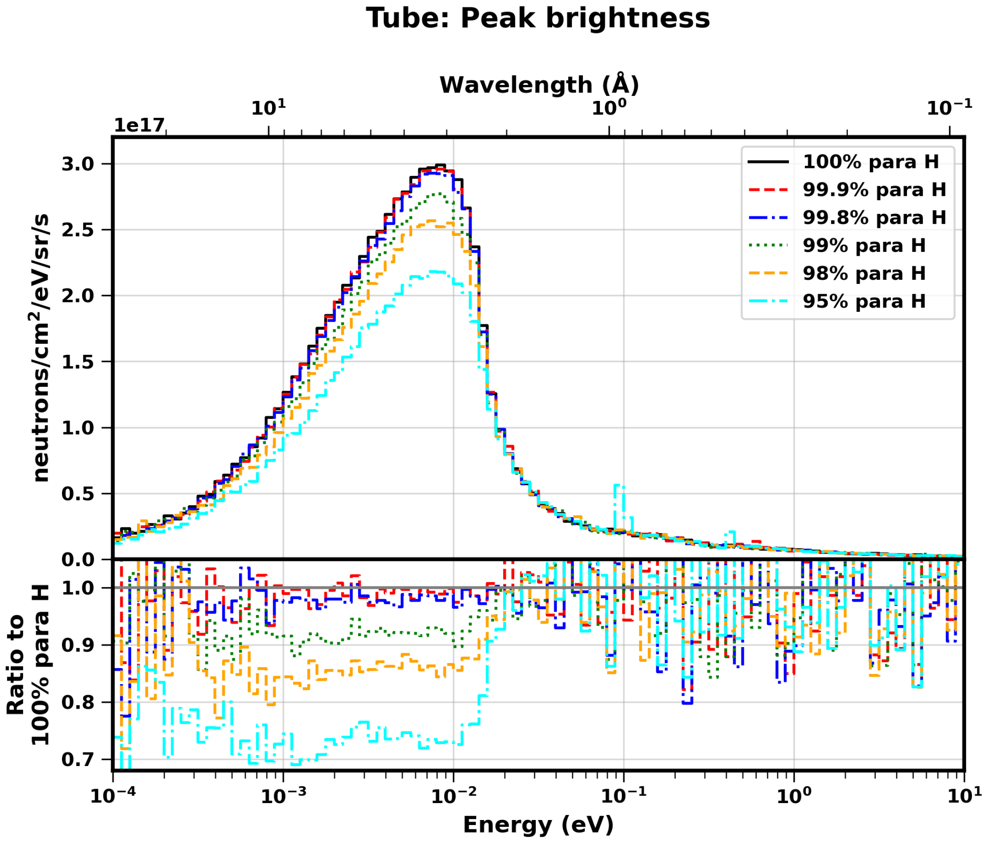
Neutronics performance

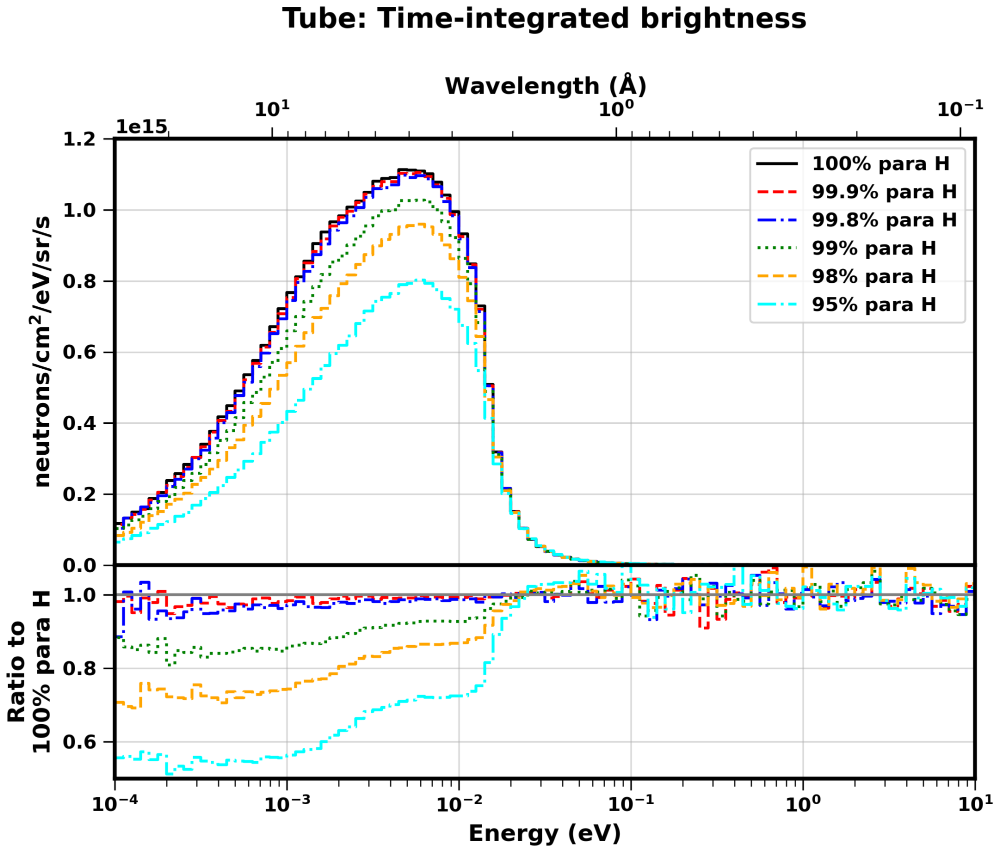




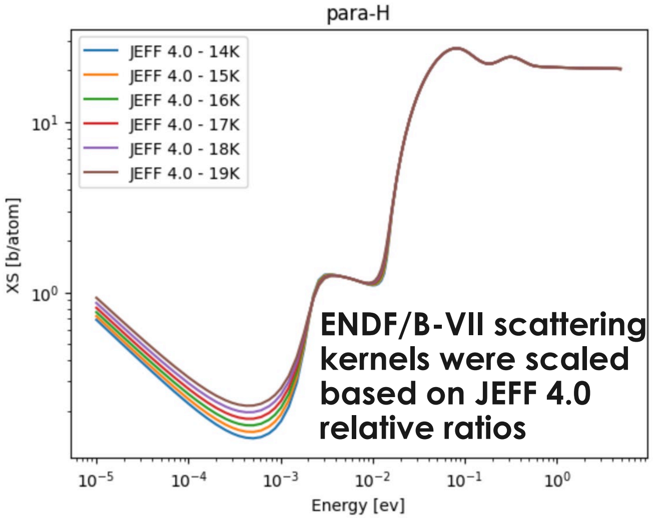
Hydrogen ortho/para fraction sensitivity study

- Default para-hydrogen fraction is 99.9%
- Sensitivity study was performed in the range of 95% to 100%

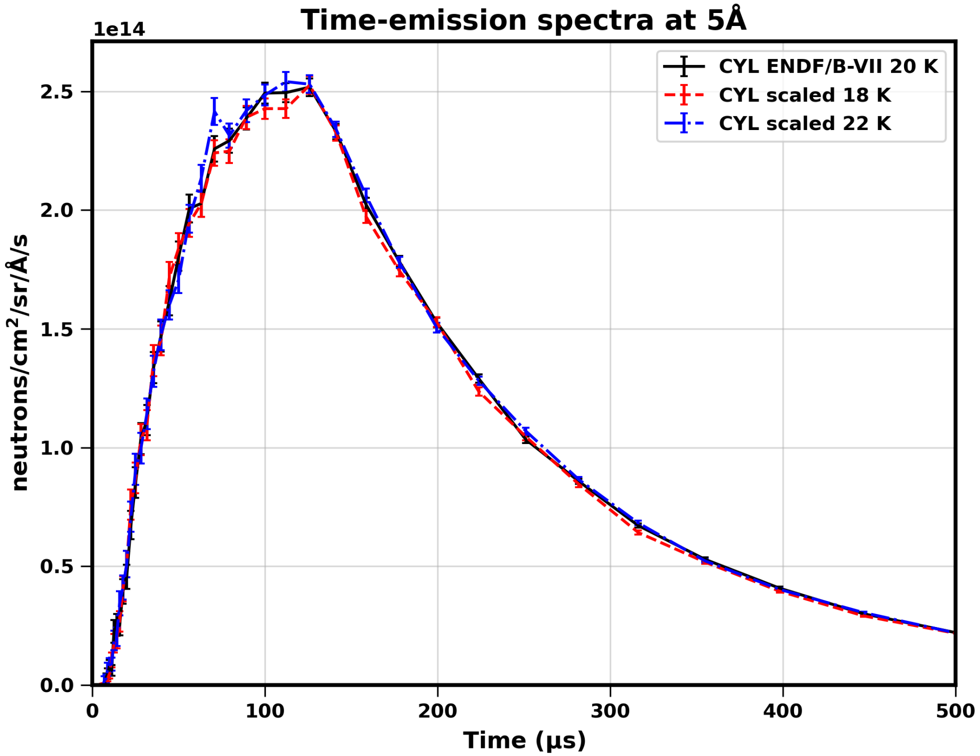


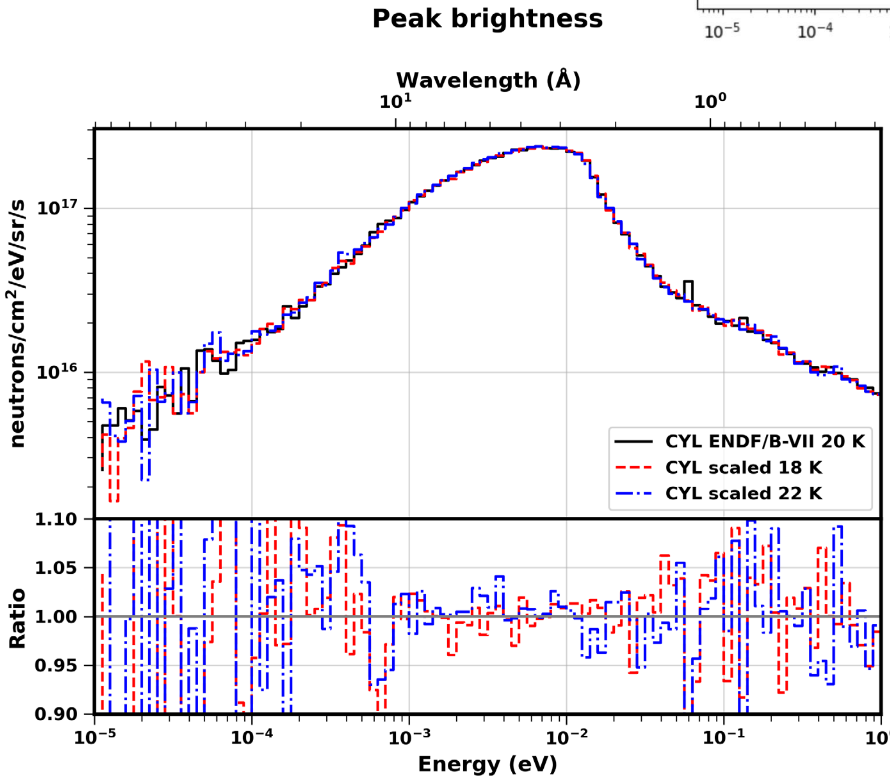


Hydrogen temperature sensitivity study



- Default hydrogen temperature is 20 K
- Sensitivity study was performed in the range of 18 – 22 K





- Max ~1% increase in performance is observed for 2 K rise in temperature

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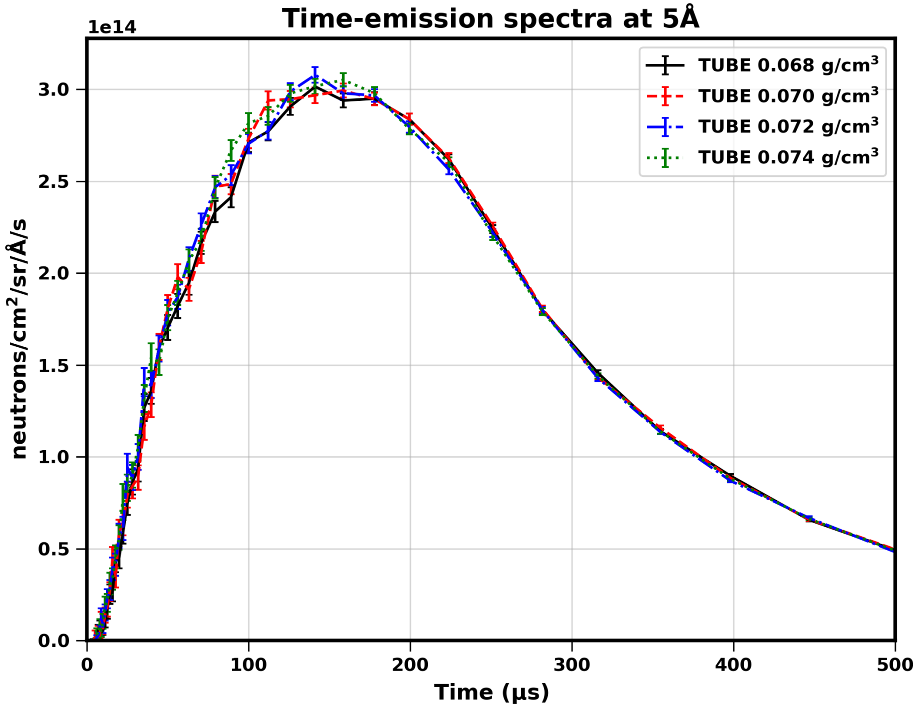
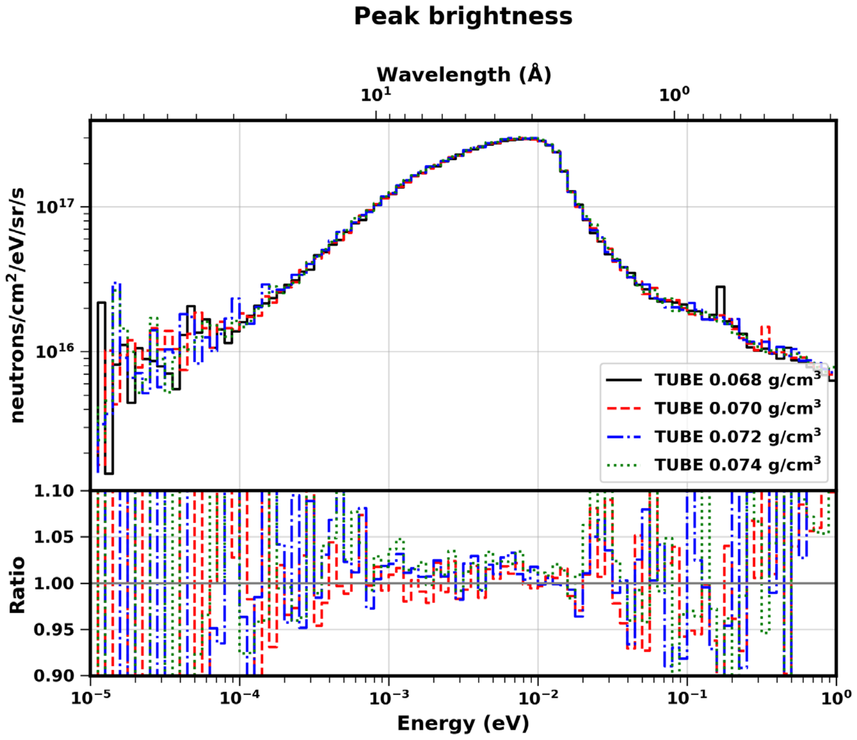
Hydrogen density sensitivity study

- Default hydrogen density is 0.073 g/cm^3 for cylinder and 0.072 g/cm^3 for tube moderators
- Sensitivity study was performed in the range of 0.068 – 0.074 g/cm^3

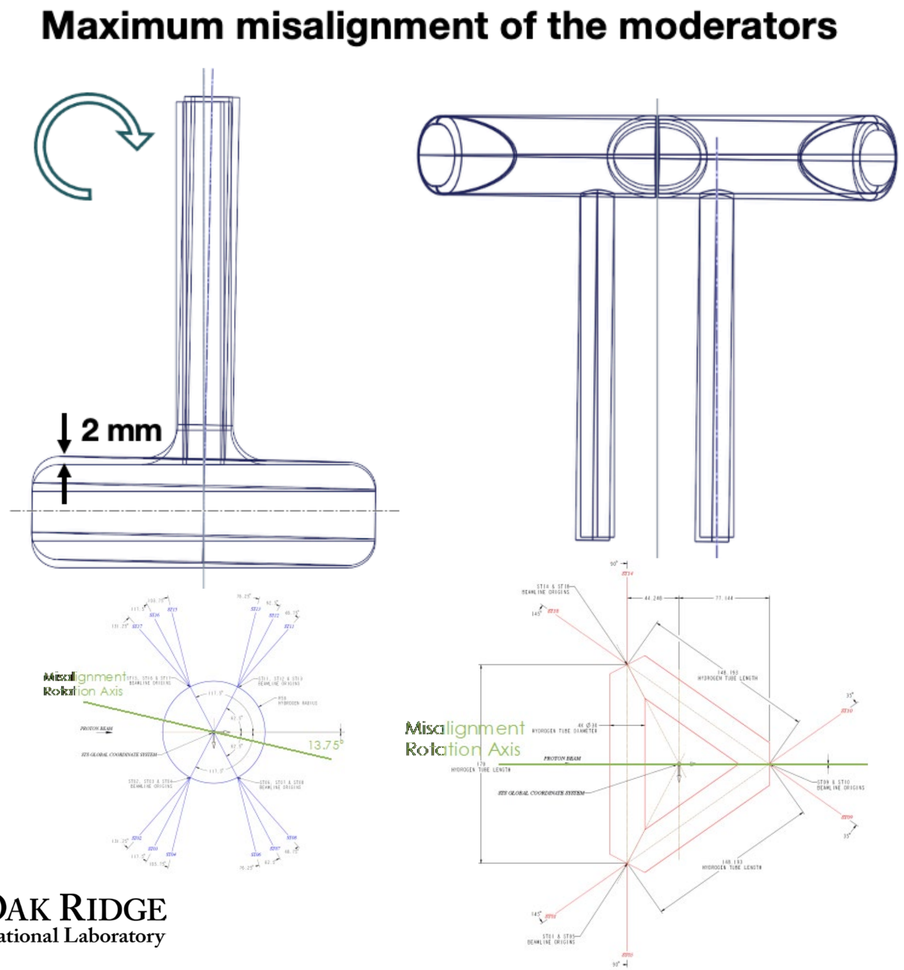




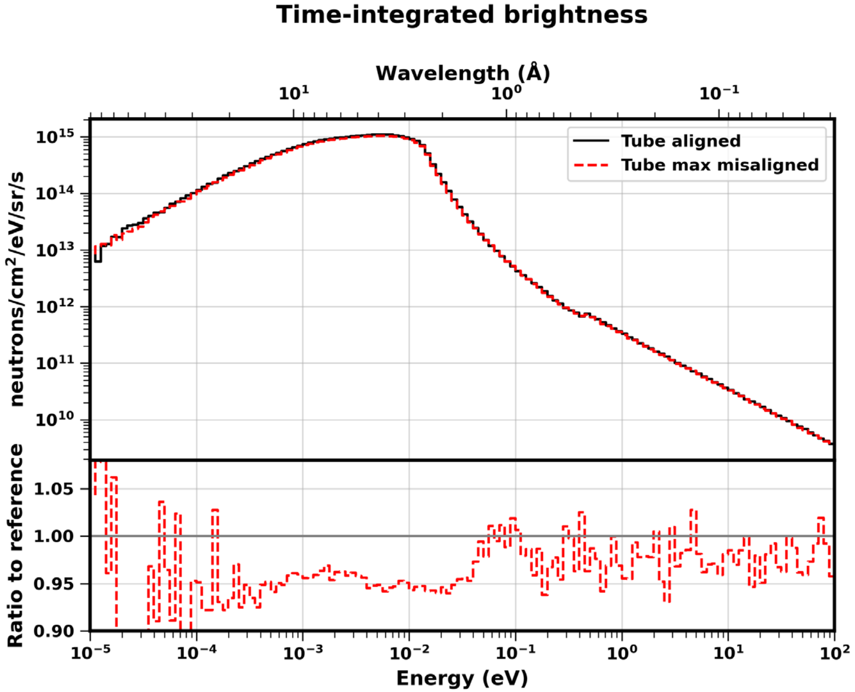
- Max ~1% increase in performance is observed for 0.002 g/cm^3 rise in density

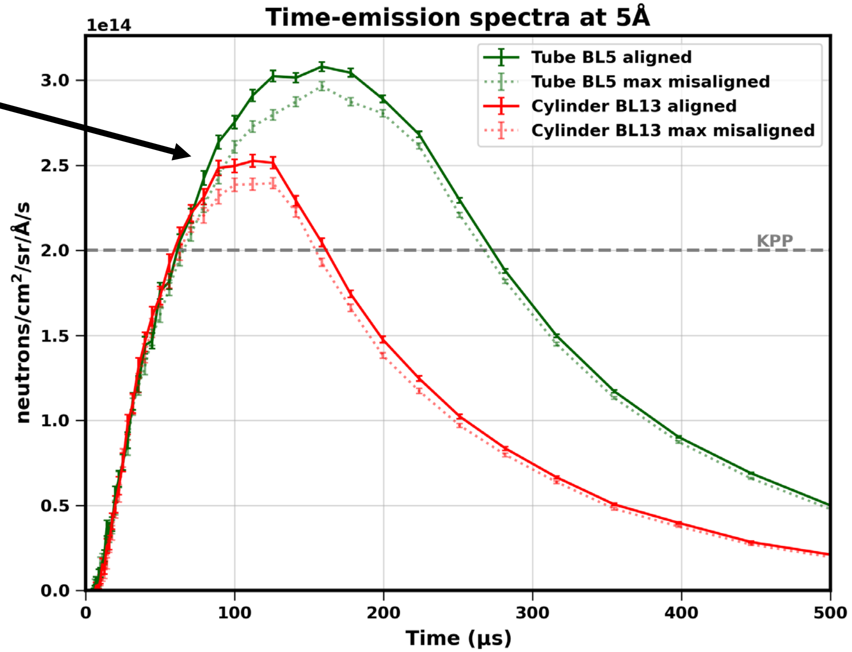
Moderator misalignment study

- Max. misalignment defined as 1.5 mm vertical shift and 1.2° rotation



5% at 5Å





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Additional sensitivity studies

- High-energy nuclear physics models
- Higher temperature tabular data for energy deposition
- Increased temperature of the water premoderator
- Heavy water for the target & MRA cooling
- Alternative design studies performed

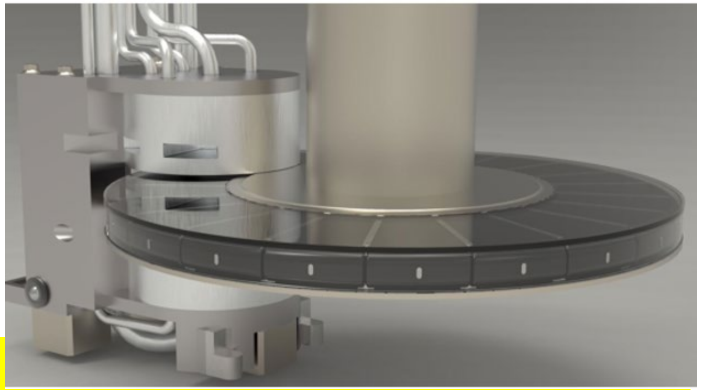
Conclusion

- Wide range of neutronics analyses performed to support target & MRA final design
- Final design positions STS as the highest peak-brightness source of cold neutrons in the world

- SP1-3 KPP threshold and objective for peak brightness met
- Target Segment DPA requirement met
- MRA Material Lifetime met


Thank you for your attention

FTS and STS



FTS (upgraded)

- Short (<1 μs) proton pulses
- 1.3 GeV protons
- 45 pulses/second
- 1.8 MW, ramping up to 2 MW beam power
- 44.4 kJ per proton pulse
- Hg target
- Large beam footprint (140 cm2)
- 4 moderators (water & hydrogen)
- Moderator viewed area 10 x 12 cm2
- Coupled & decoupled moderators
- In operation since 2006

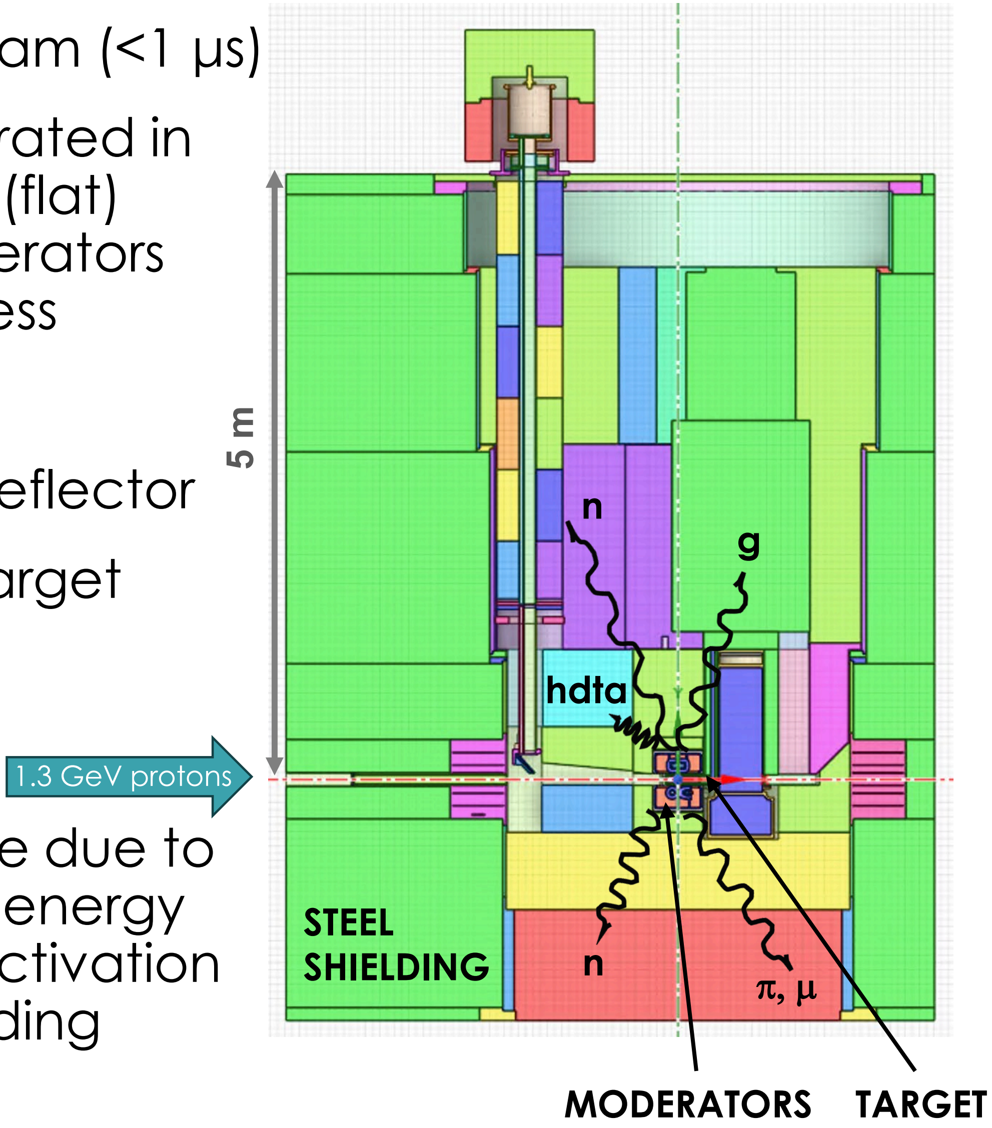
STS

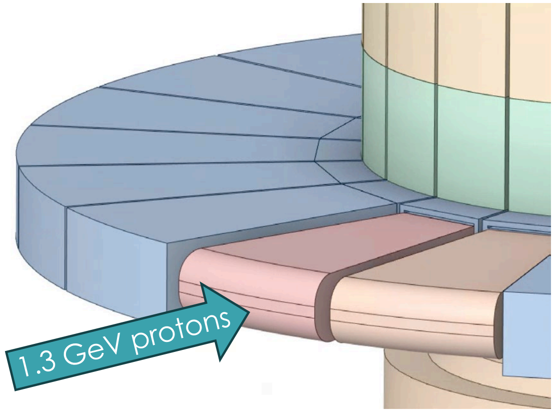
- Short (<1 μs) proton pulses
- 1.3 GeV protons
- 15 pulses/second
- 700 kW beam power
- 46.7 kJ per proton pulse
- Rotating W target (Inconel shroud, water cooled)
- Smaller beam footprint (~ 60 cm^2)
- 2 coupled moderators (para-hydrogen)
- Moderator viewed area 3 x 3 cm^2
- Start of operation ~2037-2039

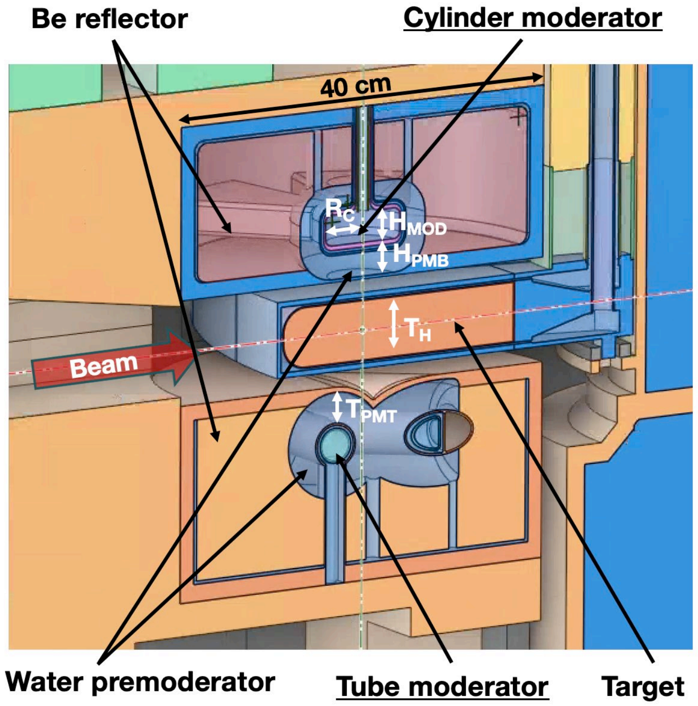
ORNL Second Target Station (STS)

- Rotating W target
- 1.3 GeV 700kW proton beam (<1 μs)
- Spallation neutrons moderated in coupled low-dimensional (flat) cylindrical and tube moderators designed for high brightness
- Para-hydrogen at 20 K
- Water premoderator, Be reflector
- Tightly coupled with the target

- **Neutronics support:**
- Neutron brightness, lifetime due to radiation damage (dpa), energy deposition, prompt and activation dose rates, radiation shielding







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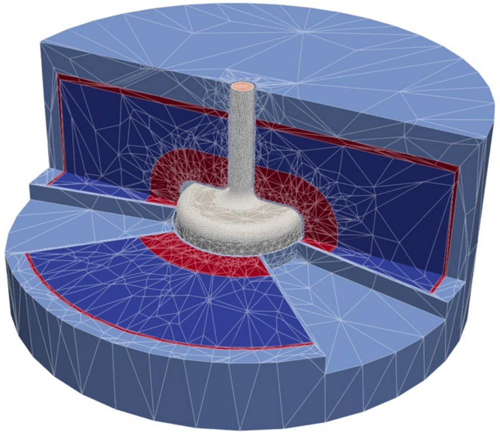
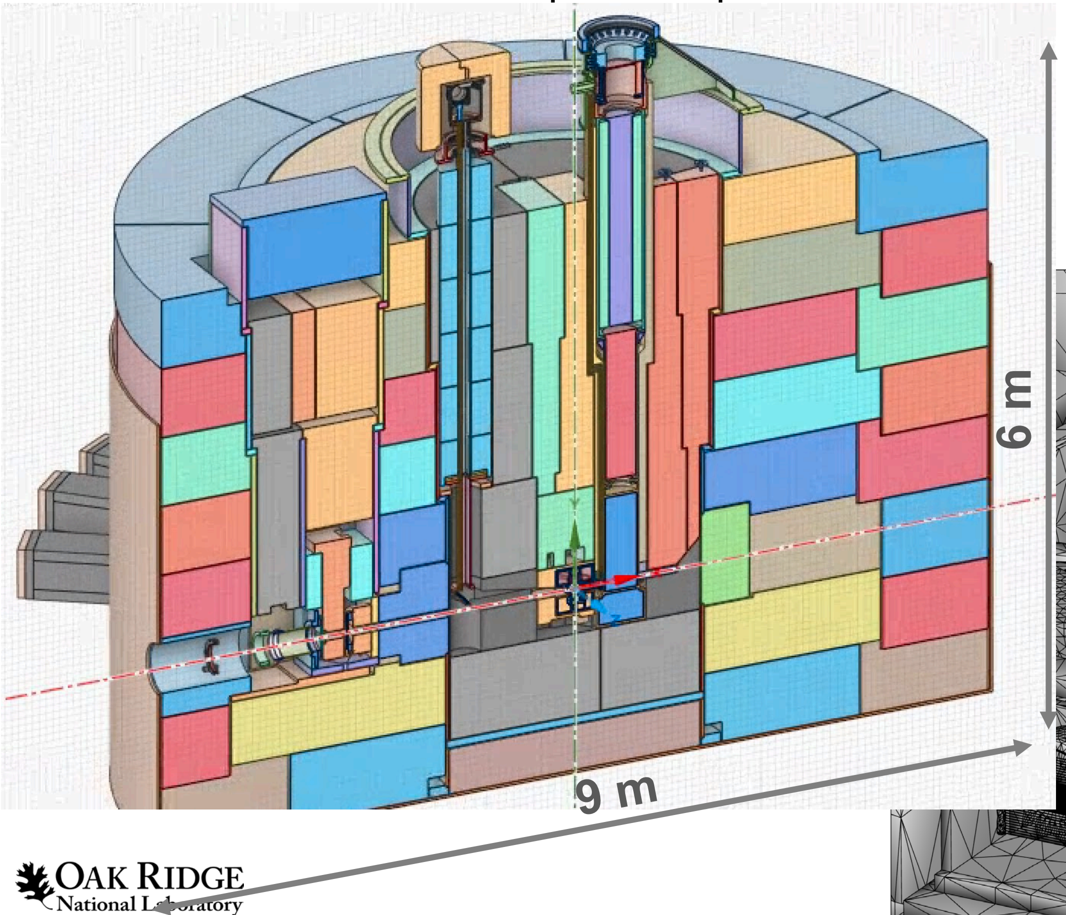
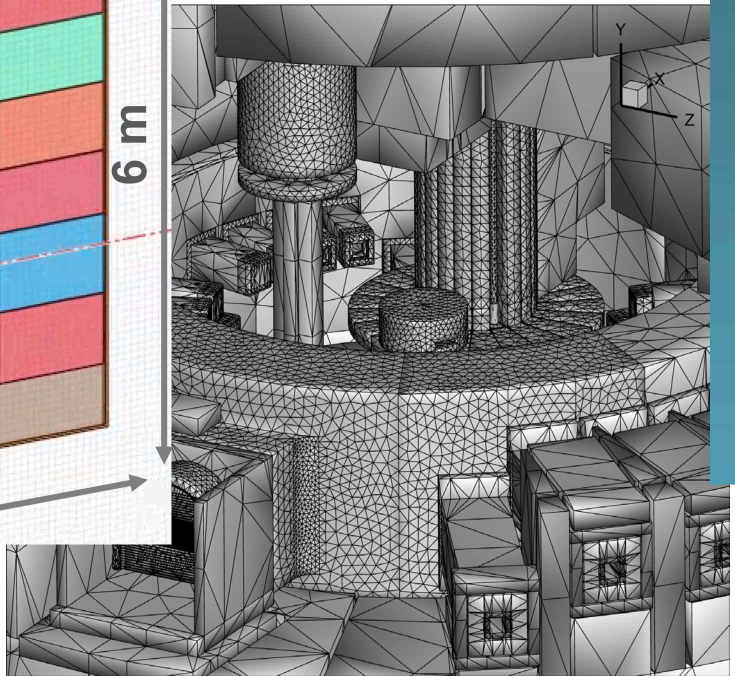
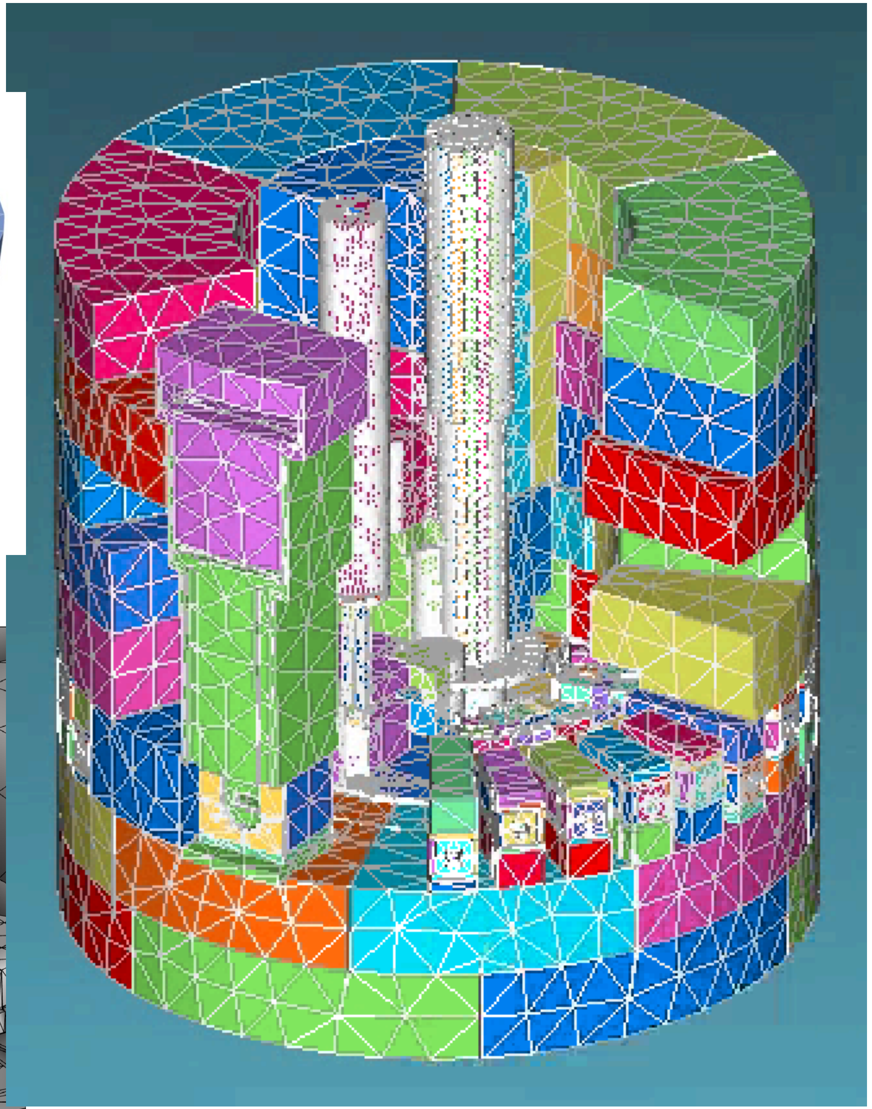
Extensive use of Unstructured Mesh (UM) at STS

- Modern radiation transport tools
- Automated CAD to MCNP conversion with Attila4MC
- CADIS/FW-CADIS variance reduction
- Advanced & coupled optimization

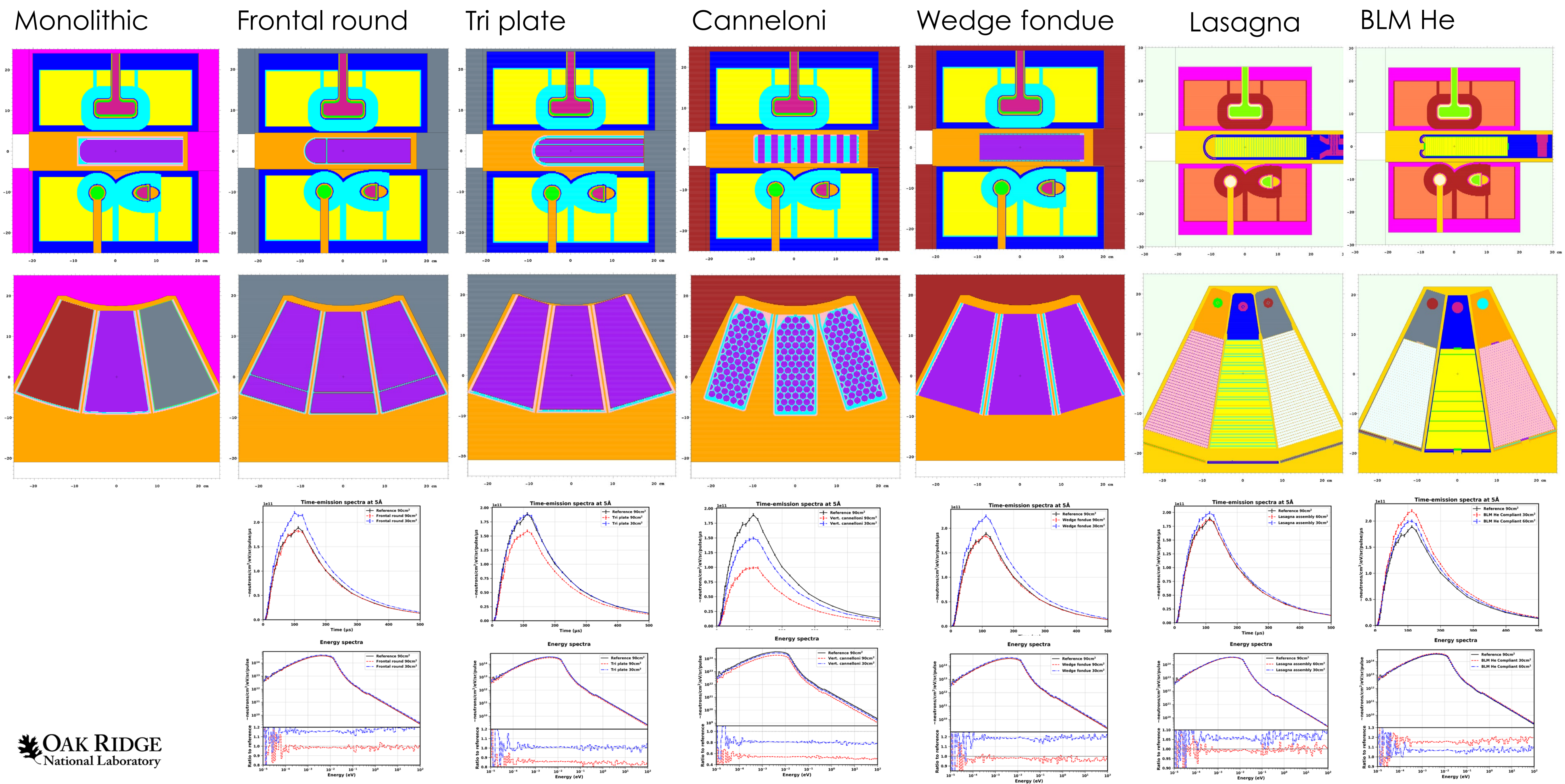








UM-based evaluation of various target designs



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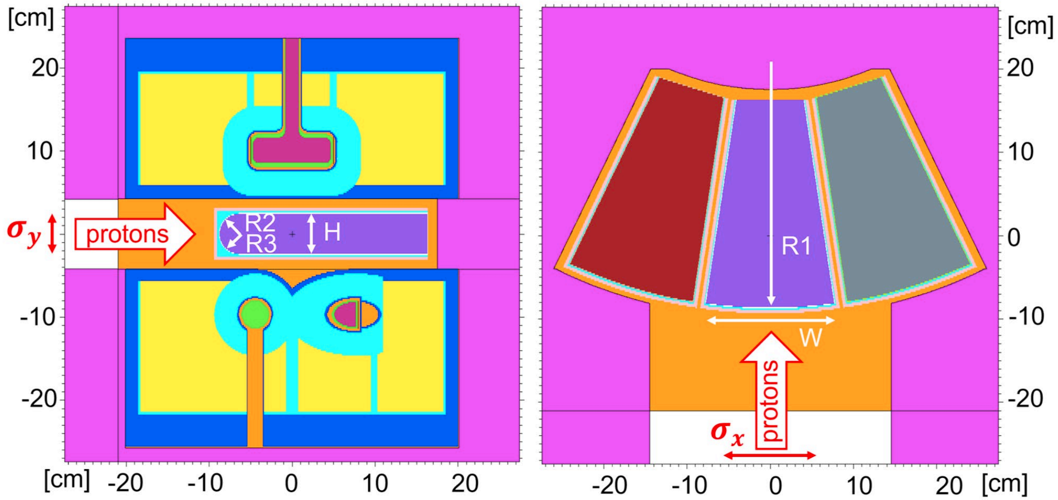
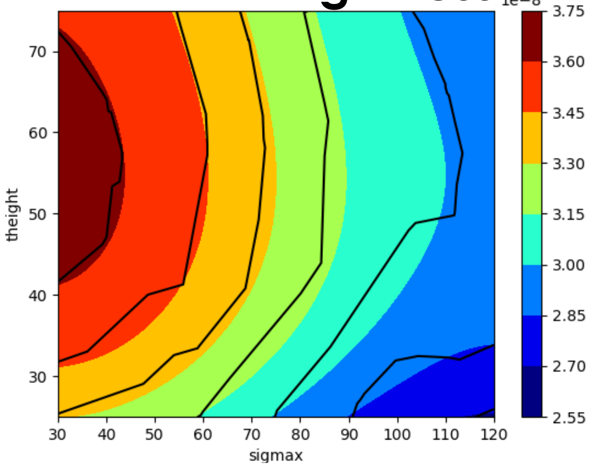
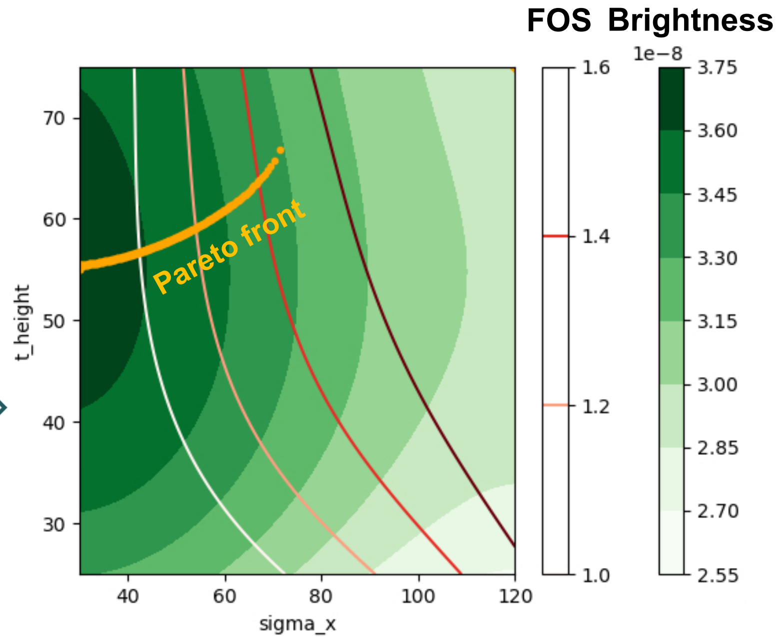
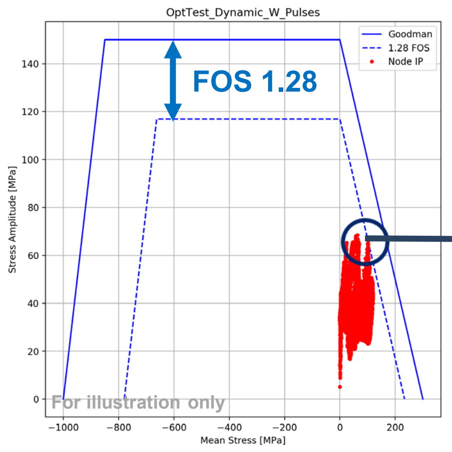
Coupled neutronics-structural stress optimization

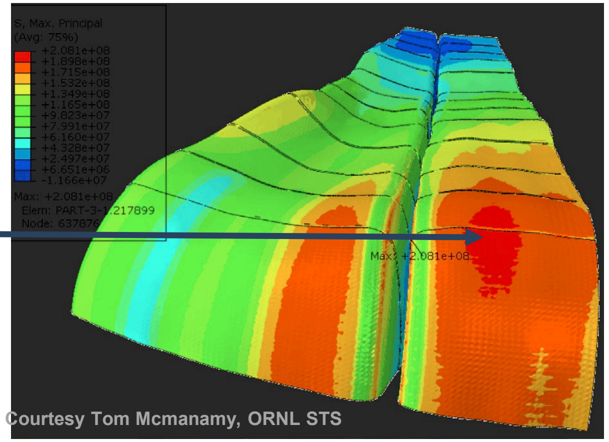
- Simultaneous calculations of brightness and energy deposition
- Factor of safety (Measure for the mechanical performance, Goodman diag.)

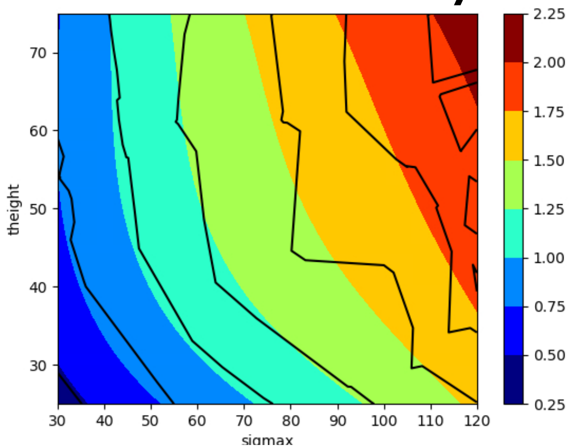






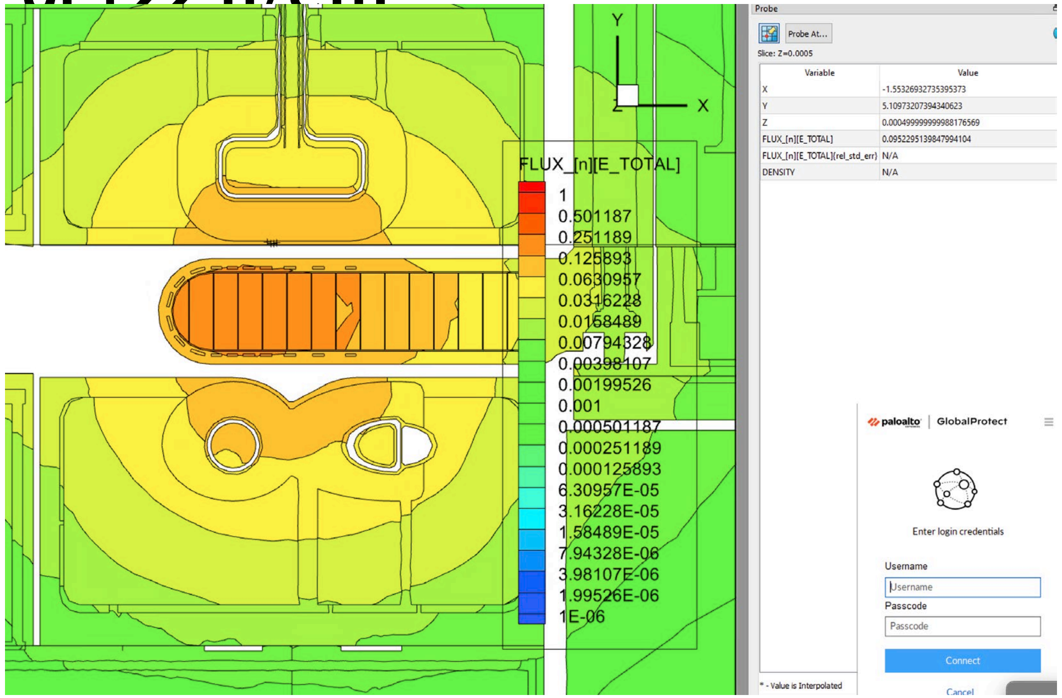






Silicon production in the MRA

- **Silicon production via thermal neutron (E < 0.414 eV) capture in aluminum**
- ${}^{27}Al + n_{th} \rightarrow {}^{28}Al + \gamma$; ${}^{28}Al \rightarrow {}^{28}Si + \beta^{-}$
- **Max thermal flux is 0.095 n/cm²/proton or 5.75E+21 n/cm²/year, which is 3.73E+22 n/cm²/6.5 years (lifetime limit due to dpa), which is below the dose limit* of 6.0E+22 n/cm²**



Dose limit from Y.J. Lee et al., Materials Handbook: STS Project