Optimizing neutron production at ORNL's Second Target Station

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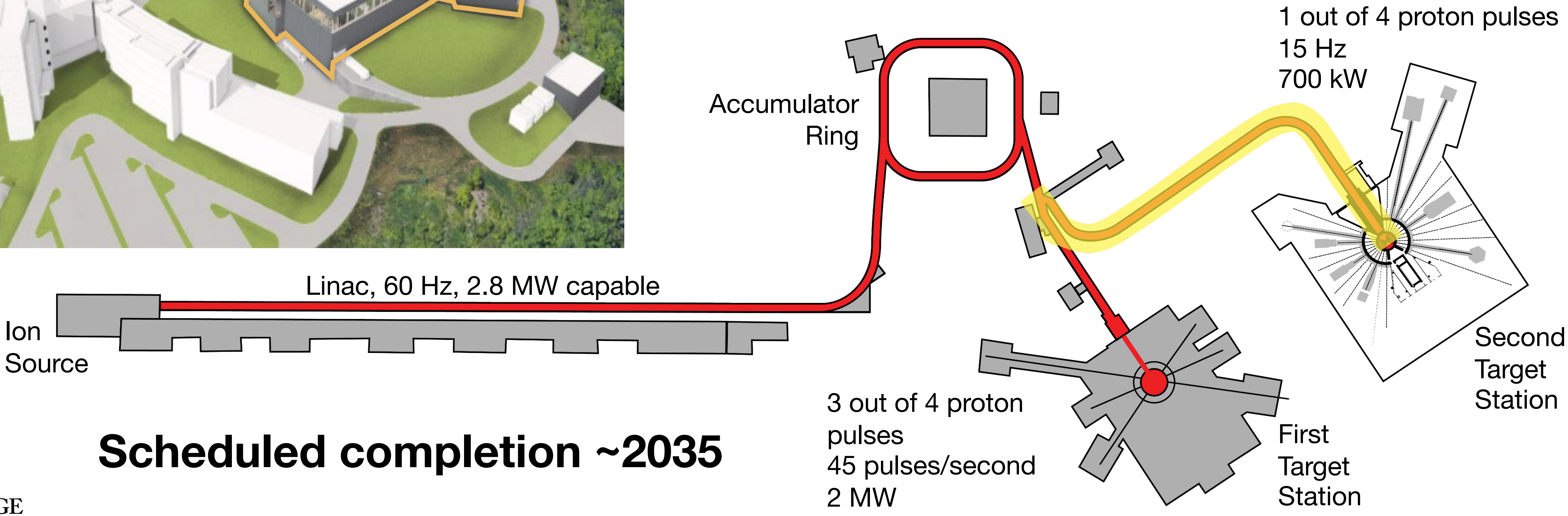
ORNL is managed by UT-Battelle, LLC for the US Department of Energy

ORNL Second Target Station (STS)

Srivastava et al., Nat. Comm. 2017
Banerjee et al., Science 356, 2017

- **Highest peak-brightness short-pulsed spallation source of cold neutrons**
- **Smaller samples, more extreme conditions, shorter time**
- **Supports up to 18 neutron instruments**



Scheduled completion ~2035

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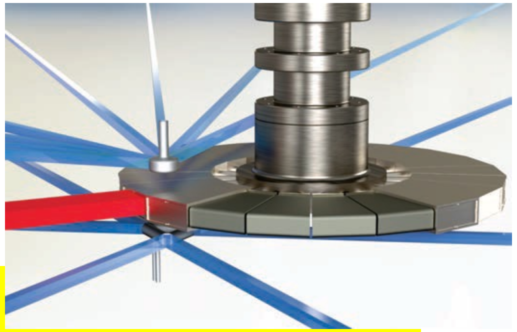
STS vs. FTS

FTS (upgraded)

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

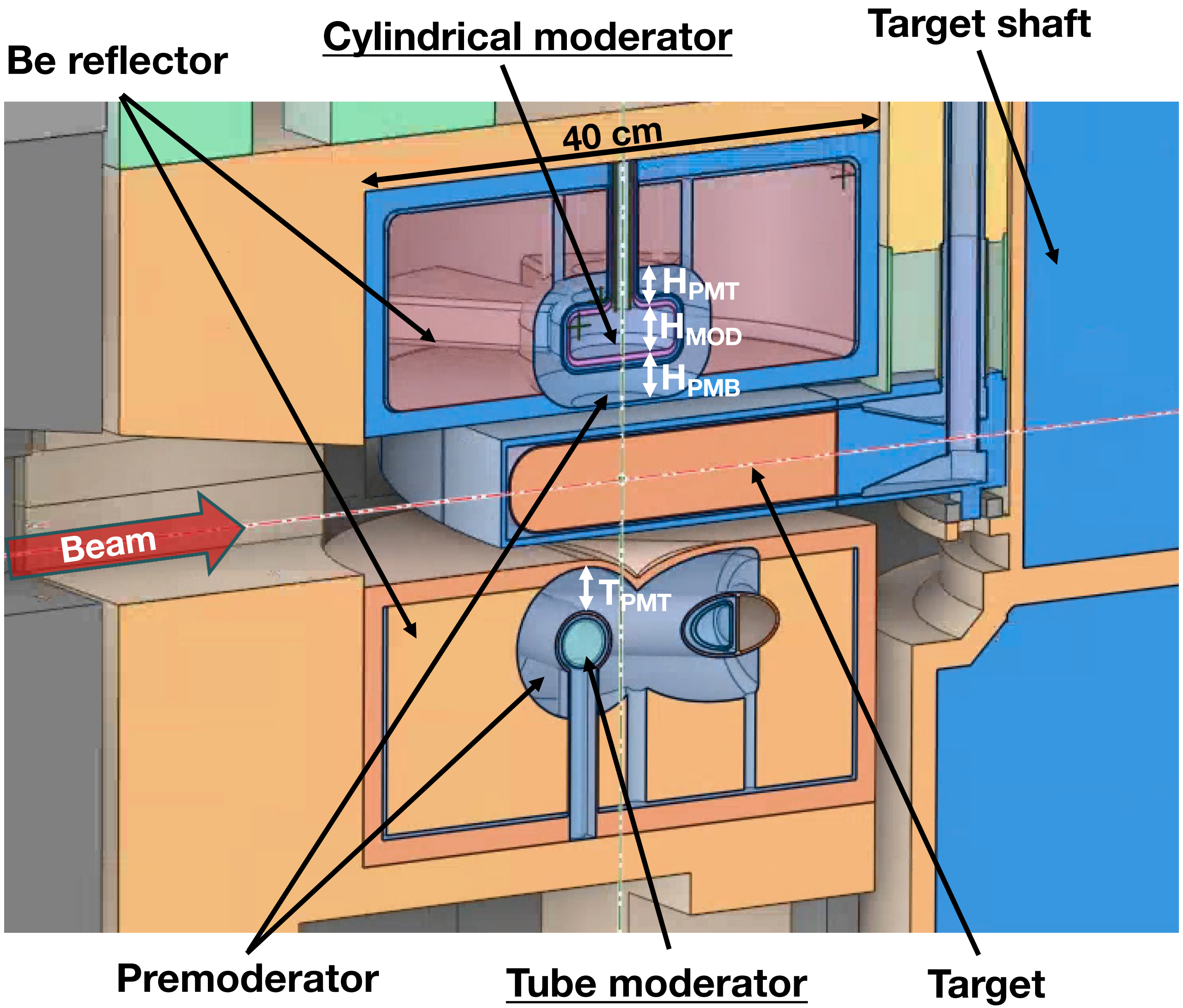


STS

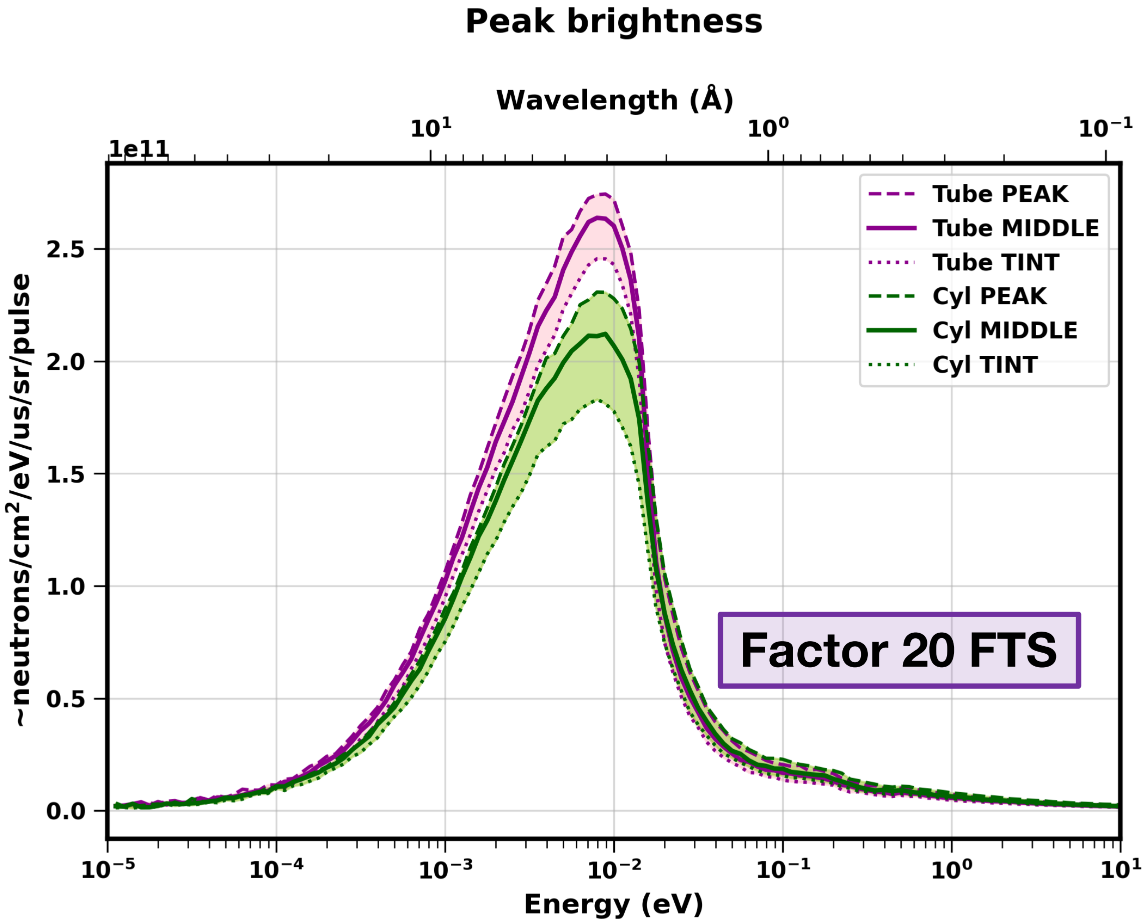
- Short (<1 μs) 1.3 GeV proton pulses
- 15 pulses/second
- 700 kW beam power
- 46.7 kJ per proton pulse
- Smaller beam footprint (30-90 cm^2)
- W target (water cooled)
- 2 cold moderators (hydrogen)
- Moderator viewed area 3 x 3 cm
- High brightness
- Coupled moderators
- Scheduled commissioning ~2035
- More compact

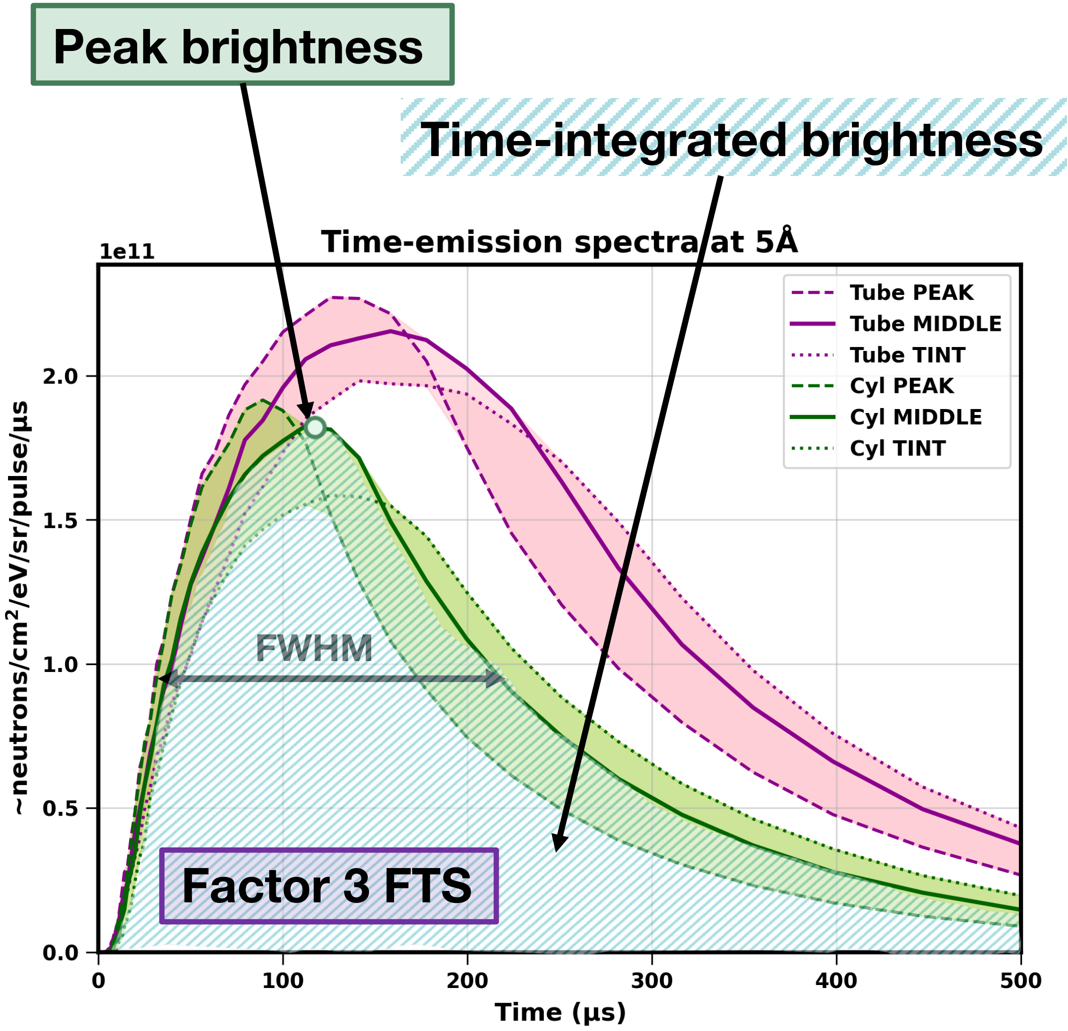
STS Moderator-Reflector Assembly (MRA)

- **Low-dimensional (flat) cylindrical and tube moderators delivering high brightness**
  - Mezei, Zanini, et al., ESS
- **Both coupled**
- **Para-hydrogen at 20 K**
- **H_2O premoderator**
- **Be reflector**
- **Tightly coupled with the target (10 mm gap)**
- **Serving 12 + 6 instruments**



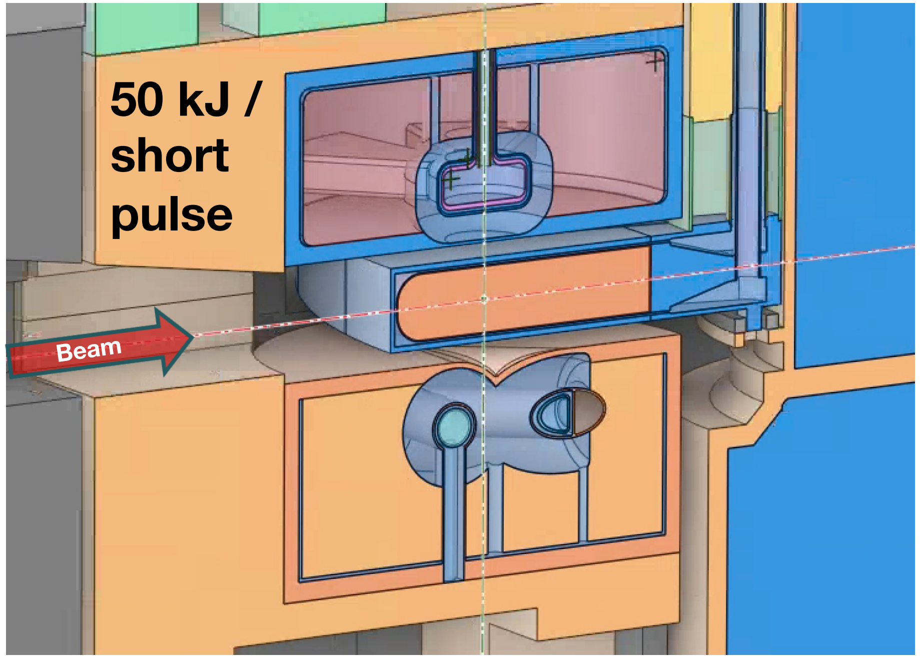
STS Moderator Performance





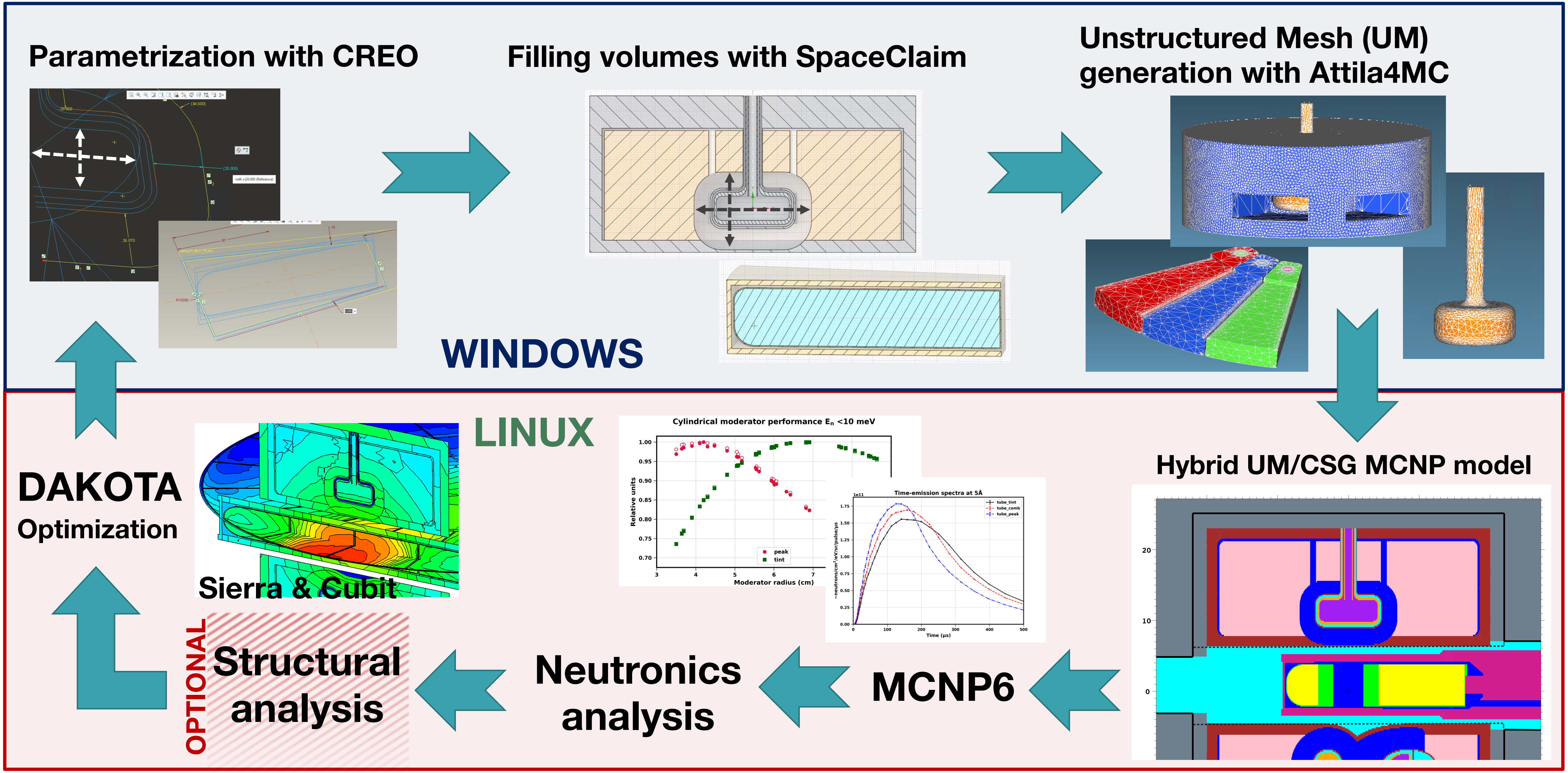
- **Tube moderator delivers superior brightness to eventually 6 instruments**
- **Cylindrical moderator has superior time resolution (event. 12 instruments)**

Motivation



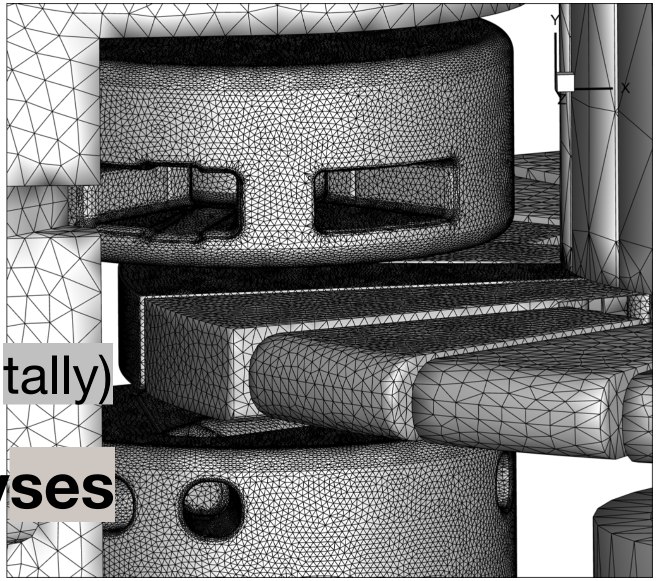
- **We need to solve problems with many design parameters**
  - Moderator dimensions
  - Target dimensions
  - Beam footprint on target
- **We need coupled neutronics and structural stress optimization**
  - Optimal parameters for separate neutronics and structural analyses can differ greatly
  - Improved structural integrity reduces neutronics performance
- **Such complex studies rarely done in the past**
- **New tools required for efficient STS optimization**

Unstructured mesh based automatic optimization workflow

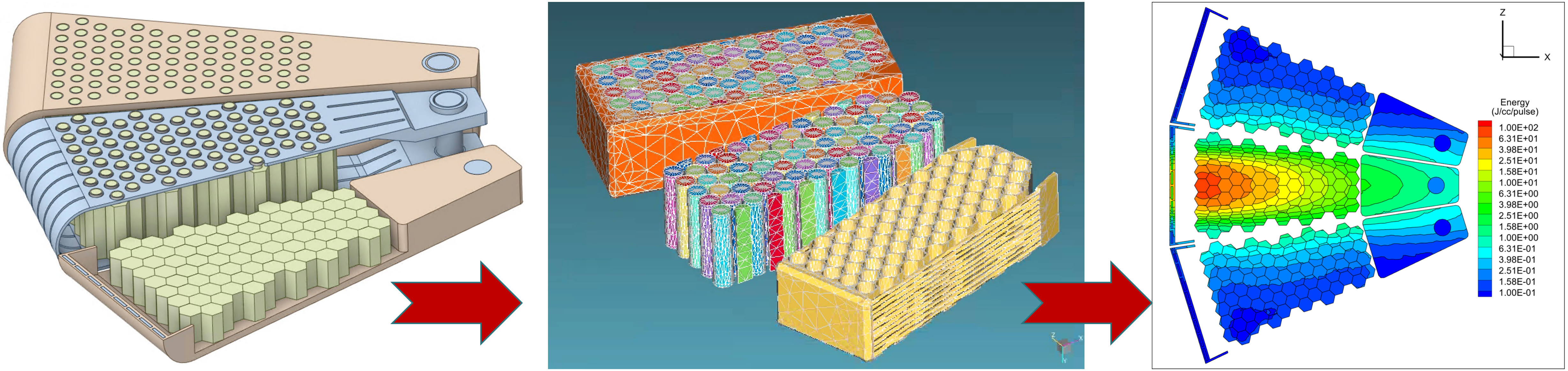


L. Zavorka et al., An unstructured mesh based neutronics optimization workflow, NIM A 1052 (2023) 168252.

Unstructured mesh based automatic optimization workflow



- **Direct CAD to MCNP model conversion**
  - Fast, efficient, reduces potential for introducing errors
- **High-fidelity neutronics models**
  - High-quality data with high spatial resolution (UM serves as a mesh tally)
- **Results (heating, dpa, …) available for subsequent analyses**
  - Direct export/import for structural stress/dynamic FEA



Unstructured mesh based automatic optimization workflow

- **Scripted model re-generation, conversion to UM, MCNP input generation**
  - CREO/Solidworks, SpaceClaim, Attila4MC, MCNP, Sierra, Dakota run from a command line
- **Controlled by in-house bat/bash scripts on Win/Linux**
- **On-line data analysis**
- **Captures errors, restarts if necessary**

target_1blk.rxmesher.xml - Notepad

File Edit Format View Help

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File Edit Format View Help

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SHROUD-m1 Steel
TA_CLADDING_SOLID_1-m1 Ta1
TUNGSTEN_BLK-m1 W1
Component1-m1 Water
SHROUD-m2 Steel
TA_CLADDING_SOLID_1-m2 Ta2
TUNGSTEN_BLK-m2 W2
Component1-m2 Water
SHROUD-m3 Steel
TA_CLADDING_SOLID_1-m3 Ta3
TUNGSTEN_BLK-m3 W3
Component1-m3 Water
end_material_assignments

end_output_abaqus_metadata

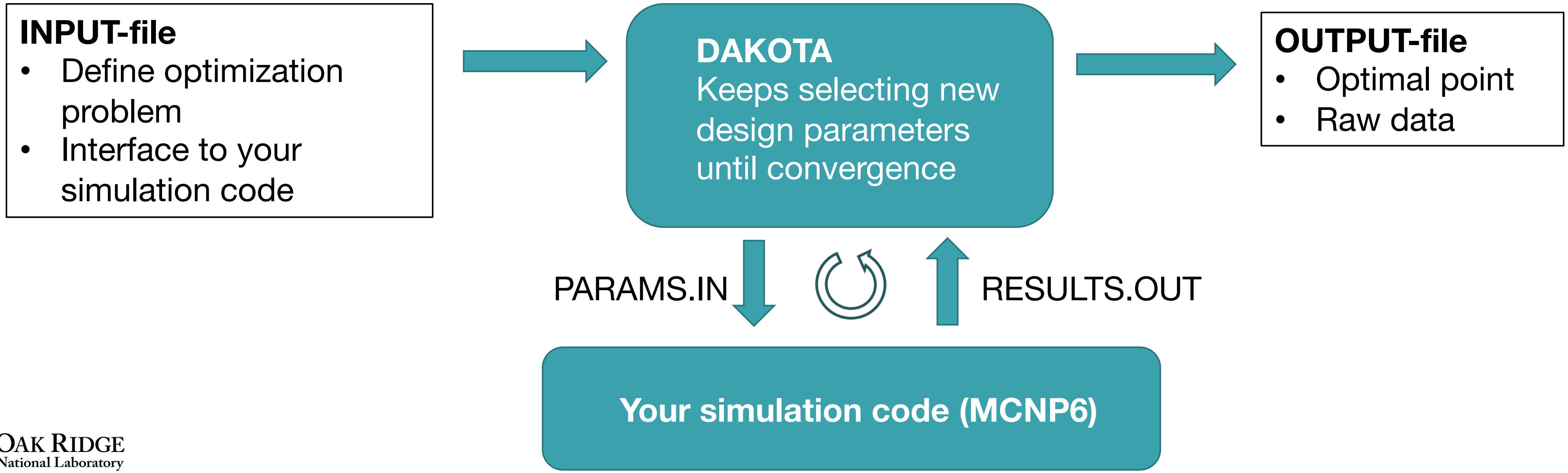
modifications
  strip_side_info true
  shift_bnd_nodes false
end_modifications

end_rtt_mesh_editor_input
```

Unstructured mesh based automatic optimization workflow

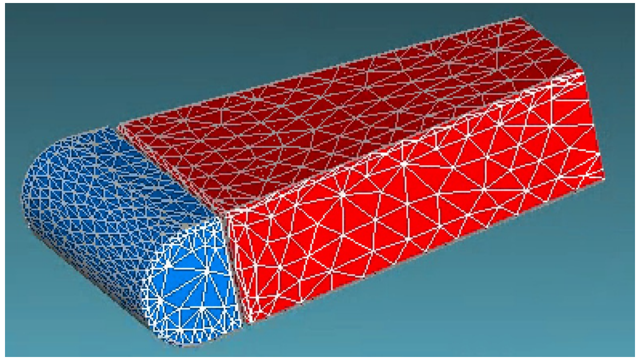
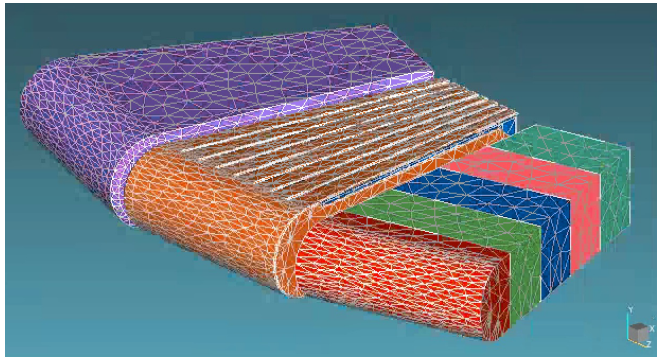
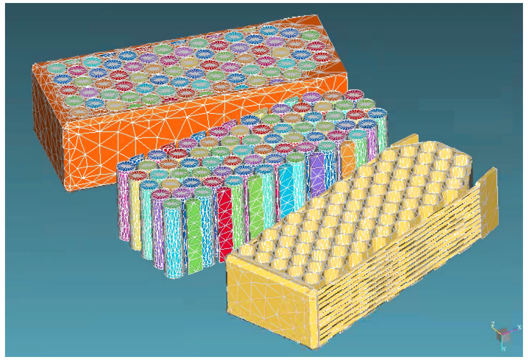
- **Controlled by Dakota Software Toolkit (free download from Sandia Natl. labs)**
- **Parameter and sensitivity study**
- **State-of-the-art optimization methods (efficient global, …)**
- **Multi-objective optimization**

$$\text{Objective} = w_1 \times \frac{\text{PEAK}}{\text{PEAK}_{\text{ref}}} + w_2 \times \frac{\text{TINT}}{\text{TINT}_{\text{ref}}}$$



Key features

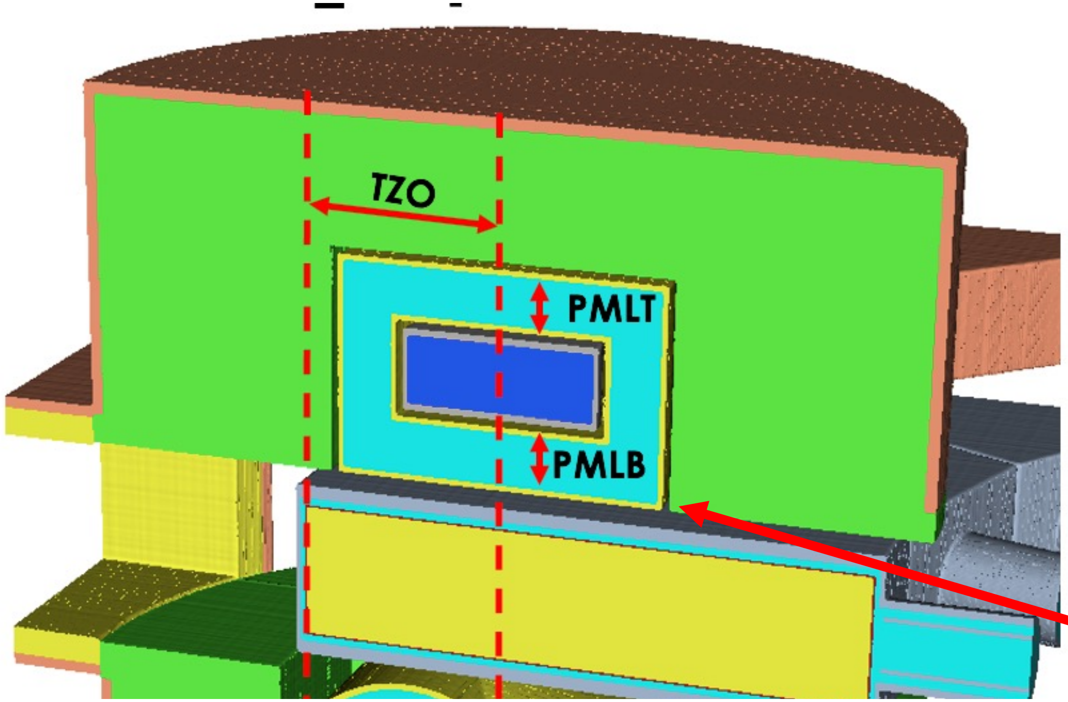
- **Only one parametric solid CAD engineering model is necessary**
  - Contains all the details + provides detailed results
  - The same CAD model is used both for neutronics and FEA
  - No manual conversion to an MCNP model (potential error reduction)
- **Reduction of the time per one iteration from weeks/months to hours**
- **Many more design options can be explored and analyzed**
- **Efficient optimization (=fewer iterations) of the coupled problems with a large number of design parameters (>10)**

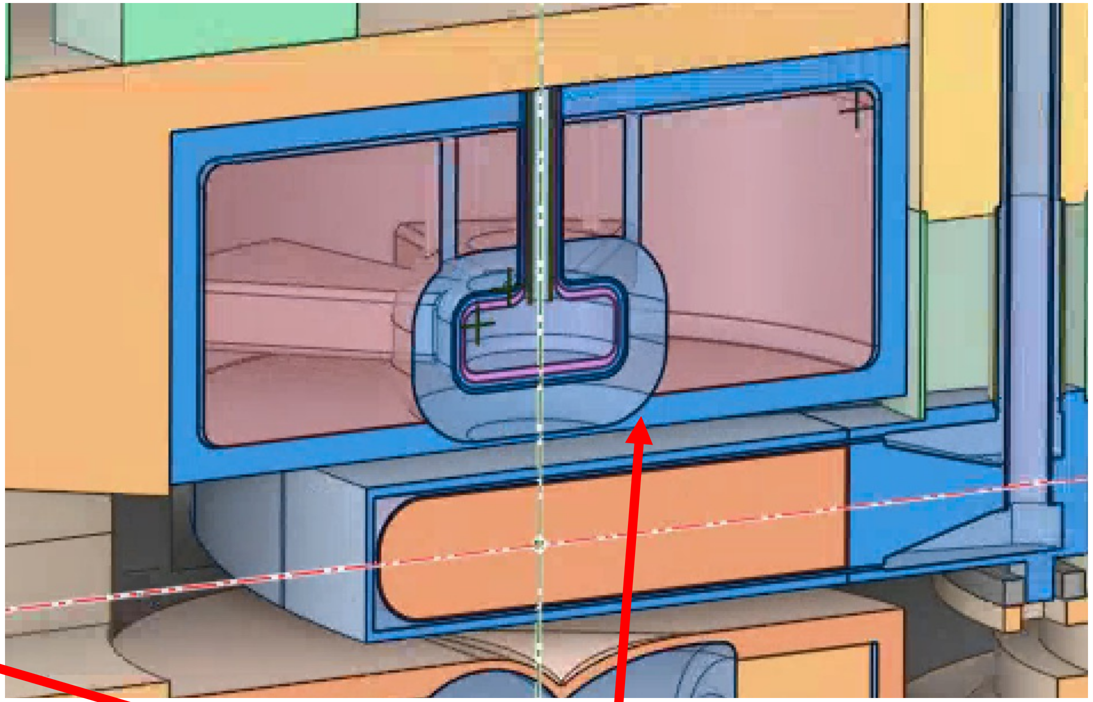




Applications

- **Neutronics optimization of the moderator-reflector assembly**
  - 10 geometry parameters
- **Neutronics and structural optimization of the target**
  - 6 geometry parameters
- **Coupled Target + Moderator + Beam optimization**
  - 10 geometry parameters for the moderator
  - 12 geometry parameters for the target
  - 4 parameters for the beam on target

Original MCNP PSTUDY vs novel UM based optimization

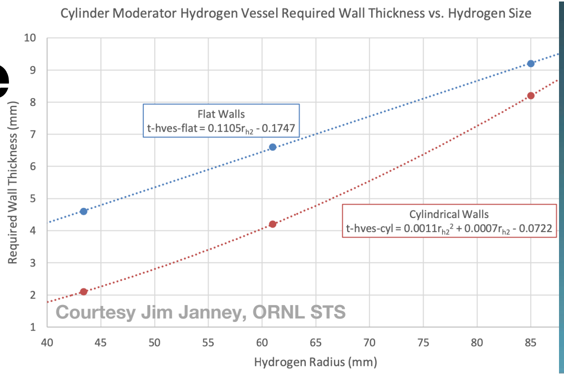


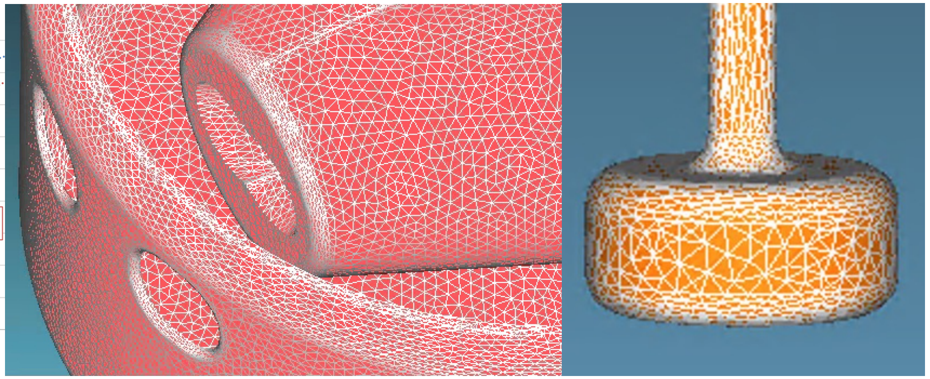


~5-10% performance difference when using a simple vs. high-fidelity model

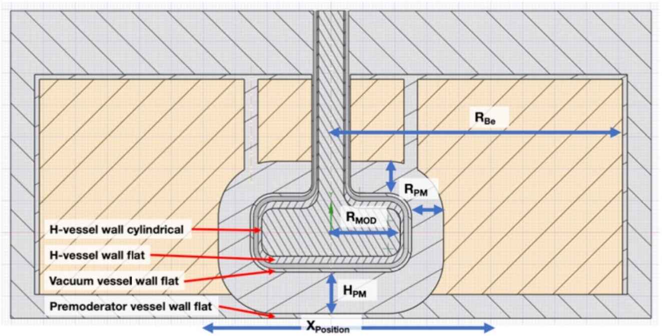
UM models contain variable thicknesses of the walls to withstand H_2/H_2O pressure

~15% difference

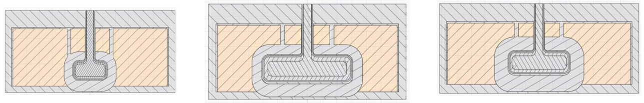




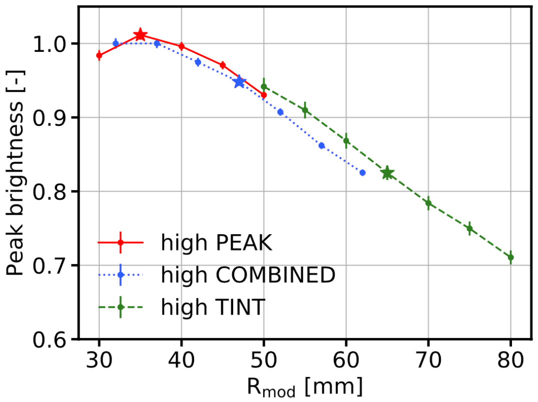
Neutronics optimization of the moderator-reflector

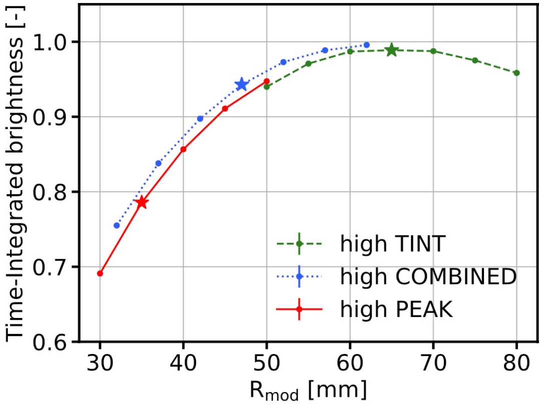


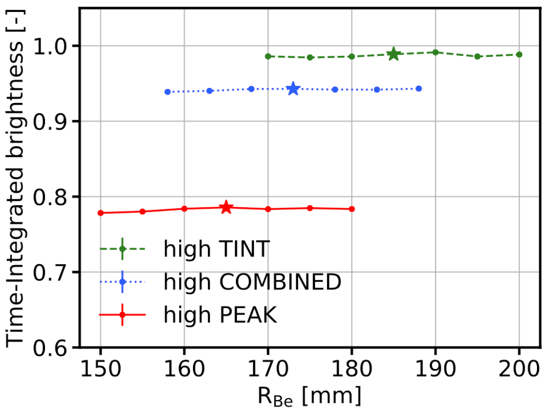
(a) Cylindrical moderator

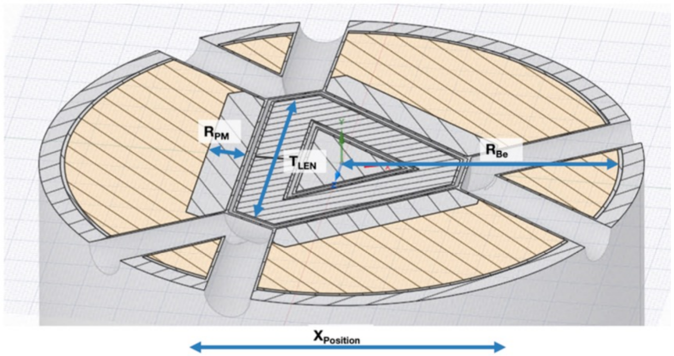


40 iterations

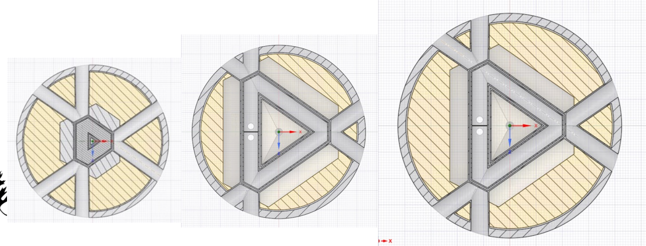


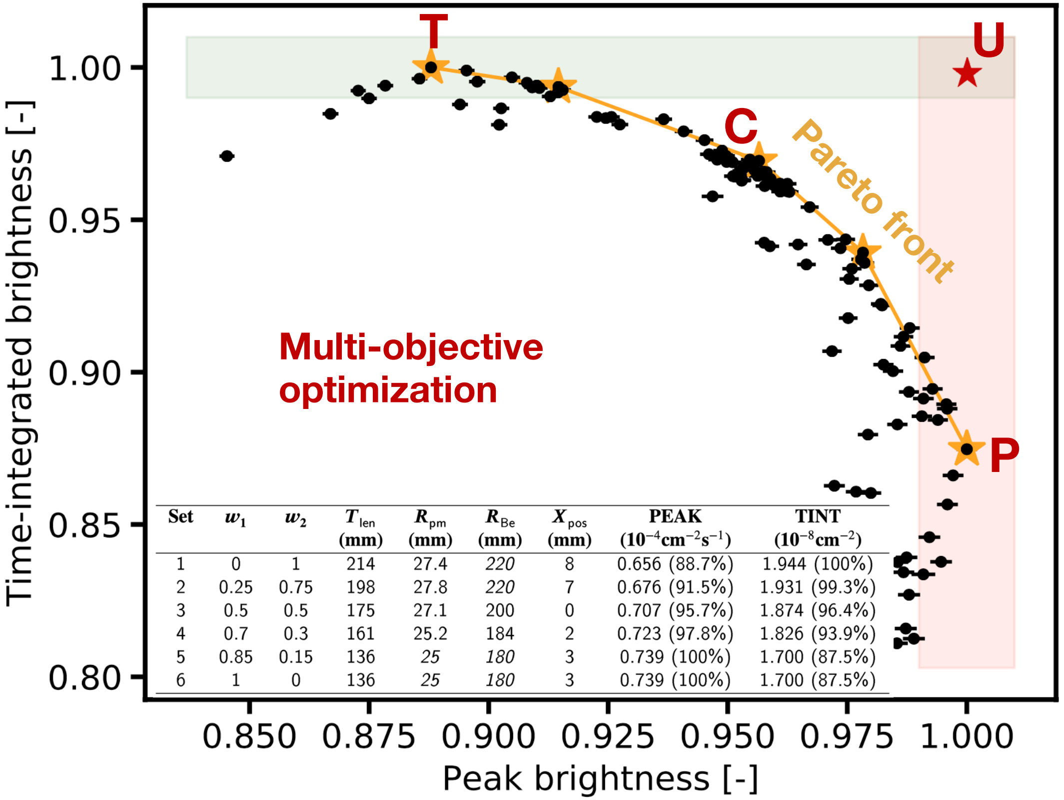






(b) Tube moderator **110 iterations**

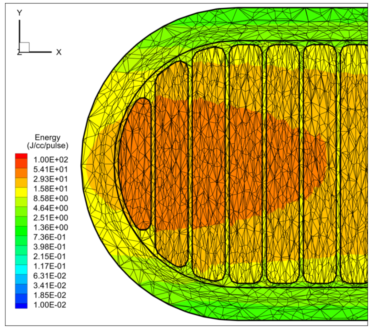


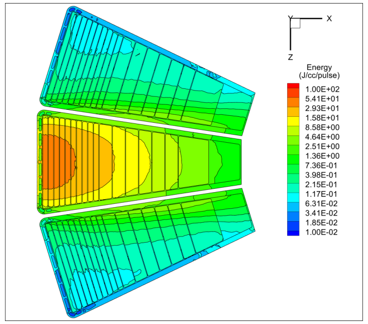


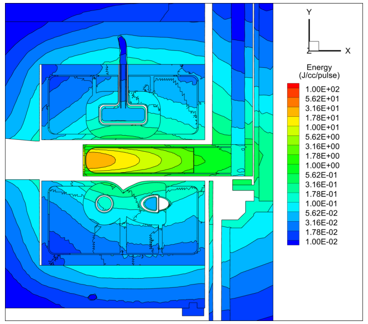
Set	w_1	w_2	T_{len} (mm)	R_{pm} (mm)	R_{Be} (mm)	X_{pos} (mm)	PEAK ($10^{-4}cm^{-2}s^{-1}$)	TINT ($10^{-8}cm^{-2}$)
1	0	1	214	27.4	*220*	8	0.656 (88.7%)	1.944 (100%)
2	0.25	0.75	198	27.8	*220*	7	0.676 (91.5%)	1.931 (99.3%)
3	0.5	0.5	175	27.1	200	0	0.707 (95.7%)	1.874 (96.4%)
4	0.7	0.3	161	25.2	184	2	0.723 (97.8%)	1.826 (93.9%)
5	0.85	0.15	136	*25*	*180*	3	0.739 (100%)	1.700 (87.5%)
6	1	0	136	*25*	*180*	3	0.739 (100%)	1.700 (87.5%)

Coupled neutronics and structural optimization of the target

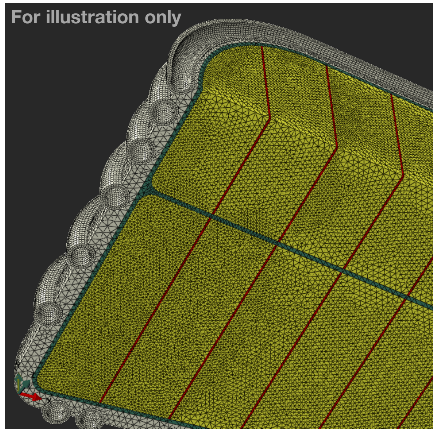
- **Neutronics performance**
- **Detailed energy deposition distribution from MCNP as input to FEA**

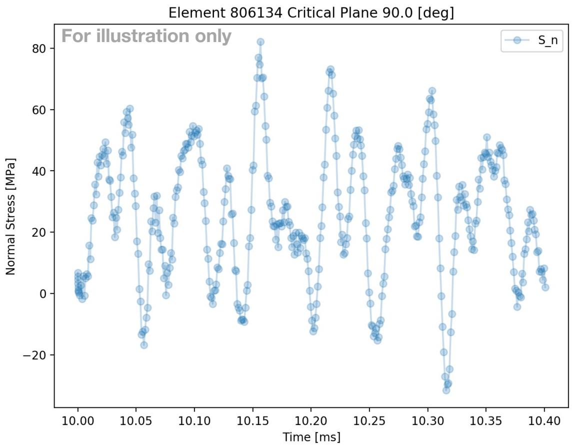


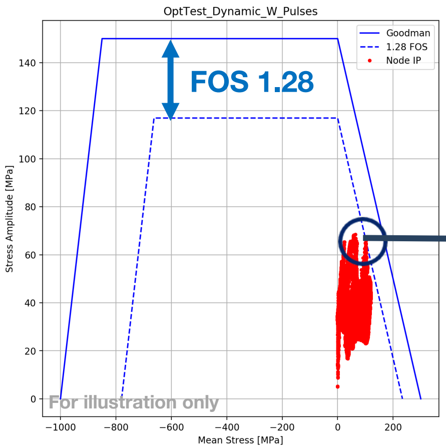


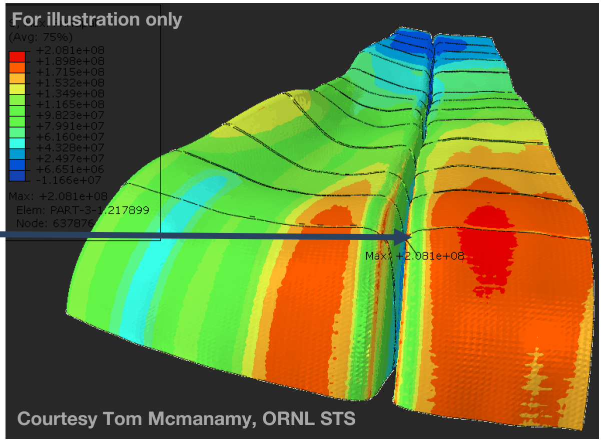


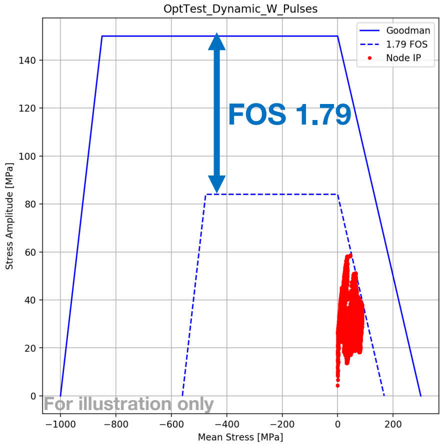
- **Evaluation of the Factor of Safety (FOS)**
  - Measure for the mechanical performance of the target (irradiated after 10 years of operation)
  - Goodman diagram of a failure theory extracted from dynamic response





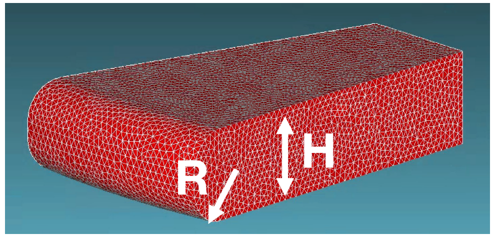


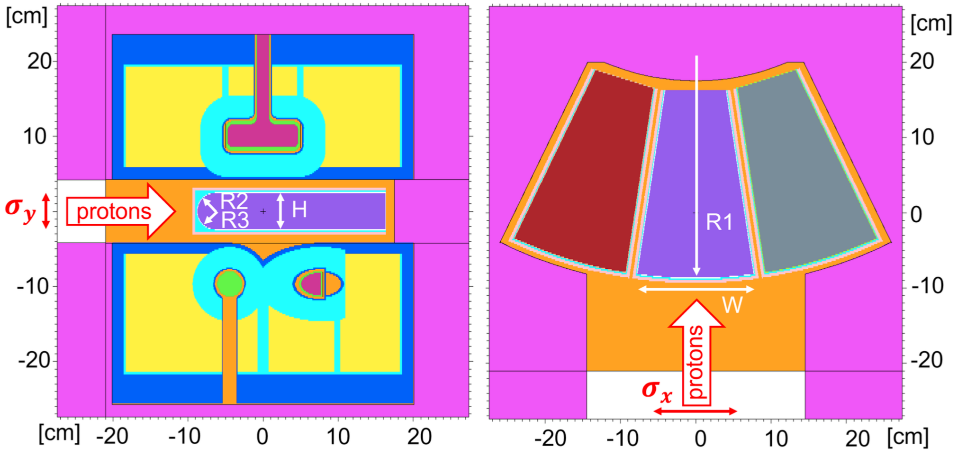


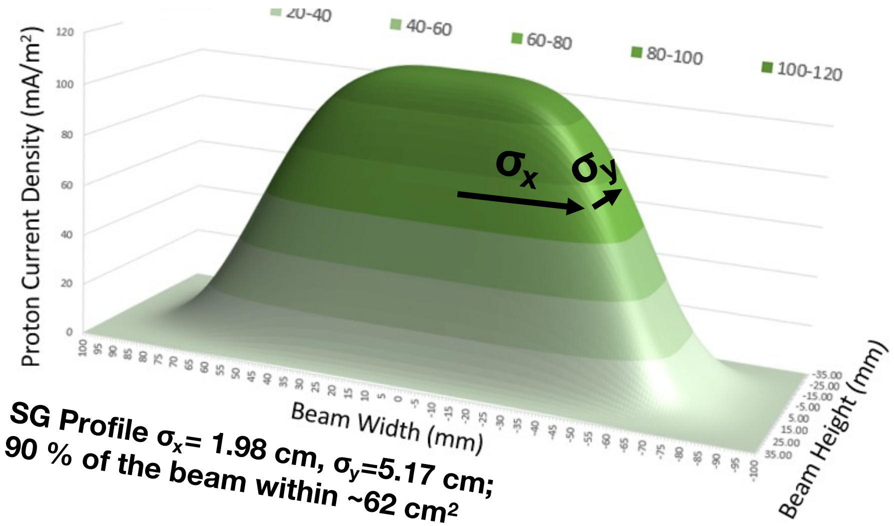


Coupled neutronics and structural optimization of the target

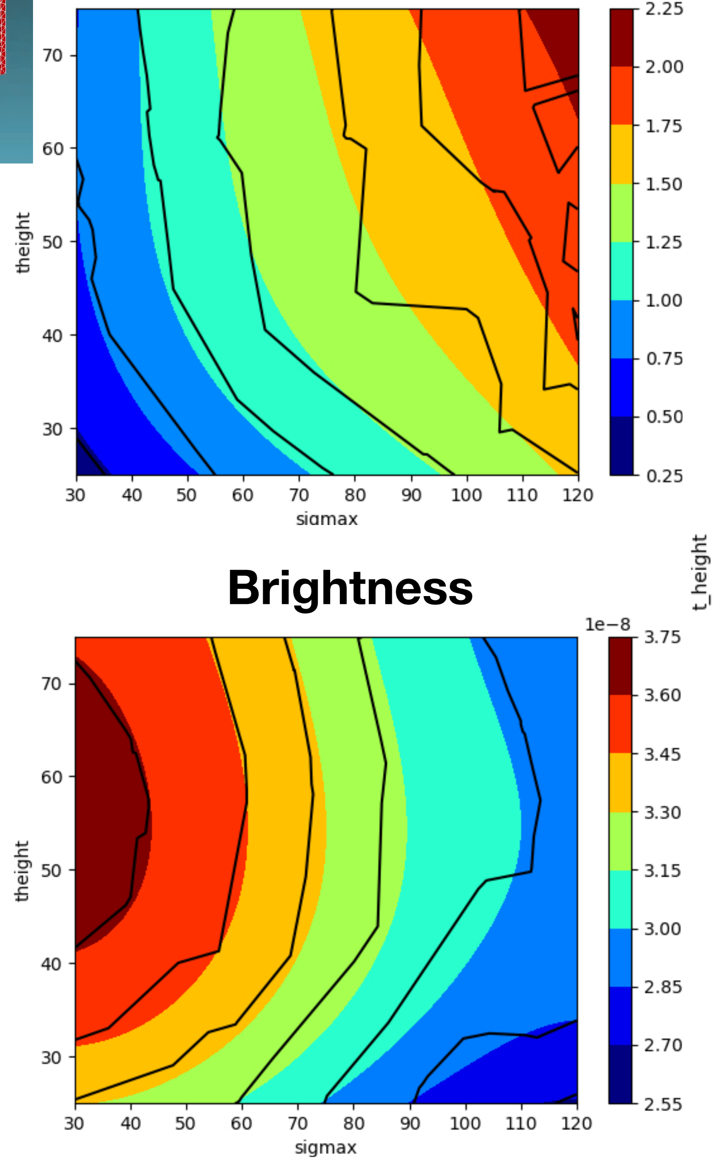
Simple monolithic target design

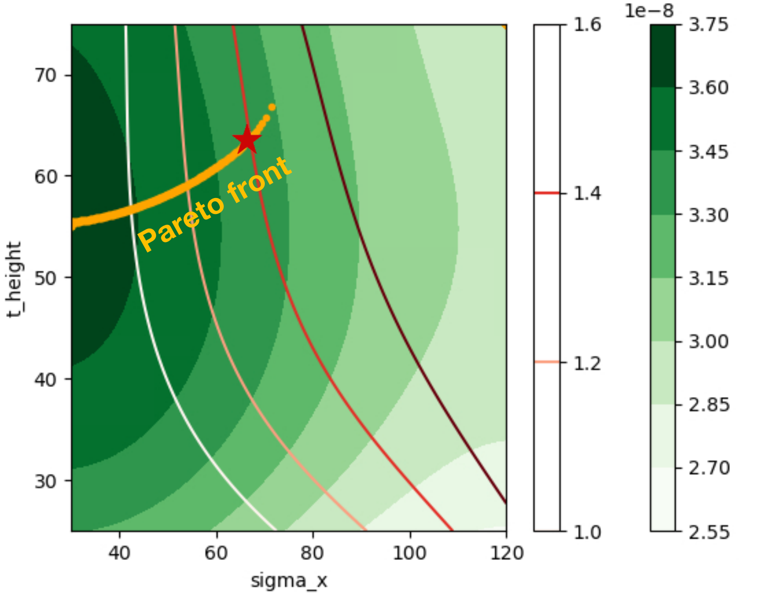






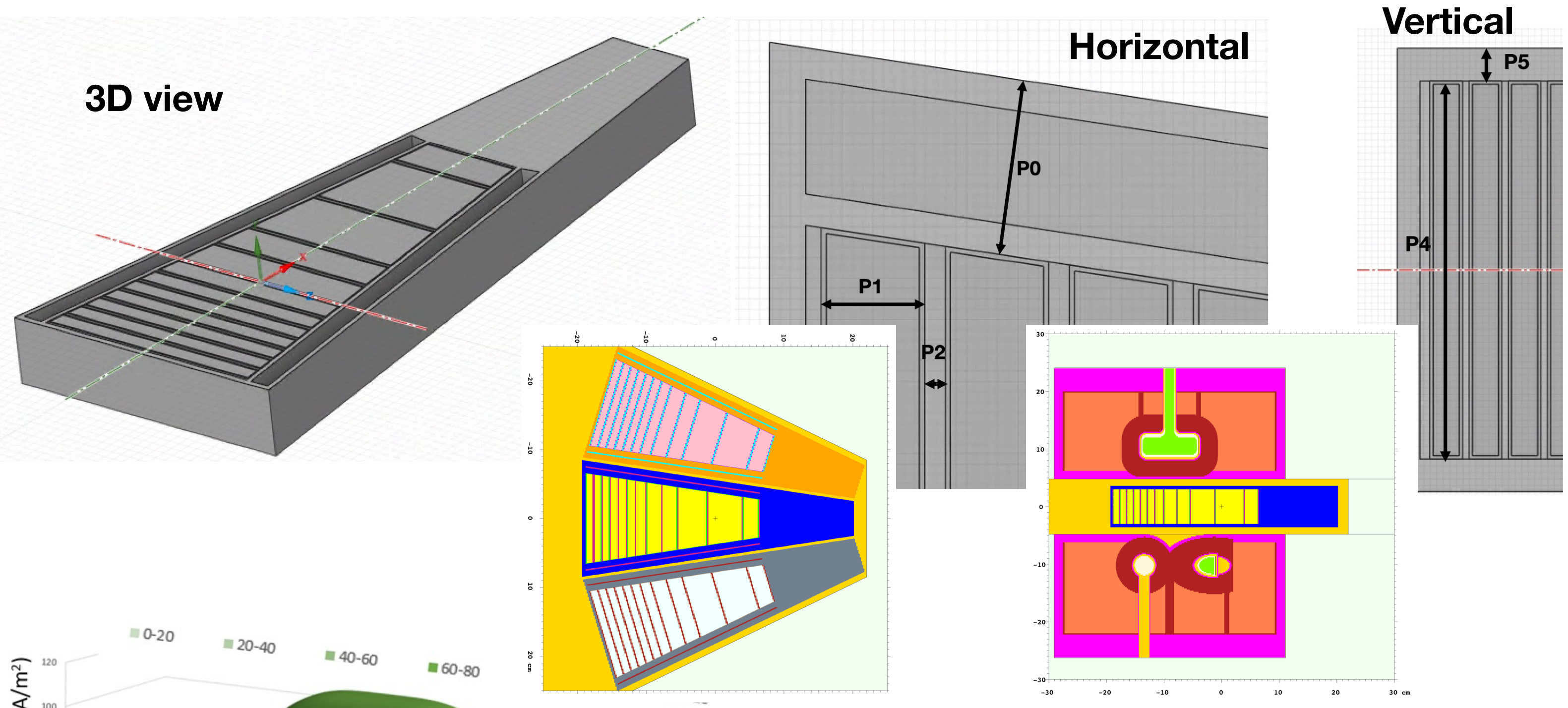
SG Profile σ_x= 1.98 cm, σ_y=5.17 cm;
90 % of the beam within ~62 cm²

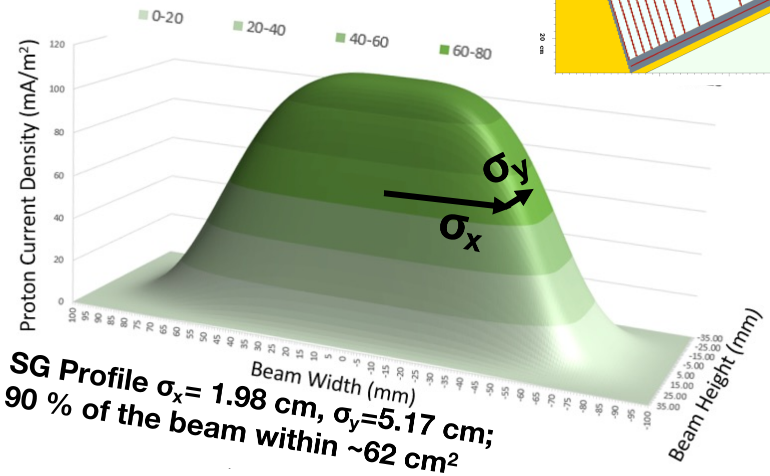




Coupled neutronics and structural optimization of the target

“Cheese wedge” target design

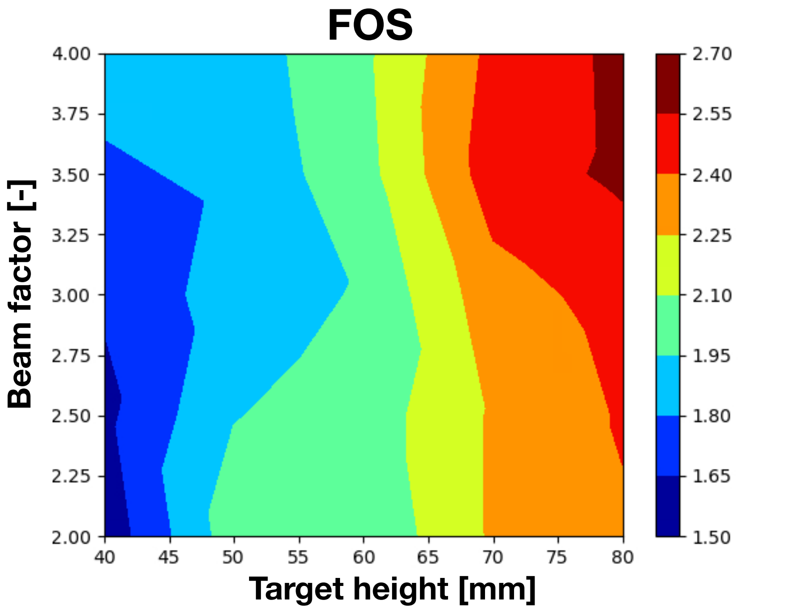


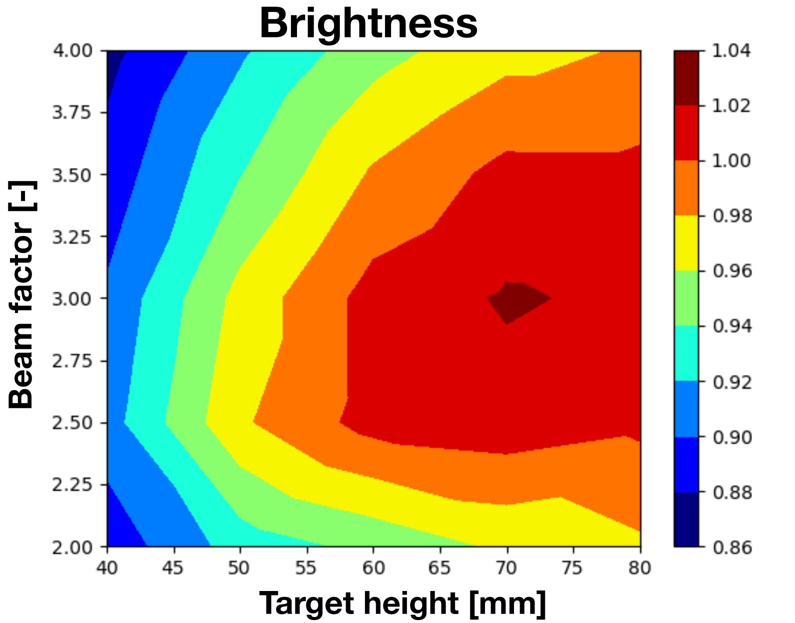


SG Profile σ_x= 1.98 cm, σ_y=5.17 cm;
90 % of the beam within ~62 cm²

$$\text{Beam factor} = \frac{\text{Target height}}{\sigma_y}$$

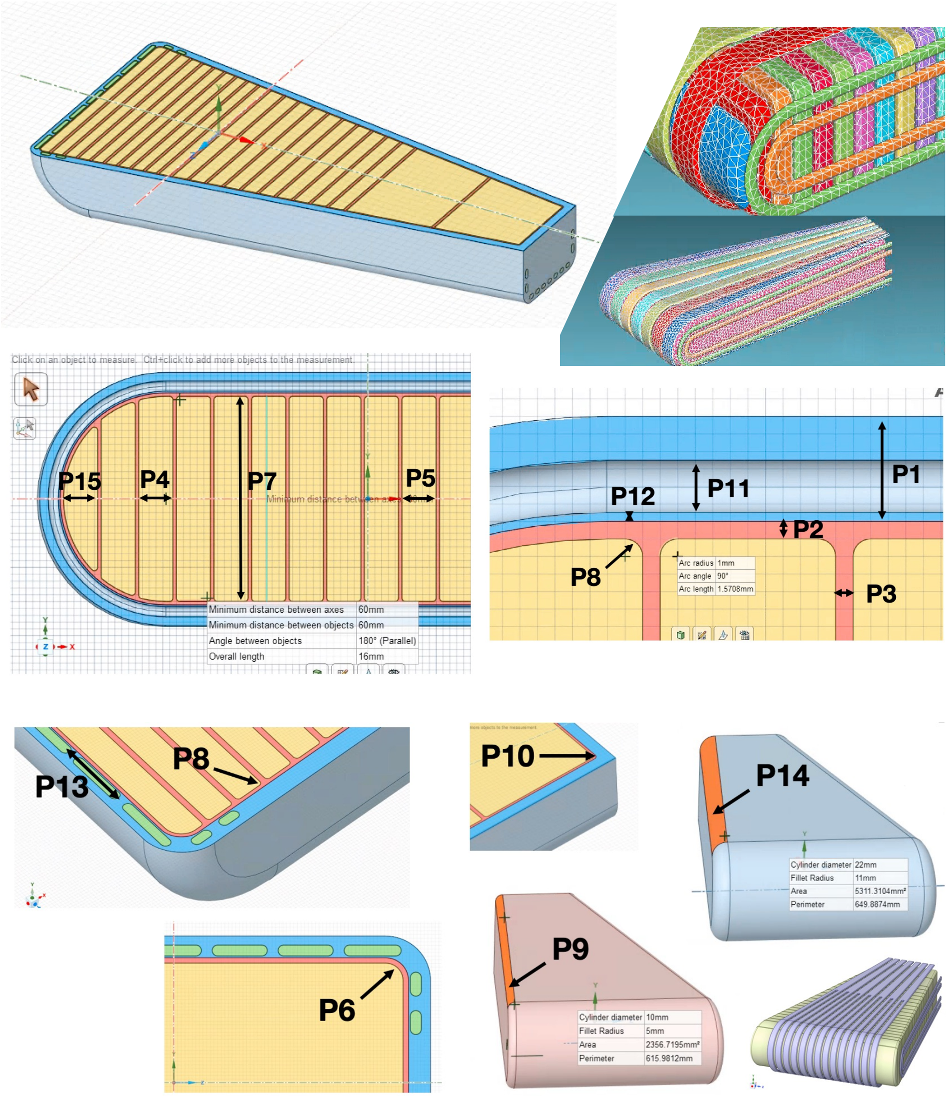
Large beam factor is
small σ_y for a chosen target height

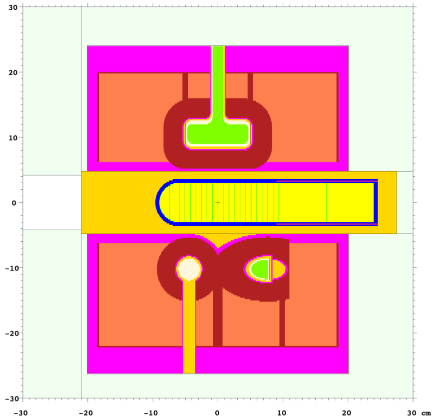


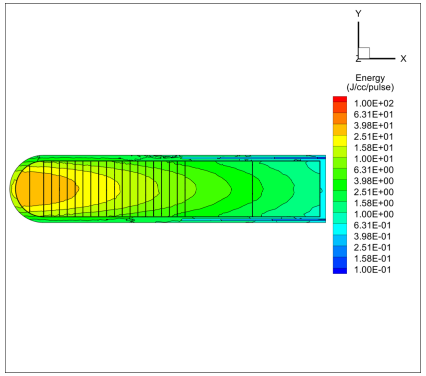


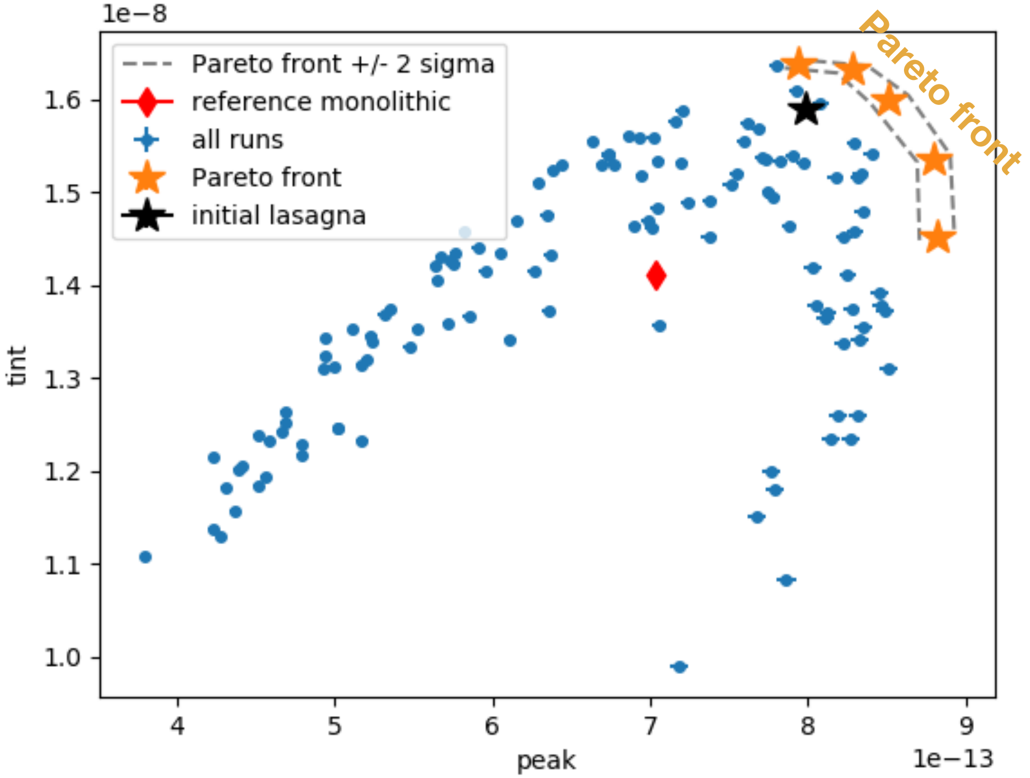
Coupled Target + Moderator + Beam optimization

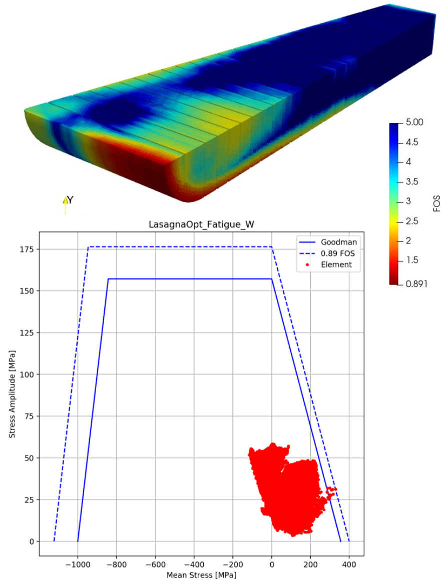
Lasagna target design

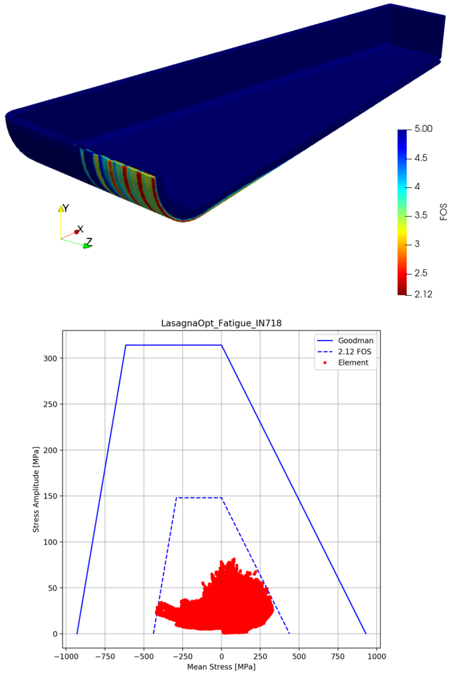












Conclusion

- Developed an automated optimization workflow for coupled neutronics and structural stress analyses
- Reduced time per one iteration from weeks/months to hours
- Reduced number of necessary iterations
- Optimized moderators and several target designs
- Getting more efficient and moving towards more complicated problems

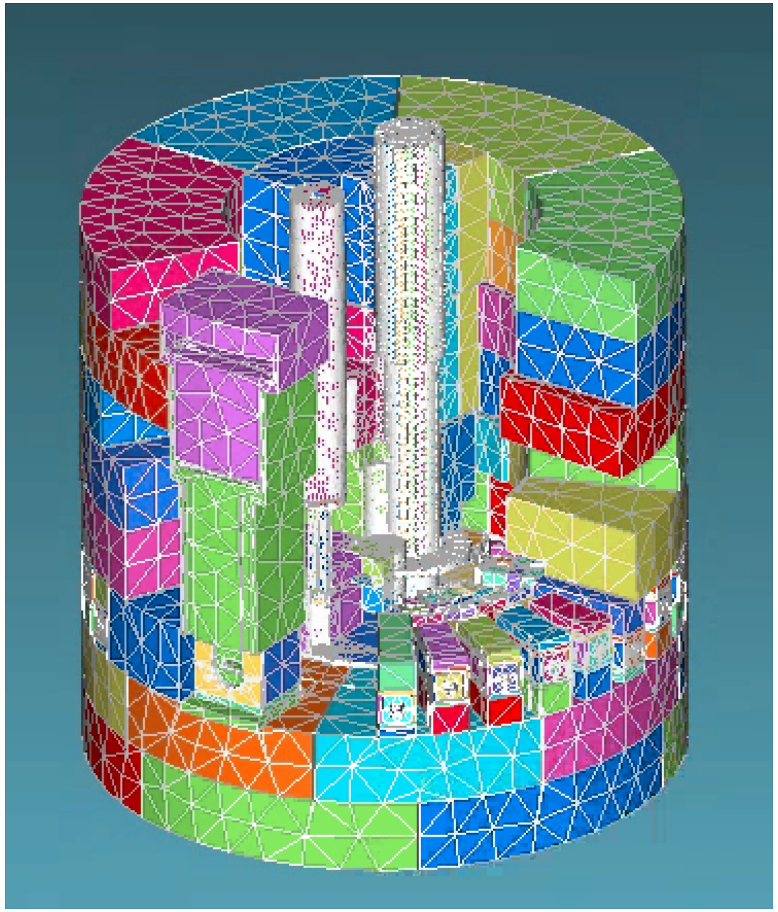
- Essential tool in the STS design process
- Can be applied at other facilities

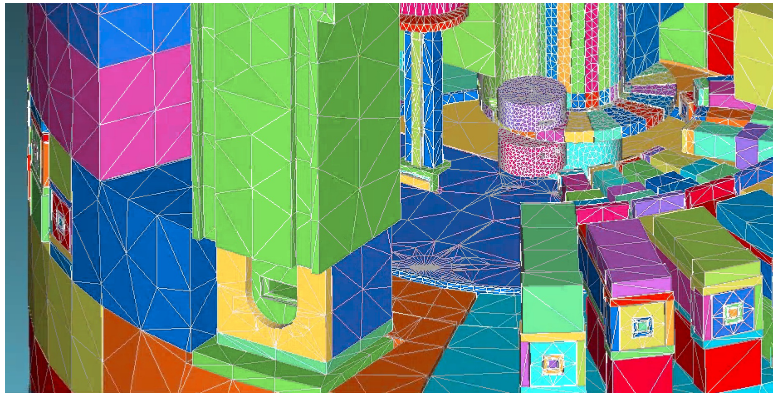
Thank you!

Backup slides

Two approaches possible: Unstructured Mesh (UM)

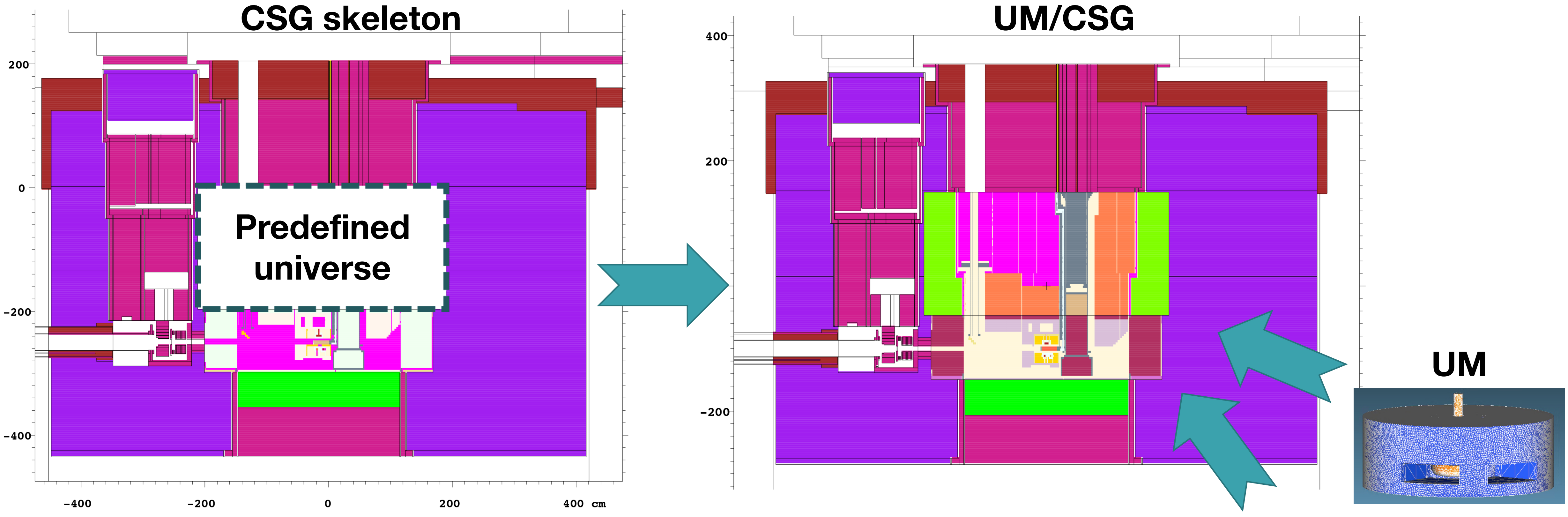
- **Efficient, accurate, but requires more RAM and longer computation time**
- **Necessary for generating Weight Windows with Attila4MC**



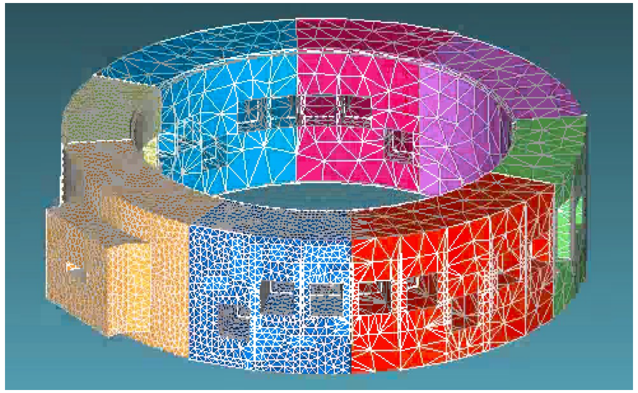


~2M cells

Hybrid UM/Constructive Solid Geometry (CSG) model

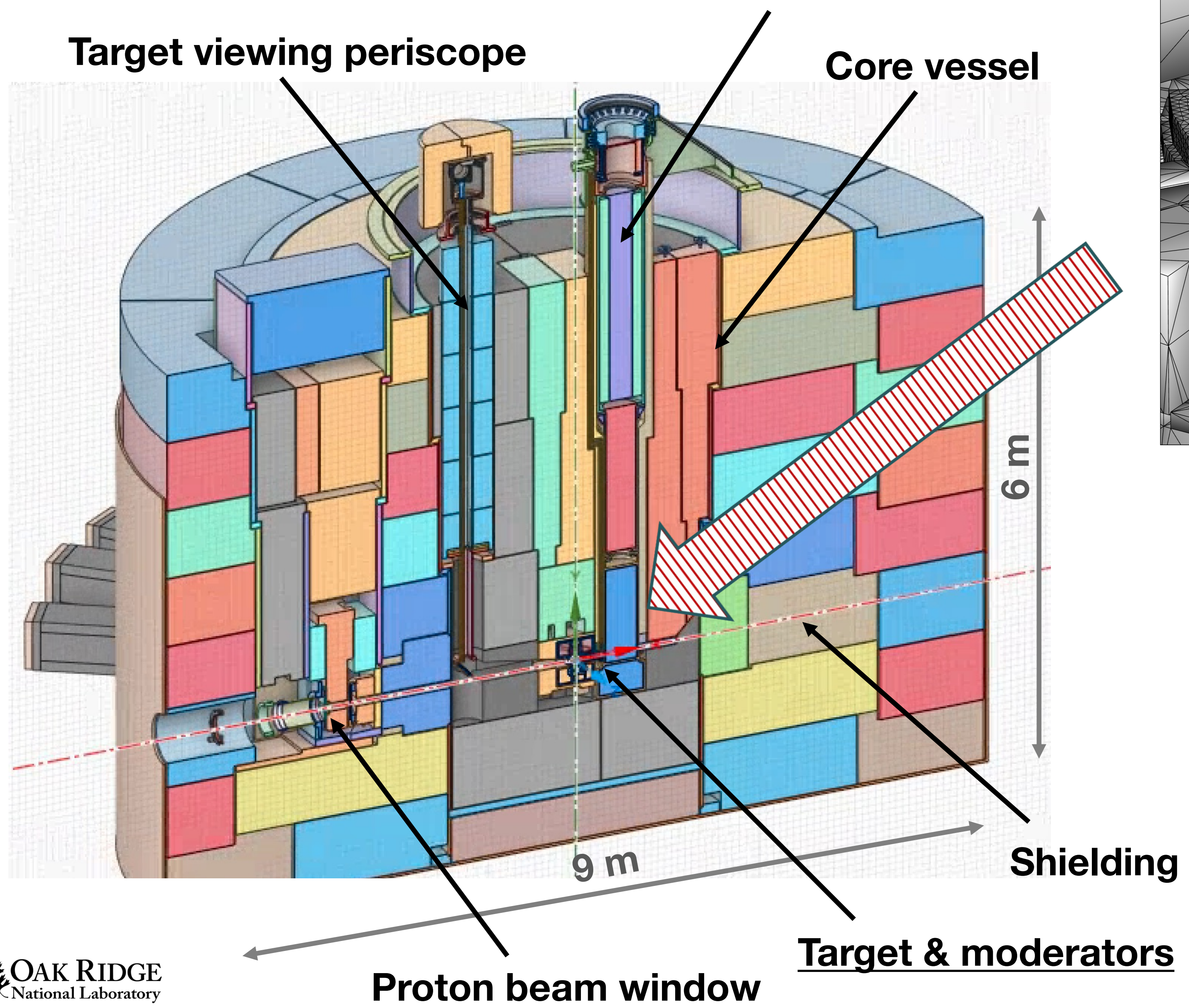


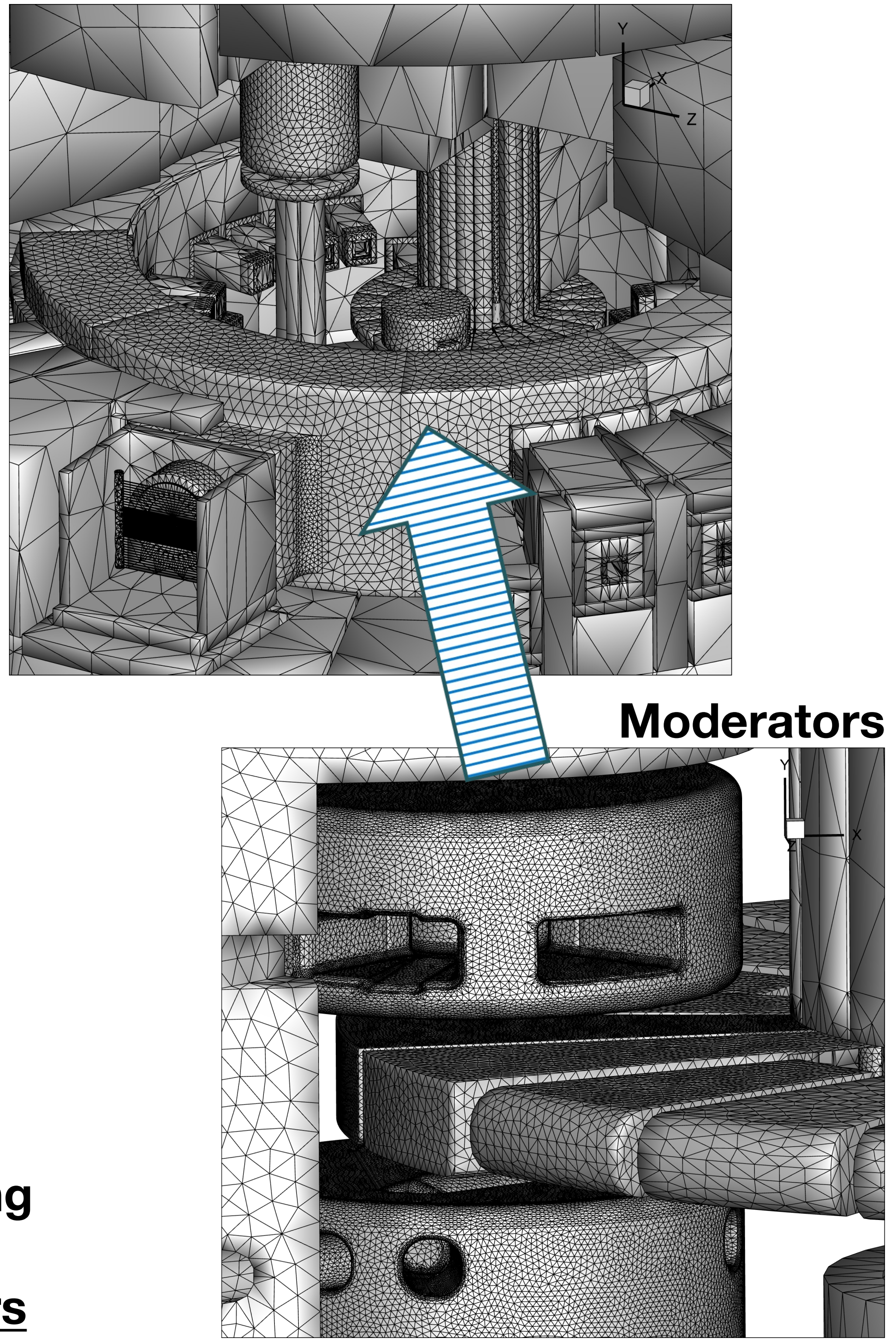
- More efficient use of RAM and faster computation time
- Requires longer time to build
- Can use Weight Windows from Attila4MC



Oak Ridge National Laboratory

STS Design





OAK RIDGE National Laboratory

STS Design

The pathway to high brightness:

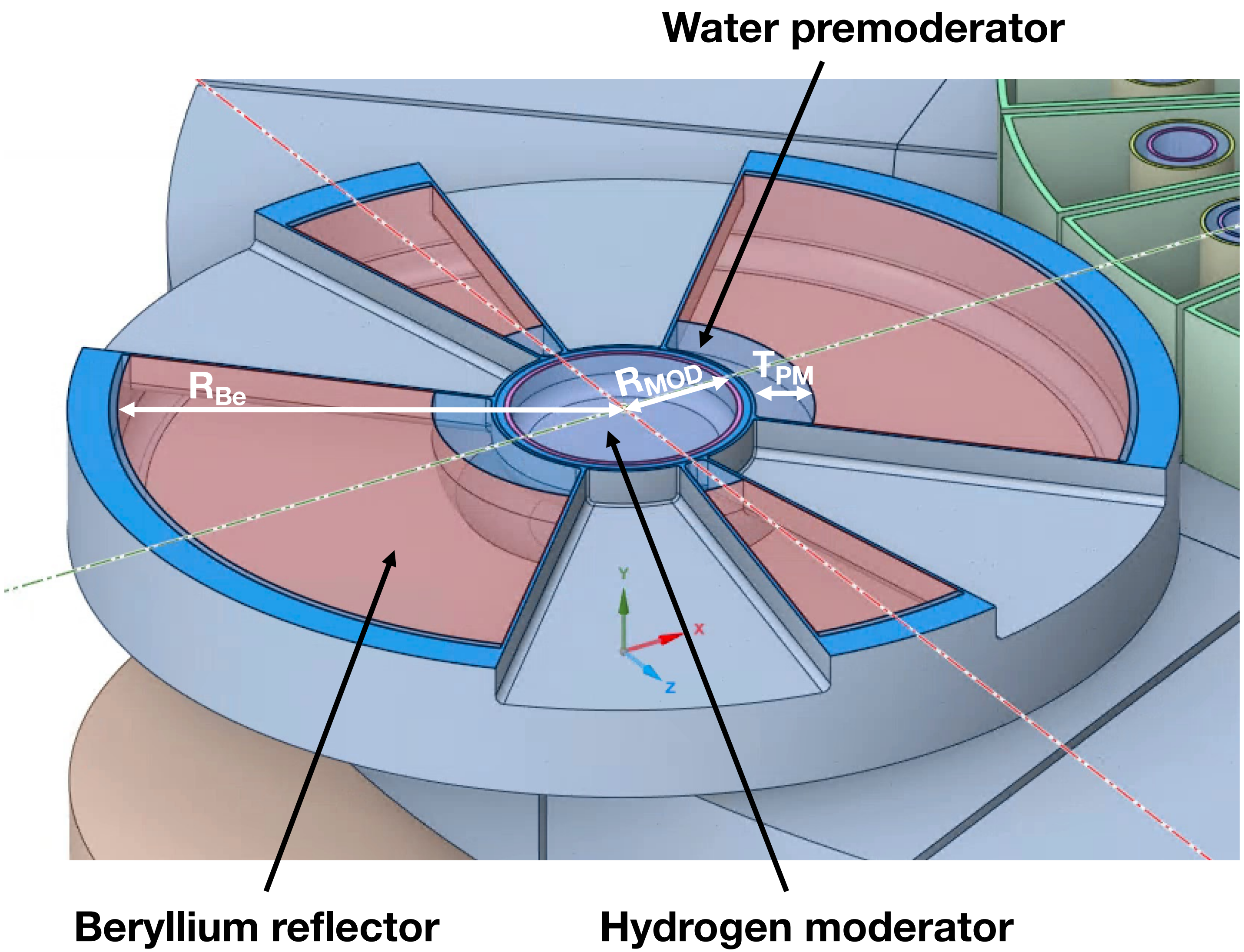
- Compact target and neutron production zone
- Tight coupling between target and moderators
- Reduce the size of the moderator emission surfaces
- Use para hydrogen as moderator material
- Include water premoderator
- Develop and use state-of-the-art optimization tools

Flip side of the coin:

- High structural stress
- Reduced total neutron intensity

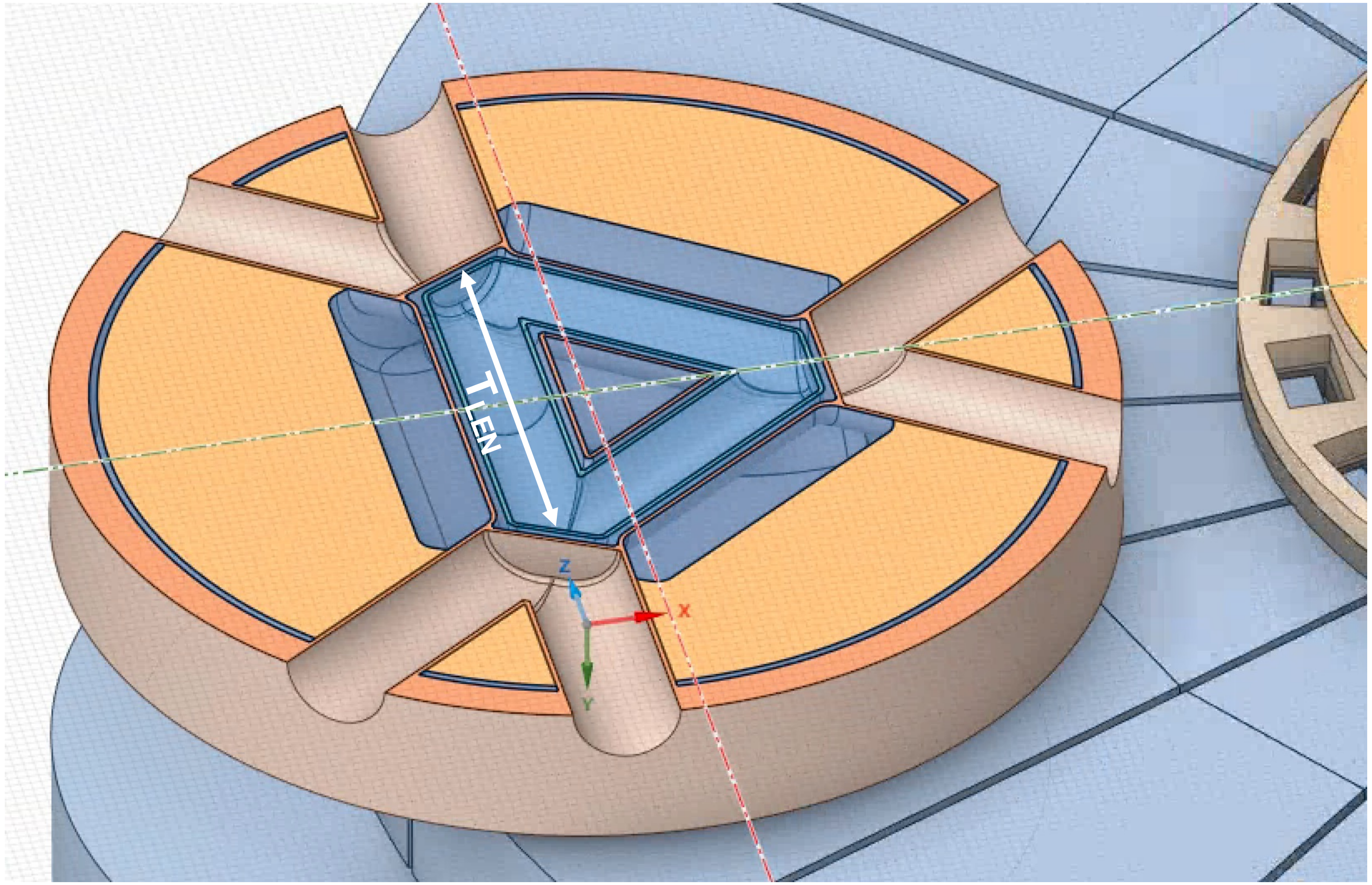
STS Cylindrical Moderator Design

- **2D geometry configuration**
- **16 beam lines**
- **3 x 3 cm² viewed area**
- **Originally optimized for peak brightness**
- **Key parameters:**
  - Moderator radius
  - Premoderator radius
  - Premoderator thickness
  - Beryllium radius
  - Moderator position



STS Tube Moderator Design

- **1D geometry configuration**
- **6 beam lines**
- **3^2 x (π/4) cm^2 viewed area**
- **Originally optimized for time-integrated brightness**
- **Key parameters:**
  - Tube length
  - Tube radius
  - Premoderator thickness
  - Beryllium radius
  - Moderator position



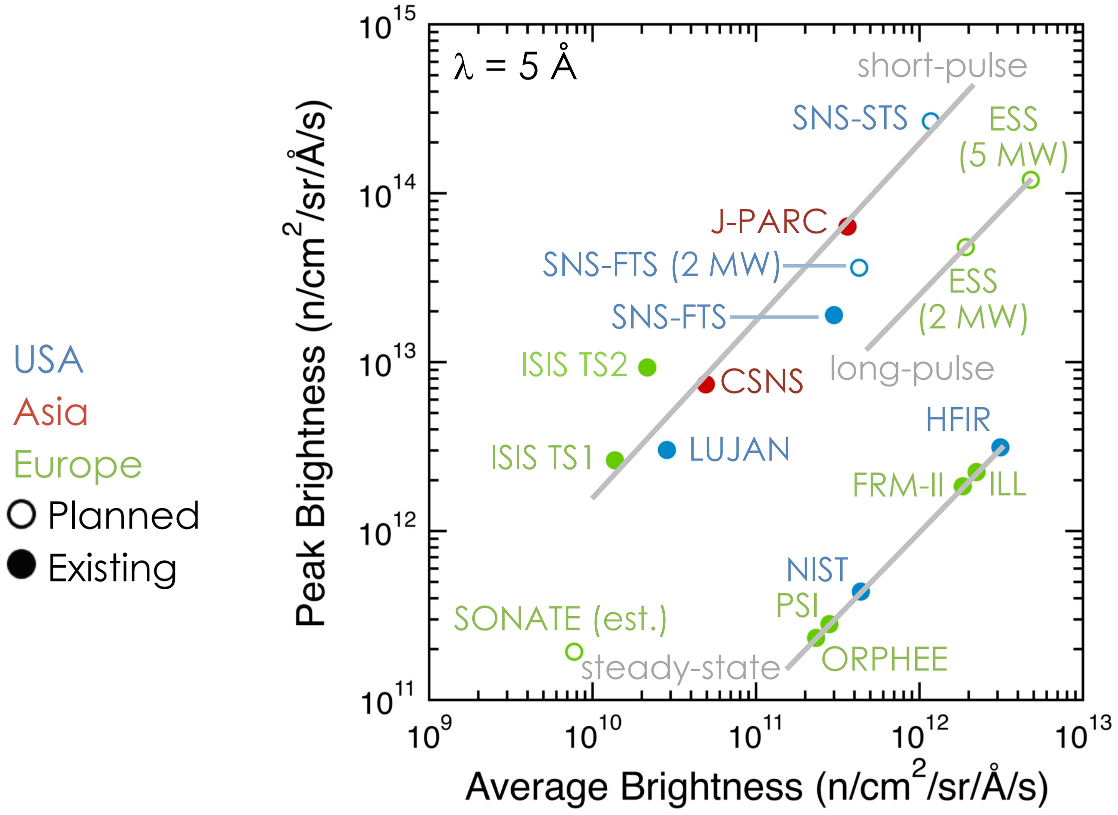
Tube moderator concept proposed by Franz Gallmeier:
"*A Liquid Hydrogen Tube Moderator Arrangement for STS*", 2018

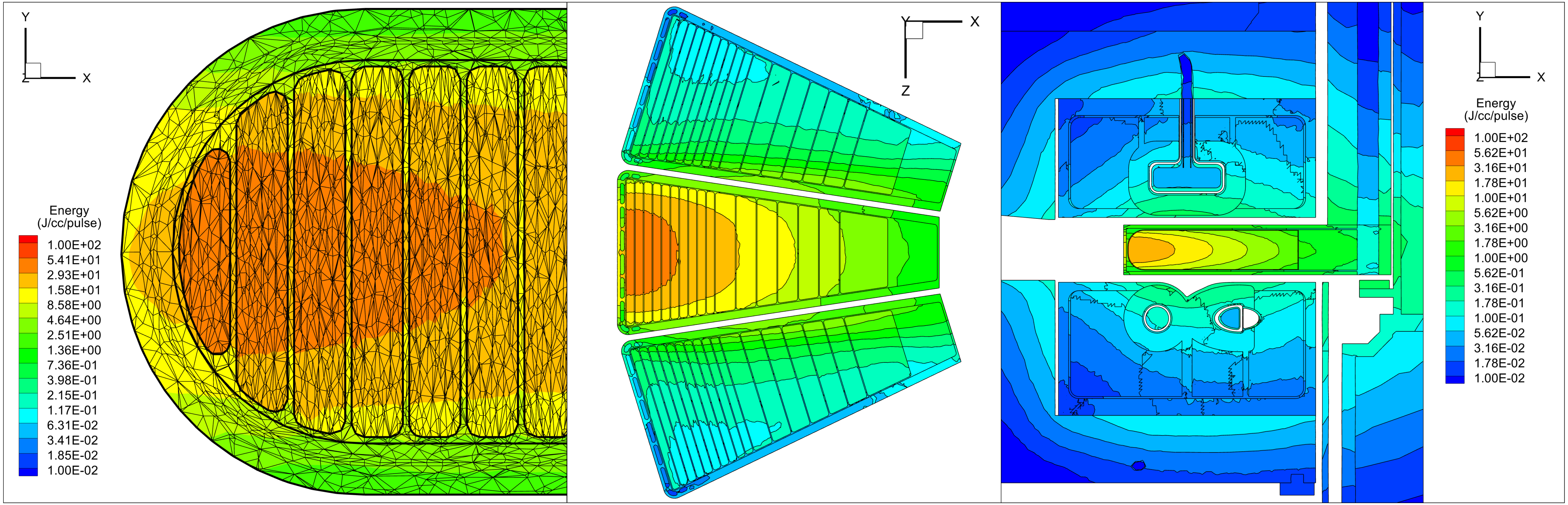
Preliminary STS KPPs

KPP	Thresholds	Objectives
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	
Demonstrate proton beam on STS at 15 Hz	100 kW beam power	700 kW beam power
Measure STS neutron brightness	Peak brightness of 2×10^{13} n/cm^2/sr/Å/s at 5 Å	Peak brightness of 2×10^{14} n/cm^2/sr/Å/s at 5 Å
Beamlines transitioned to operations	Eight beamlines successfully passed the integrated functional testing per the TTOP acceptance criteria	$\geq$ Eight beamlines successfully passed the integrated functional testing per the TTOP acceptance criteria

TTOP = Transition to Operation Parameters.

- **STS objective is to become the highest peak-brightness source of cold neutrons in the world**




Y
Z
X
Energy
(J/cc/pulse)
1.00E+02
5.41E+01
2.93E+01
1.58E+01
8.58E+00
4.64E+00
2.51E+00
1.36E+00
7.36E-01
3.98E-01
2.15E-01
1.17E-01
6.31E-02
3.41E-02
1.85E-02
1.00E-02
Y
X
Z
Y
Z
X
Energy
(J/cc/pulse)
1.00E+02
5.62E+01
3.16E+01
1.78E+01
1.00E+01
5.62E+00
3.16E+00
1.78E+00
1.00E+00
5.62E-01
3.16E-01
1.78E-01
1.00E-01
5.62E-02
3.16E-02
1.78E-02
1.00E-02