Study of a new high power spallation target concept

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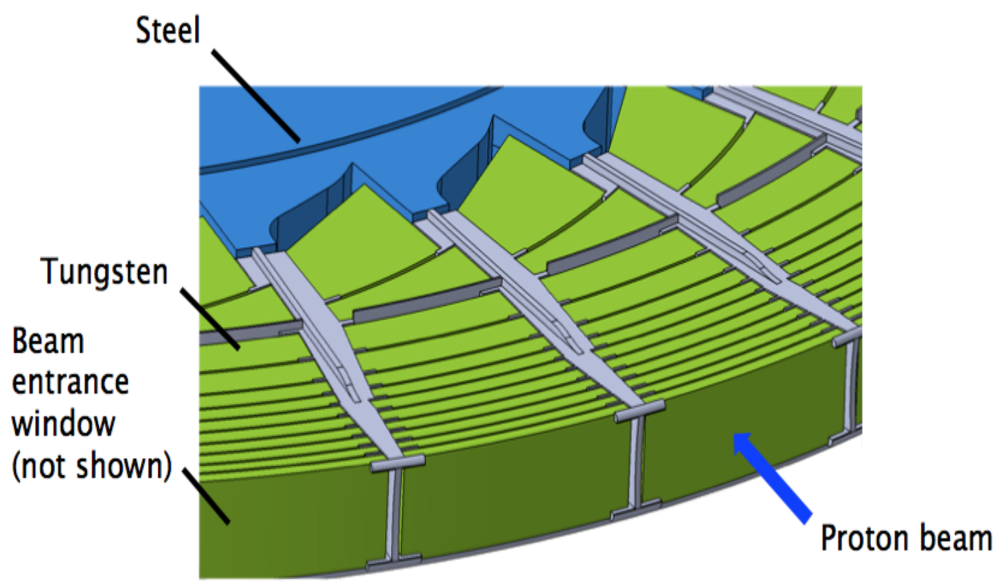
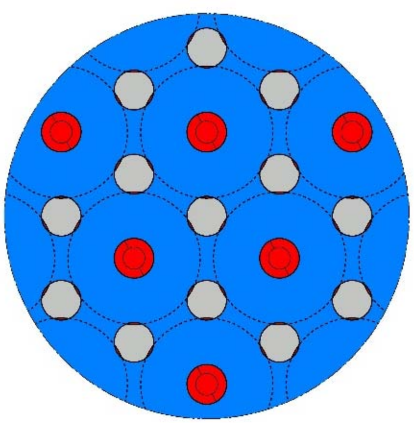
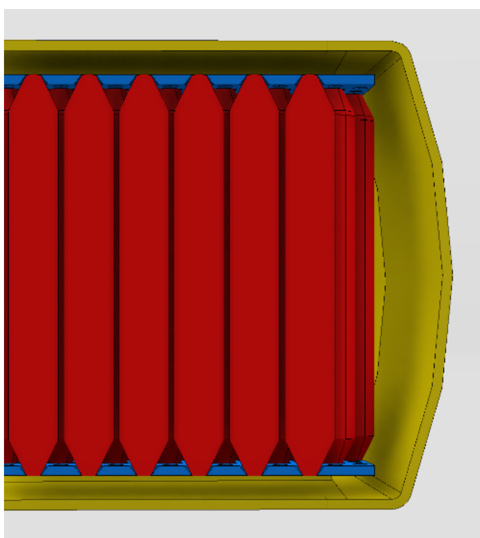
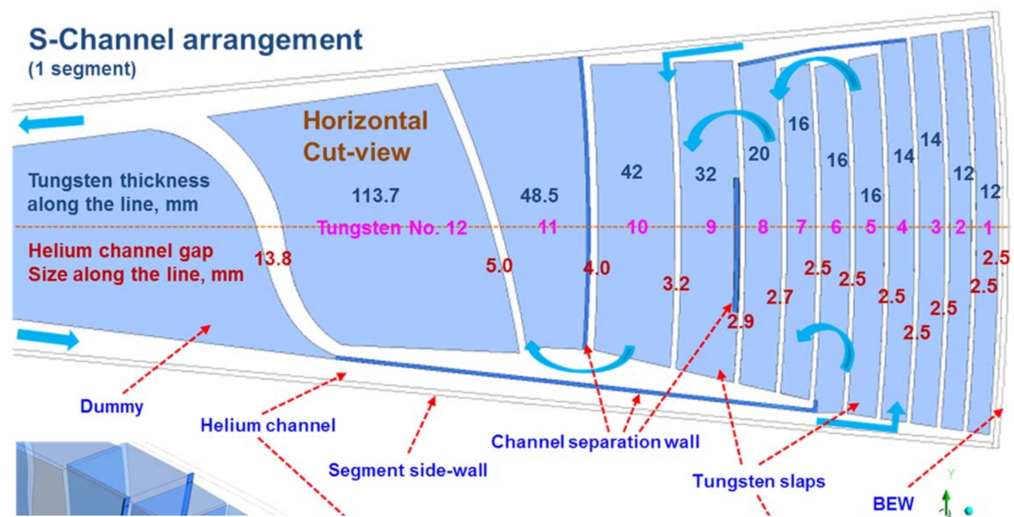
Spallation Target at ESS

- 5 MW spallation source
  - 5 MW (2.0 GeV/2.5 mA) proton beam
  - 2.86 ms long beam pulse with 14 Hz repetition rate
- Rotating tungsten target:
  - Helium cooled target with water cooled backup







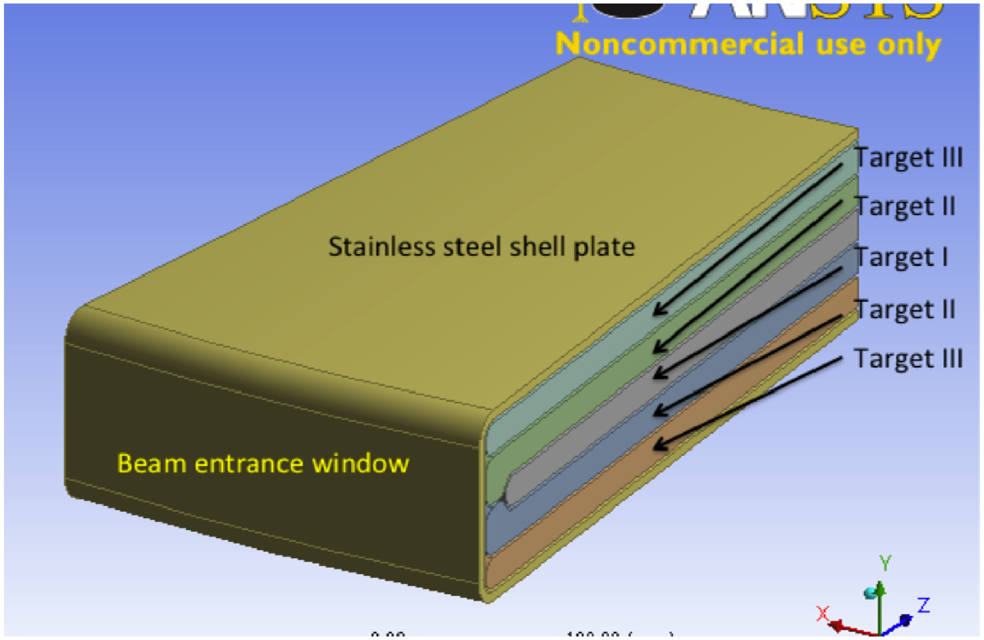


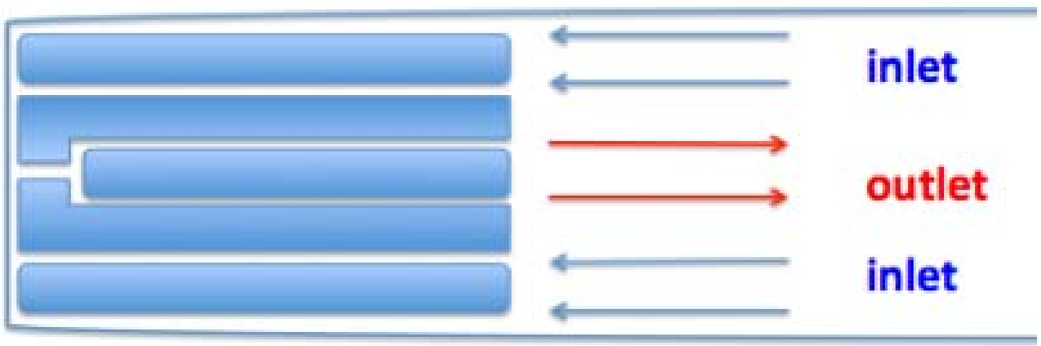
Motivation

- Looking for a target concept that is based on simple design, with small number of standard type tungsten blocks in large dimensions.
- Looking for a target concept that is based on simple cooling flow patterns such that CFD simulations have better predictability.
- Demonstration of technical feasibility of a new target concept that is readily adaptable both for helium cooled and water cooled options.

Target configuration used for this study

- Five 40 cm long horizontal tungsten slabs with equal thickness 16 mm.

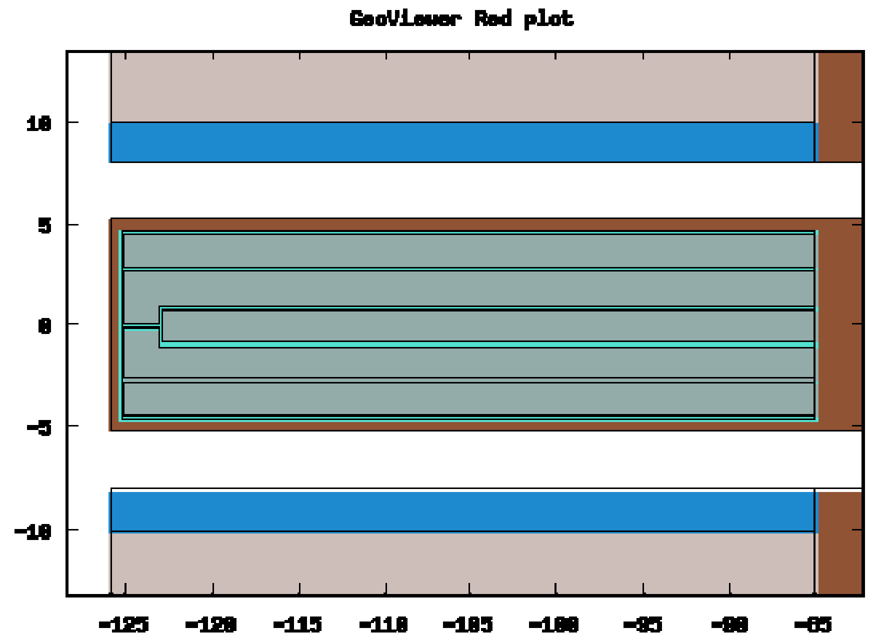


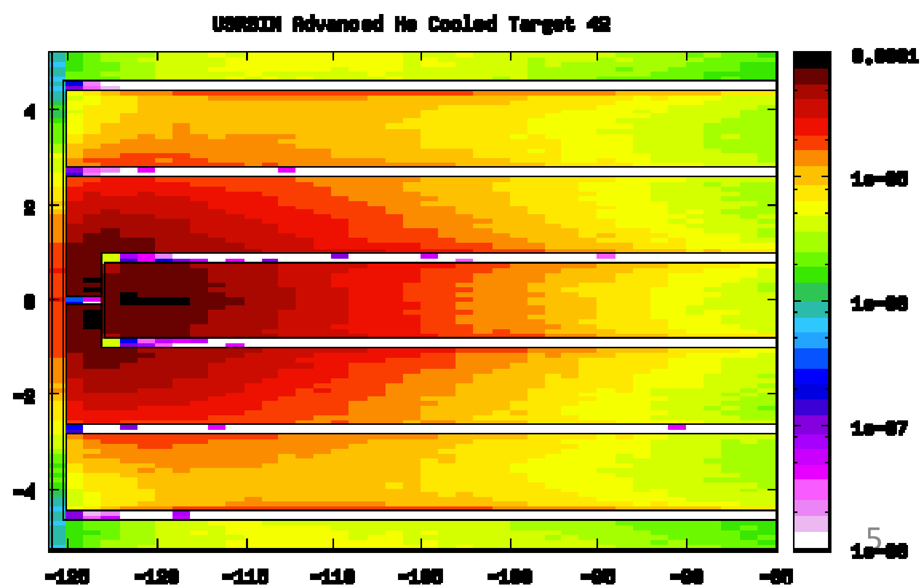


Beam power deposition

- TDR Baseline (2013):
  - 5 MW (2.5 GeV/2.0 mA) double Gaussian beam with peak current density 53 uA/cm2

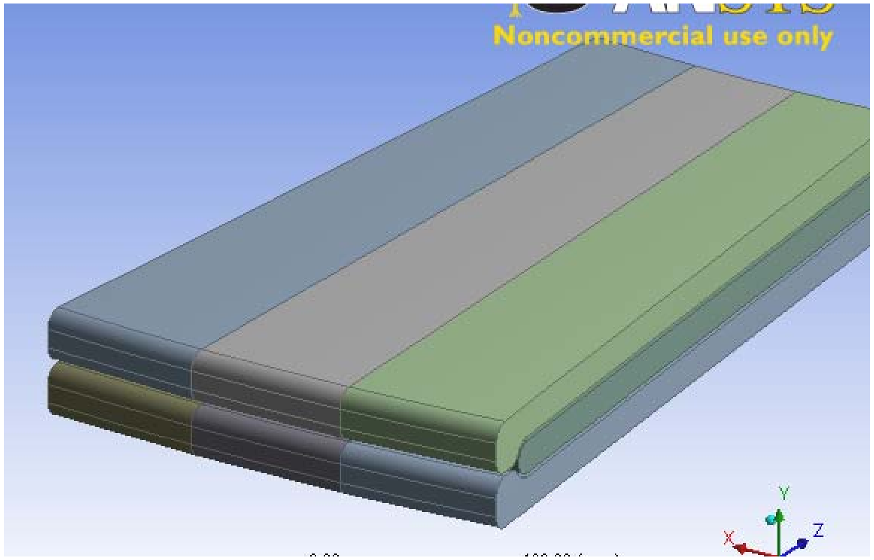
Target volume	Deposited power [kW]
Target I	820
Target II	1374
Target III	594
Total	**2788**



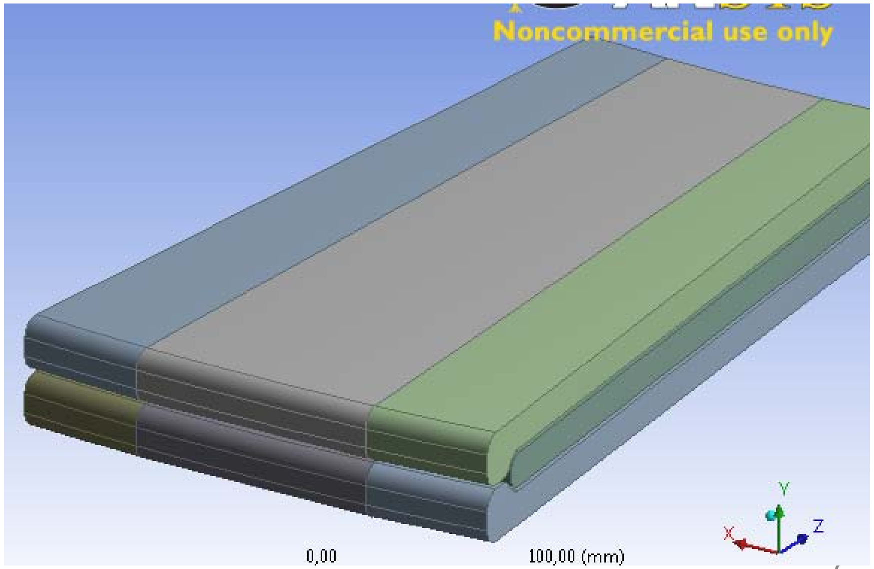


Flow analysis

- Helium cooled option
  - 3 kg/s mass flow rate
  - 3 bar operation pressure
  - Total 363 tungsten slabs

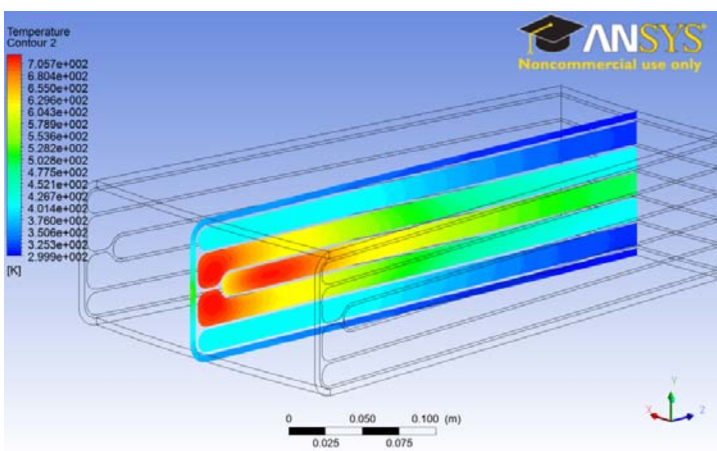


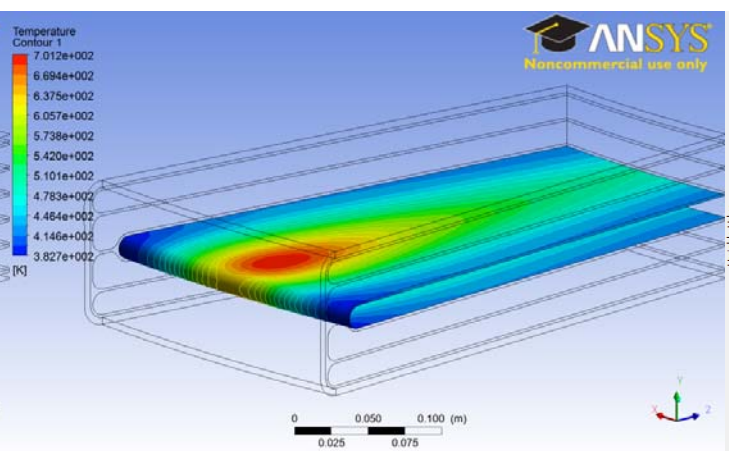
- Water cooled option
  - 99 kg/s mass flow rate
  - 6 bar operation pressure
  - Total 264 tungsten slabs

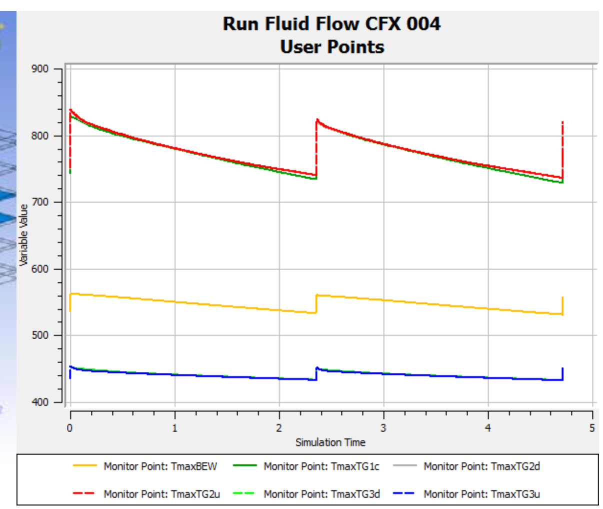


CFD: Transient helium flow analysis

Helium Cooled Target			
Target Volume	Max Temperature Pre-pulse	Max Temperature Post-pulse	Temperature Amplitude
Target I	728.5 K	813.9 K	85.4 K
Target II	736.0 K	818.8 K	82.8 K
Target III	432.8 K	450.9 K	18.1 K
Pressure Drop	97.0 kPa: Surface and time averaged		

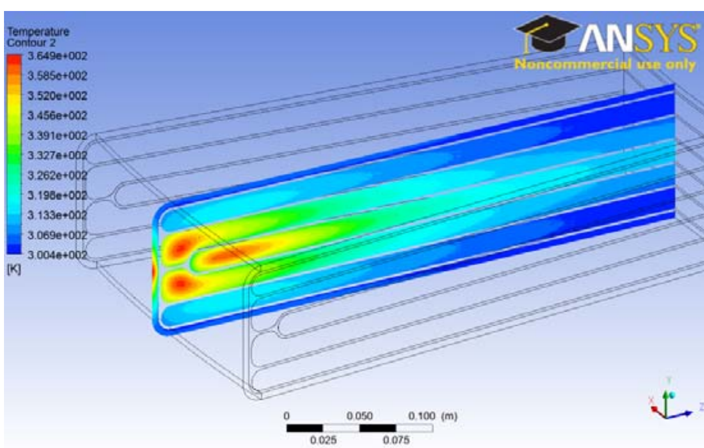


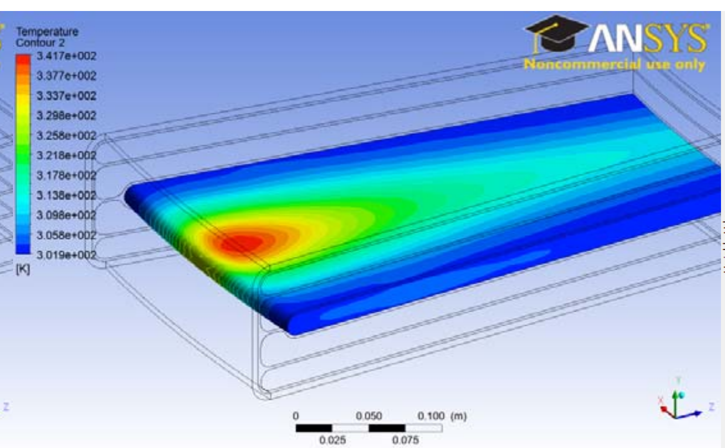


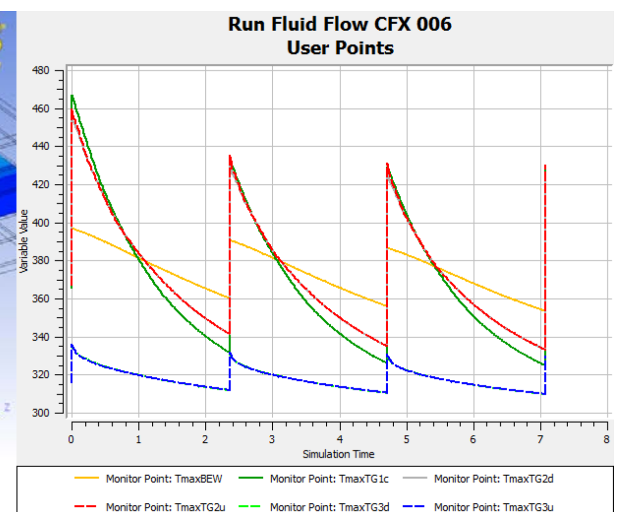


CFD: Transient water flow analysis

Water Cooled Target			
Target Volume	Max Temperature Pre-pulse	Max Temp: Post-pulse (Bulk/Surface)	Temperature Amplitude
Target I	326.1 K	429.7 K/393.6 K	103.6 K
Target II	334.3 K	428.9 K/402.3 K	94.6 K
Target III	310.0 K	329.4 K/324.8 K	19.4K
Pressure Drop	35.3 kPa: Surface and time averaged		

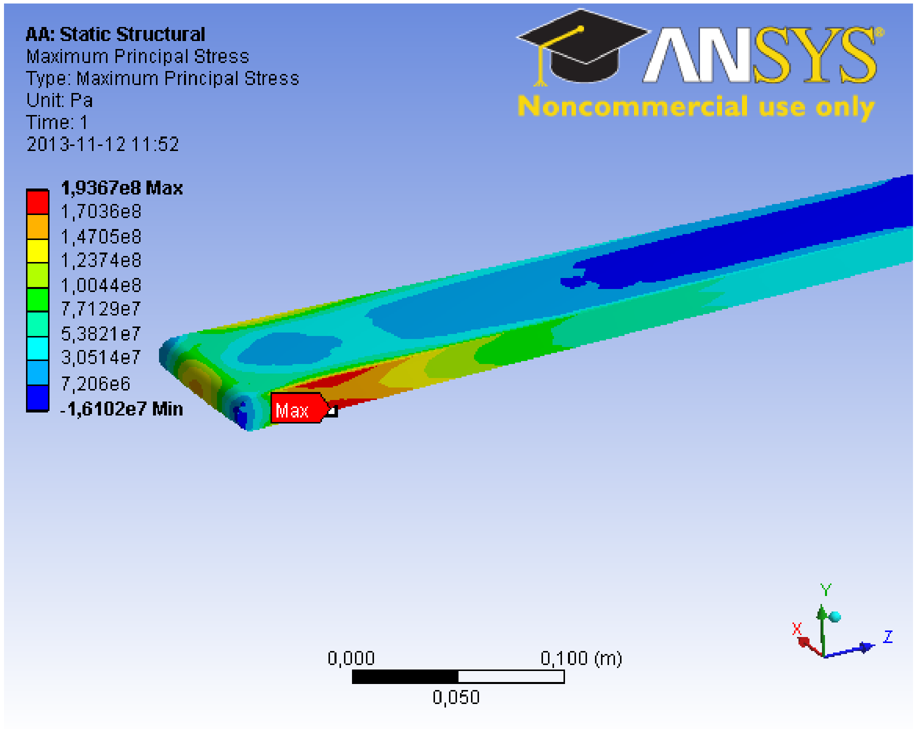


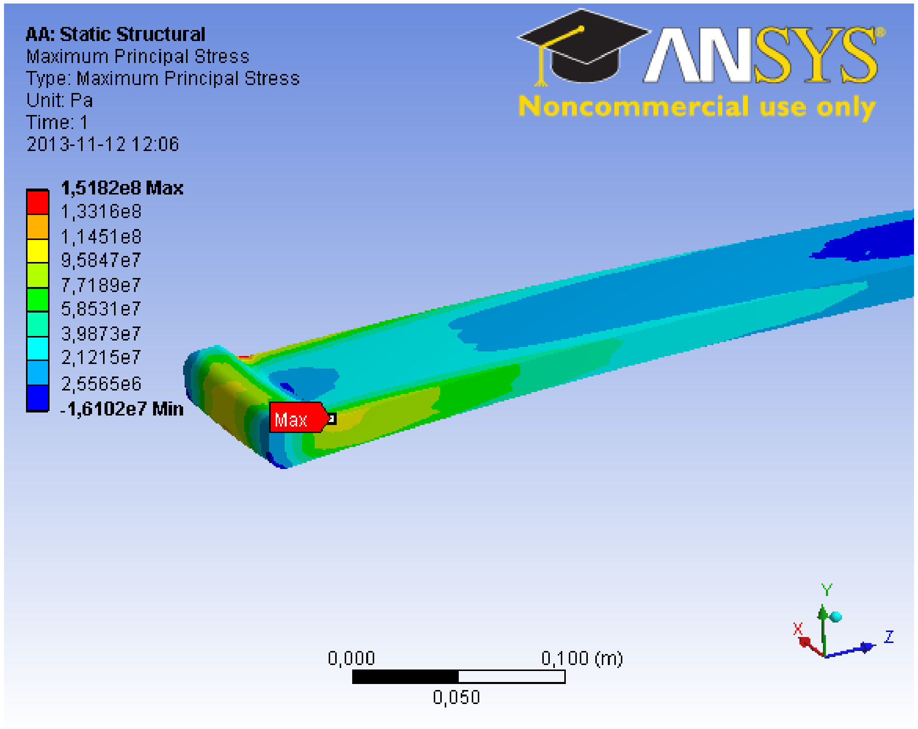




Stress analysis: Helium cooled target

Helium Cooled Target			
Target Volume	Max Principal Stress Pre-pulse	Max Principal Stress Post-pulse	Stress Amplitude
Target I	168 MPa	194 MPa	26 MPa
Target II	116 MPa	152 MPa	36 MPa





Stress analysis: Water cooled target

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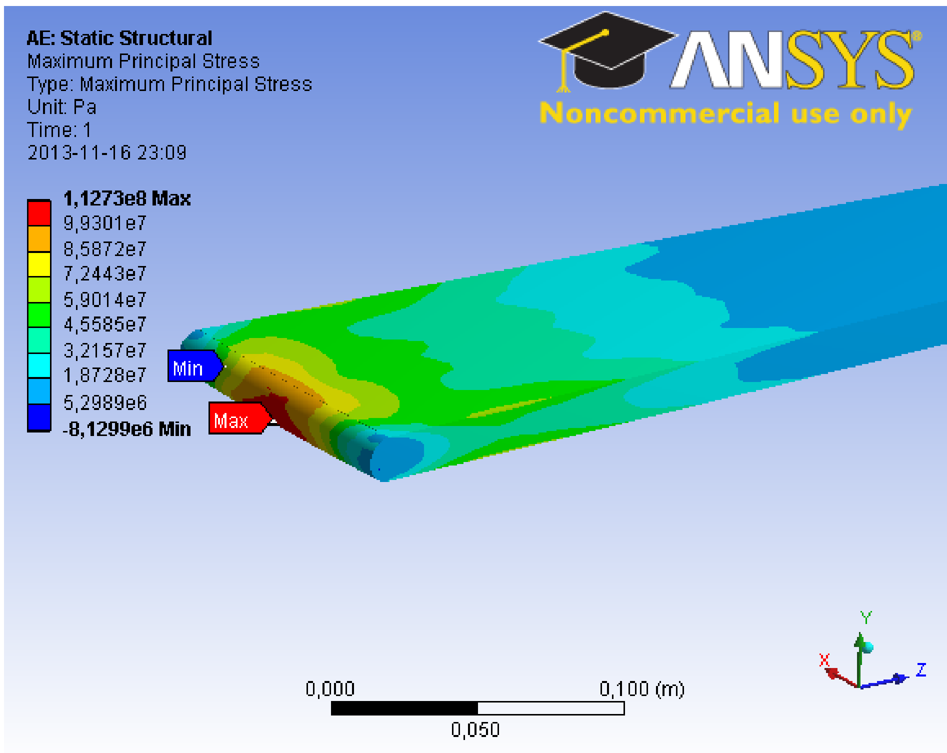
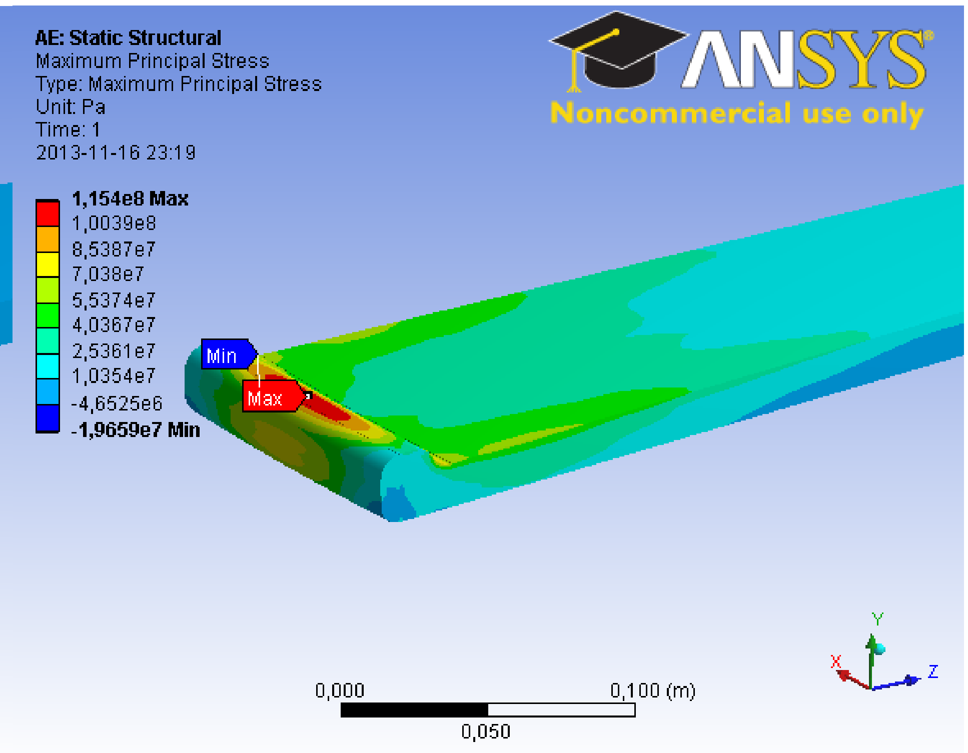
Water Cooled Target			
Target Volume	Max Principal Stress Pre-pulse	Max Principal Stress Post-pulse	Stress Amplitude
Target I	23 MPa	113 MPa	90 MPa
Target II	26 MPa	115 MPa	89 MPa





Decay heat analysis

- Irradiation history: 5 years operation with 5000 hours per year beam on target at 5 MW
- Benchmark (MCNPX): 41.5 kW in bare W at time zero

	Dose rate calculated by FLUKA in kW					
Cooling time [s]	0	3600	7200	14400	28800	86400
He-cooled Naked W	32.7	20.0	18.6	16.9	14.7	9.9
He-cooled 0.5 mm Ta-clad W	39.3	25.9	24.3	22.7	20.7	16.1
H2O-cooled 0.5 mm Ta-clad W	42.9	29.4	27.9	26.2	24.2	19.6
D2O-cooled 0.5 mm Ta-clad W	39.9	26.6	25.0	23.4	21.4	16.8

Decay heat analysis: Thermal equilibrium

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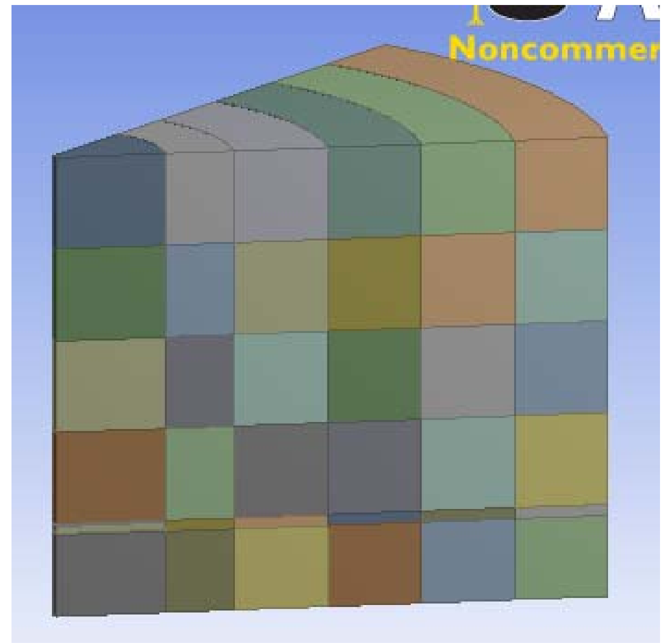
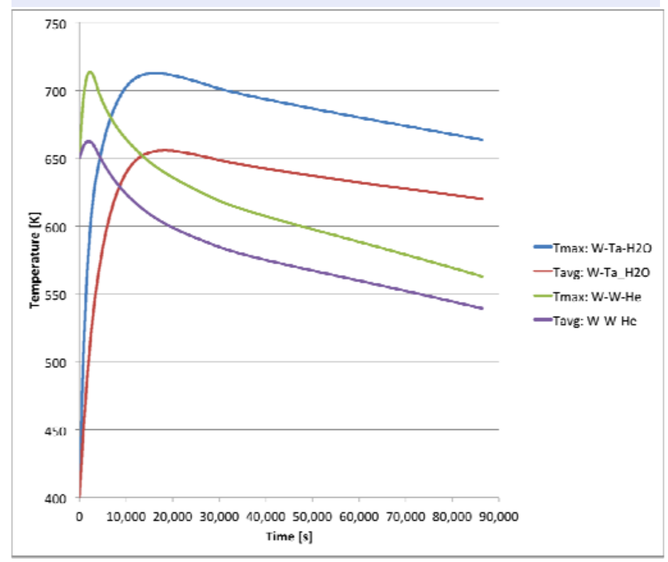
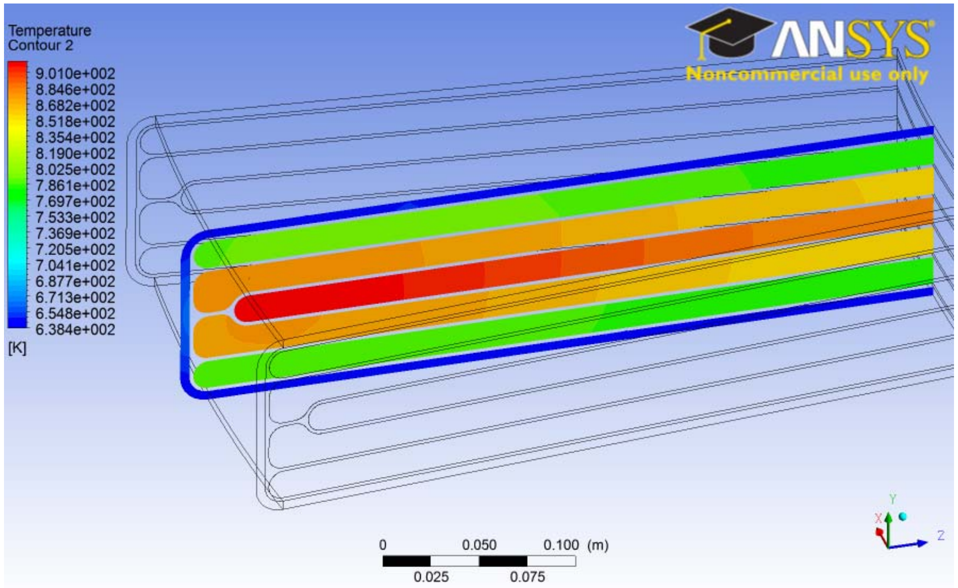
- Assumptions:
  - Normalization factor in decay heat to make it total 47 kW
  - Loss of coolant in the target and the monolith, with air ingression
- Simple tungsten disc surrounded by monolith shielding blocks with 2 cm air gap between them.

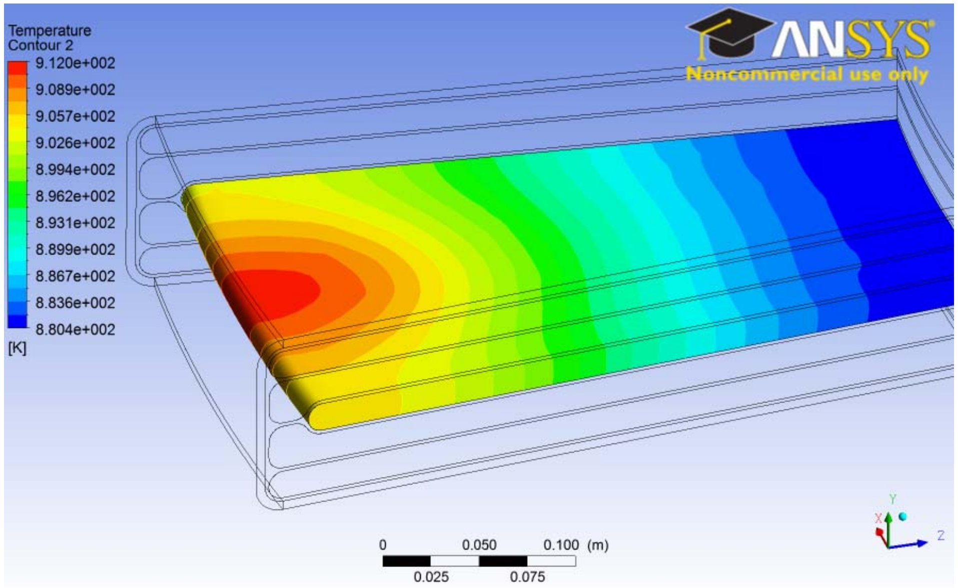




Decay heat analysis: Temperatures at thermal equilibrium

Coolant	Decay Heat at time zero	Decay heat at thermal equilibrium	Time to reach thermal equilibrium	Max. temperature at thermal equilibrium
Helium	47 kW	37 kW	40 min	**912 K**
Water	62 kW	38 kW	270 min	**928 K**



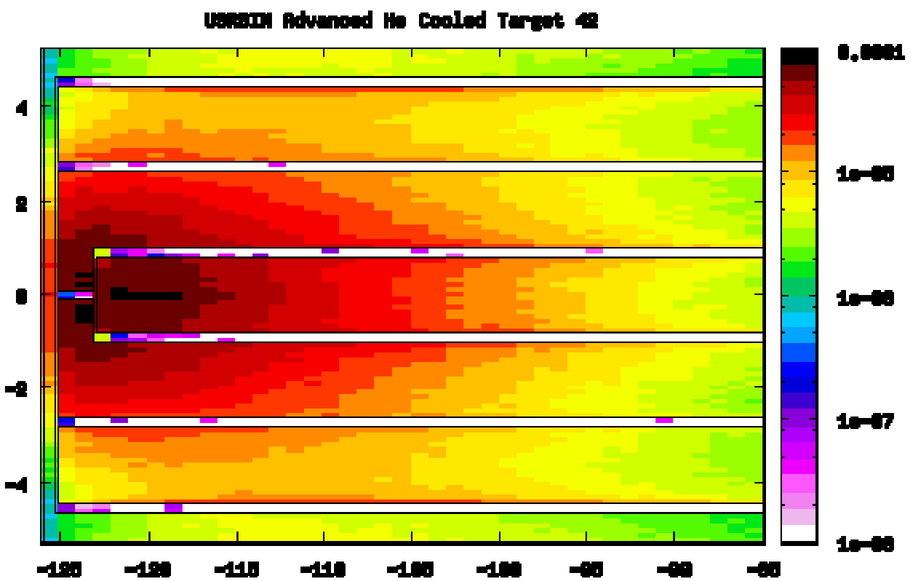


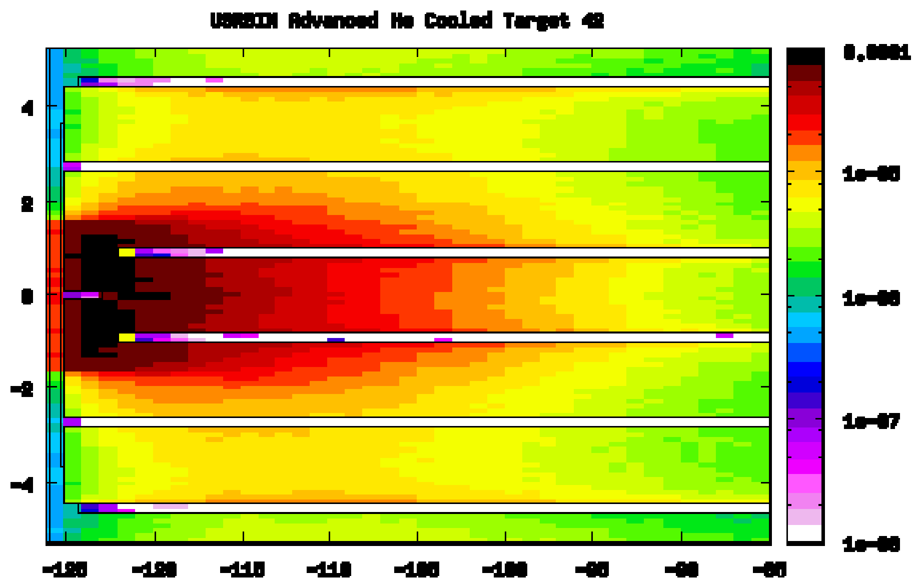
Exothermic heat analysis

- Tungsten and tantalum oxidation: exothermic process
  - W + O2 -> WO2, dH = -589.7 kJ/W-mol
  - W + 1.5*O2 -> WO3, dH = -842.9 kJ/W-mol
  - Ta + 1.25*O2 -> 0.5*Ta2O5, dH = -1023.0 kJ/W-mol
- Literature survey on tungsten and tantalum oxidation in air led to the estimation that the exothermic heat generated on the target surface will reach 10 kW at 800 C.

Thermomechanical properties under flat proton beam profile

- New accelerator baseline at ESS:
  - Rastered beam scanning a rectangular surface on beam window: dx = 140 mm, dy = 32 mm
  - Beam parameters changed from 2.5 GeV/2.0 mA to 2.0 GeV/2.5 mA, giving the peak current density on target 55.8 uA/cm2





Evolution of target configuration – V2

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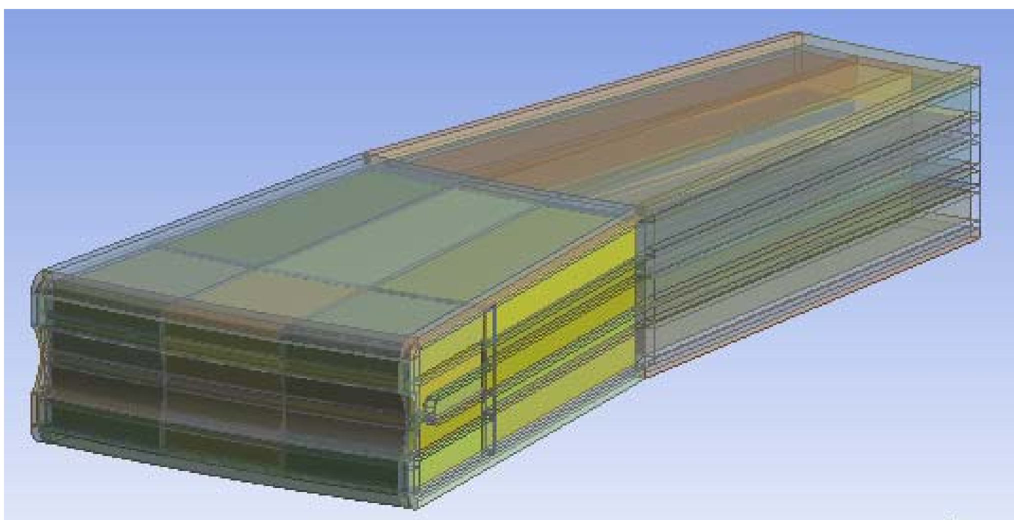
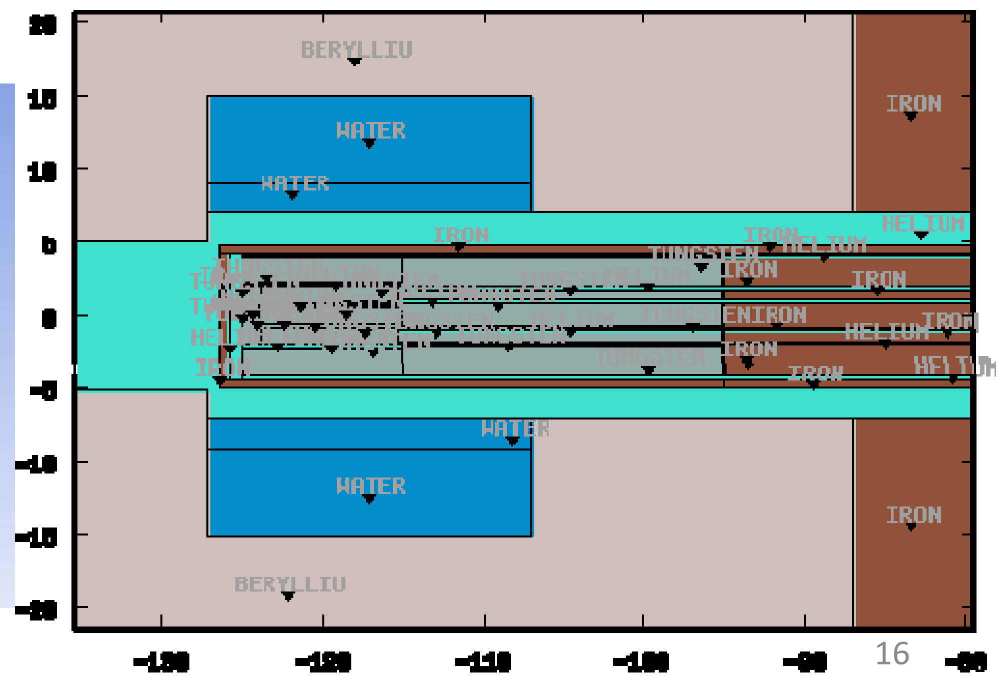
- Minimizing tungsten volume:
  - No visible neutronic penalty by reducing the W slab length from 40 cm to 30 cm and the W slab total thickness from 80 mm to 70 mm
  - Reduced W slab size reduces decay heat in W by more than 10 %.
  - Optimizing temperature and stress configurations in W volume.
  - **No through going proton beam shall be allowed!**





CFD: Transient flow analysis – V2

Helium Cooled Target: 3 kg/s @ 6 bar			
Target Volume	Max Temperature Pre-pulse	Max Temperature Post-pulse	Temperature Amplitude
Target I	697.30	753.47	56.17
Target II	714.59	800.82	86.23
Pressure Drop	49 kPa: Surface and time averaged		

Water Cooled Target: 99 kg/s @ 6 bar			
Target Volume	Max Temperature Pre-pulse	Max Temp: Post-pulse	Temperature Amplitude
Target I	320.11 K	411.76 K	91.65 K
Target II	320.31 K	417.21 K	96.90 K
Pressure Drop	34 kPa: Surface and time averaged		

Stress analysis: Helium and water cooled targets –V2

Helium Cooled Target			
Target Volume	Max von-Mises Stress Pre-pulse	Max von-Mises Stress Post-pulse	Stress Amplitude
Target I	99 MPa	93 MPa	-6 Mpa (30 Mpa)
Target II	68 MPa	125 MPa	57 Mpa (60 Mpa)

Water Cooled Target			
Target Volume	Max von-Mises Stress Pre-pulse	Max von-Mises Stress Post-pulse	Stress Amplitude
Target I	10 MPa	70 MPa	60 MPa
Target II	12 MPa	104 MPa	92 MPa

Thermal and mechanical analysis: Beam entrance window

- Each of the 33 sectors could be considered as an 150 kW spallation target.

Maximum Temperatures in Beam Window			
	Pre-pulse	Post-pulse	Temp. Amplitude
Helium Cooled Target	457.87 K	485.71 K	27.84 K
Water Cooled Target	321.63 K	351.49 K	29.86 K

Maximum Stresses in Beam Window			
	Pre-pulse	Post-pulse	Stress Amplitude
Helium Cooled Target	210 MPa	280 MPa	70 MPa
Water Cooled Target	123 MPa	153 MPa	30 MPa

Conclusions

- The feasibility of the target concept based on sectorized horizontal slabs is demonstrated, both for helium cooled and water cooled options at 5 MW proton beam power.

Coolant	Number of W slabs	Max. Post-pulse temp.	Max. Post-pulse tensile stress	Max. temp. at LOCA
Helium 3 kg/s @ 6 bar	495 bare W blocks	801 K (528 C)	125 MPa	< 639 C
Water 99 kg/s @ 6 bar	495 Ta clad W blocks	417 K (144 C)	104 MPa	< 655 C

- The exothermic heat generated from the oxidation of tungsten and tantalum could reach 10 kW at high temperatures above 700 C.
- There are relatively small number of tungsten blocks in three standardized shapes.
- The post pulse peak equivalent stress in the beam window is below 300 MPa both for helium cooled and water cooled options.

Outlook

- Next steps:
  - Thermal and mechanical optimization
  - Target vessel optimization
  - Analysis of non-axisymmetric flux distribution
  - Analysis of dynamic effects of the beam rastering
  - Down to earth engineering and prototyping
- Special thanks to Eric Pitcher, Per Nilsson and Thomas McManamy

Open discussions

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Thank you for your comments and feedback!