CERN

Target conceptual design

Beam Dump Facility (BDF)
Targetry Systems Advisory Committee (TSAC) #1
https://indico.cern.ch/event/1488161/

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With contributions from many others

04/Mar/2025

Specific questions for the Committee

1. **Do you see any feasibility issues in the proposed designs, …future production and assembly?** → Slides 6, 9, 11-13, 17, 21, 26, 28-31
2. **Do you see any potential showstopper in the FEA / thermo-mechanical calculations, for both nominal and for degraded scenarios? Are there specific topics which have been under evaluated?** → Slides 11-21
3. **Are the most important operational considerations and accident scenarios being fully addressed? Shall other situations be considered?** → Slides 6, 13-15, 27, 21, 25, 28-30
4. Do the target block R&D plans adequately support the design efforts? Do you see any potential missing aspects that would need to be considered at this stage?
5. Are the present target block design options appropriate for long-term reliability – should options be included or eliminated? • Are the plans for target prototype proton beam testing appropriate and useful to support the target development plans? Shall other complementary tests be explored?
6. **Do you identify any specific risks in the proposed target designs? Do you see areas for optimisation?** → Slides 6, 9, 11-15, 28-30,
7. Is the proposed target instrumentation package suitable for diagnosing operational and potential accident scenarios? Is there any other instrumentation you would suggest?
8. Is the current target station design in line with best operational and maintenance practices from the international community? Are there any specific improvements or design options that should be considered at this stage?
9. Is the design of the cooling and ventilation systems adequate for the needs of the target systems? Are the safety concerns associated with such a cooling system being addressed and mitigated in the current design? Including maintenance scenarios of the cooling system
10. Are radiation protection aspects adequately considered in the design of the complex, both in terms of operation as well as waste management?
11. Is the concept for the service cell in the target service building appropriate to tackle the challenges of maintenance and waste packaging of the target systems?
12. **Do we have to consider additional failure scenarios?** → Slides 6, 9, 17, 21, 29-30

Contents

https://doi.org/1

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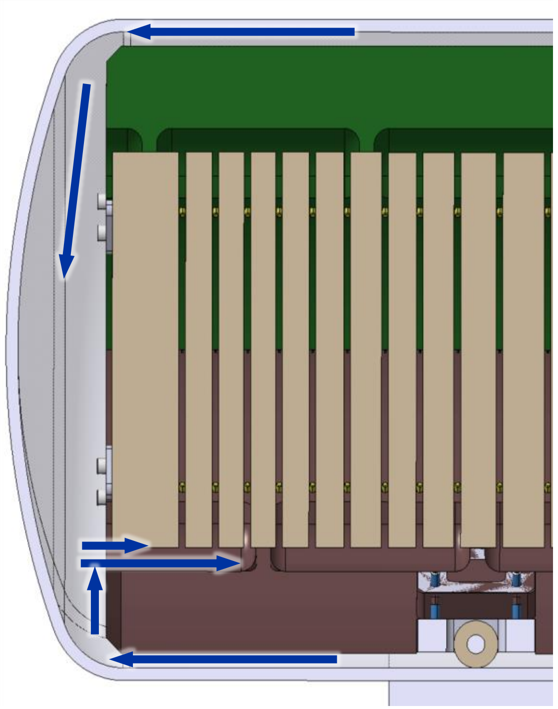
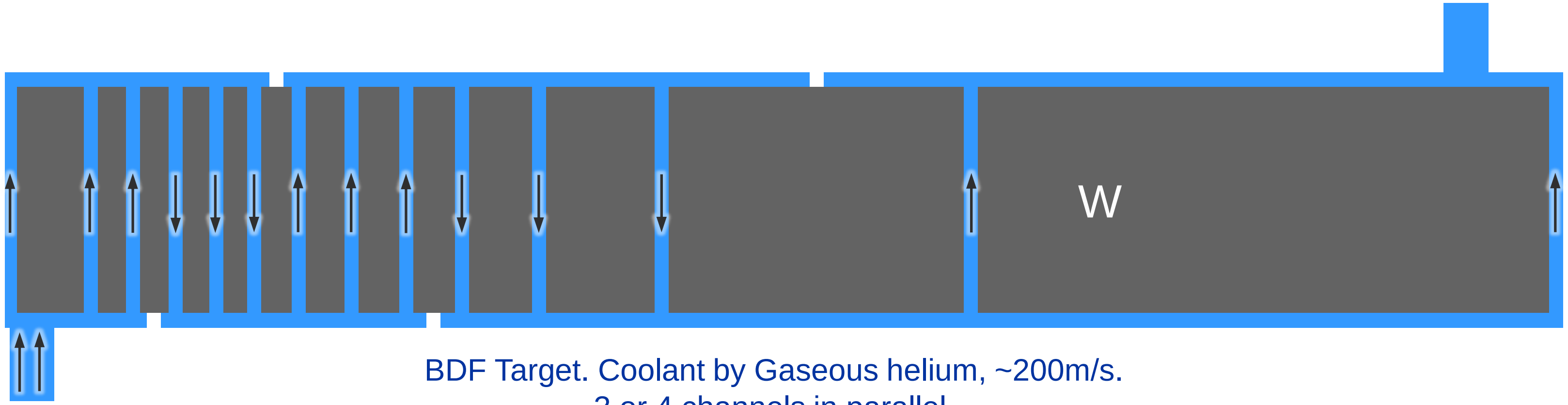
Helium cooled design on core blocks





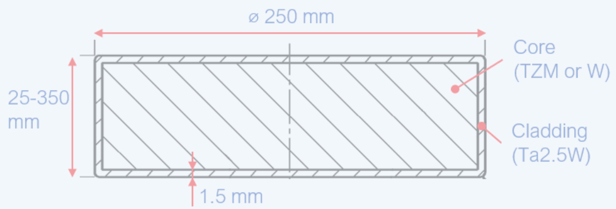
BDF Target. Coolant by Gaseous helium, ~200m/s.
3 or 4 channels in parallel.

Static

13 x TZM

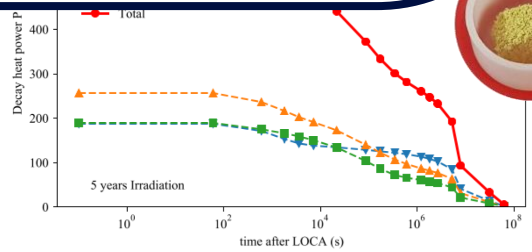
Water-c

- TZM
  cree
- W: C
- Ta2.
- Manu
  Claddi
- Cooling: 22 bar, 5 m/s, ~600l/min,



Reduce Ta cladding

4) PIE revealed W quality to be poor
→ Improve W properties



Past study: Post-irradiation examination of a prototype tantalum-clad target for the Beam Dump Facility at CERN, T. Griesemer, R.F.Ximenes, https://doi.org/10.48550/arXiv.2410.01964

W material

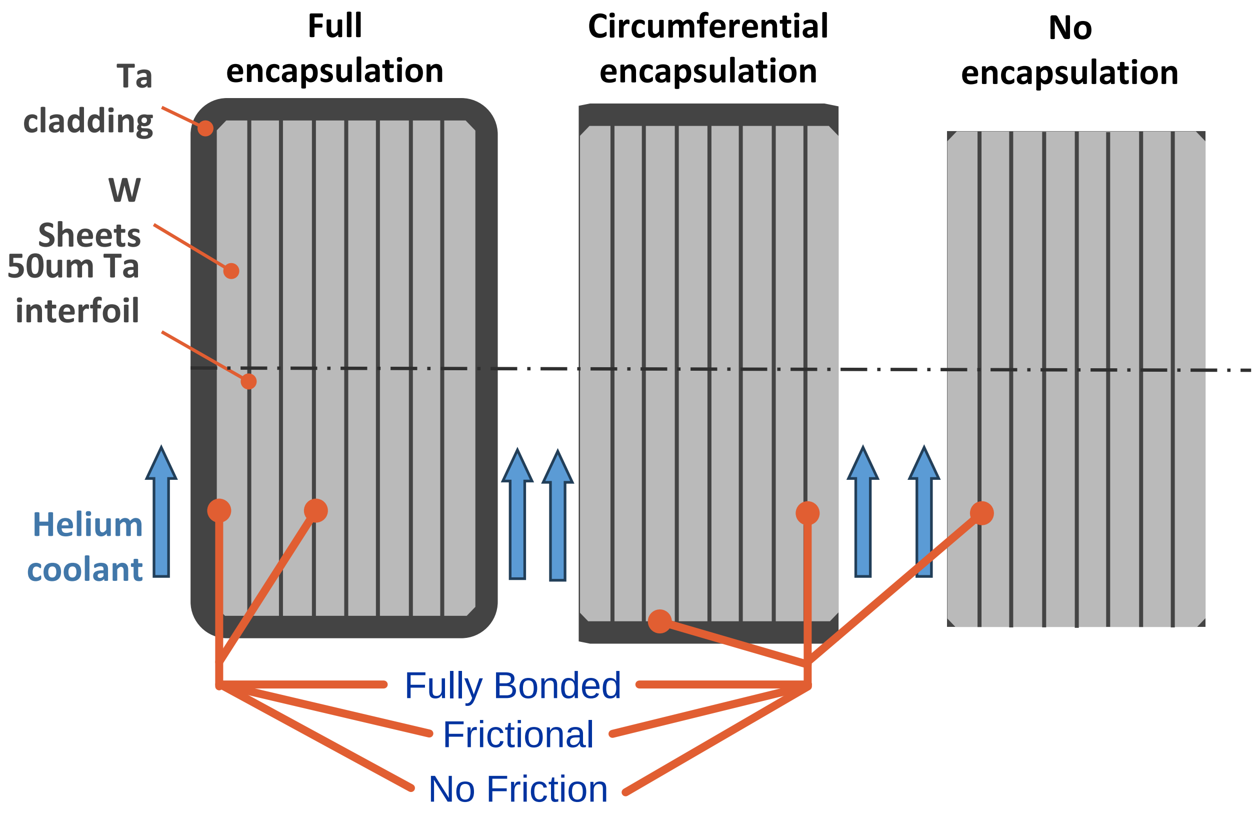
Hot rolled W & cladding

- ***Water cooled target was Sintered & HIPd; – pores, crack near cladding & poor UTS***
- **Now looking at Hot rolled W sheets**
  - Aiming for improved material properties & reduced risk of cracking
- **5mm vs 17mm** (later blocks could be SH)
  - Guaranteed properties vs reducing interlayers
- **Weak point likely to be interface**
  - Now bulk W properties much improved
- From studies, we expect **good thermal contact**
- **Lasagna structure applicable for Helium and H_2O target**
- **Investigating 3 cladding cases for He target only**
- **Is cladding needed to keep the laminations together? (& at high irradiation!?)**
- **Ongoing material testing**

Drivers:

- Must be clad for HIPing joining process
- Don't want cladding: high stresses at the cladding
- Don't want cladding: Ta produces lots of decay heat
- Do want cladding at circumference: Compressive stresses beneficial to W sheets

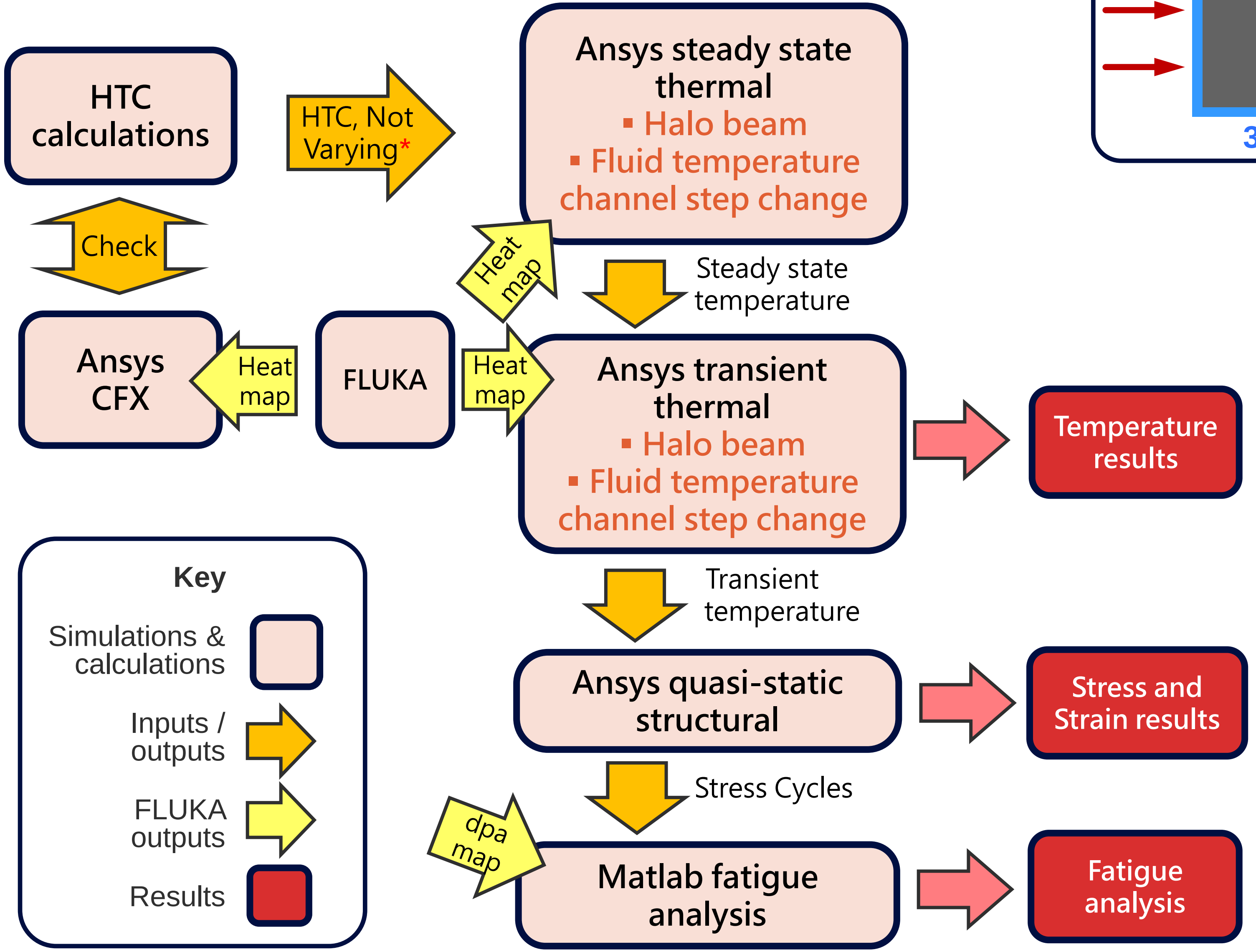
Manufacture: Cladded for HIP, then partially/fully/none machined away

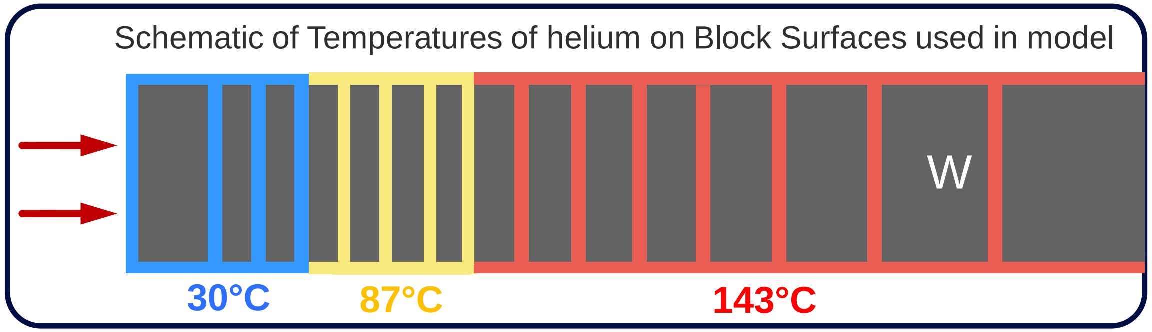


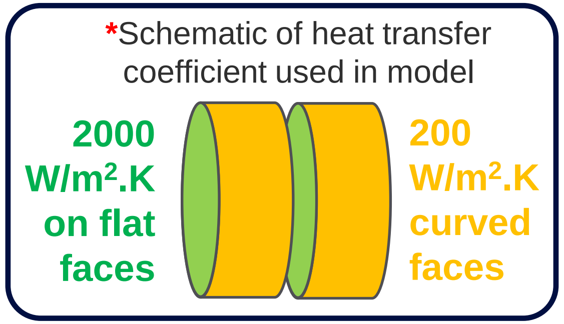
Cases to be investigated

Helium Target Modelling

He simulation Overview







Assumptions used in models so far

- **Non internal block structure**
- **Isotropic materials**
- HTC not varied in x,y,z.
- Used simplified Helium temperature change
- Halo beam used

  → 4Hz Painted beam compared to halo for many cases
- **Simulations assume steady 7.2s cycle. Supercycle is ignored, except when investigating fatigue!**

Design methodology

References:

- *[1]CERN EDMS 2648378*
- *[2]"Vaporization of tungsten in flowing steam at high temperatures", G.A Greene and C.C. Finfrock, Experimental Thermal and Fluid Science, 2001 https://doi.org/10.1016/S0894-1777(01)00063-2*
- *[3]https://doi.org/10.1016/j.jnucmat.2017.12.018*
- *[4] J. Habainy et al., "Mechanical properties of tungsten irradiated with high-energy protons and spallation neutrons," Jn Nuclear Mat. vol. 514,(2019) 189-195*
- *[5] J. Habainy et al., "Fatigue properties of Tungsten from two different processing routes," Jn Nuclear Mat. vol 506 (2018) 83-91*

Light optimisation was performed to obtain a model that was then used for investigations & sensitivity studies.

- ❑ 16mm beam σ was used
- ❑ This geometry was then used for the simulations in this talk, **including for 8mm beam**
- ❑ Optimisation will be reperformed when initial material testing / HIP results are available

Design limits chosen:

**More on fatigue methods in later slides!

Property	Limit description	Values	Limit logic used
❑ Oxidation/ Corrosion	❑ Surface temperature limit	➢ 350°C	❑ 50°C under formation of oxide WO_2 @ 400°C. [1-3]
❑ Stress	❑ UTS limit	➢ 150MPa	❑ Factor ×2 under UTS of 1cm cross rolled W plate at 2dpa [4]
❑ Fatigue limit	❑ Goodman equivalent at 1e7 cycles	➢ ≤164MPa**	❑ Back calculated equivalent stress from [5], extrapolated to 1e7c, reduced ×2 for irradiation**
❑ Stress in brittle material	❑ Christensen criterion	➢ From mech' testing results	❑ <0.5 in blocks 1-14.

Helium Target Results

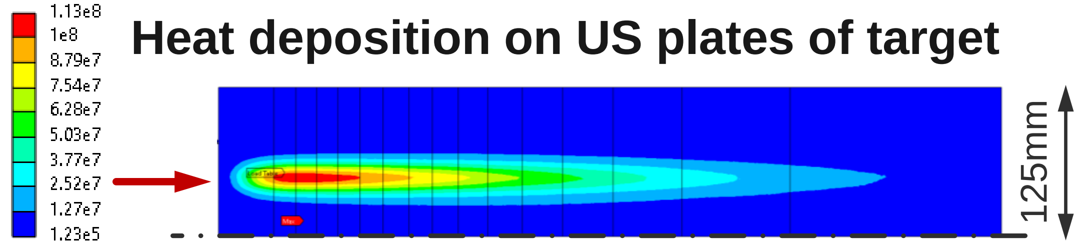
Simulation Results

Helium Target Overview

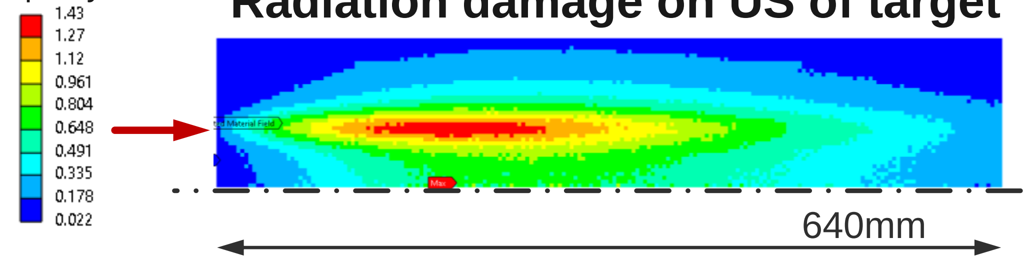
- Block temperatures not sensitive to value of HTC.
- Block temperature step-increase ‘pattern’ is highly dependent on Helium temperature.

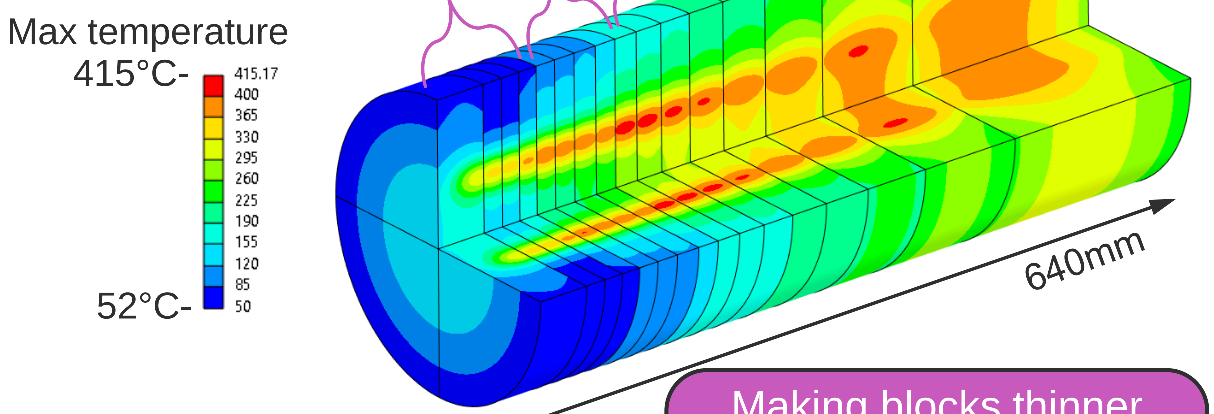
- 8mm beam, **after pulse**
- ø250mm
- Blocks 1-16 shown

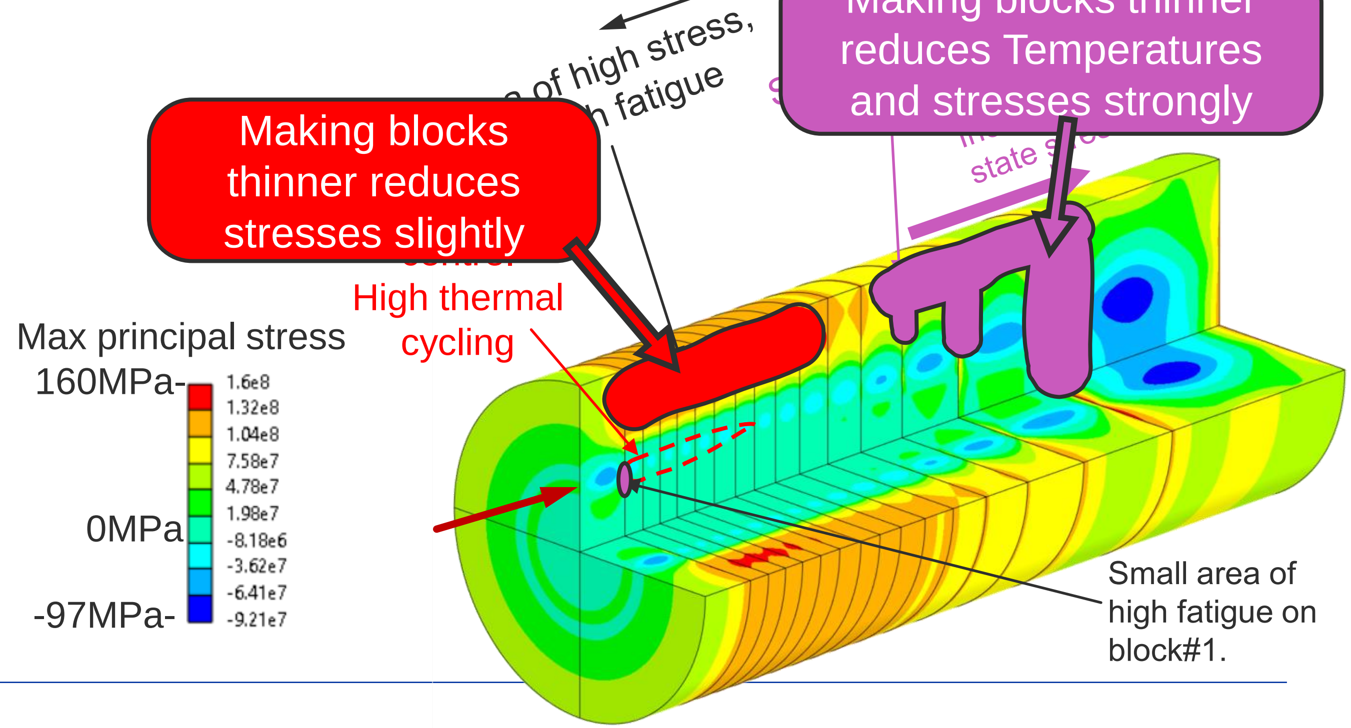
Heat deposition on US plates of target



Radiation damage on US of target





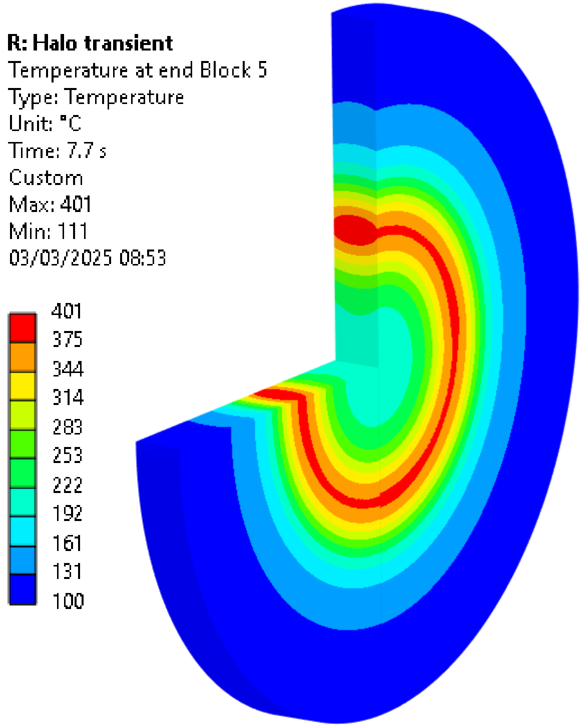


Simulation Results

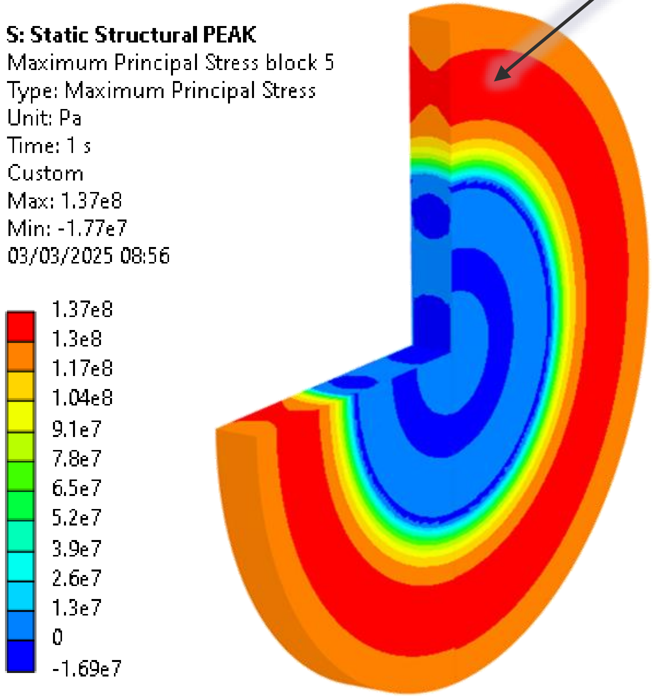
Helium Target block – σ 8mm - after pulse

Circumferential tensile stress

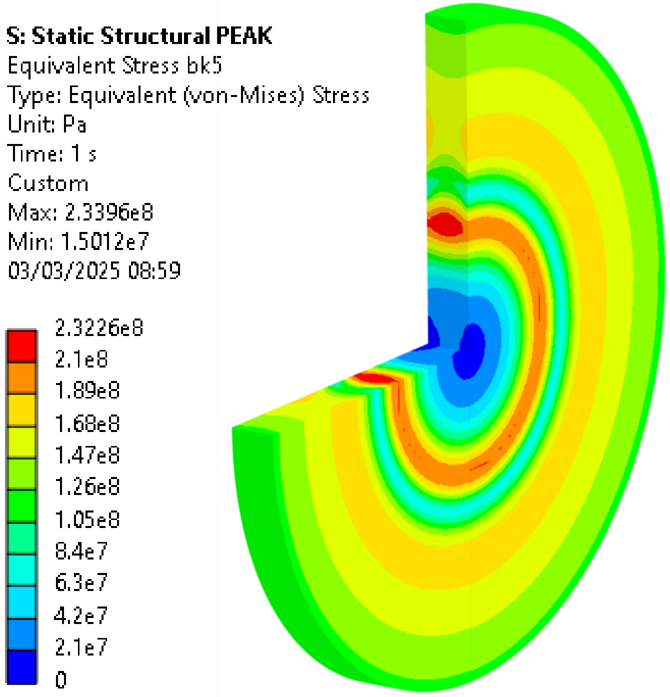
Temperature

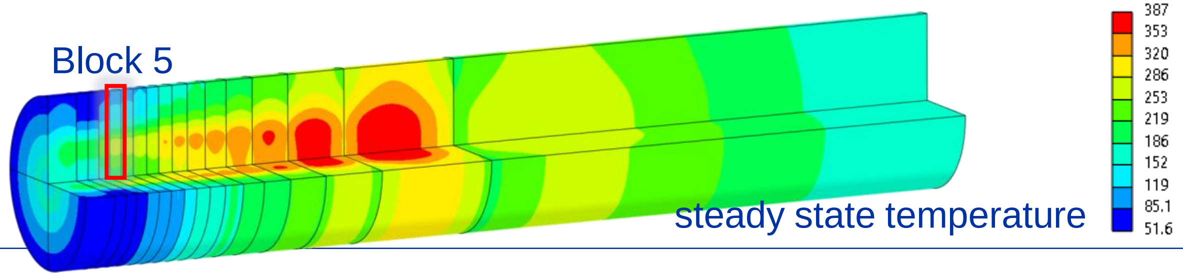


Principal stress

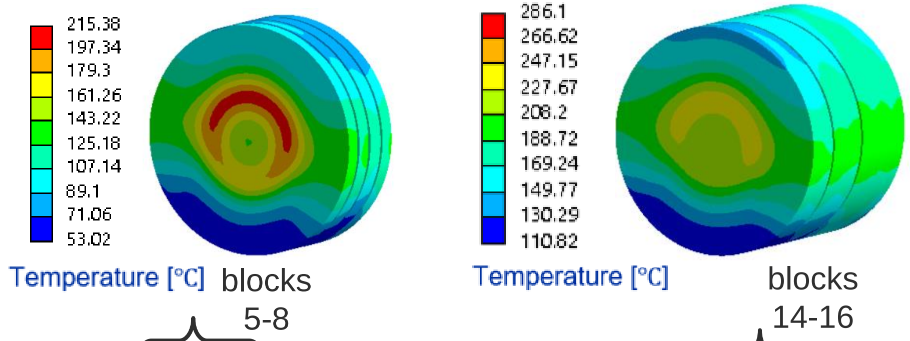


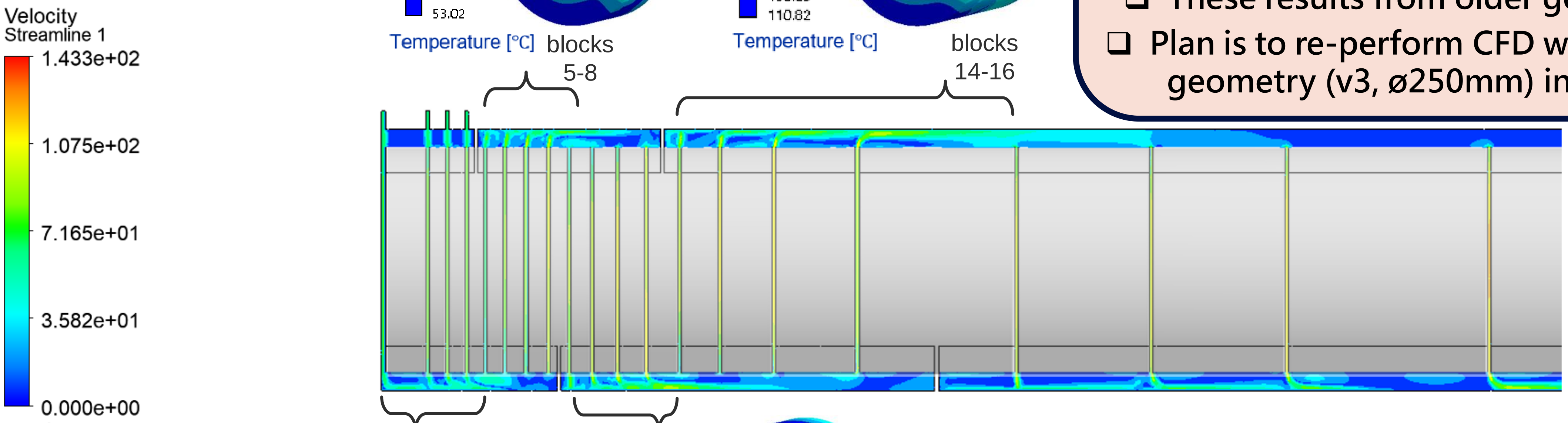
Equivalent stress

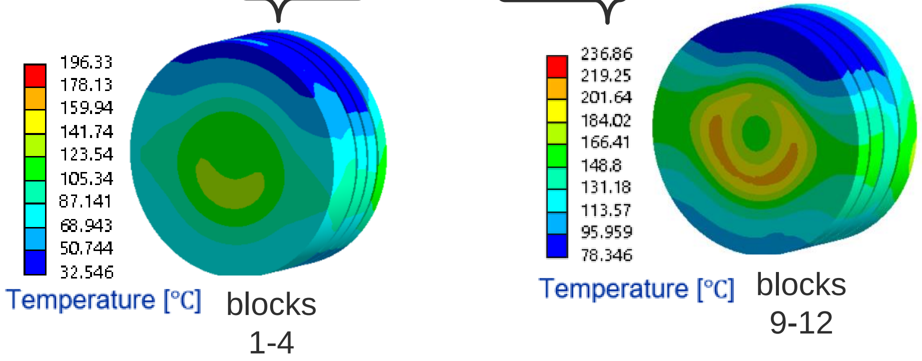




CFD







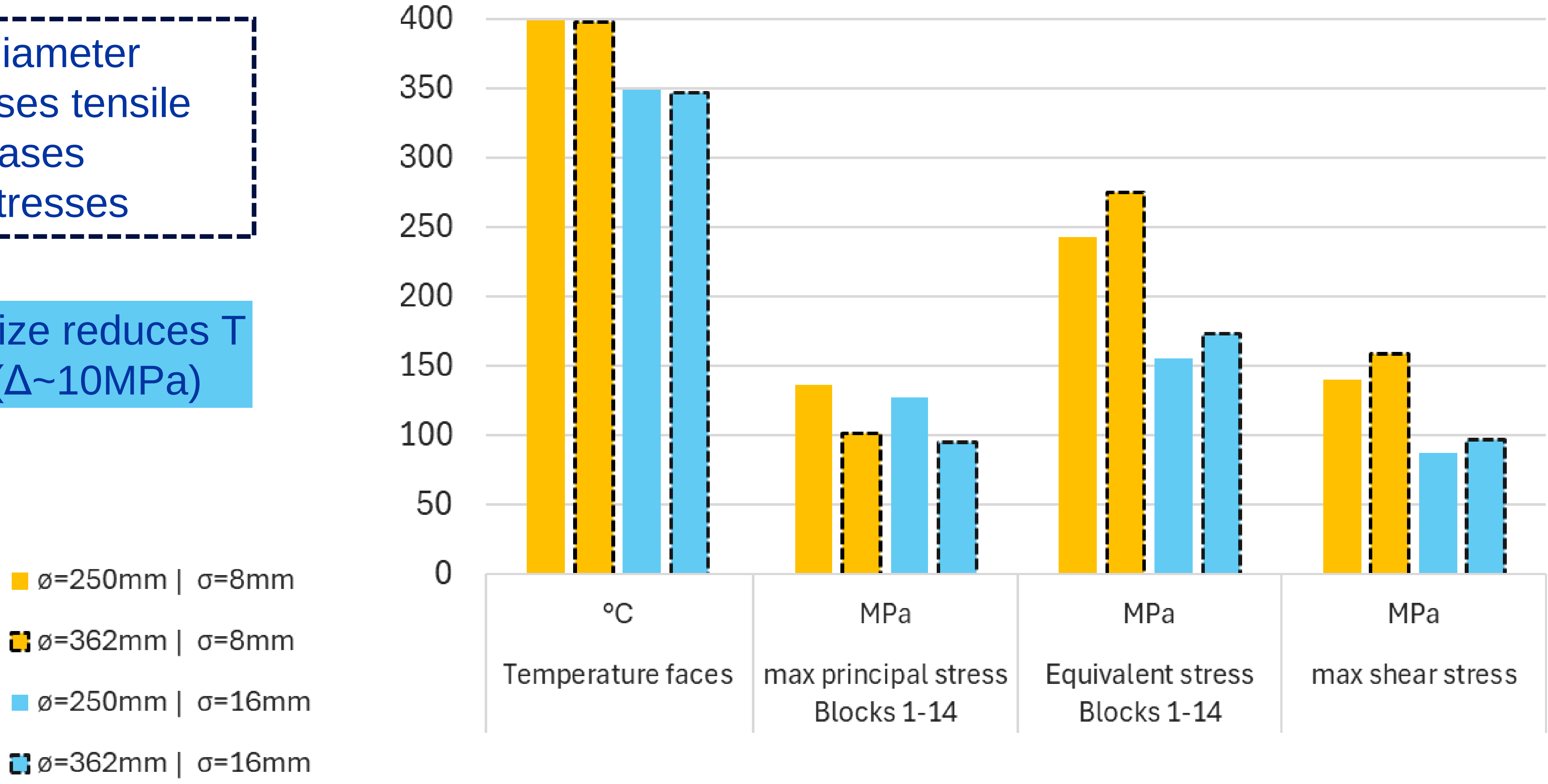
- ❑ Note uneven temperature map
- ❑ Results shown are Quasi -steady-state
- ❑ -Temperature map not included in general thermal model
- ❑ Final channel distribution TBD
- ❑ These results from older geometry (v2)
- ❑ Plan is to re-perform CFD with latest CAD geometry (v3, ø250mm) in March 2025

- **400g/s**
- **Outlet helium ~170°C**
- **Pressure at inlet = 16bar**
- **ΔP = 0.7bar**
- **Channels in parallel = 4**

Target diameter & Beam size

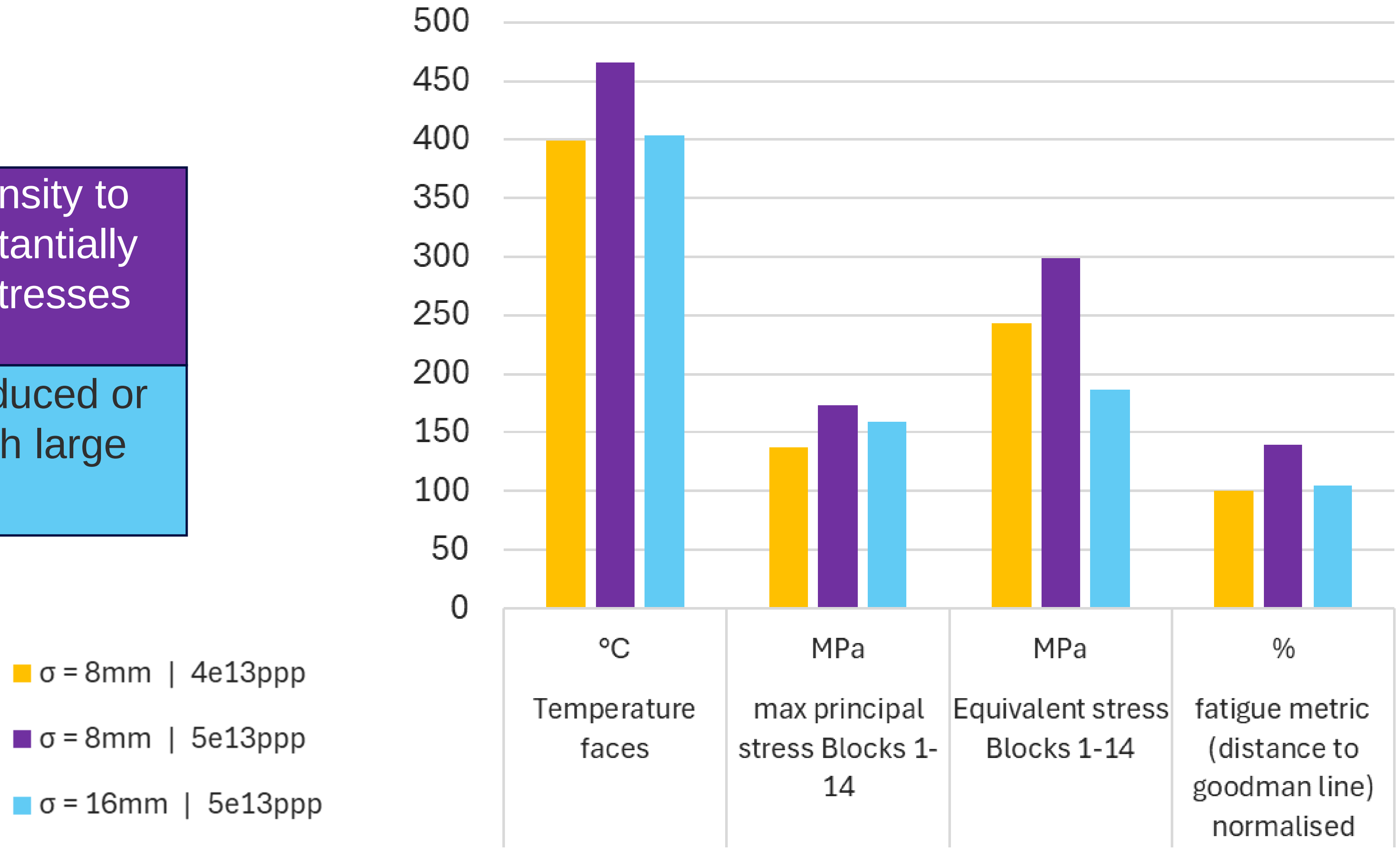
- ❑ Larger target diameter slightly decreases tensile stresses, increases compressive stresses

- ❑ Larger beam size reduces T (Δ~50°C) & σ (Δ~10MPa)



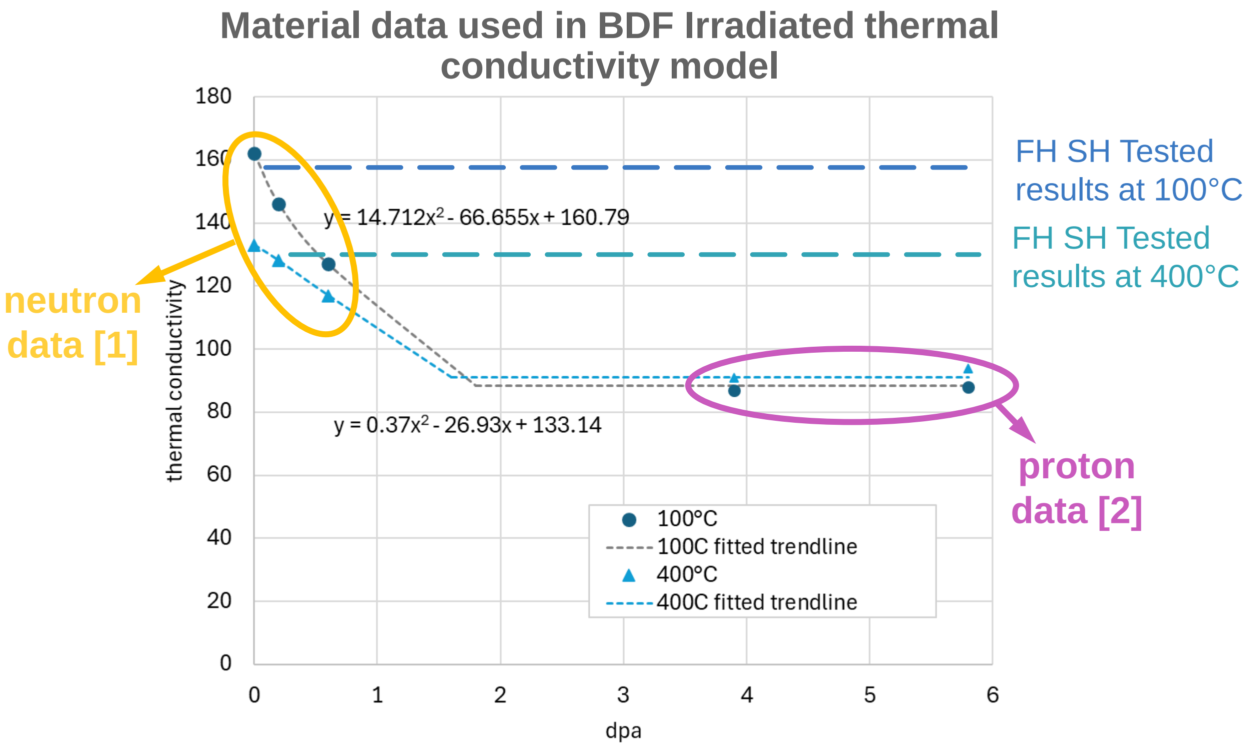
Intensity & Beam size

- Increased intensity to 5e13ppp substantially increases T, Stresses and fatigue.
- Increase is reduced or eliminated, with large beam size



Radiation reduced Thermal conductivity

- DPA dependent conductivity results from literature
  - At 100°C and 400°C
  - Mainly using neutron data at our level of dpa (<1.5)
- We applied the dpa dependent conductivity to the Ansys model…



References - Dpa dependent conductivity in the literature

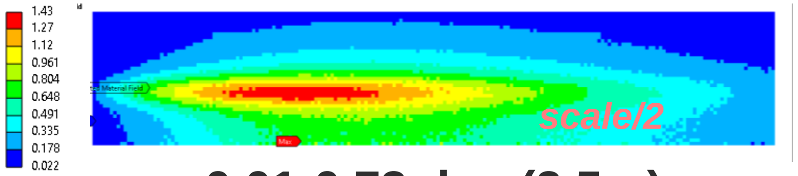
[1] Data [neutrons]: *M.Roedig et al. "Post irradiation testing of samples from the irradiation experiments PARIDE 3 and PARIDE4," Journal of Nuclear materials 329-333 (2004)766-770*

[2] Data [protons]: *J. Habainy et al. "Thermal Diffusivity of tungsten irradiated with protons up to 5.8dpa," Journal of Nuclear materials 509 (2018) 152-157*

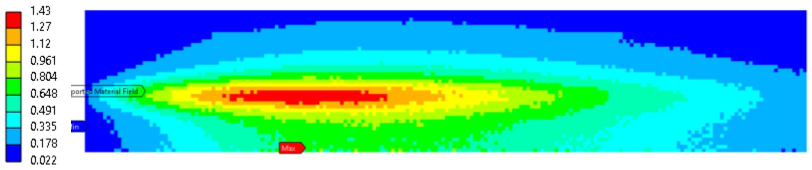
Radiation degraded conductivity – Helium target

Temperature dependent k 0 POT 0 years operation	DPA dependent k 1e20POT 2.5 years operation	DPA dependent k 2e20POT 5 years operation

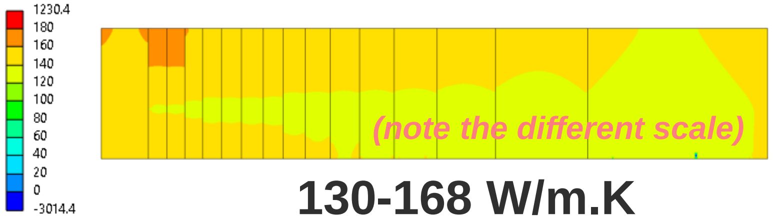
0dpa



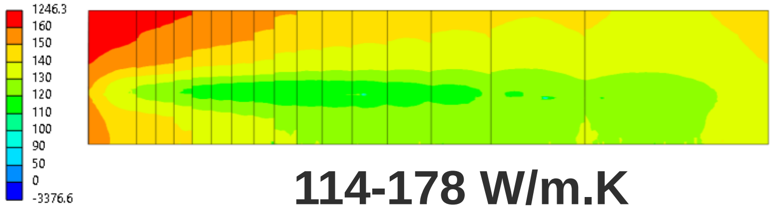
0.01-0.73 dpa (2.5yr)



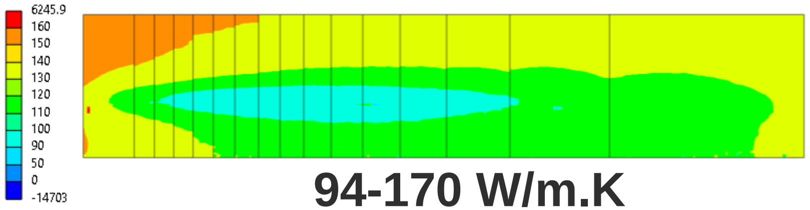
0.02-1.46 dpa (5yr)



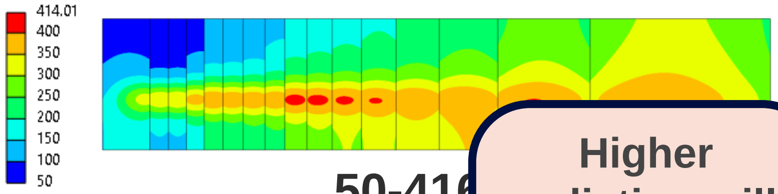
130-168 W/m.K



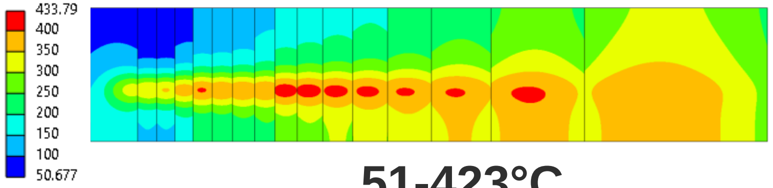
114-178 W/m.K



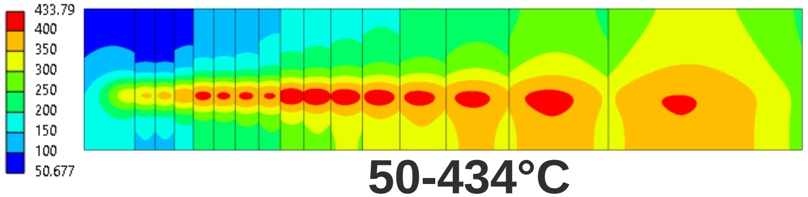
94-170 W/m.K



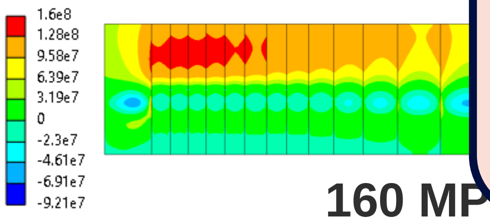
50-416



51-423°C

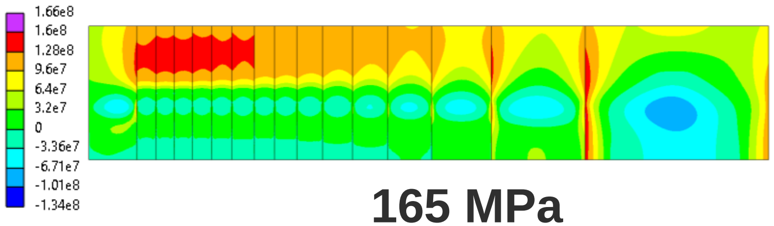


50-434°C

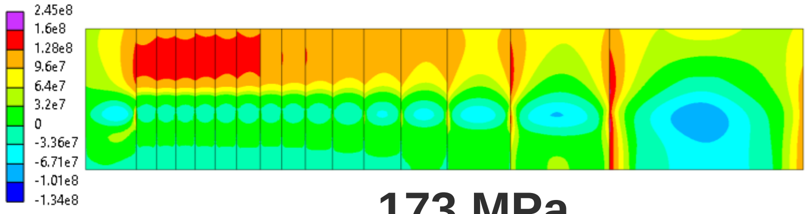


160 MPa

Higher radiation will also increase DBTT above the working temperature



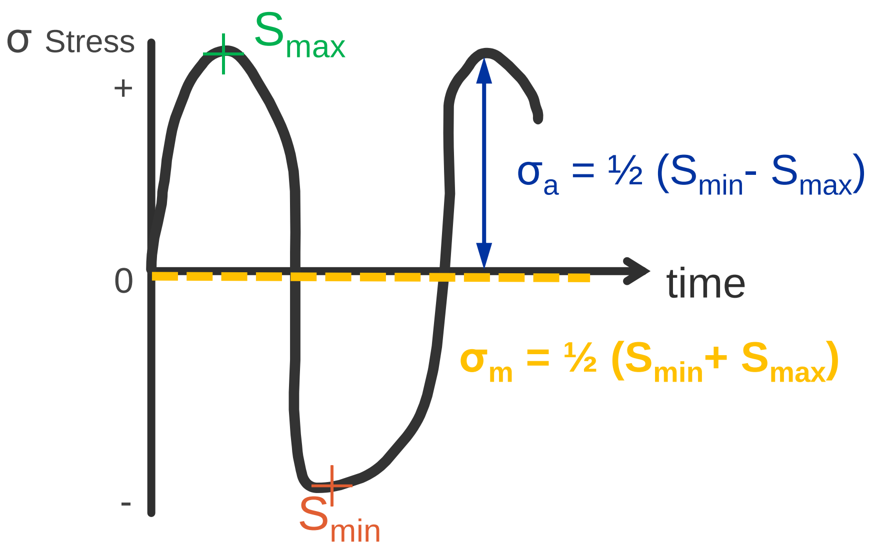
165 MPa



173 MPa

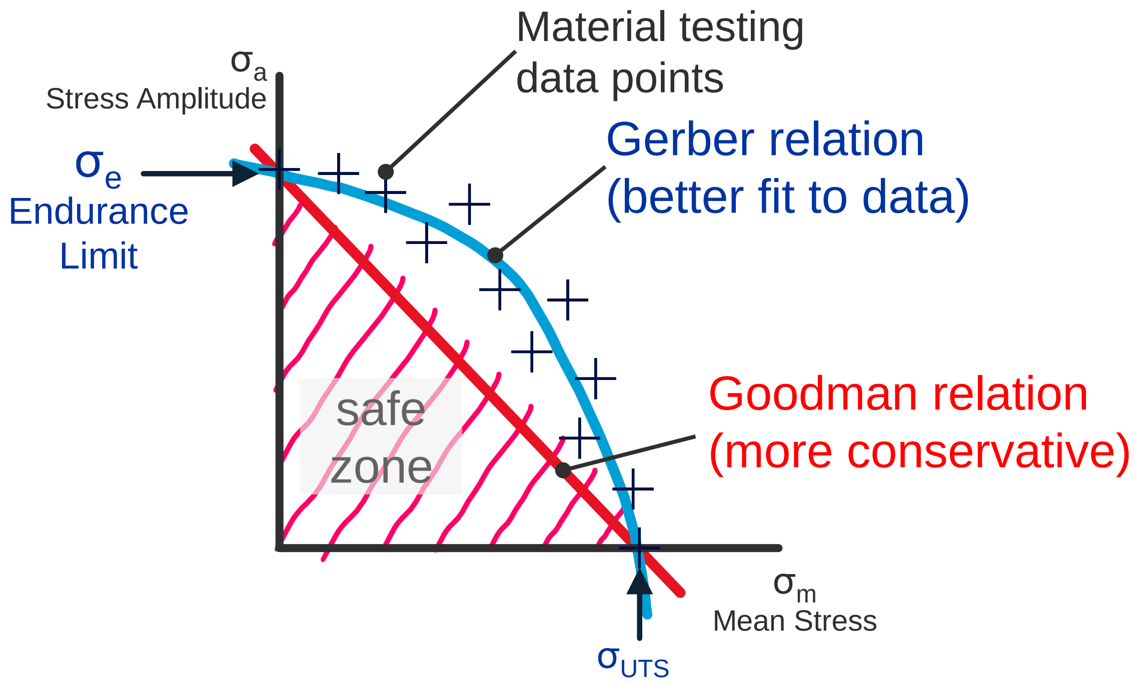
Goodman diagrams

Material testing example:
Fully reversed stress



$R = S_{min}/S_{max}$

- When test cycles are fully reversed, R= -1.
- If fully in tension, 0<R<+1



- Goodman Diagram can be used to compare stress cycles with different σ_m & σ_a.
- Goodman and Gerber lines are different fits to the material testing data.
  - Endurance limit σ_e is when σ_m stress = 0, ∴r = -1.
  - σ_{UTS} *is where* $\sigma_a = 0$.
- Without material data from fully *reversed cycles* ($\sigma_m = 0$) the Endurance limit (σ_e) is not well known
- **From the theory, it is therefore not conservative to draw/calculate σ_e using goodman from a small number of non-fully reversed testing points**

DPA fatigue damage approach

Available fatigue data			
Unirradiated W	2e6 cycles 3-point-bend tests	• Ø5mm bar Sintered, rolled & annealed • Ø5mm bar Sintered and HIPd	[1]
Unirradiated W	2e7 cycles	No data	
Irradiated W	**No data**	**No data**	

1. Obtain a dpa damage map from FLUKA

2. Convert to a damage factor based on literature

DPA	damage factor = stress increase factor
0 to 1	Linear increase from 1 to 2
>1	=2

3. Apply the damage factor map to the target stress results

- ❑ ***FACTOR OF 2****: p+ irradiated tungsten:* UTS reduced by ½ and saturated **by or before 1.3dpa** [1].
- ❑ **THEN SATURATES**: Yield stress increased steeply **up to 1dpa,** and then gradually up to 23 dpa [2].
- ❑ ***LINEAR INCREASE****: n. irradiated Tungsten*: hardness increased linearly **between 0.2 and 1dpa at 600°C** [3].

- ❑ The results for BDF target are represented on a goodman diagram (next slide) with an added general safety factor of ×2

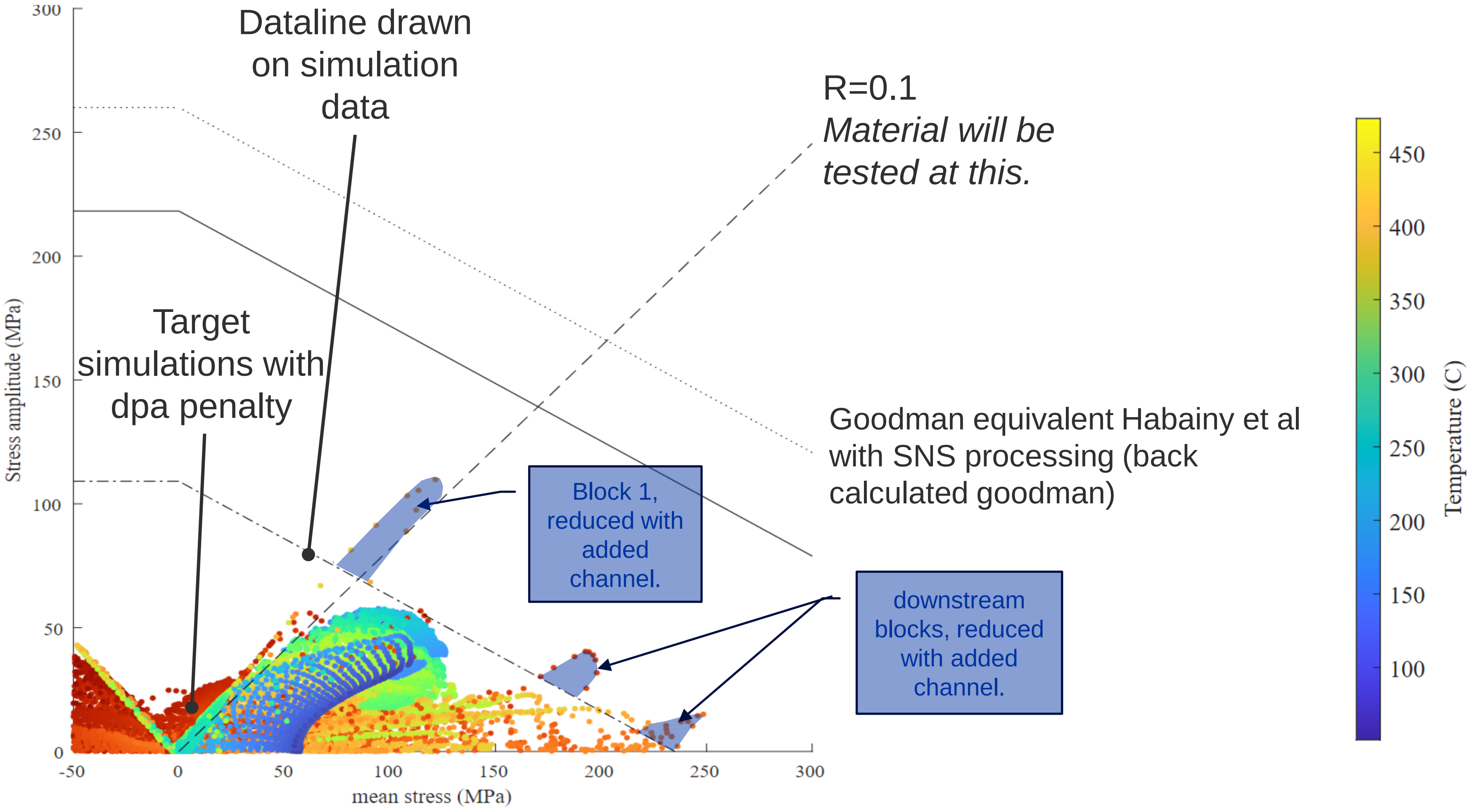
- ❑ Key to the validity of this approach is that increasing the maximum principal stress of a node through stress cycles proportionally increases:
  - Mean stresses
  - & Stress amplitudes

- ❑ We believe this approach is conservative (Applying a fatigue factor based on <u>end of life </u>dpa levels is inherently conservative) but not overly conservative.

References:
[1]"Mechanical properties of Tungsten irradiated with high-energy protons and spallation neutrons, J. Habainy, Y. Dai, Y Lee, S. Iyengar, Journal of Neuclear Materials 514 (2019) 189-195
[2]"Radiation Effects in a Couple Solid Spallation Target Materials", S.A. Maloy, W. F. Sommer, M.R. James, T.J. Romero, M.L. Lopez, Los Alamos National Laboratory, Los Alamos, NM 87545
T.S. Byun. Oak Ridge National Laboratory, Oak Ridge, TN
[3] Neutron irradiation hardening across ITER diverter tungsten armour D. Terentyev, C. Yin, A. Dubinko , C.C. Chang, J.H. You

Target Fatigue - Helium

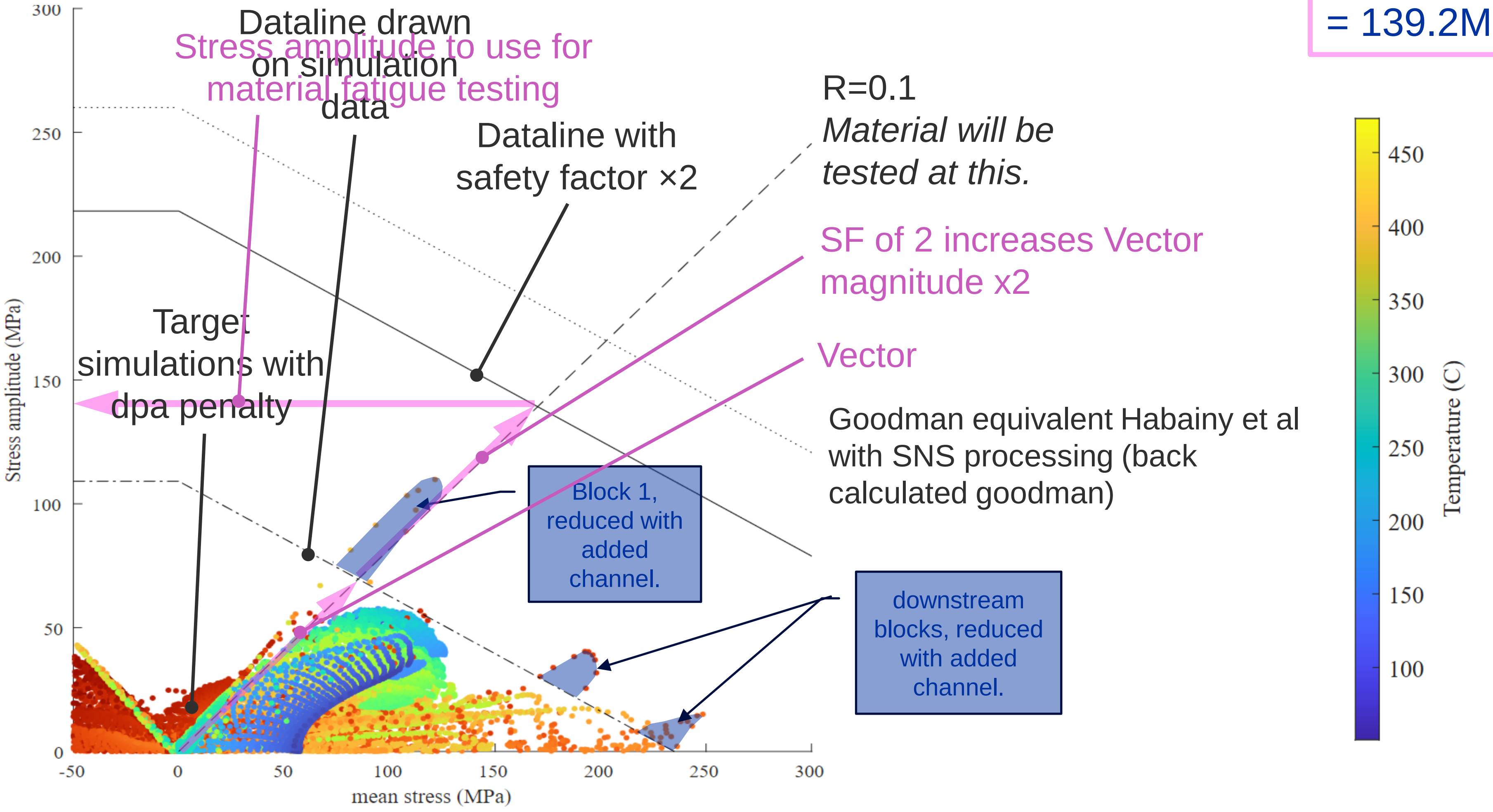
With radiation damage penalty



Target Fatigue - Helium

With radiation damage penalty

Stress amplitude when R=0.1 with safety factor of ×2 = 139.2MPa

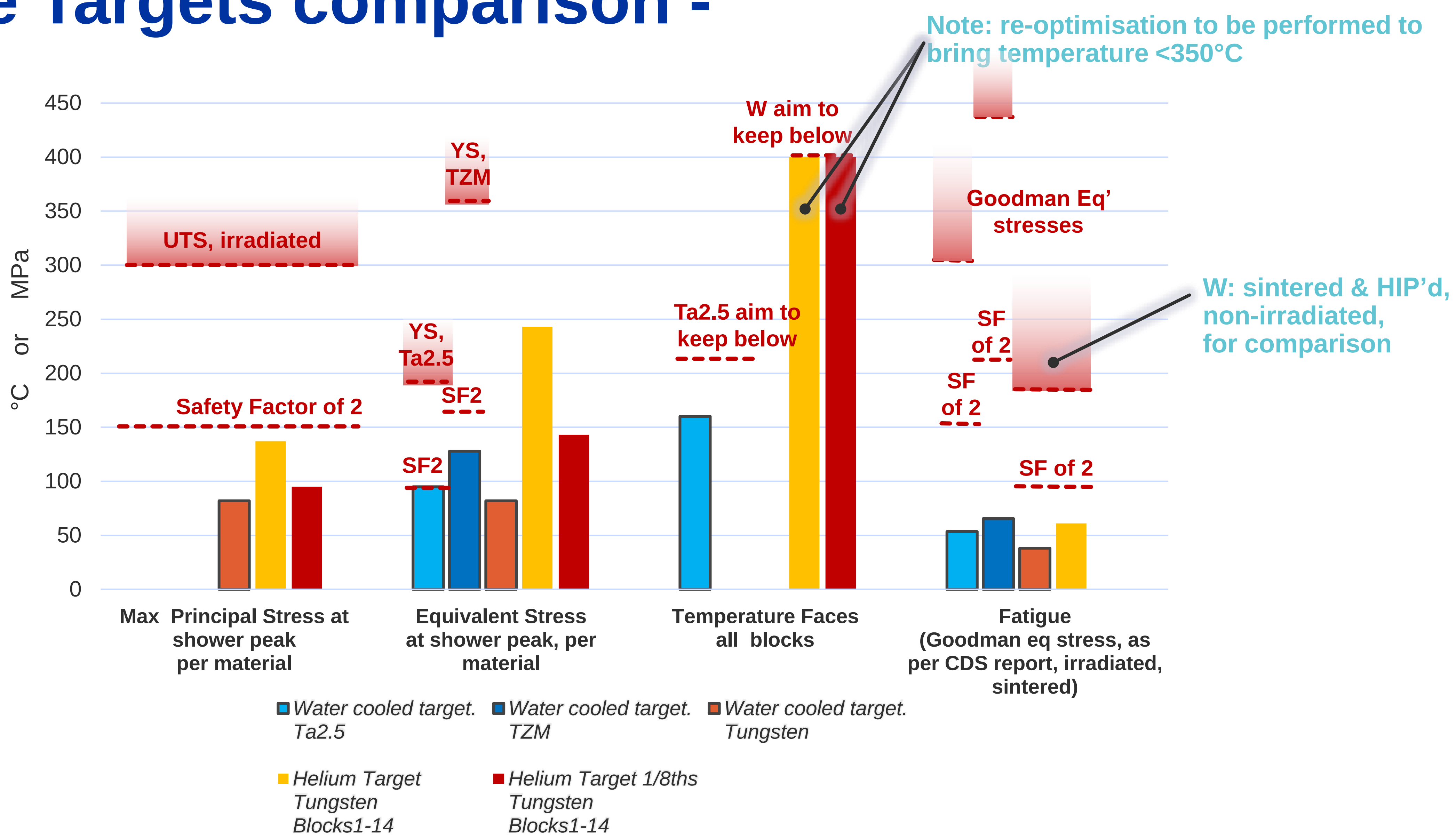


- ❑Results for swept beam @4Hz has not yet been analysed

Comparison of Helium & Water Target

H_2O & He Targets comparison - Margins

8mm beam



$H_2$0 & He Targets comparison – Results table

Material	Target design	Coolant pressure	Blocks bulk max T	Blocks Surface Temperature	Stress Max Principal	Stress Equivalent	Chrsitensen if: UTS=300MPa UCS=800MPa	σ_a	σ_m	Fatigue limit [1]	YS Sintered&Hip'd for W [2]	SF on yield / UTS	SF on fatigue
		bara	°C	°C	MPa	MPa	-	MPa	MPa	MPa	MPa		
			Whole Target	Whole Target	Blocks 1-14	Whole Target	Blocks 1-14						
All	Water Cooled	25		-									
Tungsten	Water Cooled	25	150	-	82	82		32.5	49.5	180	330 [YS] at RT *	4	5
Ta2.5	Water Cooled	25	160	160		95		45	50	310	190 [YS]at 200°C	2	5.8
TZM	Water Cooled	25	180	-		128		58	68	440	370 [YS] at 200°C	3	6.7
Tungsten	Helium Cooled (Not clad)	16	415	400	137	243	0.32	43 (unirr')	98 (unirr')		330 [YS] at RT *	2.4	2.6 (unirr') by same metric used above
Tungsten	Helium Cooled 1/8ths (Not clad)	16		400	95	143					330 [YS] at RT *	3.5	

Water cooled limits: Comprehensive design study (CDS) https://e-publishing.cern.ch /index.php/CYRM/issue/view/106/pdf_7

[1] Fatigue limits from CDS referenced as:
- TZM: H. A. Calderon et al. "Microstructure and plasticity of two molybdenum-base alloys (TZM)".In:Mater. Sci. Eng. A160 (1993), pp. 189–199.
- W: J. Habainy et al. "Fatigue properties of tungsten from two different processing routes". In:J. Nucl.Mater.506 (2018), pp. 83–91.
- Ta2.5: W. Martienssen, H. Warlimont. "Refractory metals and alloys". In:Springer Handbook of Condensed Matter and Materials Data. Springer, 2005. Chap. 3.1.9

[2] YS, UTS from CDS referenced as:
- Fraunhofer IFAM.TaW-clad Refractory Metals. Internal communication. 2017.
- Plansee GmbH.TZM Measurements. Internal communication. 2018.
- W: J. Habainy et al. "Fatigue properties of tungsten from two different processing routes". In:J. Nucl.Mater.506 (2018), pp. 83–91.

Target baseline selection

Pros and cons

Pro / manageable concerns / low risk	
Medium / substantial concerns / medium risk	
Con / large concerns / high risk	

	Physics production	Physics background	Radio-isotope production & concerns	Temperature levels	Stress and fatigue levels margins	Stress and fatigue in areas of high dpa	LOCA	Ease of manufacture / installation CORE	Ease of manufacture / installation VESSELS	Procurement / installation risk CV STATION	Instrument-ation & instrument integration	Ease of installation / replacement	Ease of maintenance of auxiliary systems	Unproven lack of W Cladding in beam
Water cooled target														
Helium cooled target							TBC Depends on cladding							
Helium cooled target 1/8^{ths}						TBC Depends on cladding	TBC Depends on cladding	Depends on cladding	Depends on cladding					

Based on simulations / calculations in other talks

Simulations covered in this talk

Estimates

Engineering Judgement

- Cladded version of helium target not yet fully analysed

Target Selection Decision

- ❑ **The BDF Target team has selected the Helium cooled option as the preferred option (so far).**

This is due to the Design mitigating or improving on the following issues:

- ➢ Improved physics production ⟶ From all W target
- ➢ Improved background → From replacing water with Helium in the coolant channels
- ➢ Lower activation of coolant → Due to removal of water from the beam shower
- ➢ Potential to improved LOCA situations. → Potential for removing Ta cladding

Using a helium system does come with risks:

- ➢ *Increased leak rates & additional risk in procuring items such as compressors, valves, seals etc for helium at elevated temperature and pressure.*

Backup options, failure modes & Future work

Helium Target

Backup target design options

Optional areas to benefit target

Positive impact	
Small positive impact	
Neutral / negligible impact	
Small negative impact	
Negative impact	

Proposed change to benefit target mechanics	Impact for physics	Impact on target thermal / mechanical	Impact on target fatigue	Impact on target manufacture
1/8th slices	Negligible change if gaps are at angle to beam direction	• **Significantly reduced temperature and stress or number of channels** ☺ • High stresses moves to **location of high DPA** ☹	• Lower stresses, but high fatigue moves to areas with high dpa **-to be studied**	Increase of difficulty, especially if clad.
Increased target core radius	Slight improvement in background.	• Decrease of maximum principal stresses due to **compressive effect of increased material** at circumference. • Change to max plasticity of cladding? To be studied	• Estimated improvement due to compressive effect of extra material	Extra cost (minor consideration)
Increased beam spot size	Slight decrease.	• **Decrease in max stresses.**	• Substantial improvement	-
Increased number of channels	Negligible decrease	• **Large improvement in DS** (steady state) areas of target. • **Fair improvement in US**, high irradiation, high stress areas.	• **Improvement on DS** blocks and small area of 1st block. • Very **minor improvement in US** blocks	Negligible

FMEA

- FMEA was performed for HL-LHC beam dump – this model and experience will be used as a guide for performing FMEA of BDF target
- **At beginning of process – very much ongoing**

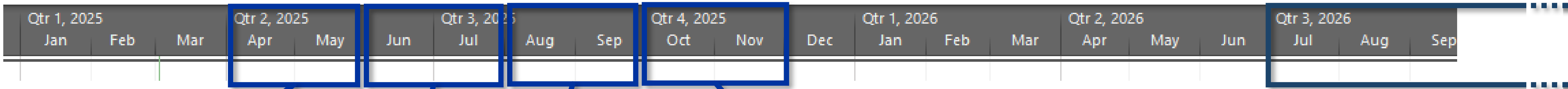
Number	Category	Function	Upstream influences	Downstream effects	Failure mode	Failure cause	Likelihood	Effect on TDE operational requirement	Effect severity	Detection mechanism	Probability of detectio[illegible]	Overall severity (max = 3[illegible])
1	4 Operation	4.02.01 Absorb all HL-LHC	Failure scenario beam absorption	Thermal shock Safety	Under absorb beams	Reduction in absorbing material density	5	Less beam energy absorbed by dump. Higher activation of shielding. Possible risk to	5	Could be detected with endoscopy during periodic inspection, but not	6	150
18	3 Failure	3.01.01 Resist failure scenarios during HL operation (2 MKBH missing)	Parameters of failure scenario	Beam absorption Energy density & temperature rise Differences to load on containment Different response to nominal	Under-resist failure scenarios	Partial damage to materials. Insufficient material strength/temperature resistance.	5	Dump degrades faster and has shorter lifetime	5	Could be detected with endoscopy during periodic inspection, but not proven. Has been proven that BLMs currently not capable of detecting damage to core.	6	150
10	6 Thermomechanical resistance	6.03.01 Resist thermal shock (stress gradients and strain rates) induced by beam impact.	Thermal shock - nominal and accidental beam impacts	Configuration of dump changes Containment Measurement of dump displacement	Under	Local plastic deformation or fissures. Design issue or unforseen stress states.	4	Reduction in life. Dump may need replacement before end of service.	5	Pressure sensor, LDV, LVDT, visual inspection. Not clear whether life-limiting damage could be detected by these methods.	7	140
18	3 Failure	3.01.01 Resist failure scenarios during HL operation (2 MKBH missing)	Parameters of failure scenario	Beam absorption Energy density & temperature rise Differences to load on containment	No	Catastrophic failure of core or containment	3	Dump has to be replaced	6	Not detectable	7	126

FMEA example: HL-LHC-beam dump

Expected Steps

1. **Systems description**
   1. Interviews
   2. lists
   3. Interfaces
2. **Functional requirements**
3. **Functional modeling**
   1. Systems tree functions
   2. Systems context diagrams
4. **Failure modes and effects**
   1. Workshop
   2. FMEA results
5. System breakdown (optional)
6. Quality Function Deployment analysis (optional)

Timeline



Systems description

Functional requirements & modelling

Review & FMEA

Review, Systems breakdown & QFD analysis

Production Phase…

Target failure scenarios

- **FMEA to be done in future**
- Main concerns shown here

Severity

Severity	
Low	Green
Moderate	Yellow
High	Pink
Unacceptable	Red

Failure decscripiton	System requirement affected	Consequence	Likeli-hood	Severity	Action to compensate?
Target core delamination / disintegration…		5. Hotter block – target damage, Major increased species release, target disintegration	2	10	Experiment affected / replace target
Tungsten chip / dust release into helium		5. Major increased species release	2	10	Monitor / replace target
Cooling channel blockage	Reduced target cooling efficiency	4. Hotter block – target damage, increased species release	1	4	Reduce beam power
Helium leak path in target	Reduced target cooling efficiency	2. Hotter block – target damage, increased species release	4	8	Reduce beam power
Small helium leak to vacuum vessel	Reduced cooling efficiency	2. Hotter block – target damage, increased species release	4.	8	Increase helium 'top up'. Reduce beam power.
Major helium leak to vacuum vessel	Reduced cooling efficiency	4. Hotter block – target damage, increased species release	2	8	Experiment affected / replace target

PRELIMINARY DRAFT

Further work ongoing

What ifs? – Cladding

- What if material results / Ta interlayer is particularly weak?
- What if core blocks are prone to delayering?
- **What if highly irradiated W crumbles?**

Areas for more detailed study in the coming months

- **LOCA**
- **Continue Cladding plasticity**

Fatigue

- w.r.t shear/lamination planes
  - Is $\sigma_{max\ principal}$ direction same as greatest σ_a?
- 16mm beam - include lower dpa! of 1.2!
- Pulse structure (4 revolutions /s) contribution to fatigue →waterfall analysis

- **Mechanical calculations of wider assembly:**
  - Vessel & Beam window calculations
  - Weight of assembly, rollers etc
- **CFD of full model (ongoing)**
  - Optimise fluid channel temperature step changes
  - Include gradient of HTC & He temperature on Stress calcs

Realistic pulse supercycles

- Work so far shows detrimental contribution to fatigue

Future optimisation process

Material testing results & initial 2025 prototype results → re-optimsation of core thicknesses, channel structure, & number of channels → Possibly adjust blocks to be repeated thicknesses, all 15mm in shower for example → - re-run of T, σ, fatigue analysis

Summary – Key takeaways (TLDR!)

Helium Target

1. Cladding & Block Material structure → Lasagna structure. Helium maybe not clad.
2. Helium Modelling Assumptions & Design Methodology →Stress, fatigue, temperature limits were based on literature.
3. Helium Simulation Results →Larger beam size very good. Larger target good. Higher intensity likely not possible unless beam size >8mm
   - Target size & beam parameters
   - Radiation damage – stress
   - Radiation damage – Fatigue →DPA map approach developed.

Helium & Water Target →Mixed picture, needs more study

4. Comparison →Helium cooled target is current preferred option
5. Helium target 'Backup' options →Several options exist for easing target conditions
6. FMEA →To be done in near future
7. Further work →Lots! first is updating & incorporating CFD, & Cladding
8. Key takeaways →When initial material testing results / prototype results known, target geometry will be re-optimised

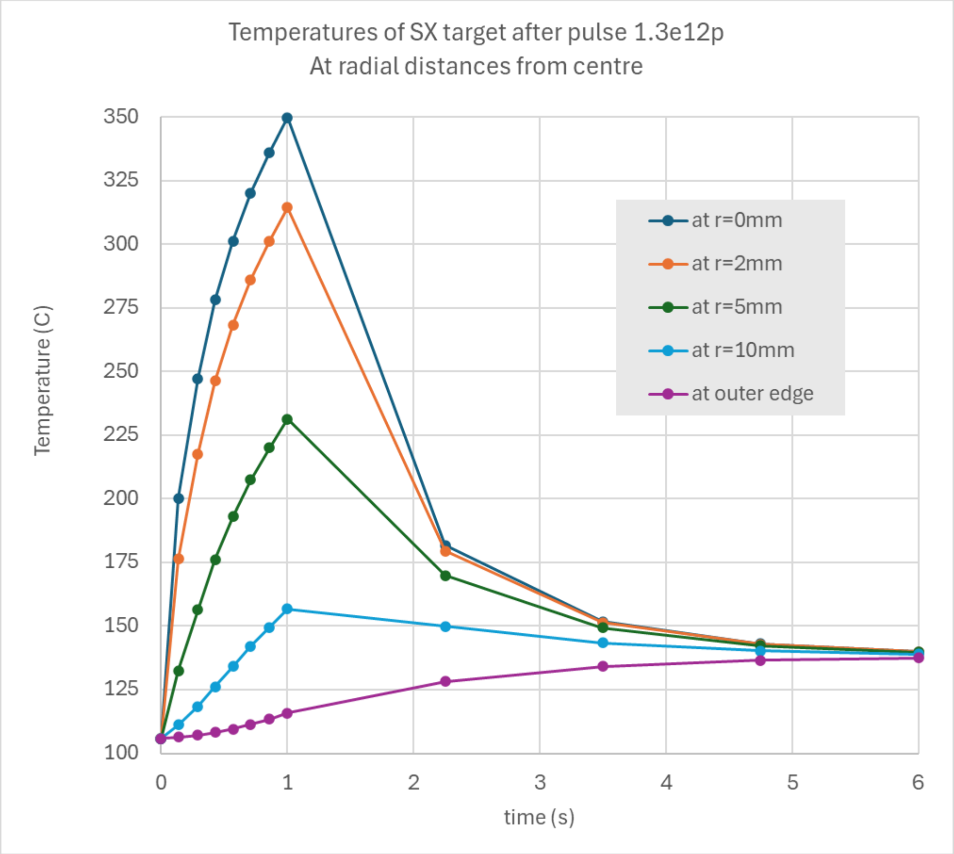
Many thanks

home.cern

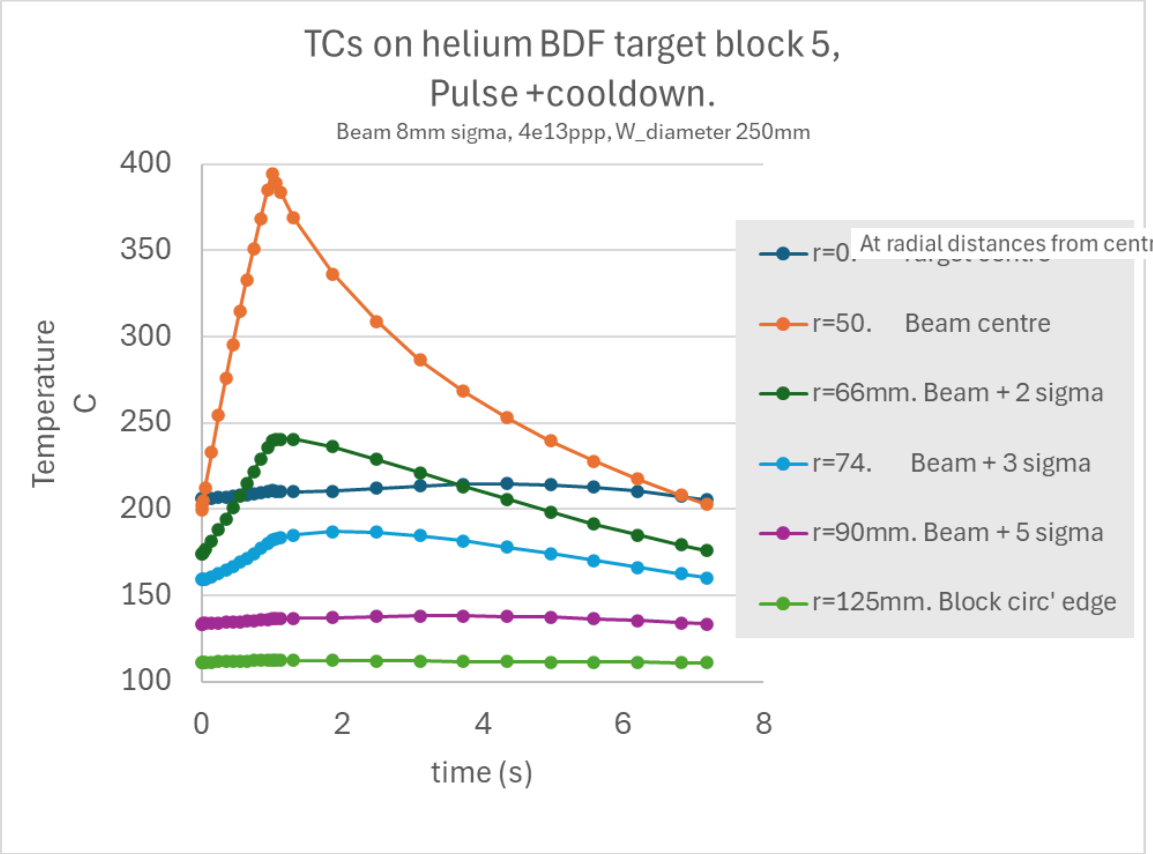
Comments on verbal questions at TSAC

Thermocouple location at various depths

Prototype



Full target

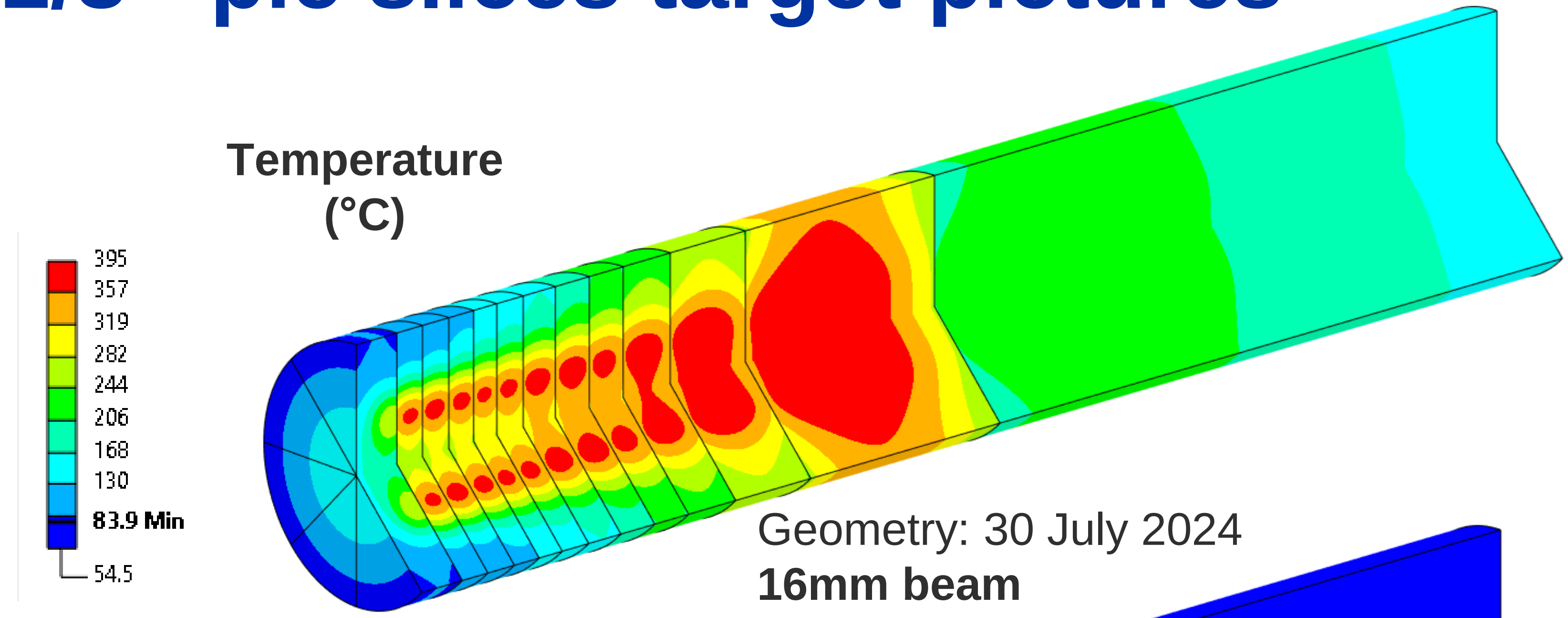


- TC location 5-10mm from centre sees ΔT>25°C rise due to pulse - (easily detectable)
- Die sink tests managed a hole all the way to centre.

- r= 66mm (beam sweep+2 sigma) sees ΔT=67°C & peaks at 0.2s after pulse end.
- r= 74mm (beam sweep+3 sigma) sees ΔT=28°C & peaks at 0.9s after pulse end.
- r= 90mm (beam sweep+5 sigma) sees ΔT=5°C & peaks at 2.5s after pulse end.

1/8th pie slices target pictures

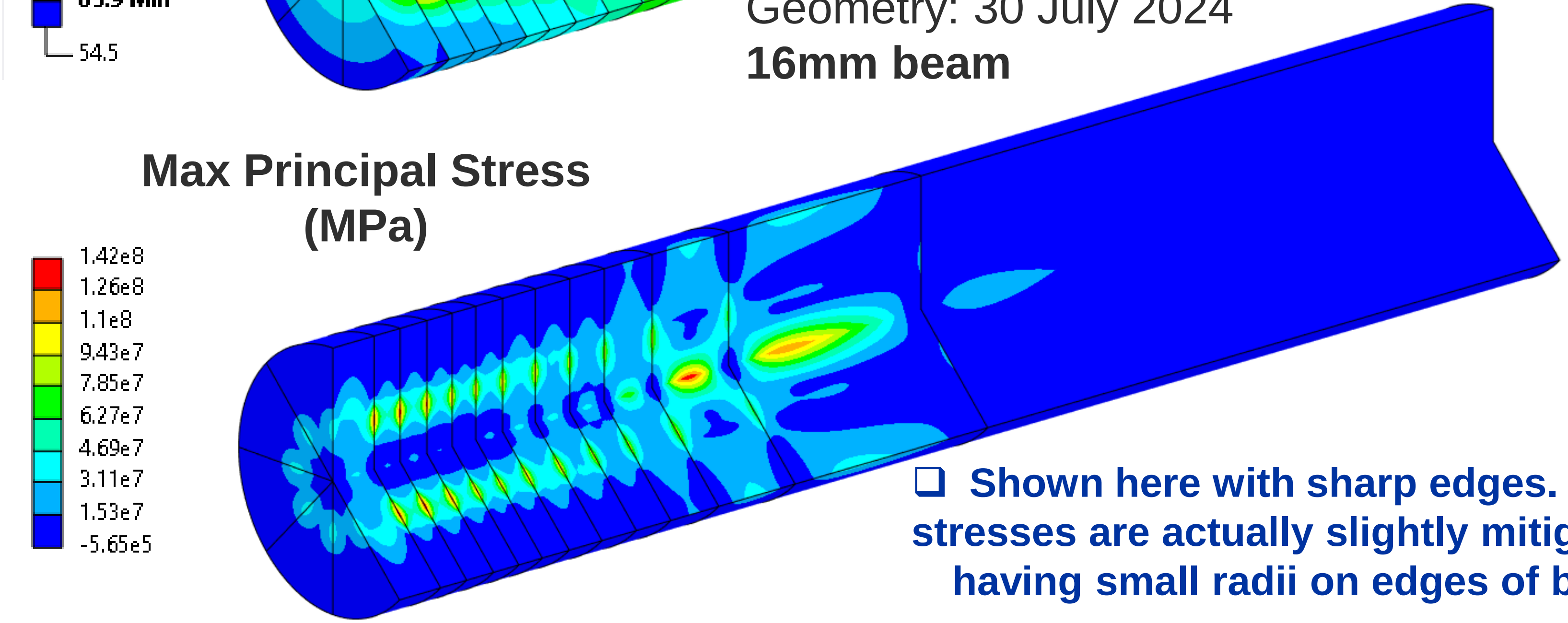
Temperature (°C)

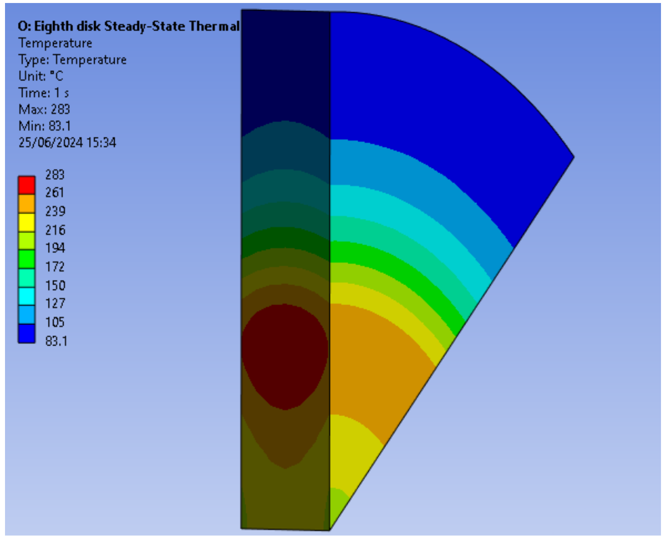


Geometry: 30 July 2024

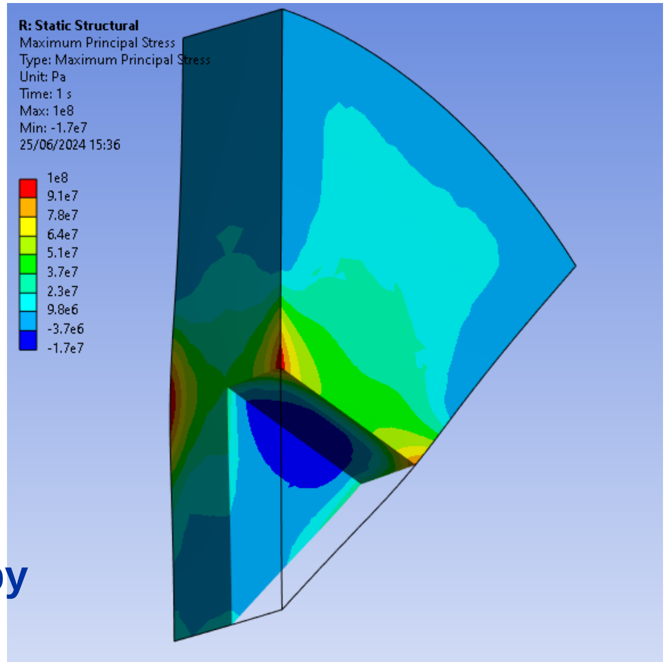
16mm beam

Max Principal Stress (MPa)





- ❑ different beam parameters to the simulation on the left but show the stress distribution

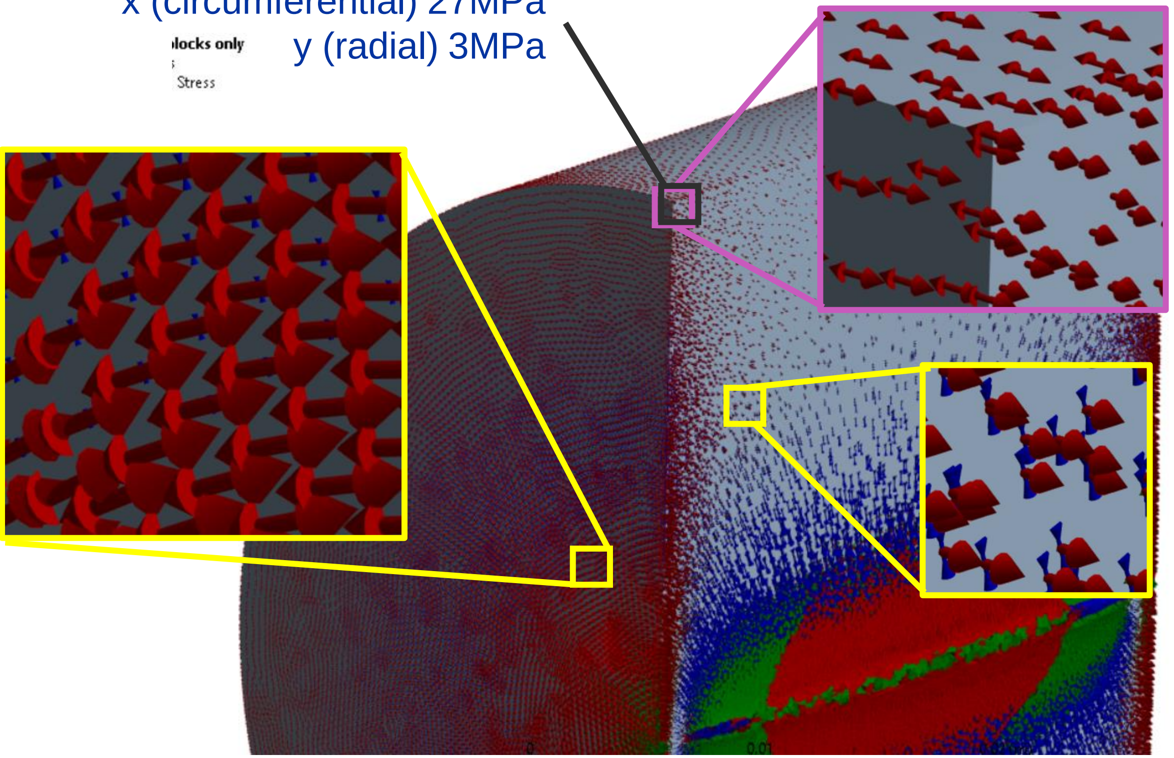


- ❑ **Shown here with sharp edges. peak stresses are actually slightly mitigated by having small radii on edges of blocks**

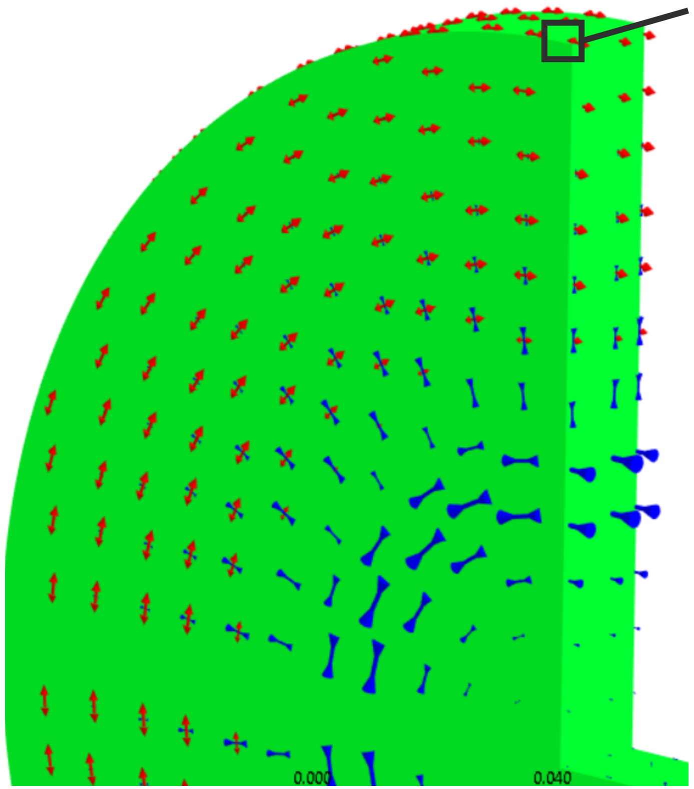
TDR to protype target stress states

Matching prototype block

x (circumferential) 27MPa
y (radial) 3MPa



TDR block



Out of plane stresses TDR block

x (circumferencial) 128MPa
y (radial) 0.08MPa
z(out of plane) 0.06MPa

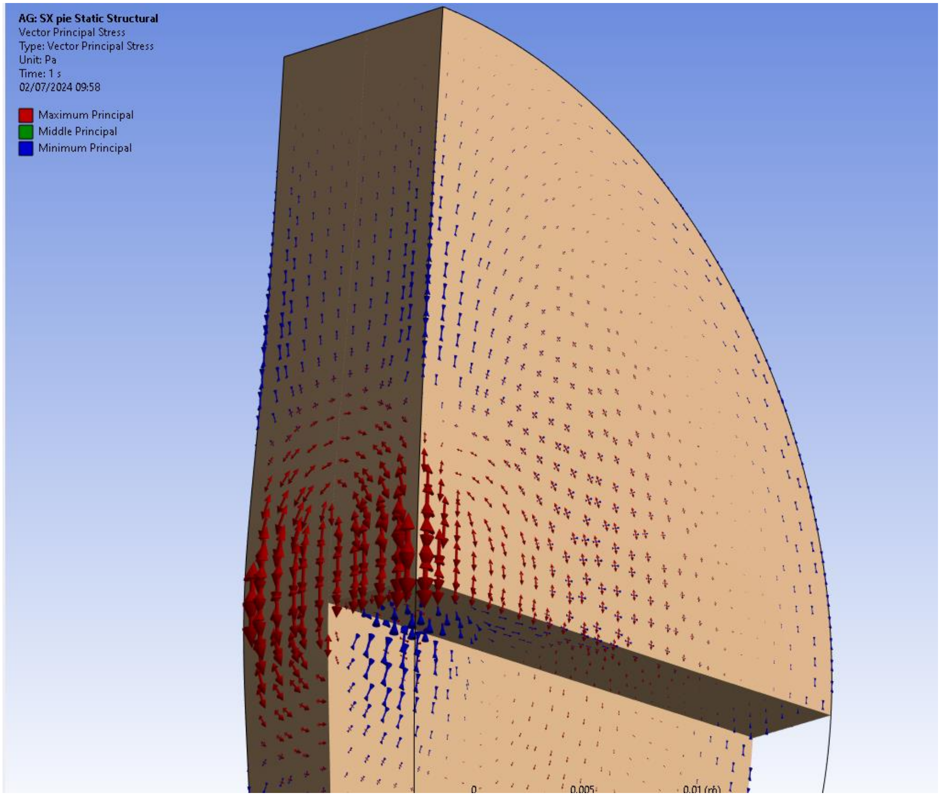
- ❑ out of plane stresses not a concern here.

- ❑ **Largest tensile stresses in prototype & TDR are in the same direction (circumferencial direction) – this was planned. With compressive stresses in radial direction**
- ❑ **However the larger stress magnitudes in the prototype are largely locally confined to the flat faces. – magnitudes are quite different at the circumferencial edge.**
- ❑ **The prototype has much larger compressive stresses (at centre)**
- ❑ **Out of plane stress levels not a concern.**

1/8 slices target has different stress state.

Could be tested in 2026 prototype with semicircle blocks that match the stress state very well.

Matching prototype block



1/8th slices TDR block