August 2026

Target Assembly Segment Design

Aaron Jacques

Second Target Station

U.S. DEPARTMENT of ENERGY

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FOR THE US DEPARTMENT OF ENERGY

Charge Question 2: Has the design been shown to meet the requirements?

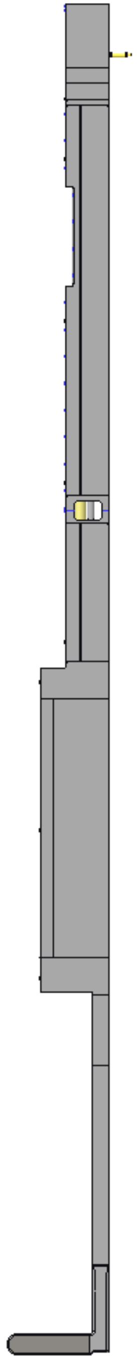
Charge Question 3: Do DACs and other supporting documentation adequately support the final design?

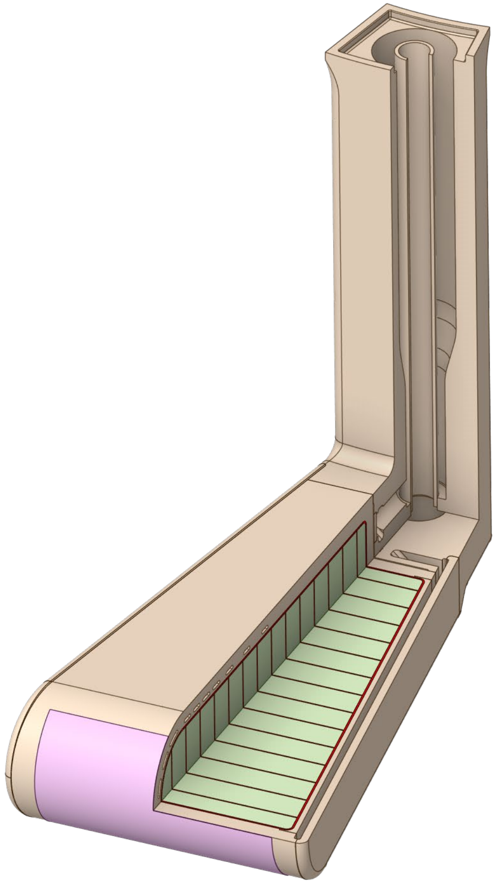
Question 5: Is the design sufficiently mature to proceed with finalizing the procurement package?

Key deflection and tolerance requirements are based upon error & deflection budget (unchecked)

Segment Key Parameters

- **Segment Mass:** 577 kg
- **Segment Height:** 5055 mm
- **Segment Angle:** 18 degrees
- **Gaps:**
  - 5mm between segments
  - 2mm between segment-shaft
- **Thermal load:** 21.5kW
- **Flow Rate:** 7.5 gpm
- **Beam Spot Size:** 60-90cm^2

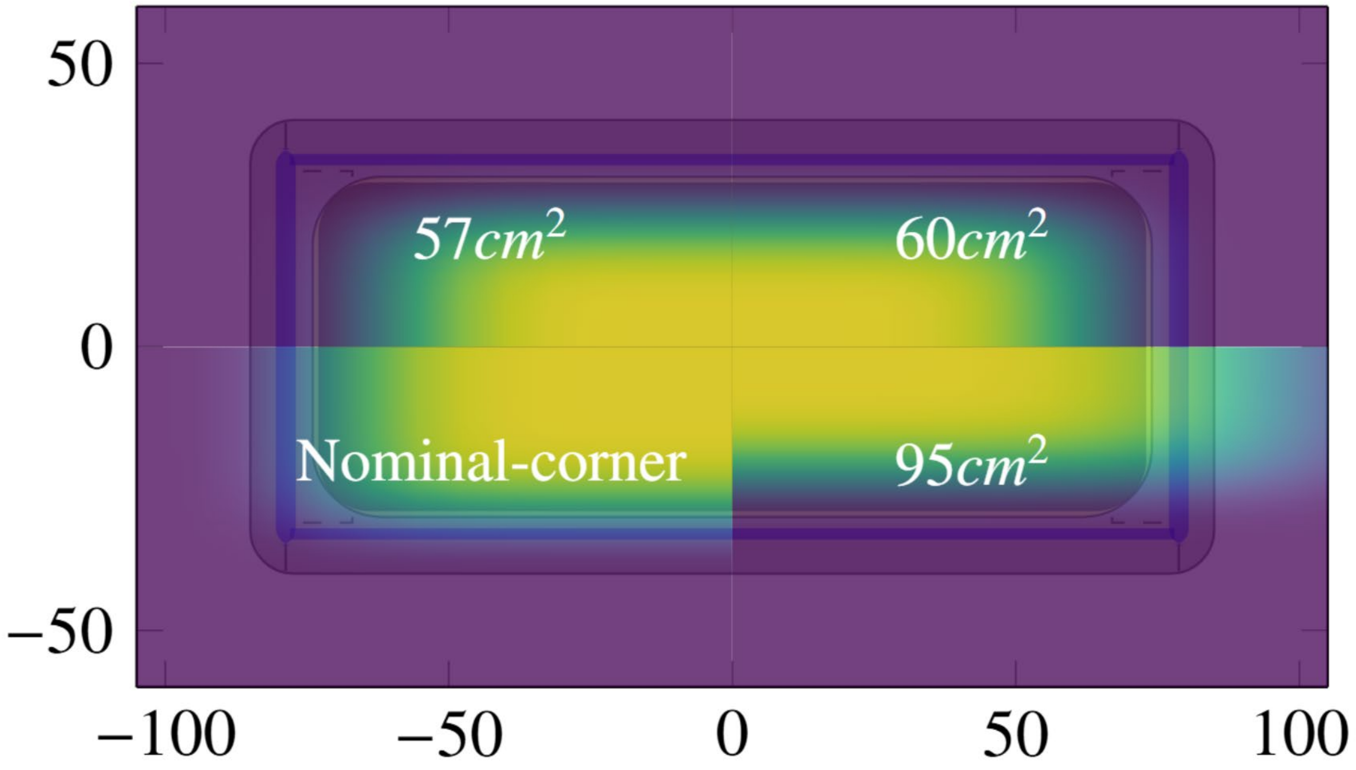




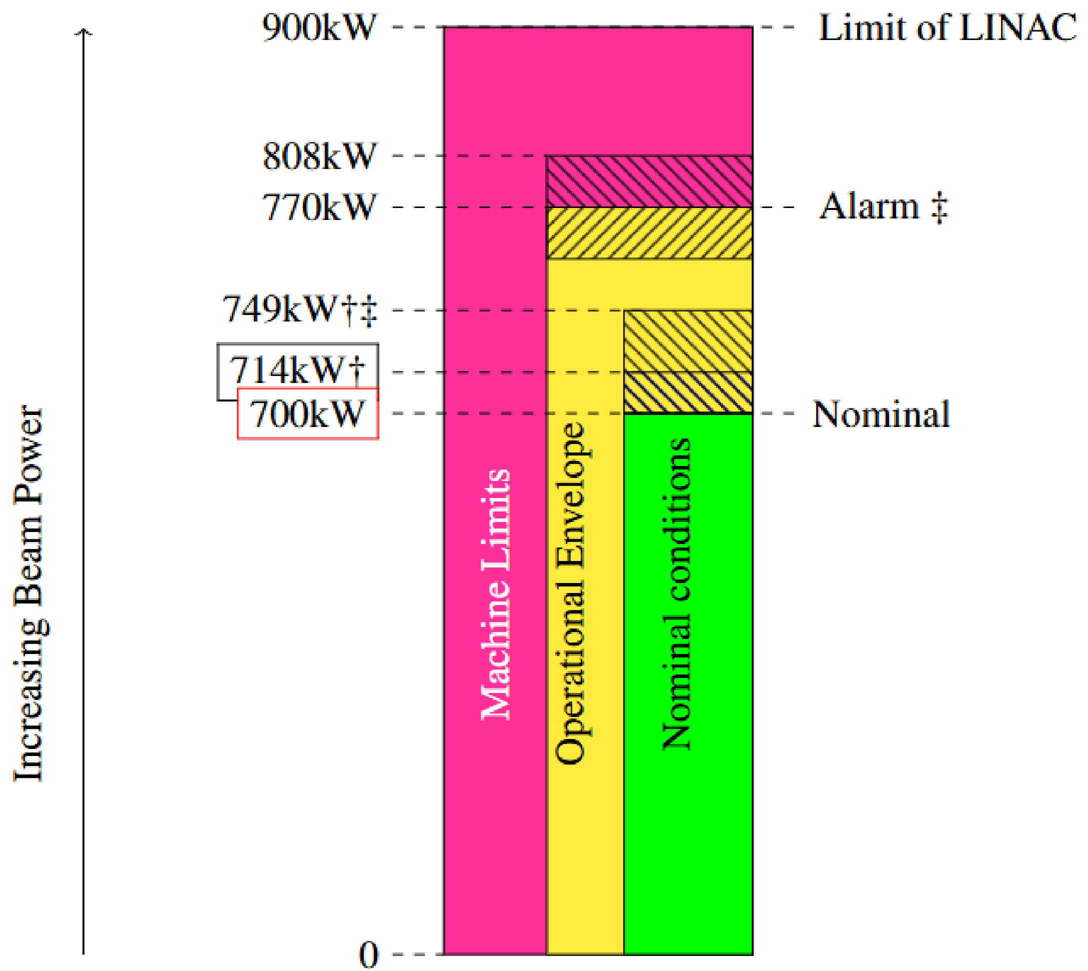
Proton Beam Interface

Proton Beam Interface

- 1.3GeV, 700kW
- 2.2×10^{14} protons/pulse
- 700 ns spill duration
- 15Hz repetition rate
- Profile: 60-90cm^2 (+5% Error)
- Super Gaussian
- Vertical offset: +/-4mm
- Horizontal offset: +/-6mm



Beam power



Key

Measurement errors, uncertainty, delays, etc.

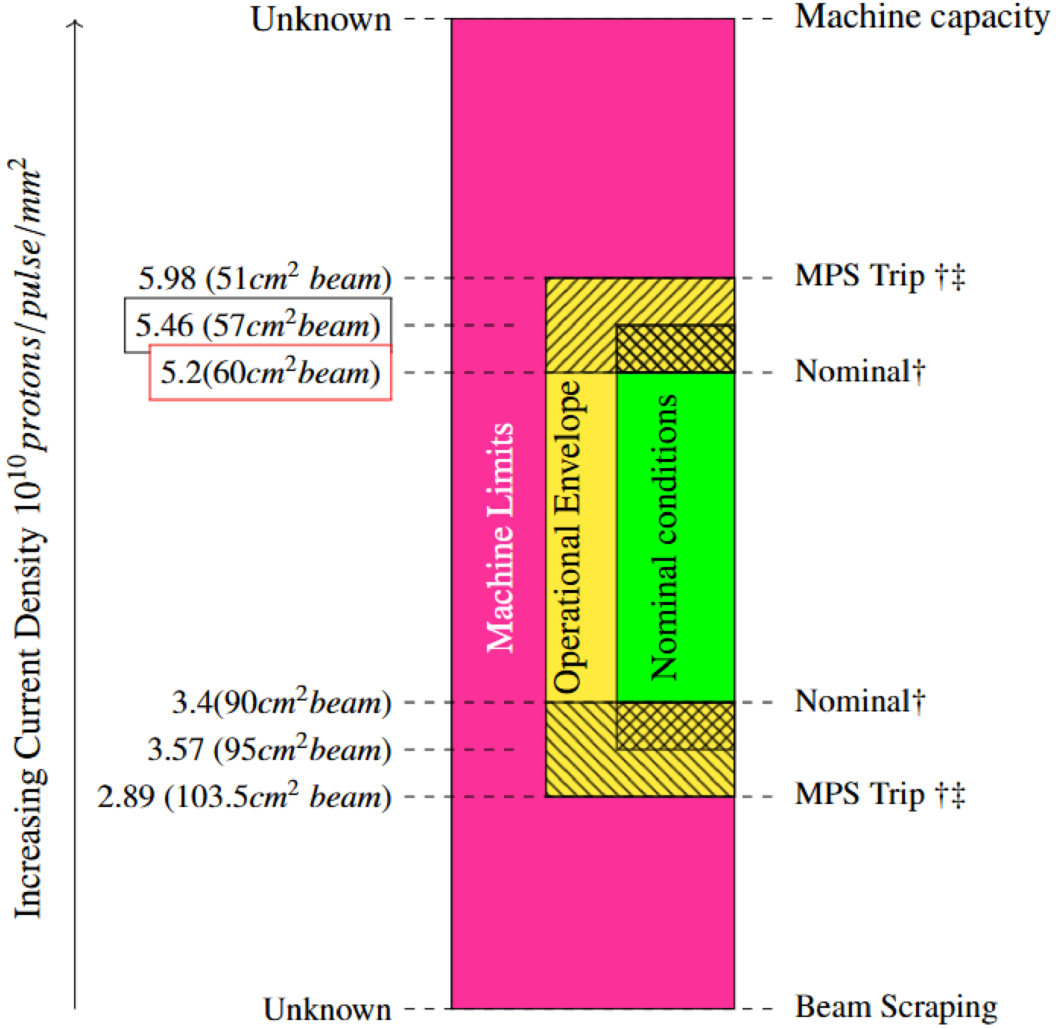
XX Value used for analysis of the peak brightness KPP

XX Value used for target fatigue analysis

† Expected ripple in beam power, due to distribution of beam energies ±2%

‡ Alarm only. Measured by the Beam Current Monitor (±5%)[34] (measures the the quantity of protons located at the beginning and end of the RTST)

Beam Focus



Key

Measurement errors, uncertainty, delays, etc.

XX Value used for analysis of the peak brightness KPP

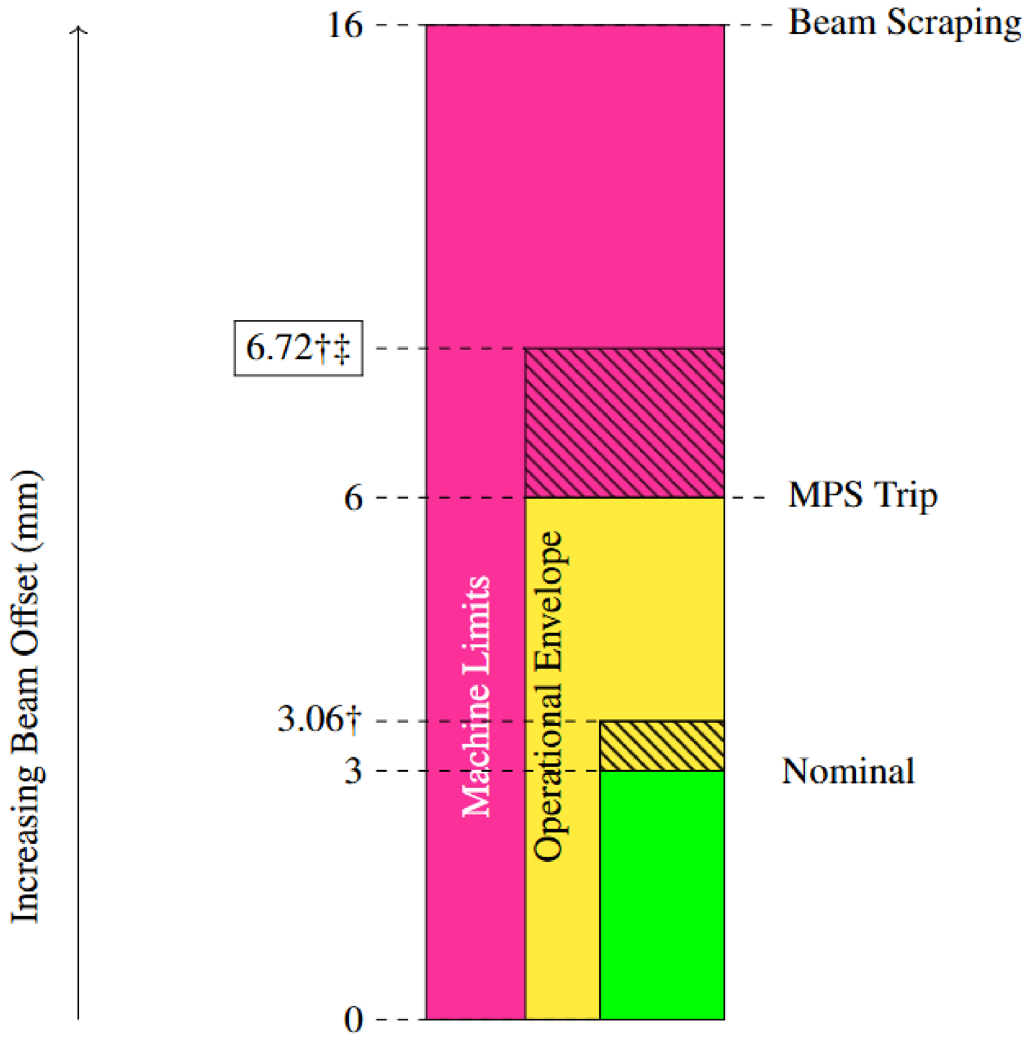
XX Value used for target fatigue analysis

† Measured by the HARP and wire scanners within ±5% of setpoint

‡ ±2% MPS Limit on power supply current variation results in ±10% variation of the beam at the target face.[76]

The Harp and wire scanners are used for tuning at low power and have a combined accuracy of ±5% (estimated). Once appropriately tuned, the magnet currents are stored as a baseline. The DCCTs measure current against the baseline and trip if current varies beyond ±2%. This power supply variation results in a ±10% change in proton density on the target face.[76]

Horizontal offset



Key

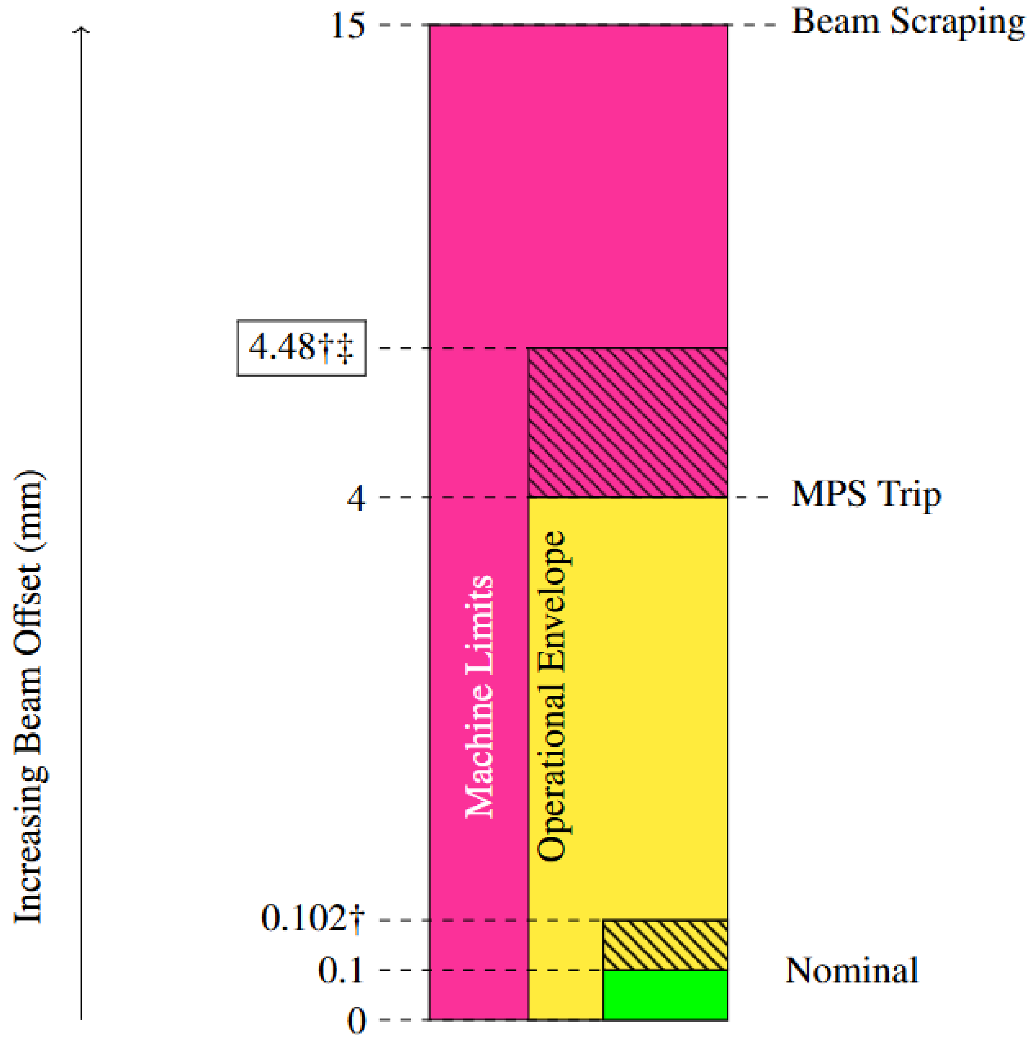
Measurement errors, uncertainty, delays, etc.

XX Used in target fatigue analyses

† The BPMs have an accuracy of ±2% (estimated).

‡ The DCCTs measure current against the baseline and trip if current varies beyond ±2%. This power supply variation results in a ±10% change in location on the target face

Vertical offset



Key

Measurement errors, uncertainty, delays, etc.

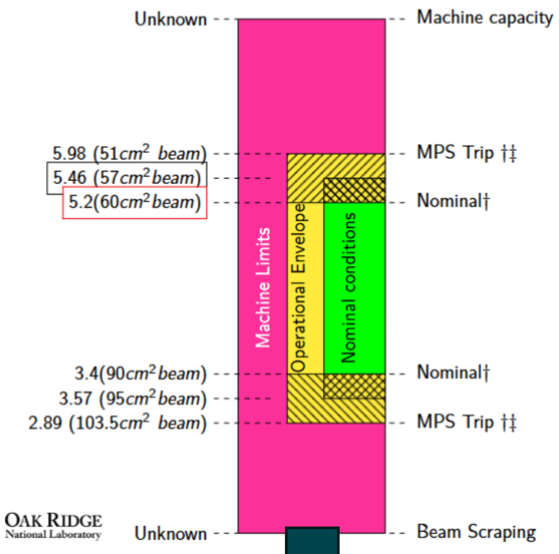
XX Used in target fatigue analyses

† The BPMs have an accuracy of ±2% (estimated).

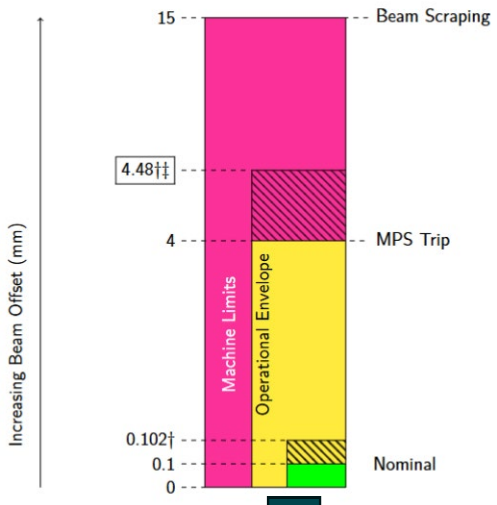
‡ The DCCTs measure current against the baseline and trip if current varies beyond ±2%. This power supply variation results in a ±10% change in location on the target face

Fatigue analyses can be relied upon to cover the bounding set of beams integrated from multiple error sources.

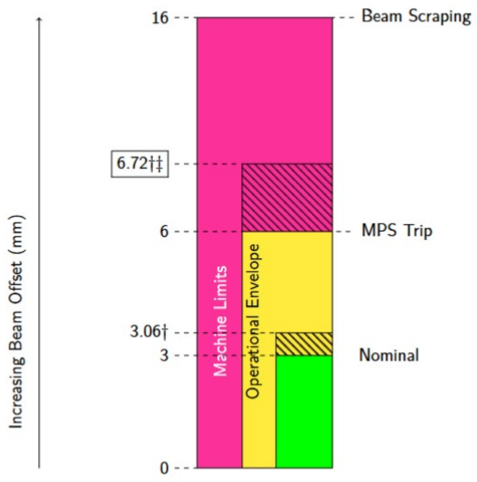
Beam Focus



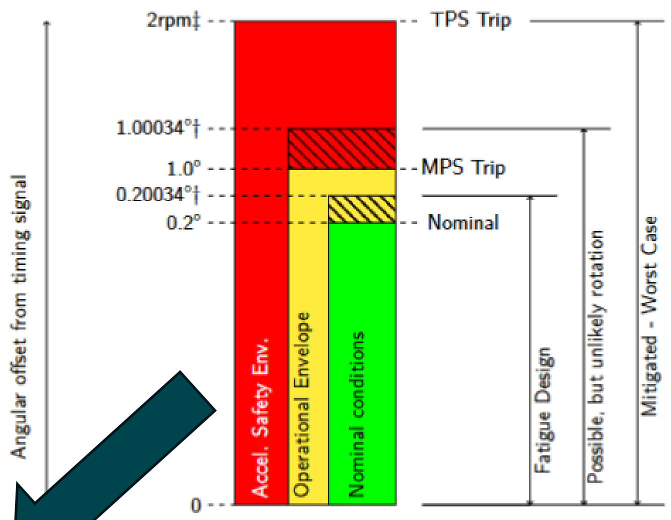
Vertical offset



Horizontal offset



Angular control



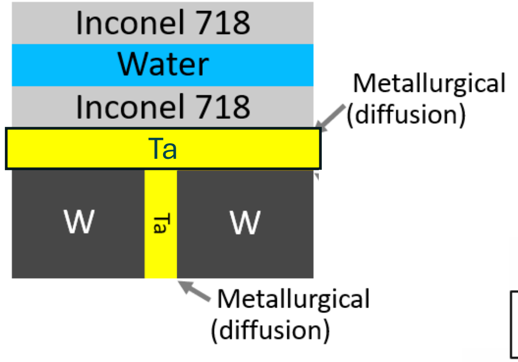
Case		Beam Loads						Body Loads			Water			State	Criteria
ID	Case	Power kW	Focus[a] 10^{11}	Profile Name	Offset v/h, mm	Pulses 10^8	Trips 10^5	Grav	Rot	Accel	Temp °C	Flow gpm	Press psi	State	Criteria
A	Nominal	700	6.24	$60cm^2$	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL[b]	Req 1574[c]
B	Nominal-corner	700	6.24	$60cm^2$	8.5/12	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL[b]	Req 1574[d]
C	Nominal-low flow	700	6.24	$60cm^2$	0/0	1.35	1.25	Y	Y	N	32.2	5.71	36	WOL[b]	Req 1574[d]
D	Overfocused	714	6.6	$57cm^2$	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL[b]	Req 1574[c]
E	Diffuse	700	4.61	$94.5cm^2$	0/0	1.35	1.25	Y	Y	N	32.2	7.5	36	WOL[b]	Req 1574[d]

[a] $protons/mm^2/sec$
[b] Worst of Life material conditions (irradiated elastic modulus and thermal condictivity, but not strength)
[c] Fatigue methodology (weld reduction factors, etc.) determined in accordance with ASME ASME BPVC Sec. VIII.2, Part 5; allowable stresses are determined from best-in class irradiated material limits and not ASME fatigue curves.
[d] Fatigue lifetime criteria to be evaluated; minor deviations in life are acceptable for edge, corner, and worst case conditions

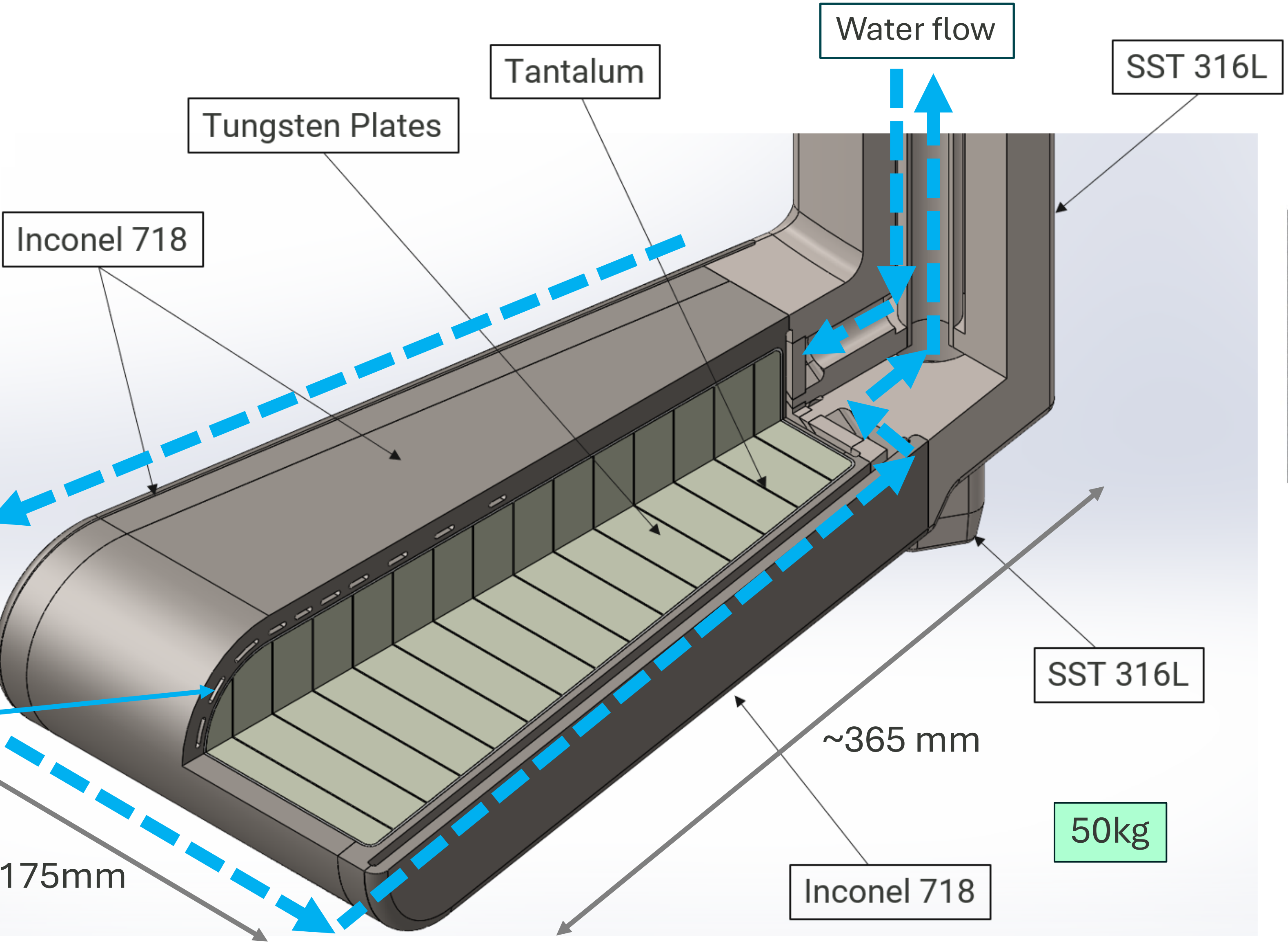
Mechanical Errors

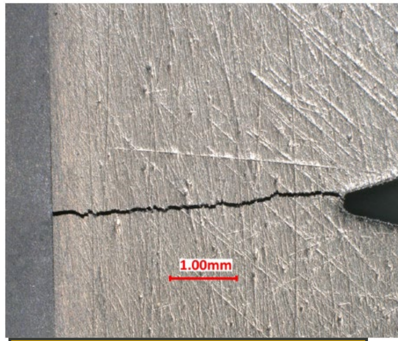
Target foot

The target design is a robust package for handling the challenges of Tungsten



~3x CTE mismatch from 718 to W





Crack deflection

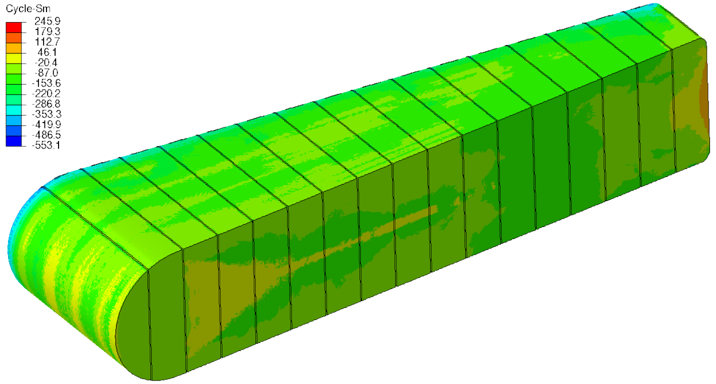
Design Premise

- Inconel is a tough, fatigue resistant outer boundary for containing water
- Separate water from tungsten as far (robust) as possible
- Reduce decay heat
- Plan for tungsten cracks and handle gracefully
- Place tungsten in a state of residual compression
- Provide a compliant layer for cracks & redistribution
- Small passages not large diaphragms for water routing
- Failures cause leaks and do not contaminate water process loop (and are detectable)

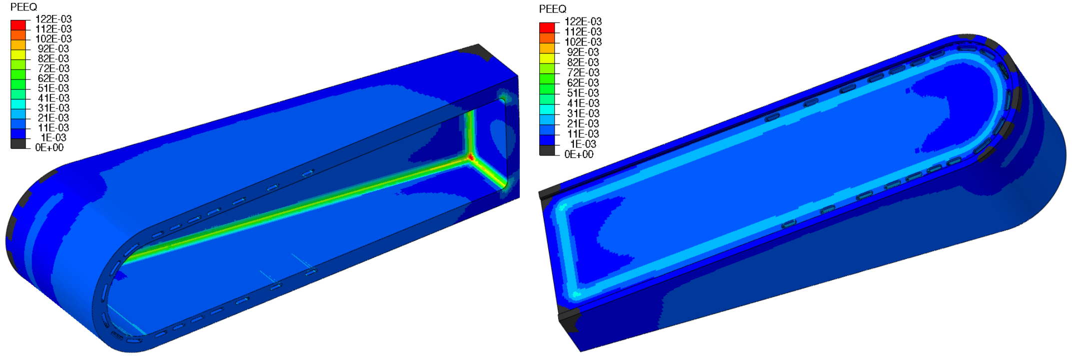
HIP Process places the tungsten in a state of compressive residual stress

Material	CTE (10^{-6})
Tungsten	4.5
Inconel	14.1
Tantalum	6.3

- W + Inconel CTE mismatch
- HIP temperature and pressure
  - Stress free, conformal state @ 950°C
  - High pressure forces contact @ temp
- Tungsten Compressive stress
- Inconel in tension
- Tantalum flows/yields during HIP
- “Shrink fit” the tungsten in Inconel
- Requires modeling & verification of residual stresses



Tungsten BOL mean stress (Pa) for each element’s worst-case cycle.

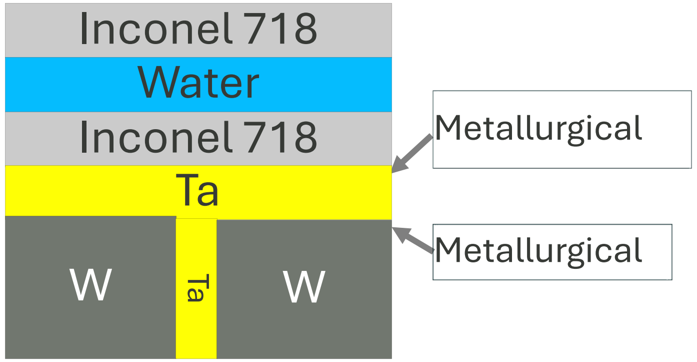


Inconel BOL yield state after manufacturing simulation.

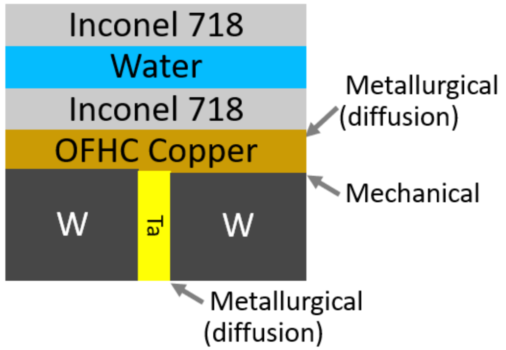
Spallation Material - Laminated W/Ta stacks

- Tungsten is the STS spallation material
- Off-the Shelf (Cost & lead time)
- Laminate offers superior performance
- Leverage W+Ta bonding experience
- Not a structural member
- Uncertain fatigue performance

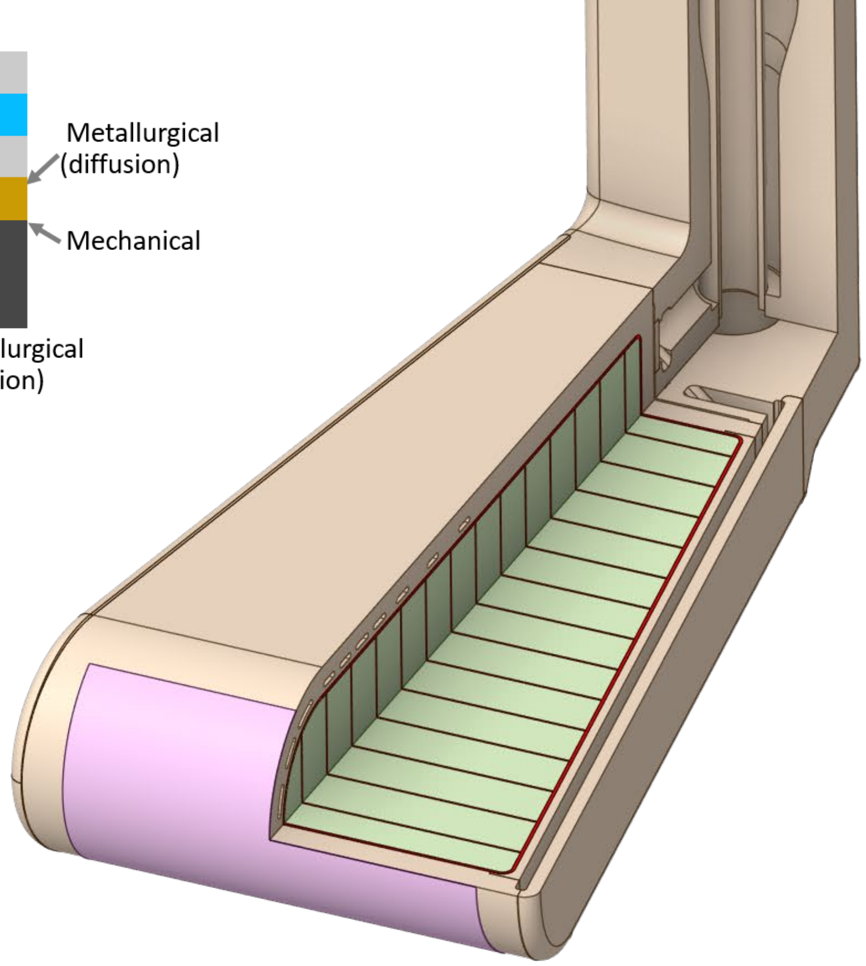
Description	Direction	Un-irradiated
		UTS
60 mm plate	In Plane (rolling)	669 (bend) @ 150 °C (should be below DBTT)
	Out of Plane (normal)	233 (bend) @ 150 °C (should be below DBTT)
48mm Forging	In Plane	538
	Out of Plane	315
58mm Forging	In Plane	560
	Out of Plane	174
Rod <80mm	Radial	804
	Circum.	579
10 -20mm Plate	In Plane	998 (Bend) [Haibany]
	Out of Plane	677
Rod (<18mm)	N/A	980 (ASTM E288)
1mm Sheet		1200



Inconel Shell

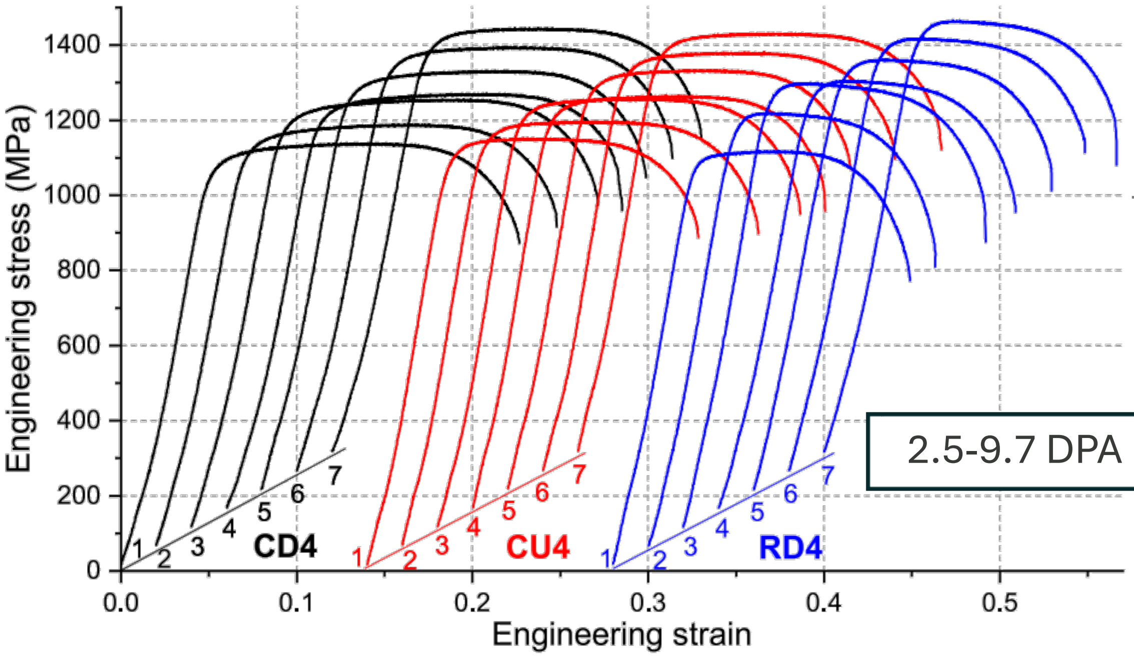


- Strong external boundary
- History of irradiation at LANL, SNS
- Higher strength and fatigue performance than 316L
- SA favored over PH718*
- Water corrosion resistance
- Welds to 316



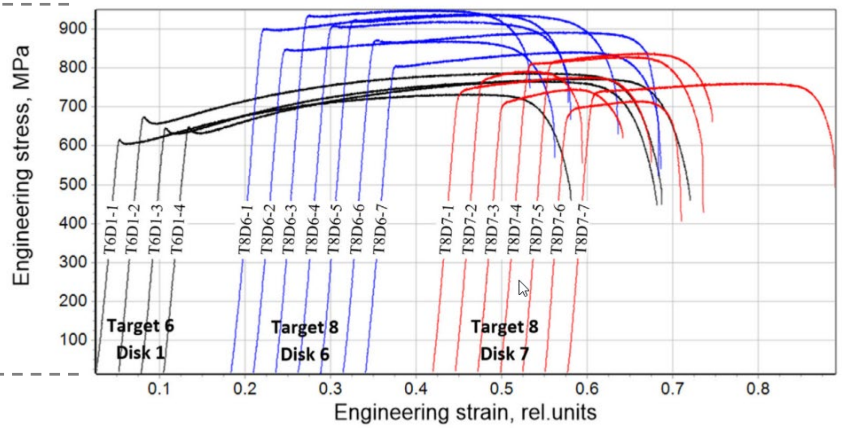
"The mechanical properties of an Alloy 718 window after irradiation in a spallation environment"
James, Maloy, Somer

Solution annealed Inconel has superior strength, maintains ductility and provides a higher compressive initial state than 316L



2.5-9.7 DPA

0-7.6 DPA



McClintock et. Al. “Observations of radiation-enhanced ductility in irradiated Inconel 718: Tensile properties, deformation behavior, and microstructure” Acta Materialia 231 (2022)

McClintock et. Al. “Characterization of mechanical properties and deformation behavior of highly irradiated 316L stainless steel from target modules at the Spallation Neutron Source using digital image correlation analysis” J. Nuclear Materials, 545 (2021)

Materials Summary

Inconel

Strong & tough

Retains ductility in radiation

Proven beam intercepting device material

High strength & fatigue capacity

Used in windows & targets

Not an ASME vessel material

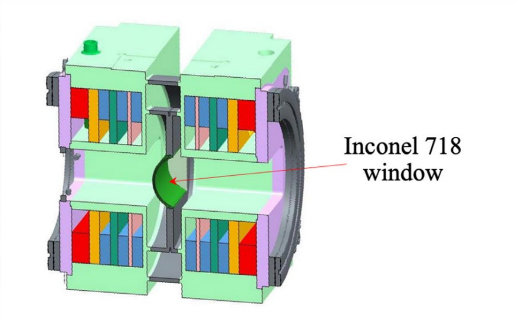


Image source: McClintock, et. al. **Observations of radiation-enhanced ductility in irradiated Inconel 718: Tensile properties, deformation behavior, and microstructure** 2022

Tantalum

Well known in spallation community

Good performance in radiation environment (LANSCE)

Ductile behavior

Excellent bonding to tungsten to provide ductile interlayer

ISIS, LANSCE

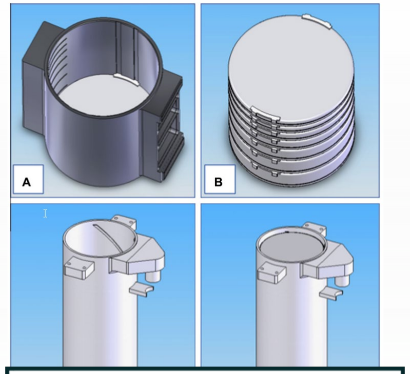


Image source: Nelson, et. Al. **Fabrication of a tantalum-clad tungsten target for LANSCE**

Tungsten

Characterized by Haibany

Good spallation material

Brittle structural material

Loss of thermal conductivity

Loss of strength & fatigue upon radiation

ISIS, ESS, LANSCE

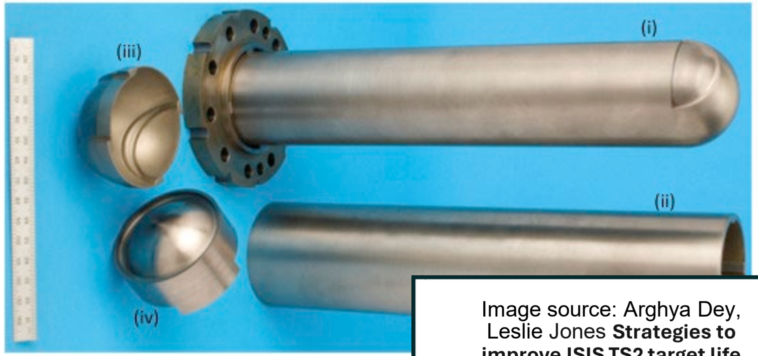


Image source: Arghya Dey, Leslie Jones **Strategies to improve ISIS TS2 target life**

Worst of Life of life criteria is considered the most conservative approach

Beginning of Life

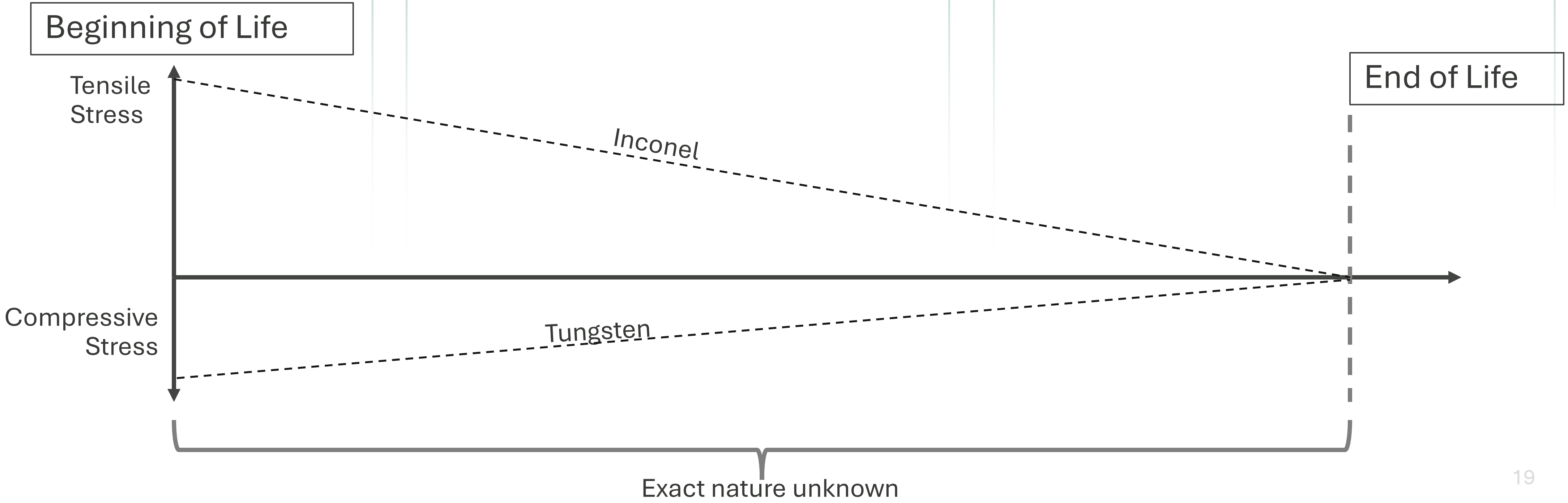
- Unirradiated material properties
- Residual stresses from manufacturing (i.e. HIP and machining)
- All 130M beam pulses applied at RT (i.e. cold start)

Worst of Life (Design criteria)

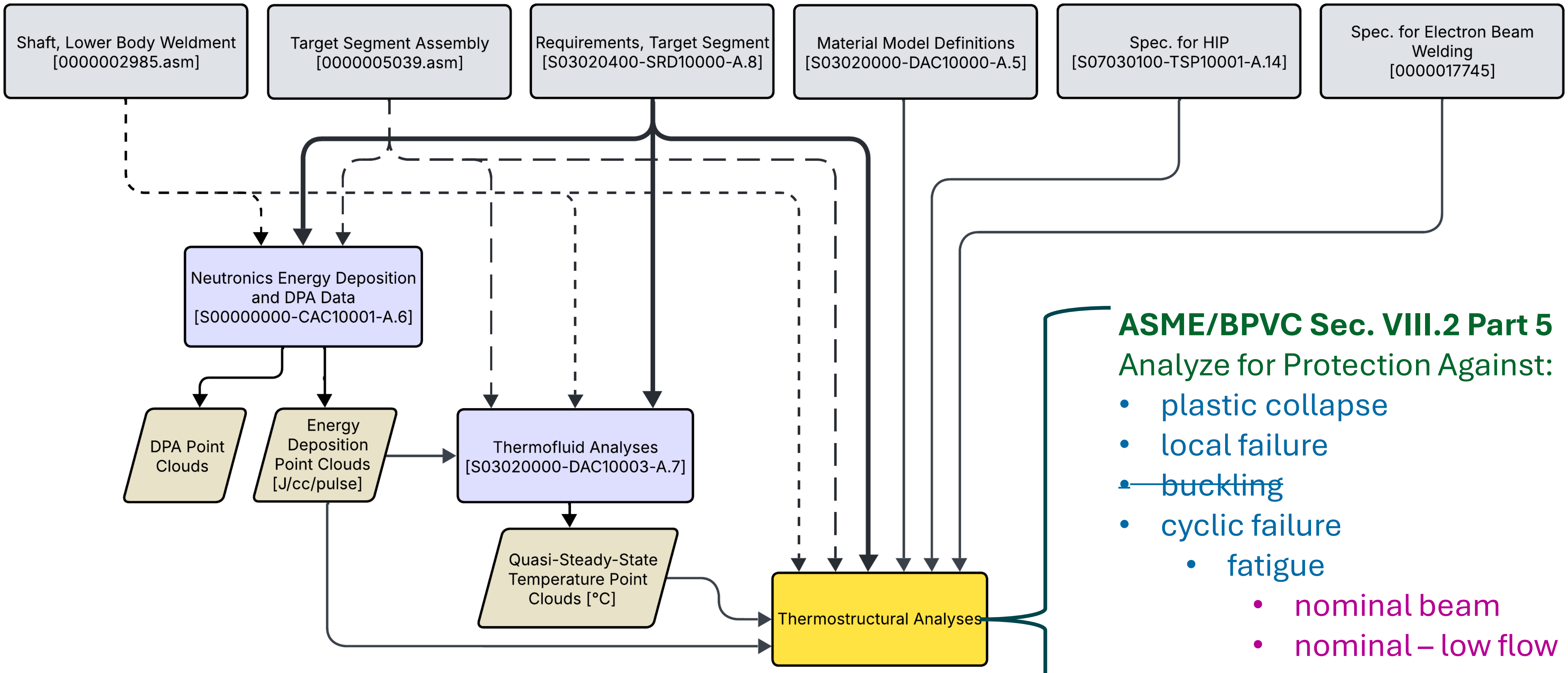
- Irradiated material properties
- Residual stresses from manufacturing (i.e. HIP and machining)
- All 130M beam pulses applied at RT (i.e. cold start)
- May occur ~0.2 DPA; tungsten irradiated material properties

End of Life (Debond evaluation)

- Stress-free state at operating temperature (i.e. all manufacturing residual stresses have been removed by radiation induced stress relaxation)
- W irradiated material properties where appropriate/available.



Detailed analyses harmonized with process and specifications give high confidence in fatigue lifetime

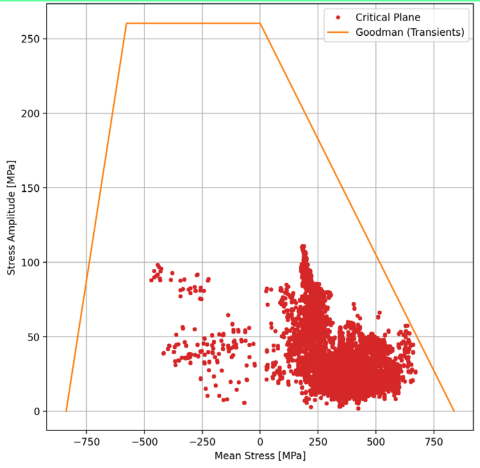
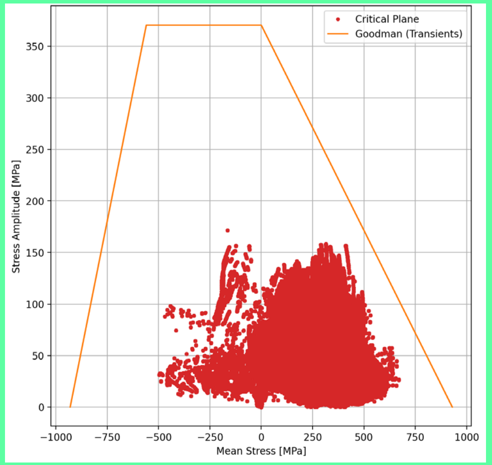
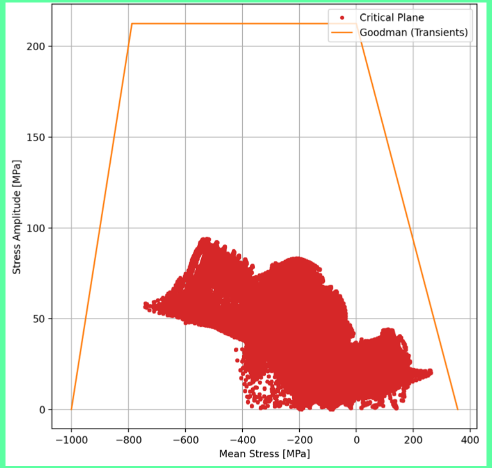
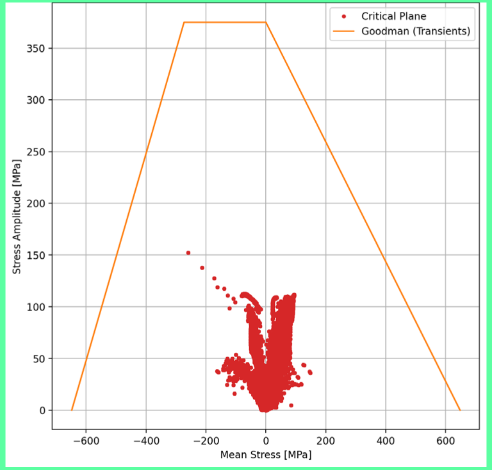
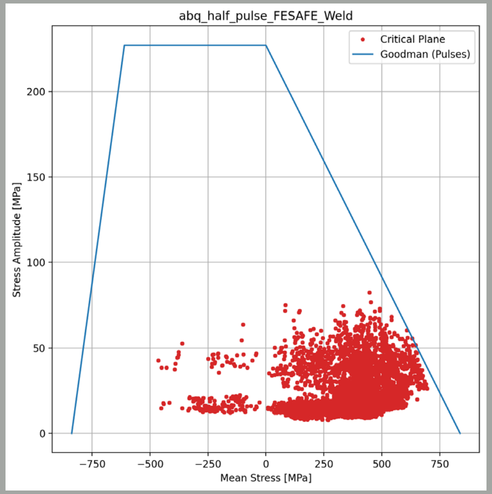
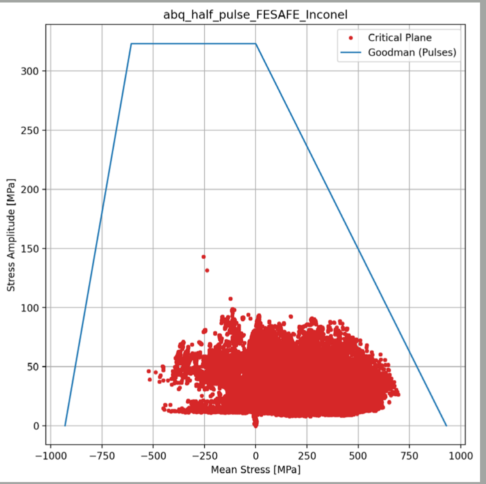
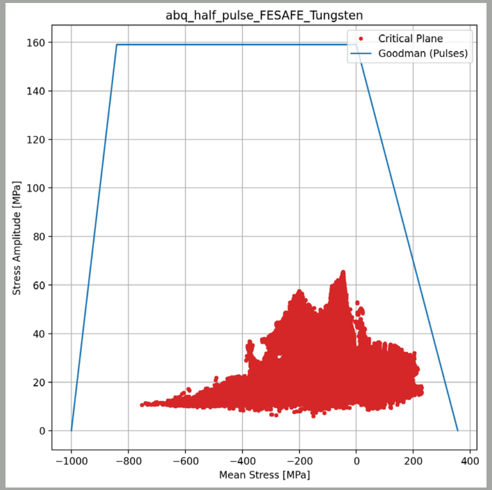
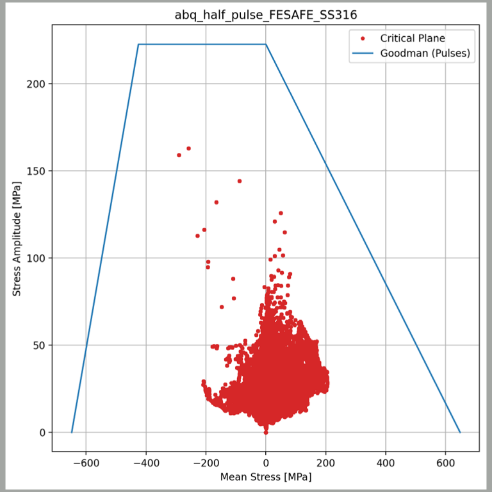


ASME/BPVC Sec. VIII.2 Part 5

Analyze for Protection Against:

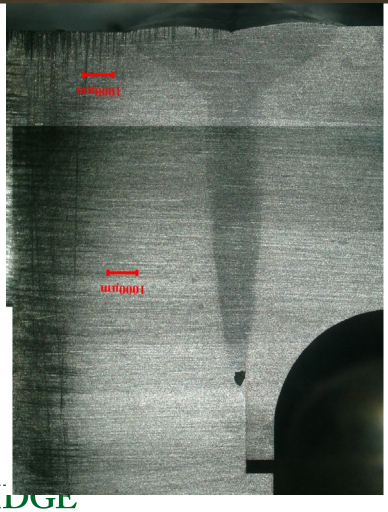
- plastic collapse
- local failure
- ~~buckling~~
- cyclic failure
  - fatigue
    - nominal beam
    - nominal – low flow
    - nominal – offset beam
    - focused beam
    - diffuse beam
  - ratcheting

Fatigue lifetime of foot demonstrates acceptable margins over 10 years of operation

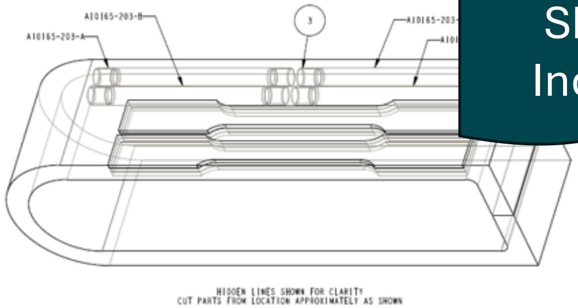
	Inconel Side Weld	Inconel 718 (SA)	Tungsten	SS316L
Beam Trips				
Beam Pulses				

Verification of key processes, geometry, and specifications have been completed and will be employed in a full scale vendor qualification article

Weld joint

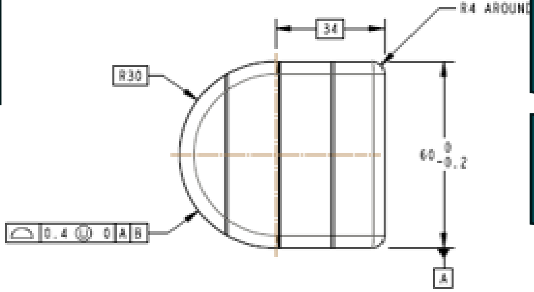


Inconel forging & grain size



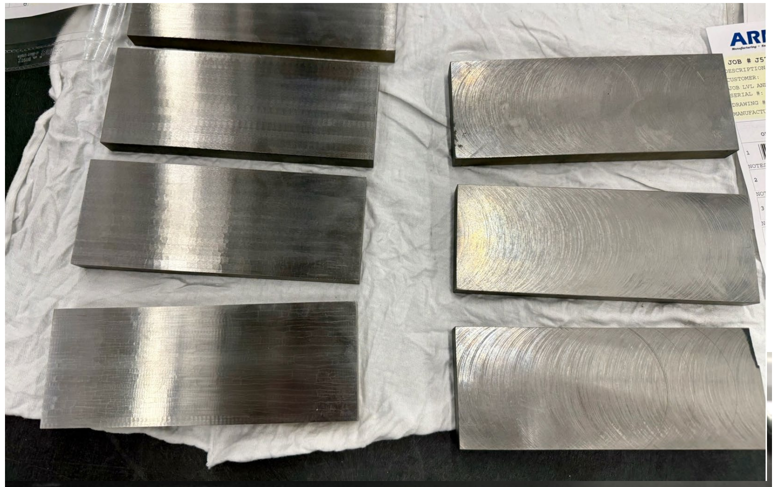
SPEC-Inconel

VHP Stack & machining



Spec-VHP

SPEC-W

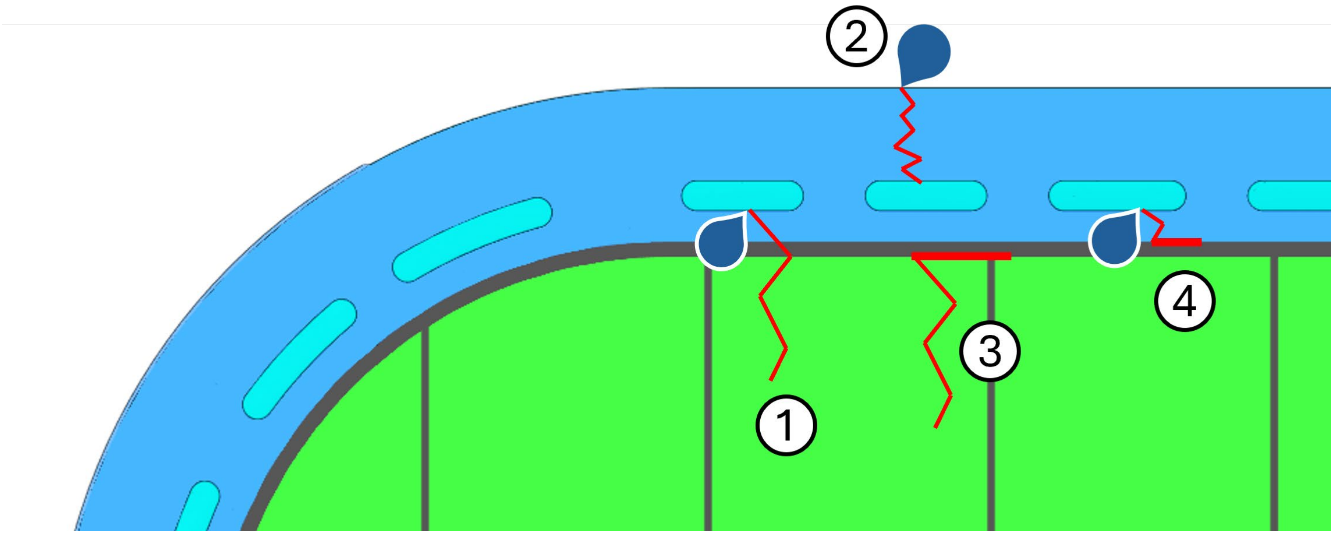


Postulated Failure Modes

How can the target foot fail?

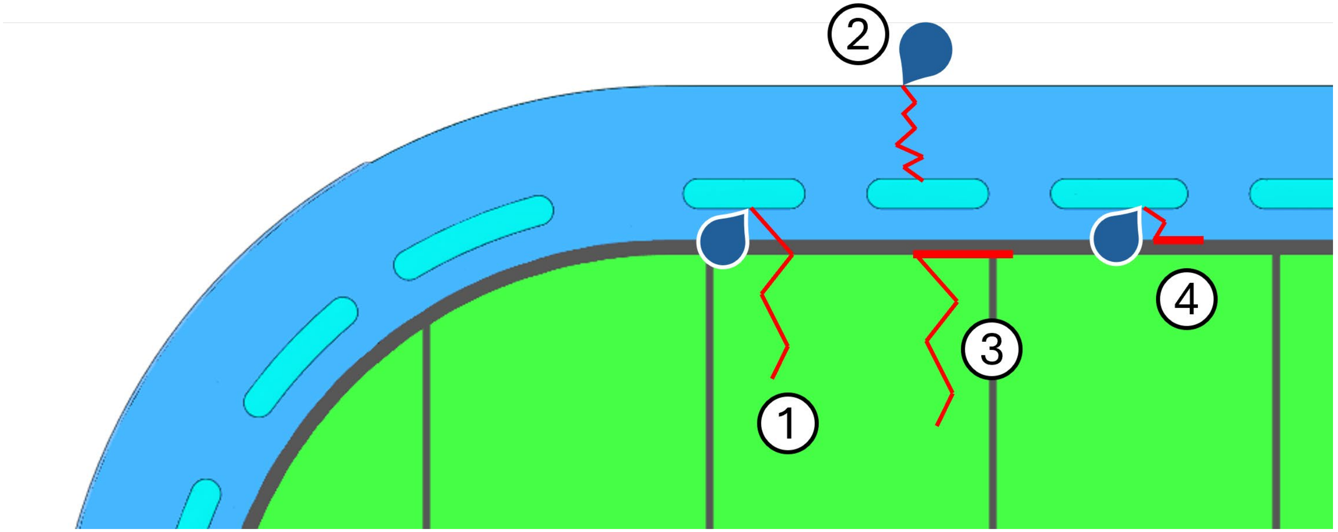
Postulated Failure Modes

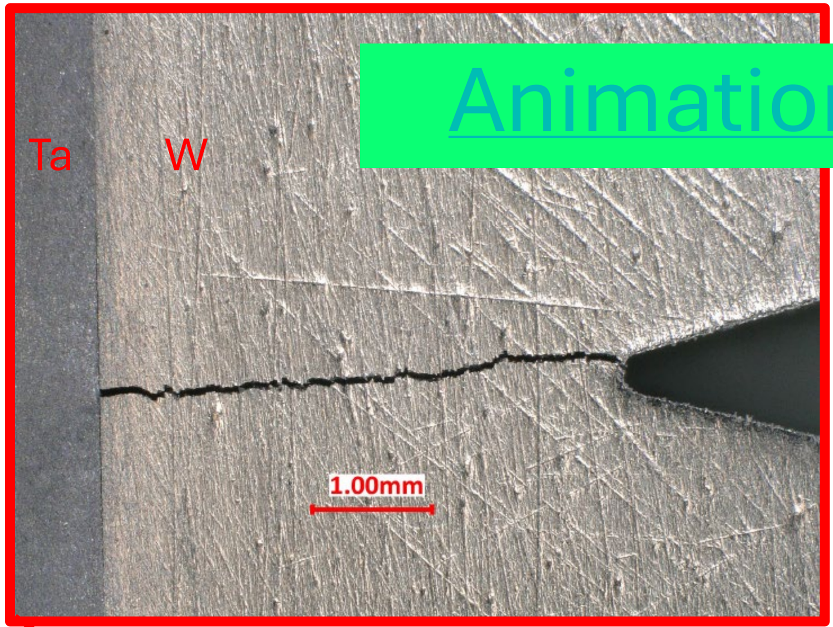
	Description	Probability of effect	Effect
1	Crack in W propagates, causing internal water leak (undetected)	Unlikely	W in water (Detected only in water activity)
2	Housing cracks (fatigue or other)	Unlikely	Shutdown - Leak
3	Tungsten cracks, debonds at interface	Likely	Increased temp, maintain operation
4	Debond, overstress, leak	Unlikely	Cu in water (Detected only in water activity)



Crack Deflection

- R&D - Cracks initially arrest and debond
  - Debond length is finite & fixed
  - Fatigue failure in Tantalum at **2x** design fatigue loading
- Confirmed by Fracture Mechanics by J. Mach





Animation

Debonding

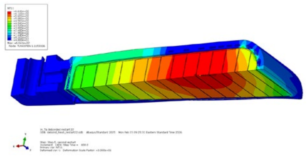
What happens if the crack propagates and causes debonding?

What happens to the heat transfer if any of the HIP joints fail or is not fabricated properly?

Fabrication

- Contamination at bond interface
- Insufficient contact pressure due to stiffness
- Weld pool intrusion

Fabrication R&D and vendor qualification



Evaluate operation without bonds ✓

Service

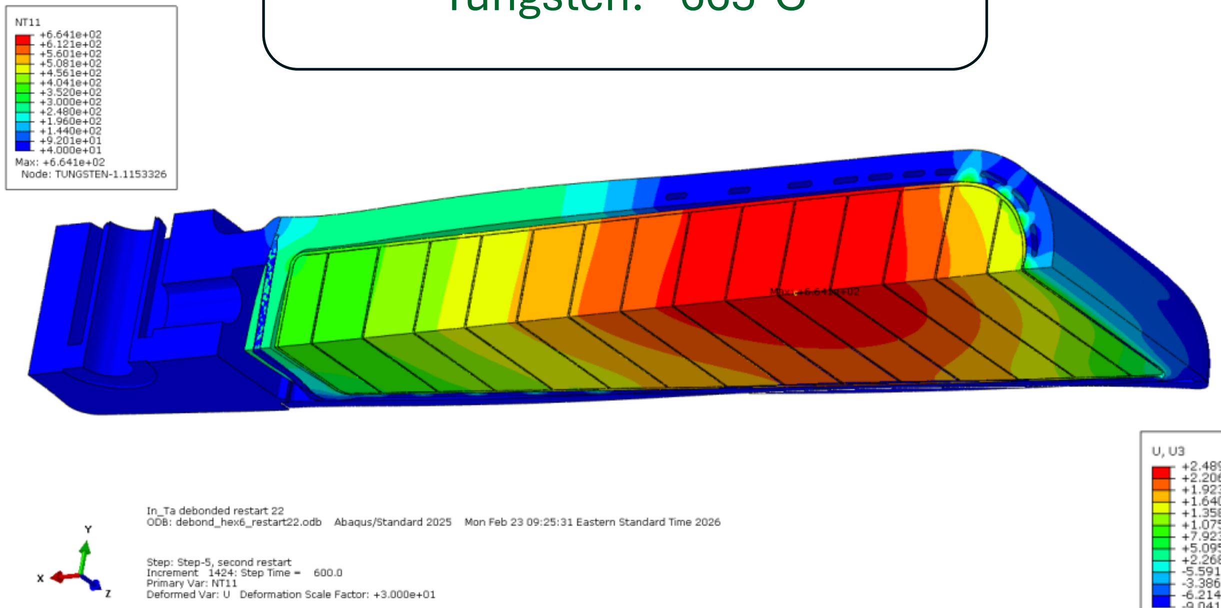
- Fatigue crack propagates to surface & debonds
- Decay heat – Inconel pulls away
- Service interruption – Water trip

Air cooling and water cooling

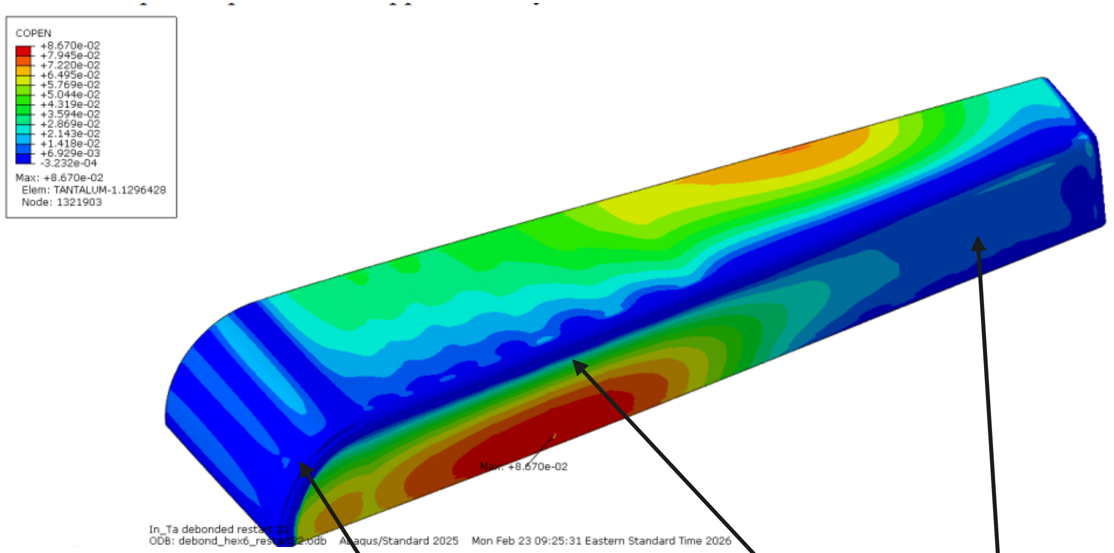
OAK RIDGE National Laboratory

Target can continue operation in the event of debonding

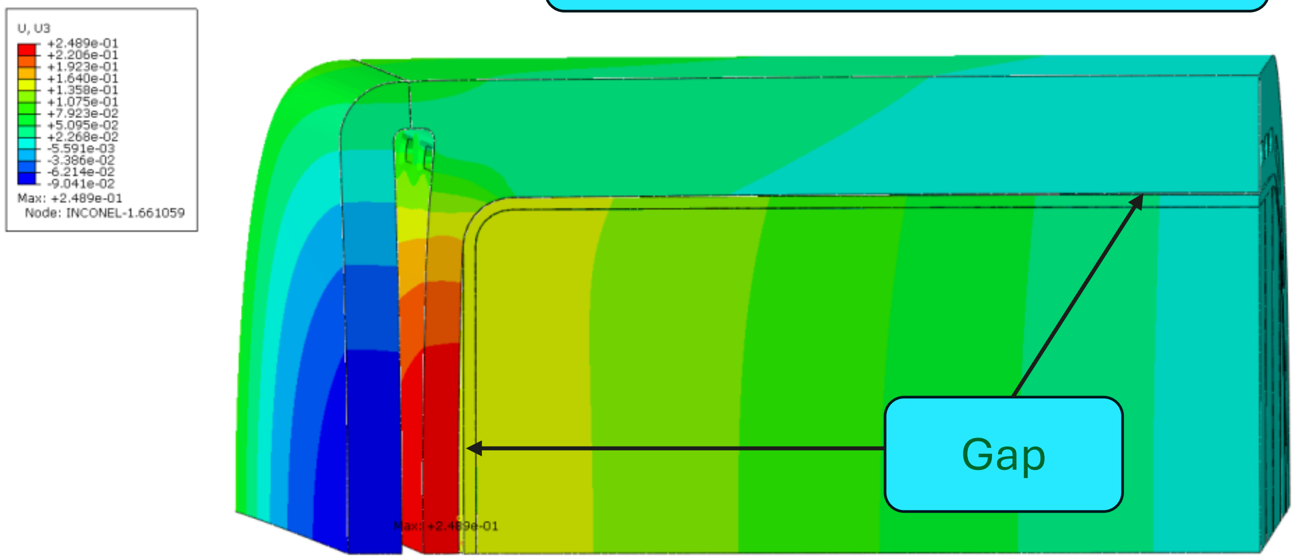
Operating temp in center of Tungsten: ~665°C



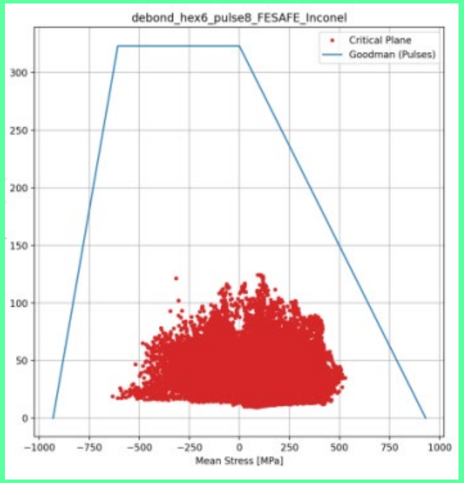
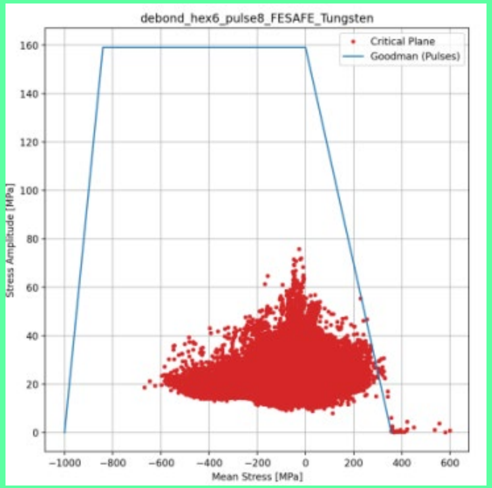
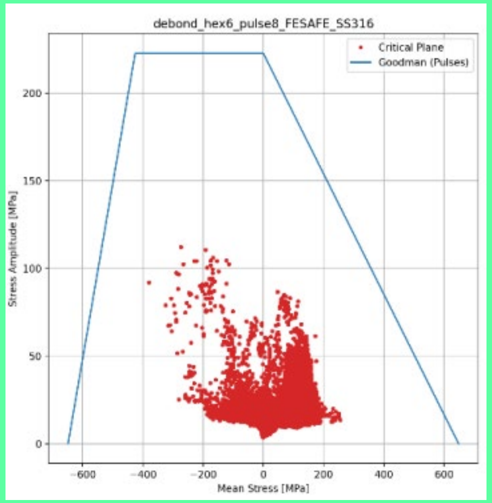
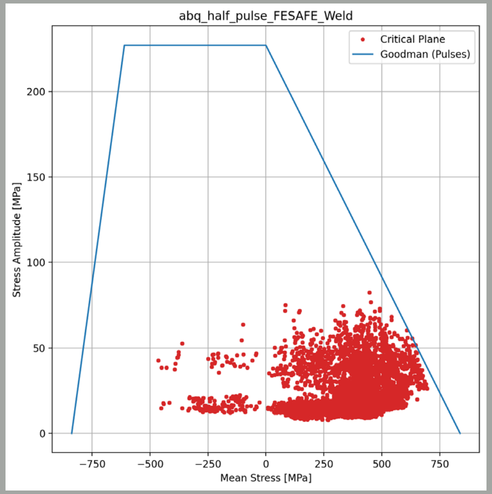
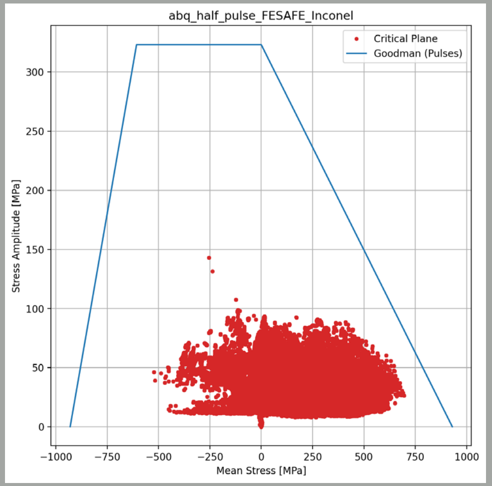
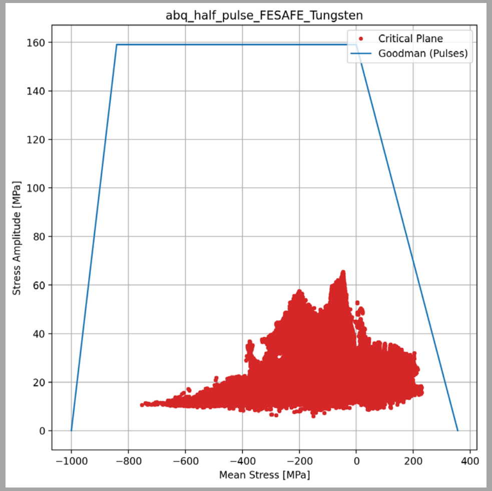
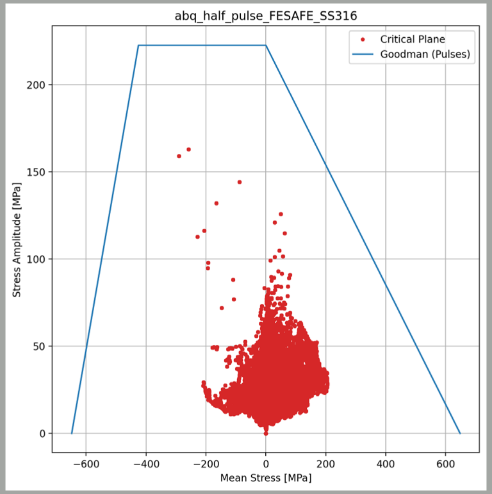
Tungsten grows into the cold Inconel



Contact in nose and edges



Debonded Inconel fatigue results are improved over baseline operation

	Inconel Side Weld	Inconel 718 (SA)	Tungsten	SS316L
Debond				
Bonded				

So why not proceed with a debonded target as the baseline design?

Tungsten fatigue limit

Ambiguous contact is hard to define

Exact nature of cracked Tungsten is unpredictable

High temperature nature of Tungsten and Tantalum during operation

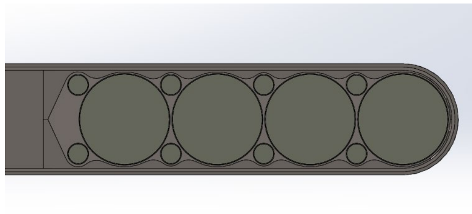
The target Assembly team has selected a more predictable baseline design

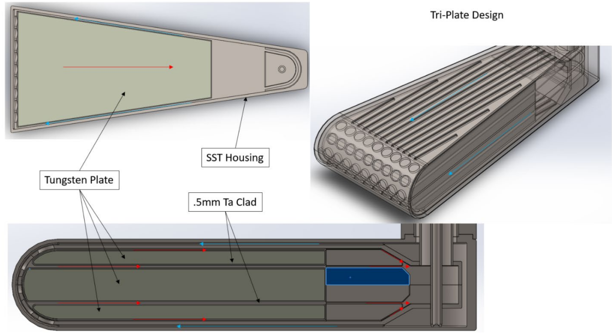
Knowledge that the worst-case failure mode is acceptable eases the burden of proving the exact condition of the HIP bond state

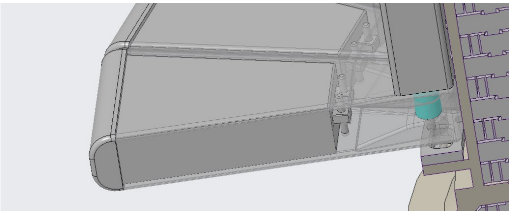
Refinement of design & alternatives

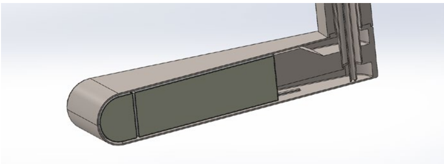
Why is this the best design?

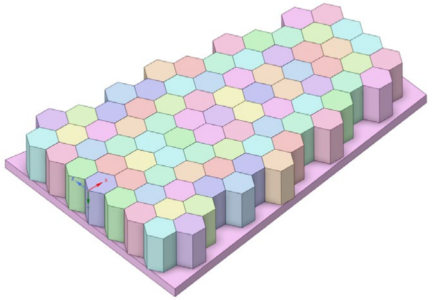
Alternative design studies - 2024

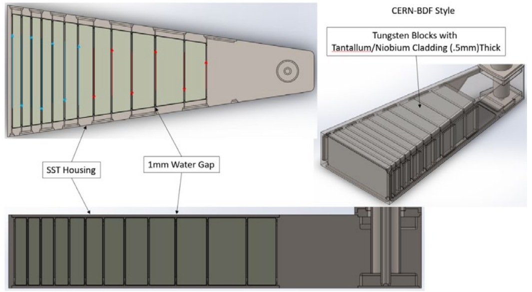


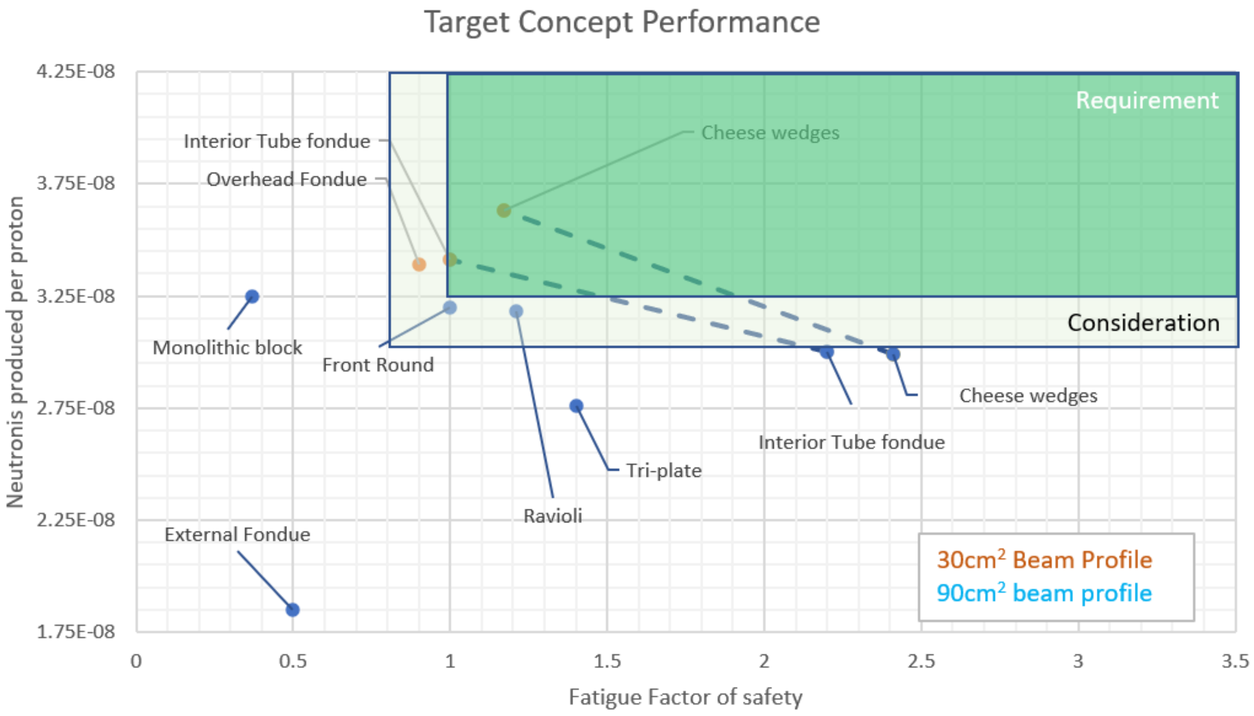


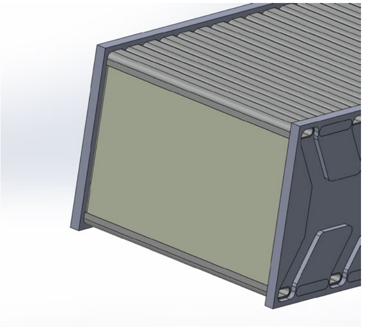


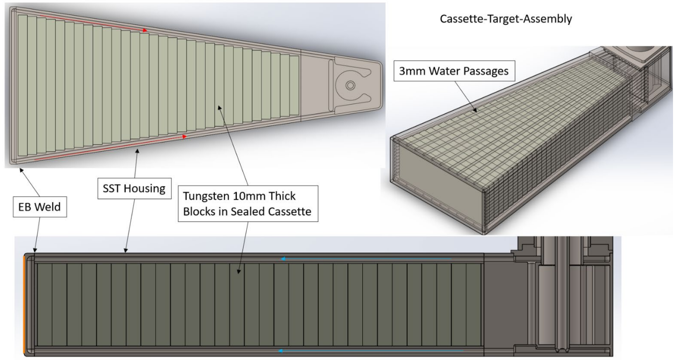


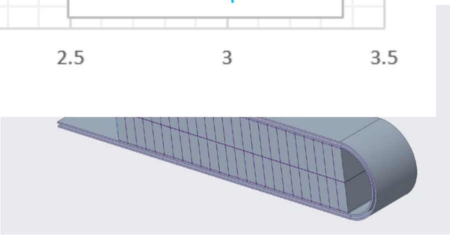


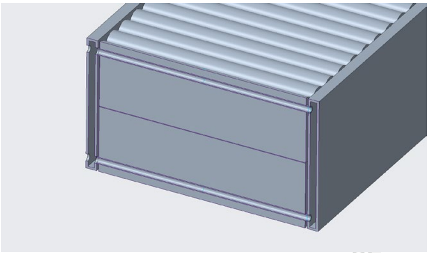




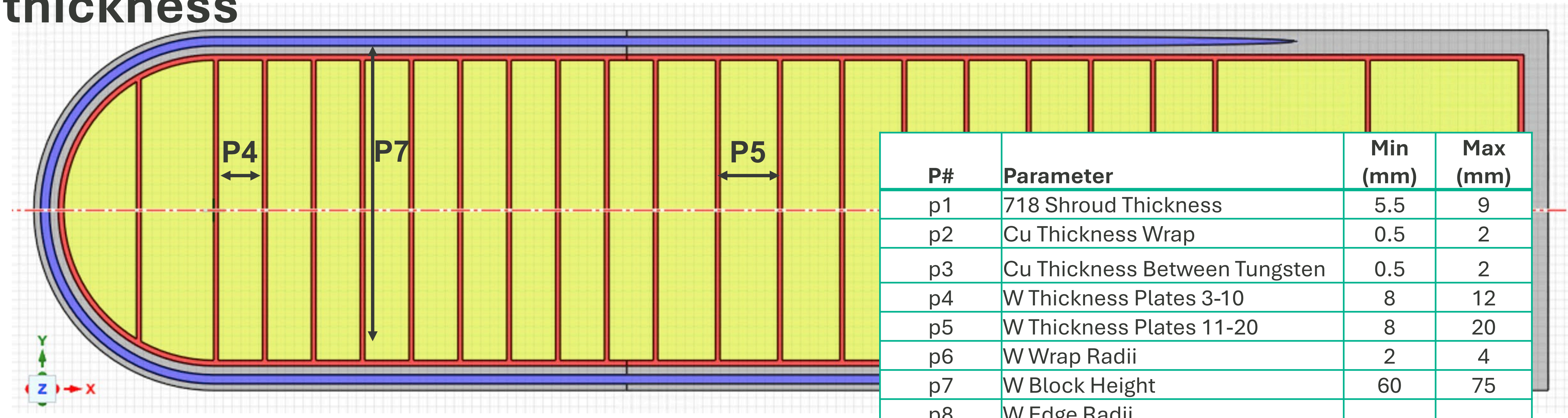




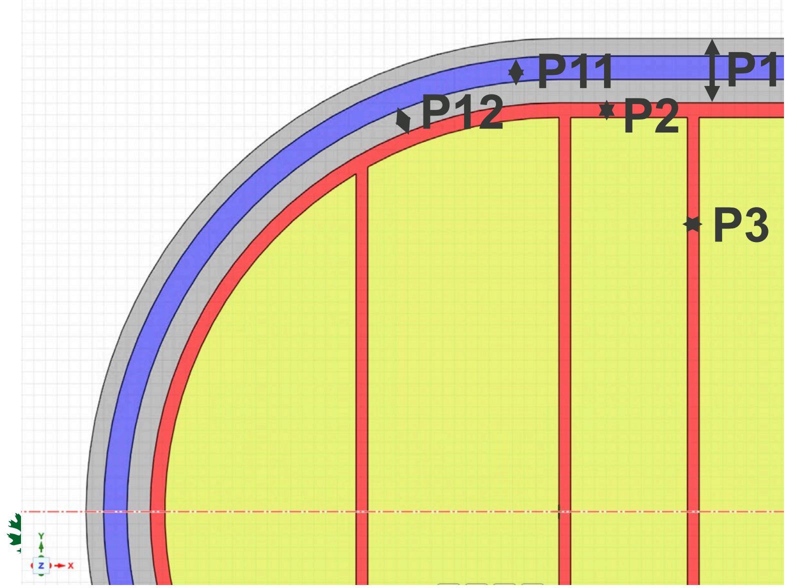


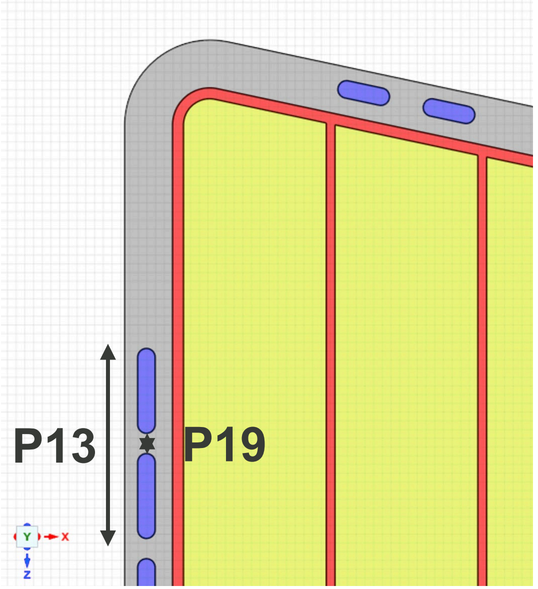


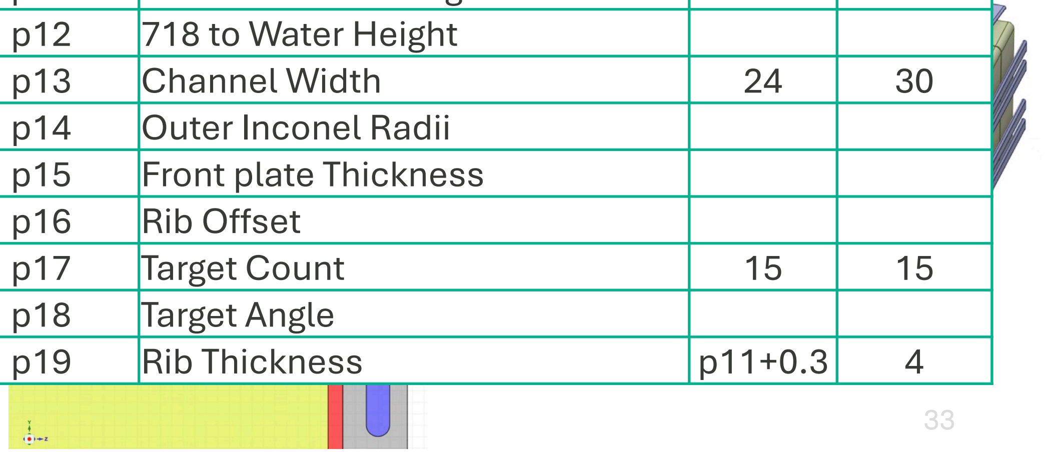
Optimization studies located water channels and Inconel thickness



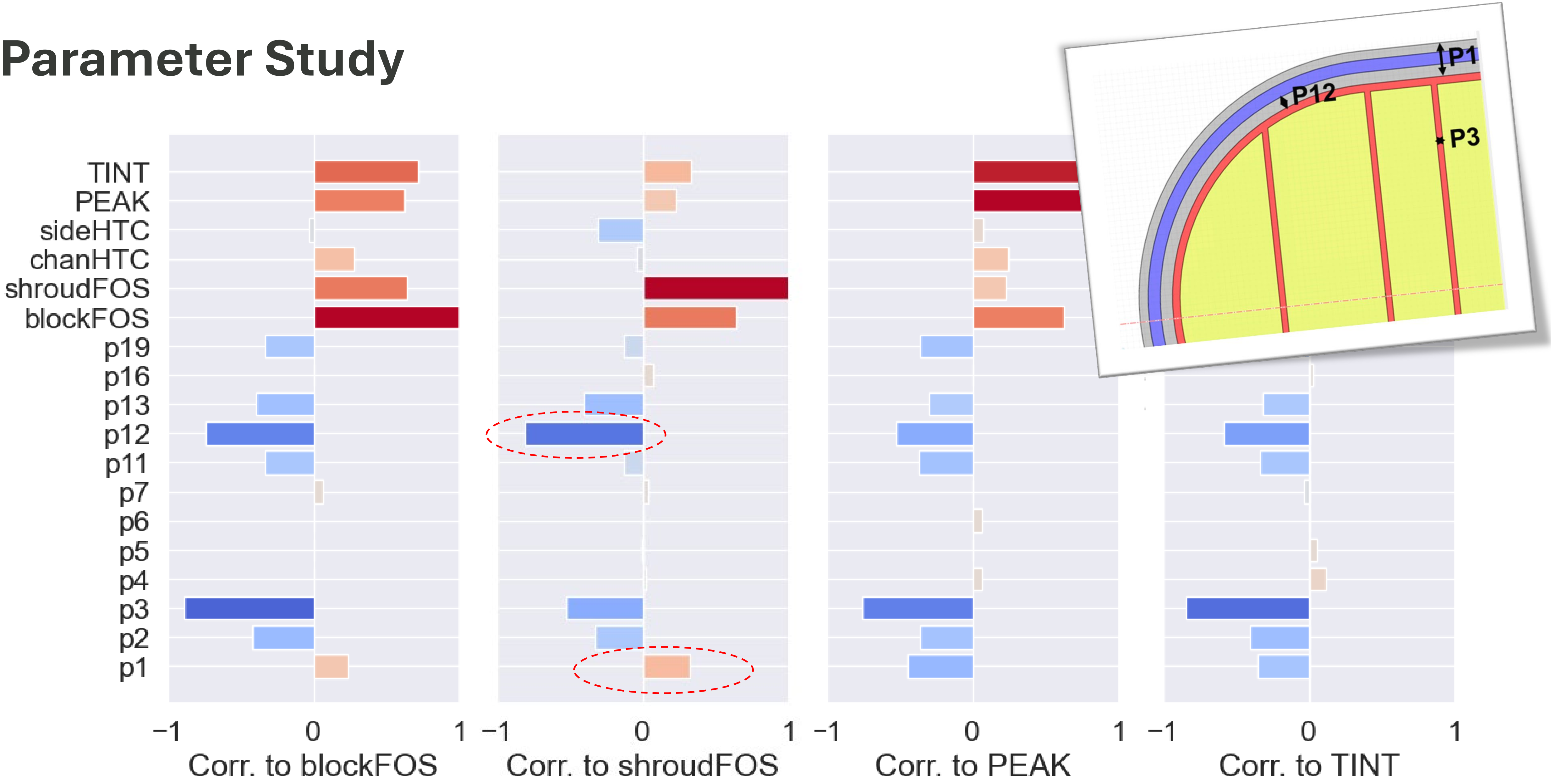
P#	Parameter	Min (mm)	Max (mm)
p1	718 Shroud Thickness	5.5	9
p2	Cu Thickness Wrap	0.5	2
p3	Cu Thickness Between Tungsten	0.5	2
p4	W Thickness Plates 3-10	8	12
p5	W Thickness Plates 11-20	8	20
p6	W Wrap Radii	2	4
p7	W Block Height	60	75
p8	W Edge Radii		
p9	Outer Cu Wrap Radii		
p10	718 Cu End Radii		
p11	Water Channel Height	1	3
p12	718 to Water Height		
p13	Channel Width	24	30
p14	Outer Inconel Radii		
p15	Front plate Thickness		
p16	Rib Offset		
p17	Target Count	15	15
p18	Target Angle		
p19	Rib Thickness	p11+0.3	4



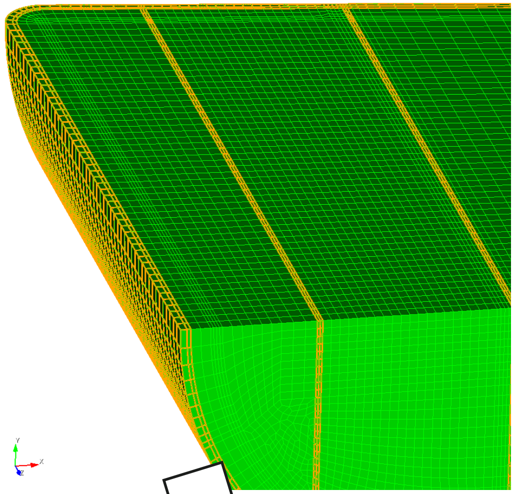


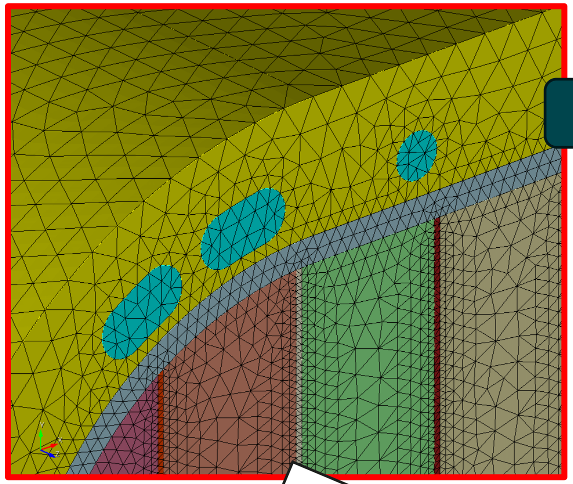


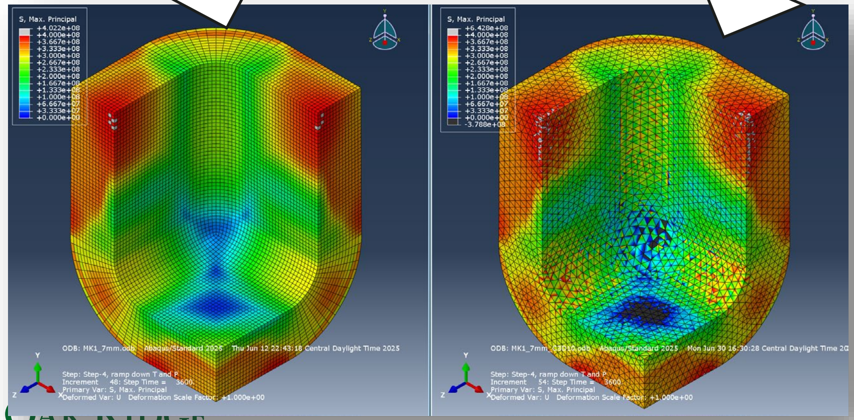
Parameter Study



The tantalum thickness was selected for reliable predictions (computation) and manufacturability – not just decay heat!

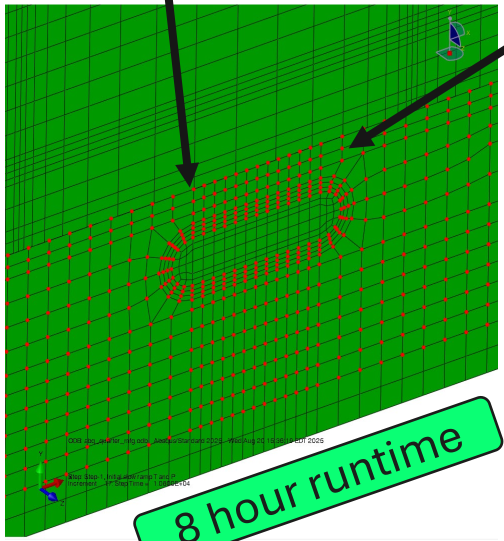






Contact surfaces

Goal: Two elements through the thickness



8 hour runtime

```
            P R O B L E M   S I Z E

NUMBER OF ELEMENTS IS                              1247100
NUMBER OF ELEMENTS DEFINED BY THE USER AND *TIE    1151128
NUMBER OF INTERNAL ELEMENTS GENERATED FOR CONTACT    95972
NUMBER OF NODES IS                                 1409254
NUMBER OF NODES DEFINED BY THE USER                1217310
NUMBER OF INTERNAL NODES GENERATED BY THE PROGRAM   191944
TOTAL NUMBER OF VARIABLES IN THE MODEL             3939846
(DEGREES OF FREEDOM PLUS MAX NO. OF ANY LAGRANGE MULTIPLIER
 VARIABLES. INCLUDE *PRINT,SOLVE=YES TO GET THE ACTUAL NUMBER.)
```

4x elements

540 hour runtime

```
            P R O B L E M   S I Z E

NUMBER OF ELEMENTS IS                              5630689
NUMBER OF ELEMENTS DEFINED BY THE USER AND *TIE    5534717
NUMBER OF INTERNAL ELEMENTS GENERATED FOR CONTACT    95972
NUMBER OF NODES IS                                 5917043
NUMBER OF NODES DEFINED BY THE USER                5725099
NUMBER OF INTERNAL NODES GENERATED BY THE PROGRAM   191944
TOTAL NUMBER OF VARIABLES IN THE MODEL            17463213
(DEGREES OF FREEDOM PLUS MAX NO. OF ANY LAGRANGE MULTIPLIER
 VARIABLES. INCLUDE *PRINT,SOLVE=YES TO GET THE ACTUAL NUMBER.)
```

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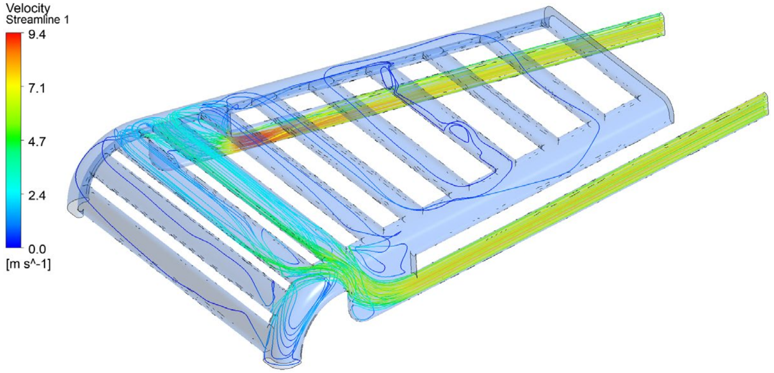
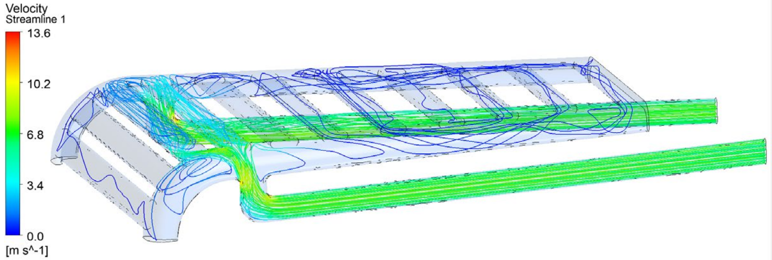
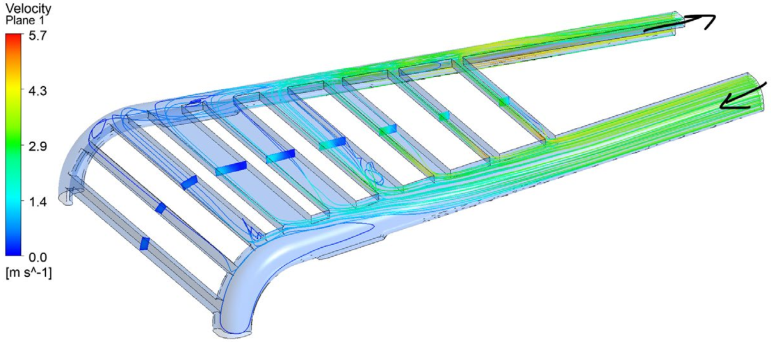
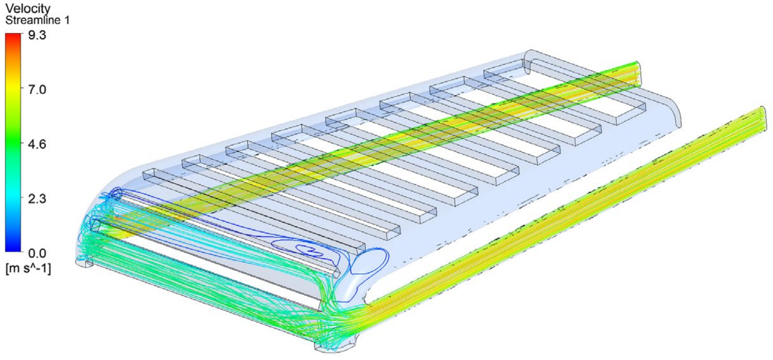
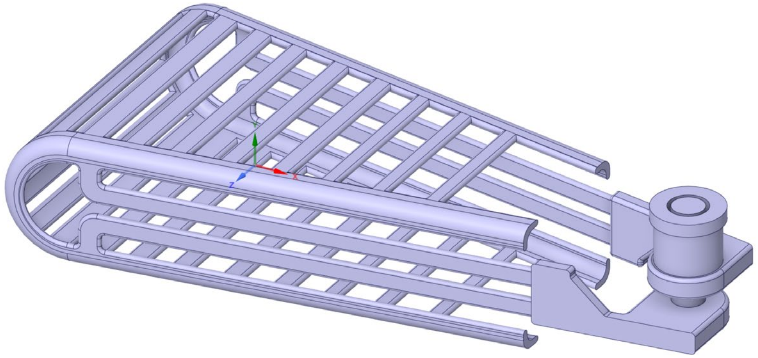
Cooling channels have been carefully selected over several iterations to minimize temperature and provide uniform flow

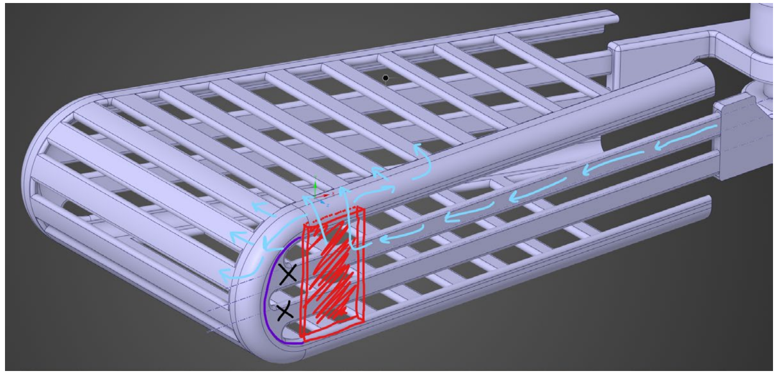




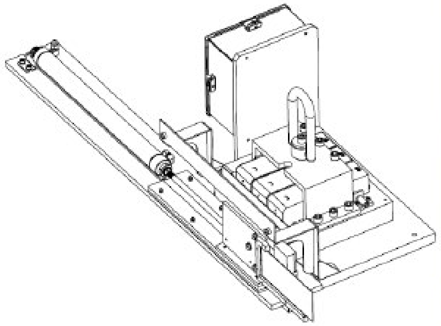


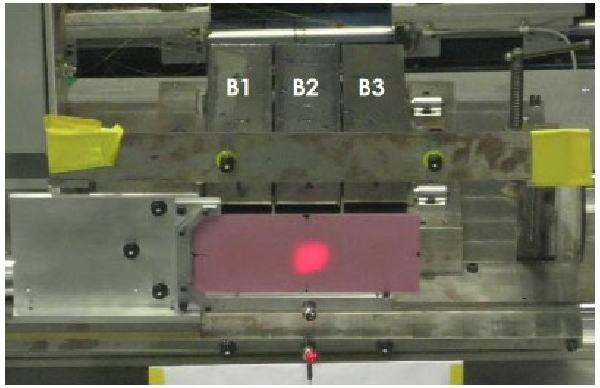


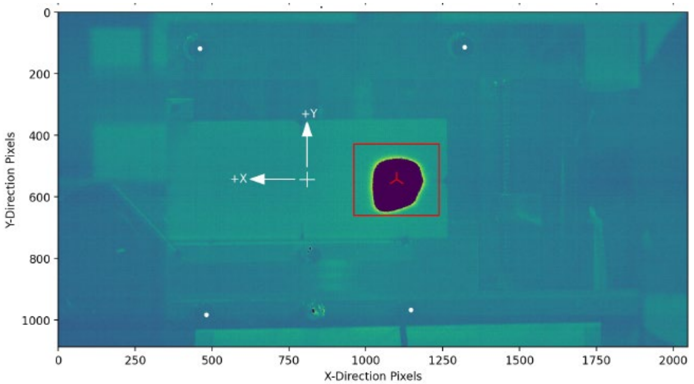


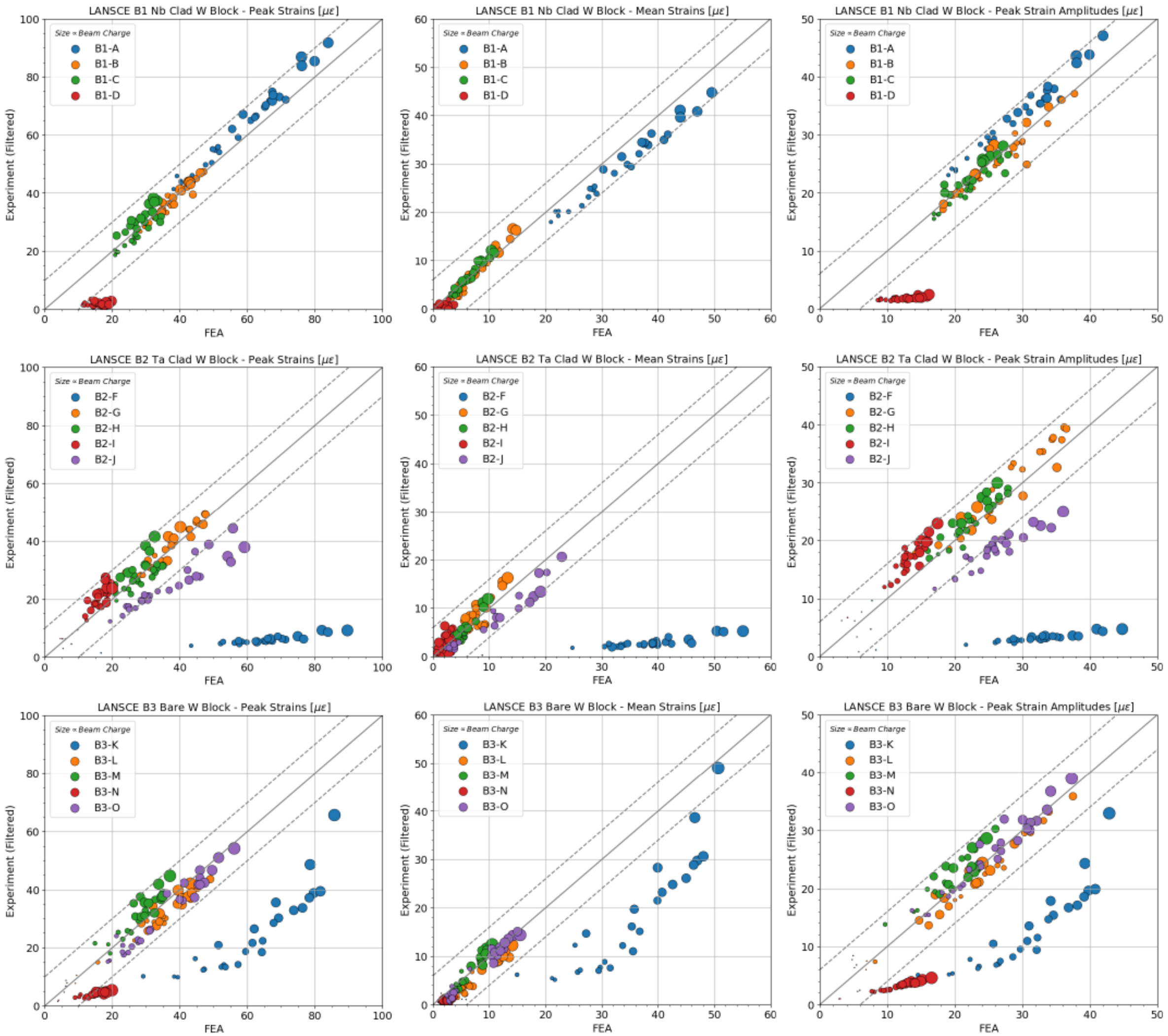


Blue room experiment validated the end-end approach used in fatigue analysis



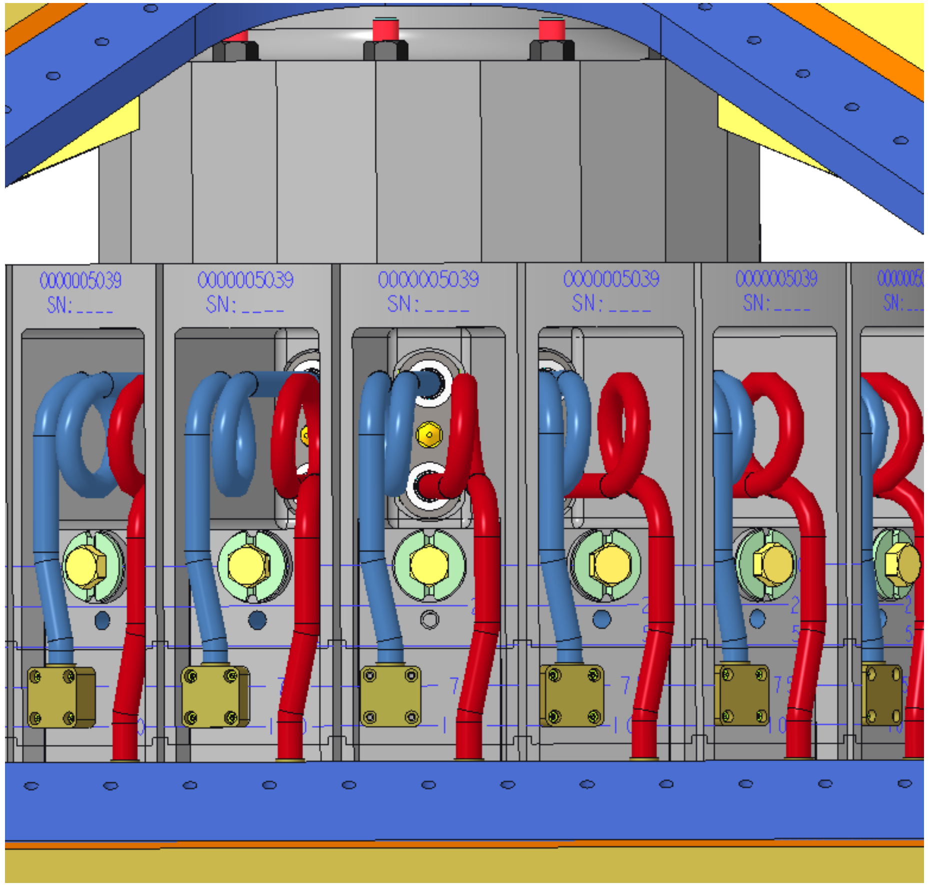


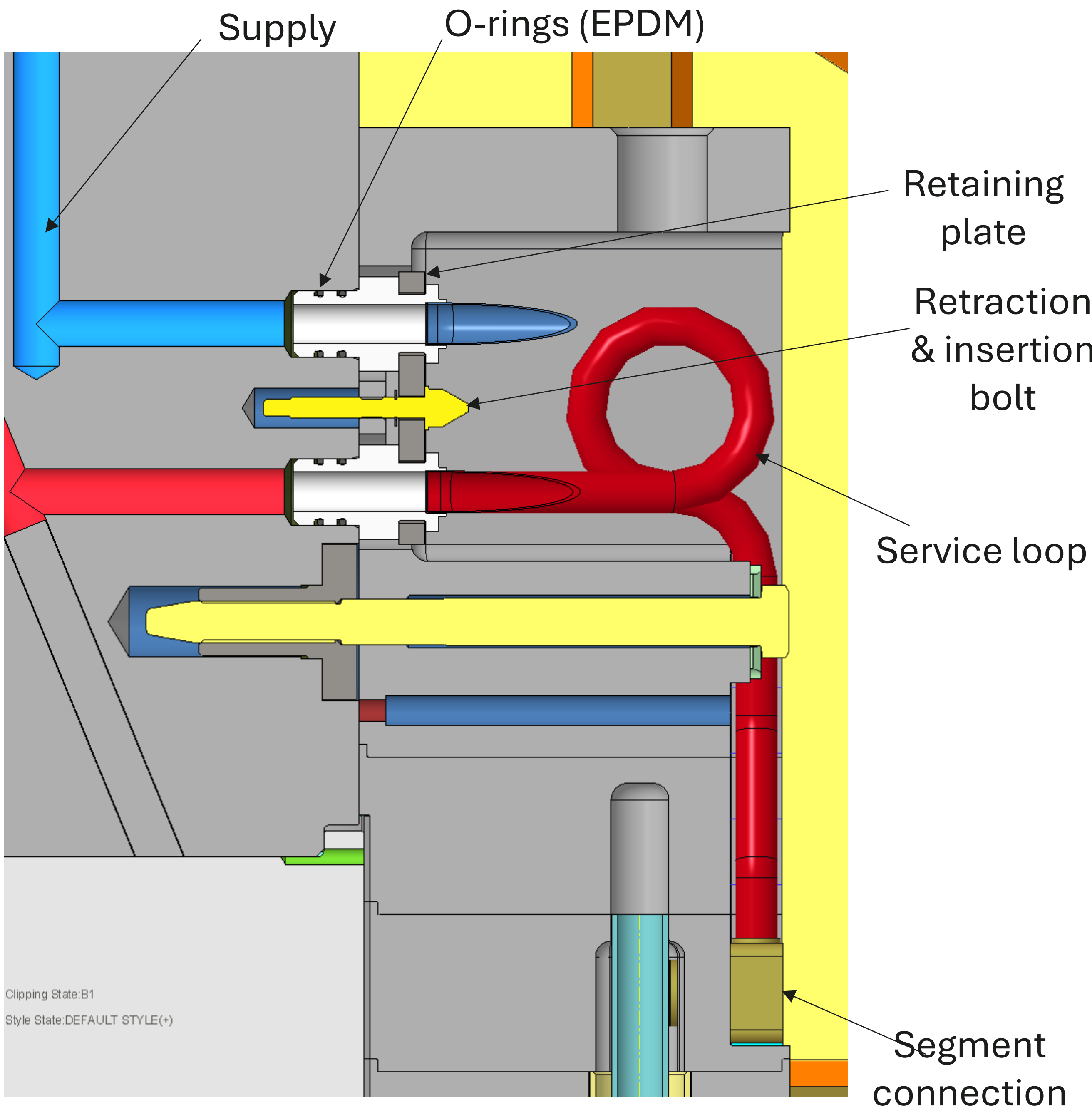




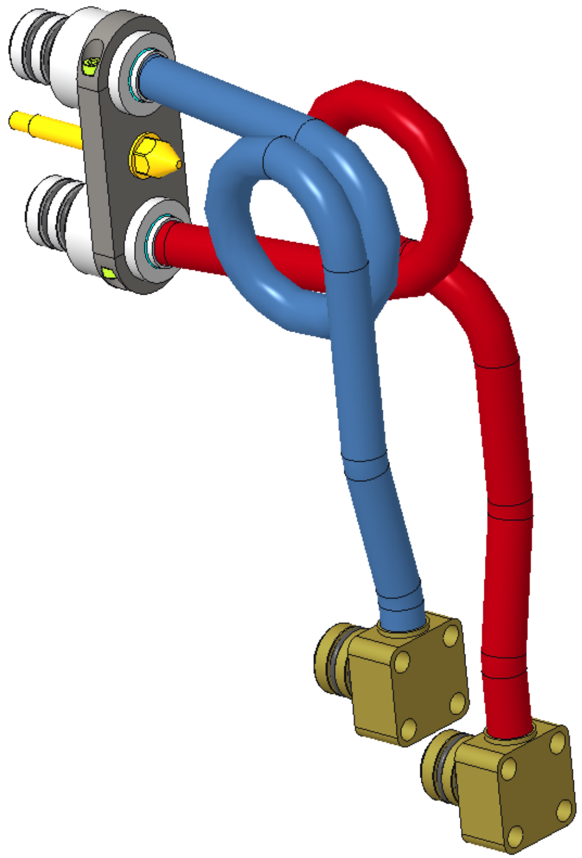
Segment Leg

Segment water connections

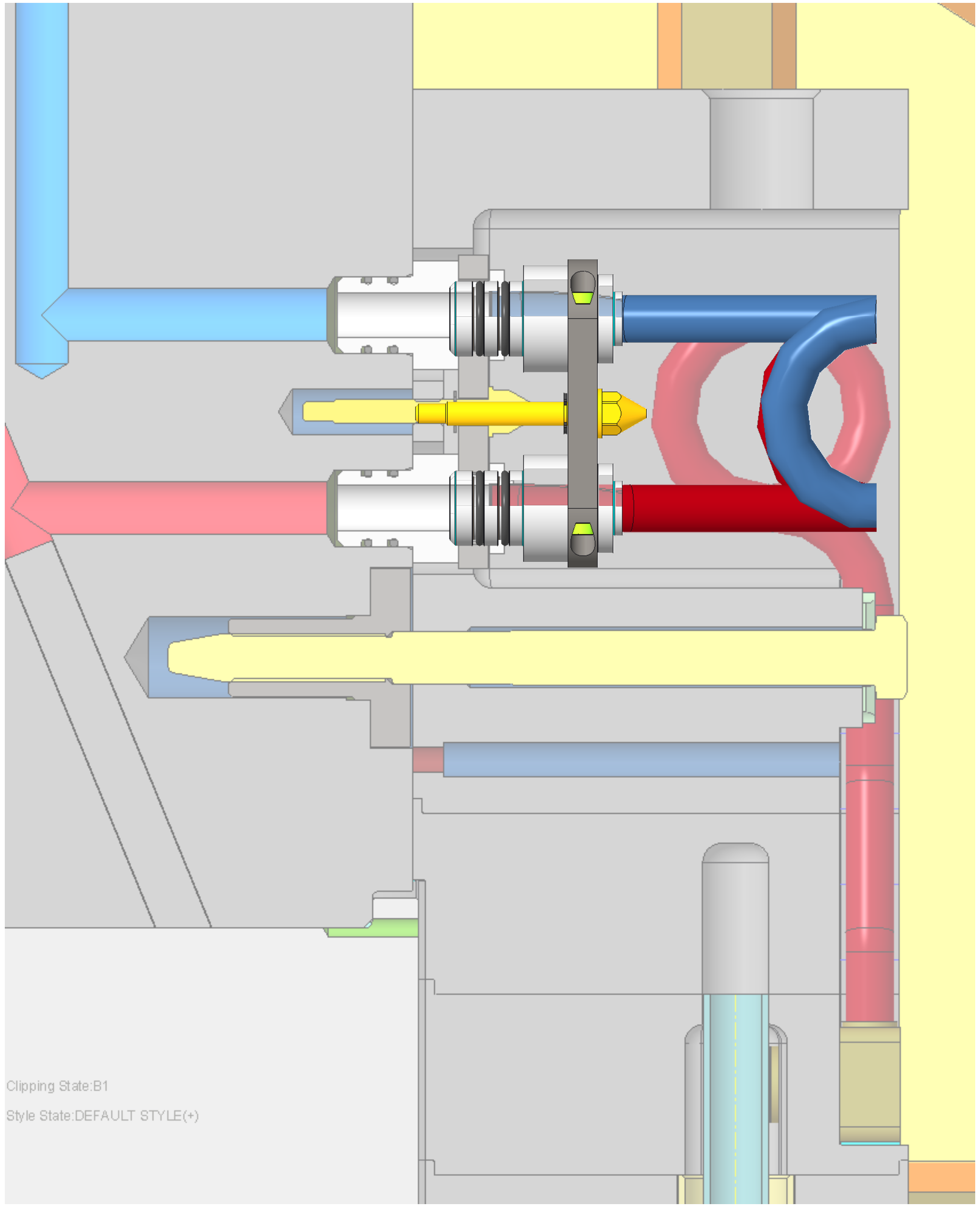




Segment connection mechanism & apparatus



Water seals can be replaced in-situ (w/out removing segment)



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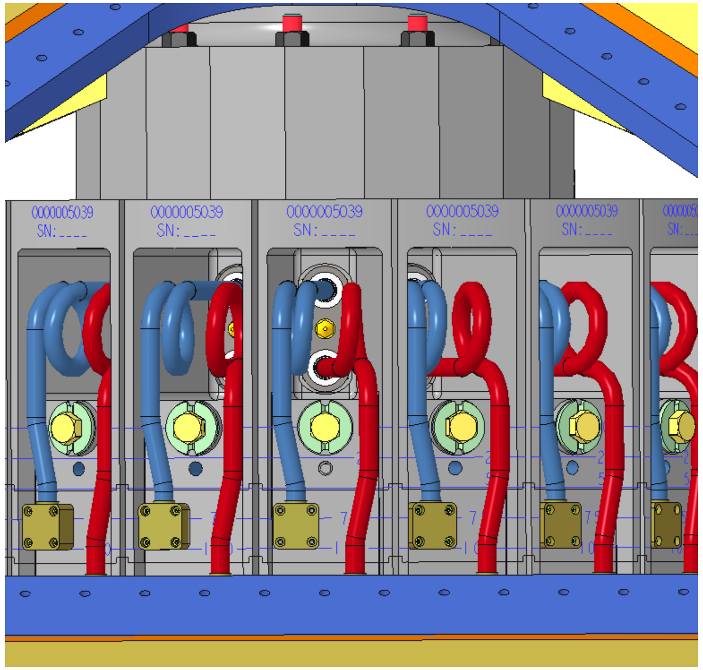
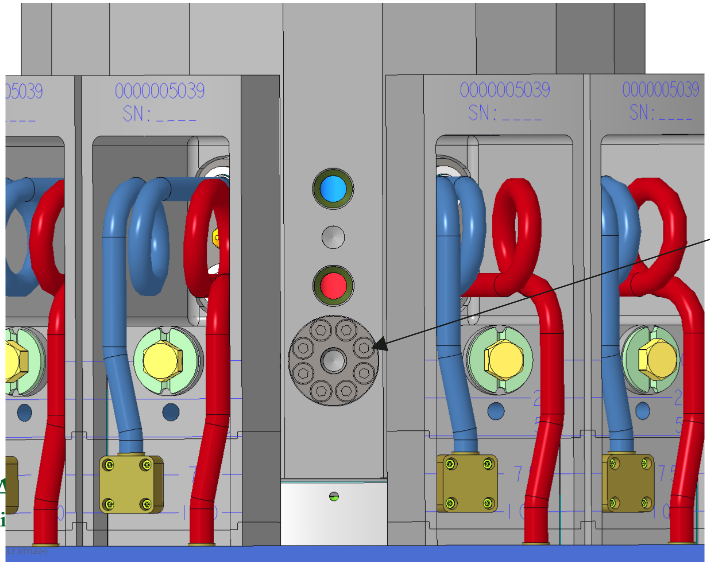
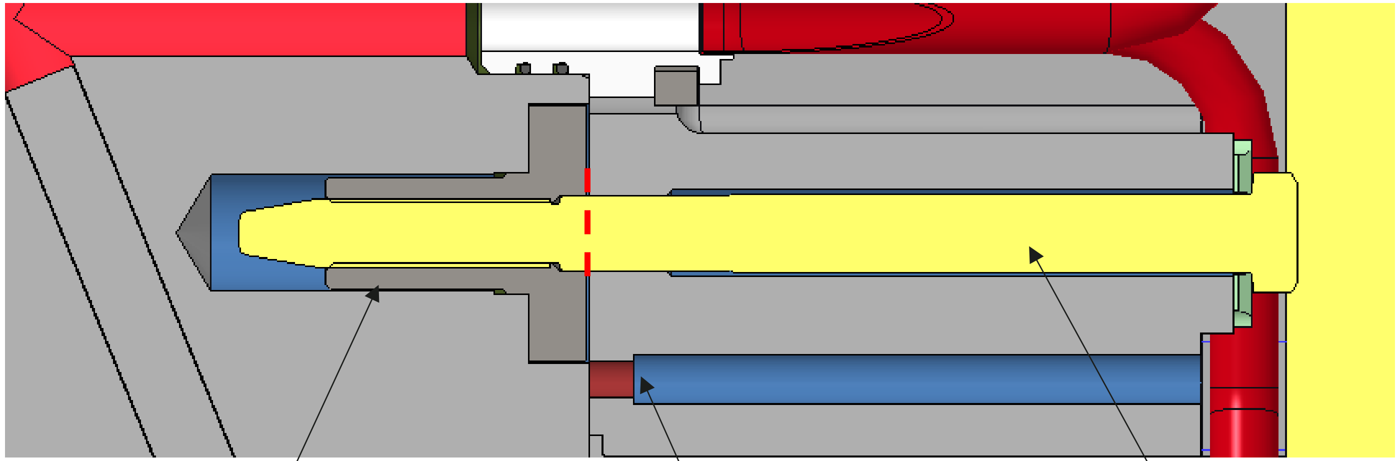
Segment attachment bolt







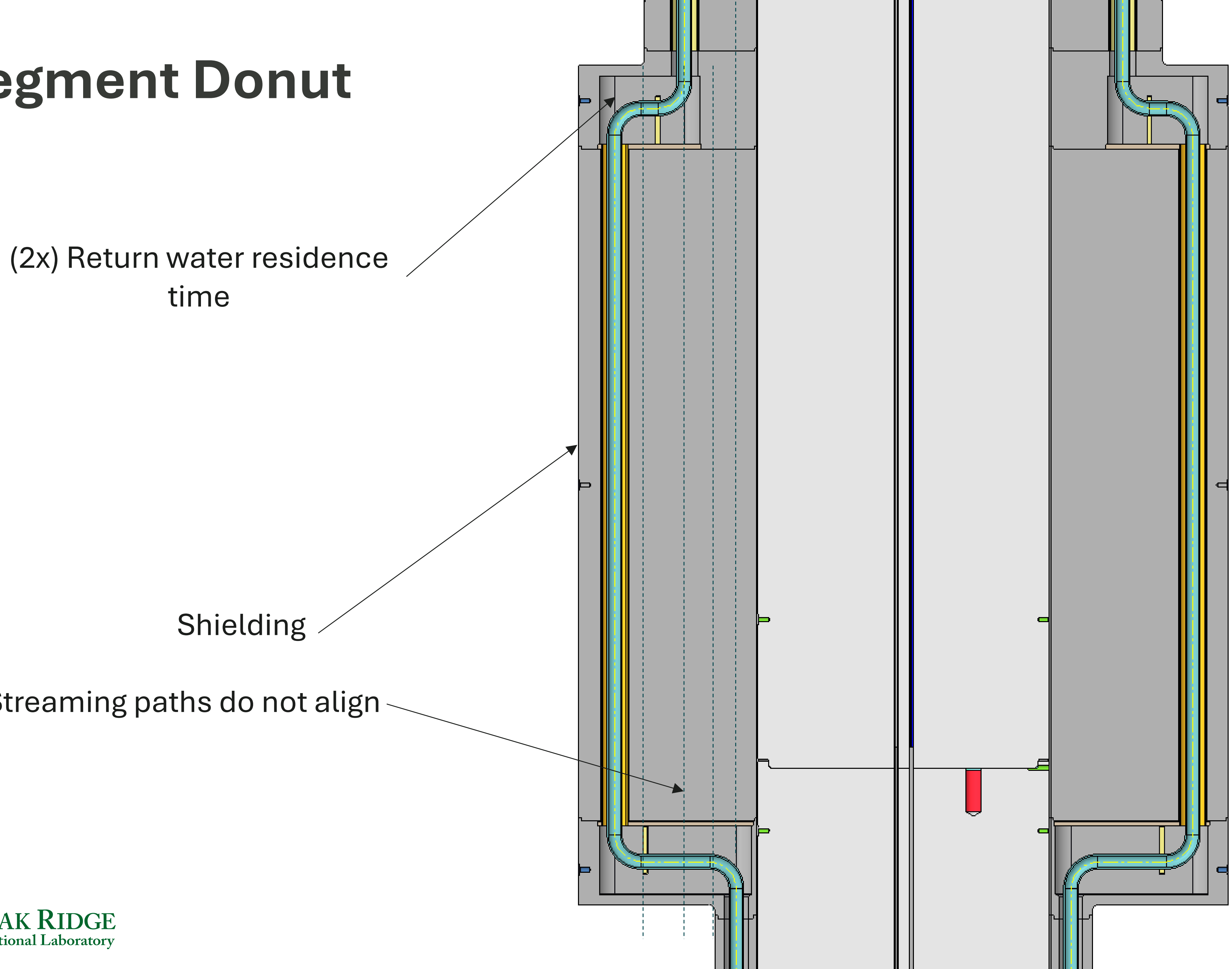
Threaded for jack bolt

Threaded insert

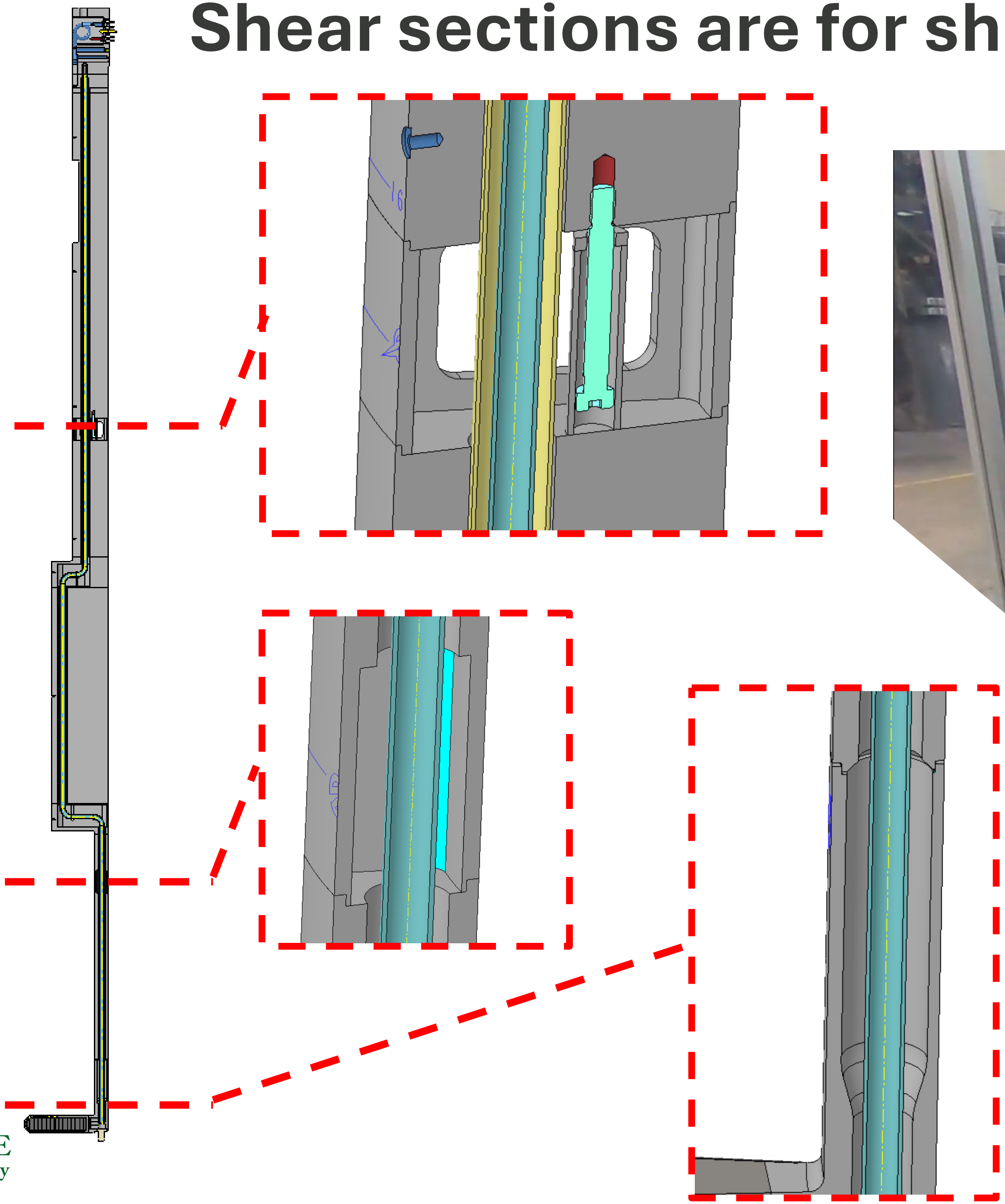
Attachment bolt (IN718)

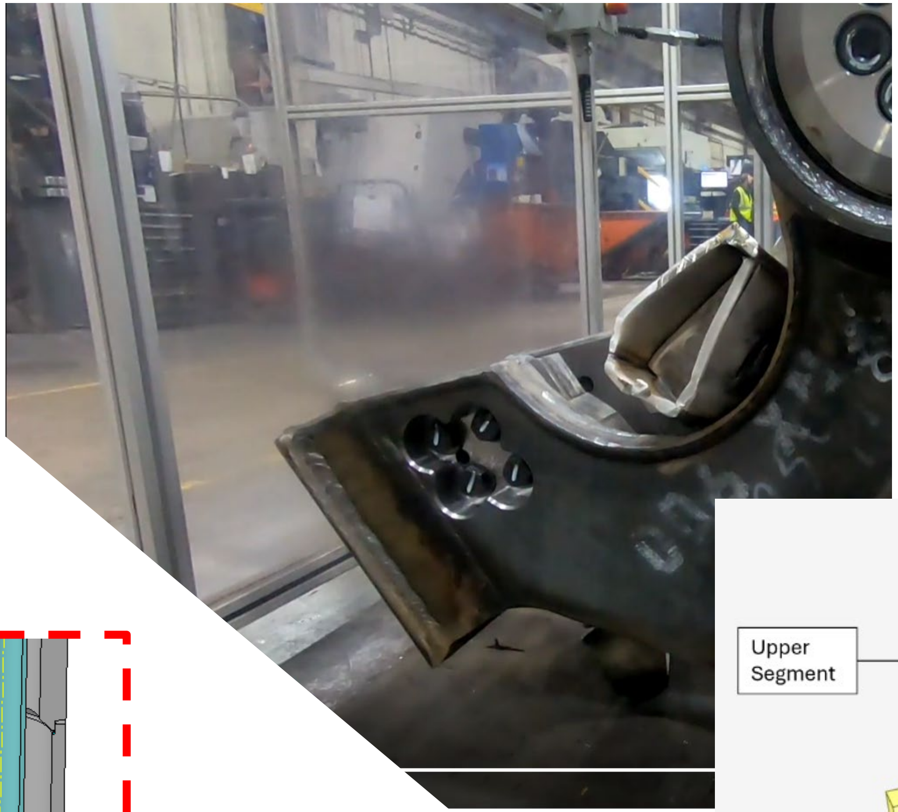
Insert secured to crown

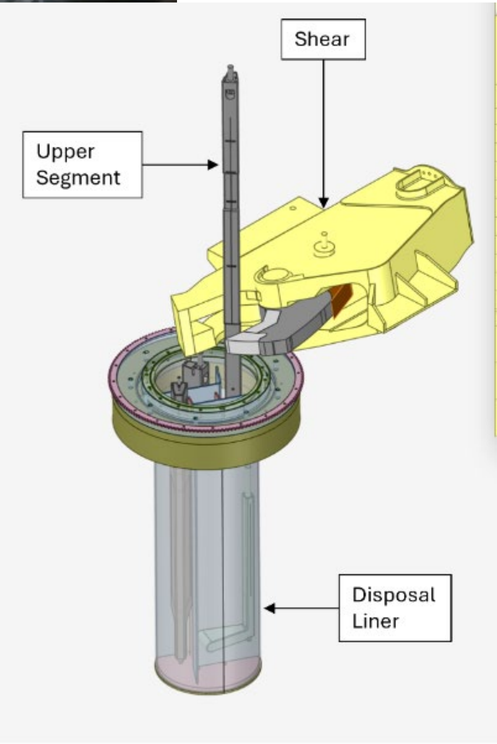
Segment Donut



Shear sections are for shipment preparation







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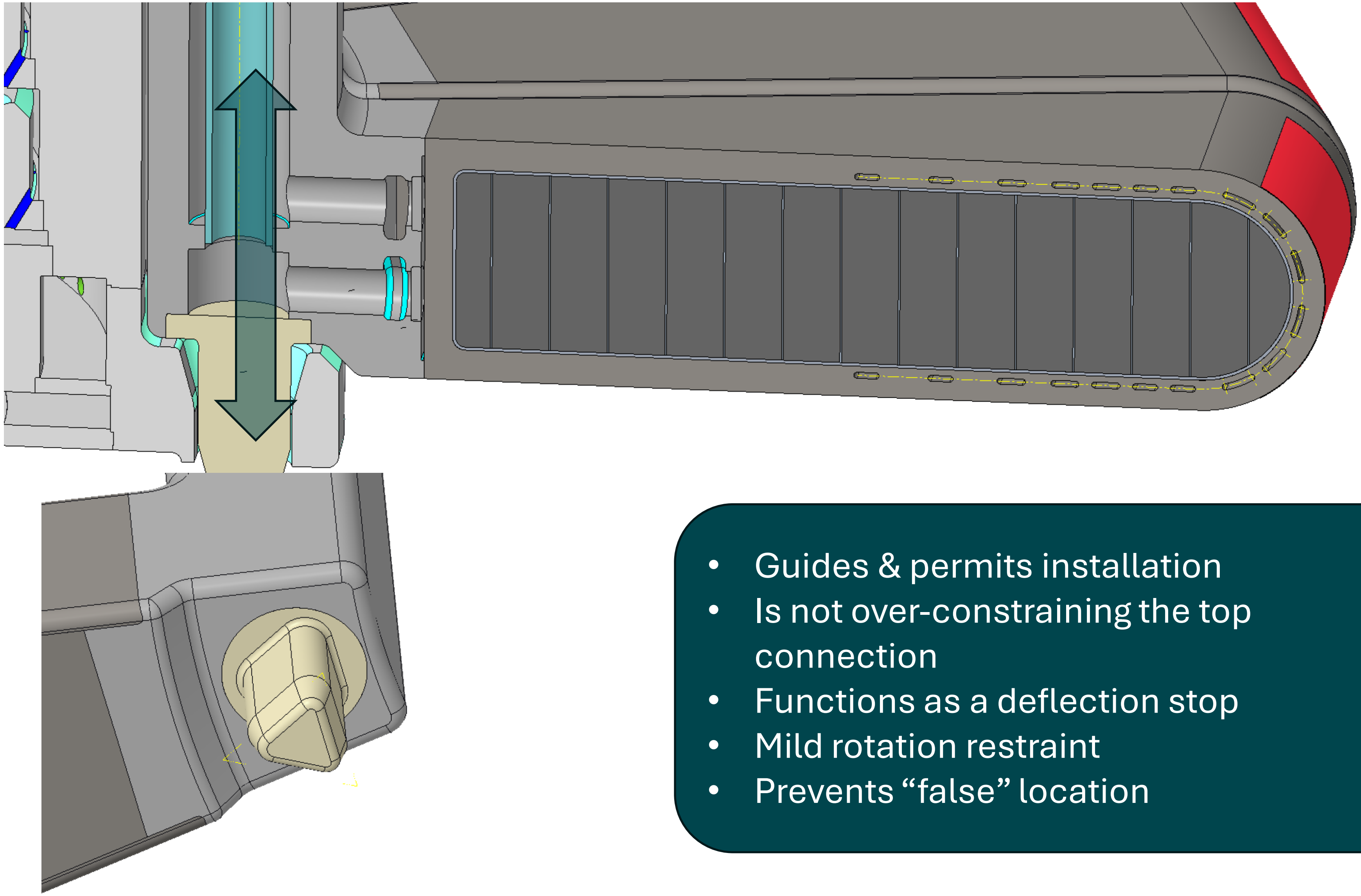
Segment pin provides guidance and restraint without over constraining the system



- Guides & permits installation
- Is not over-constraining the top connection
- Functions as a deflection stop
- Mild rotation restraint
- Prevents "false" location

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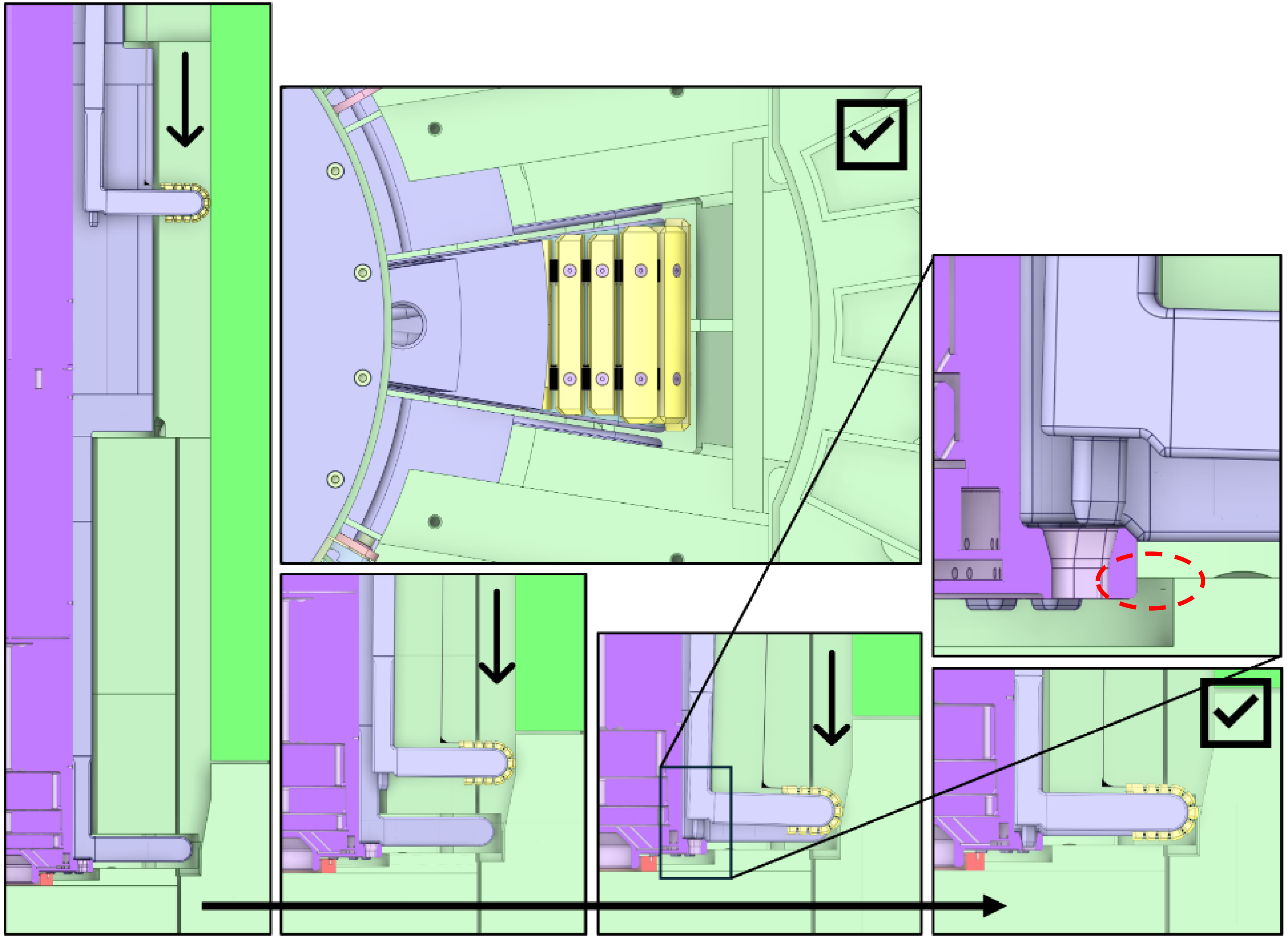
Installation sequence



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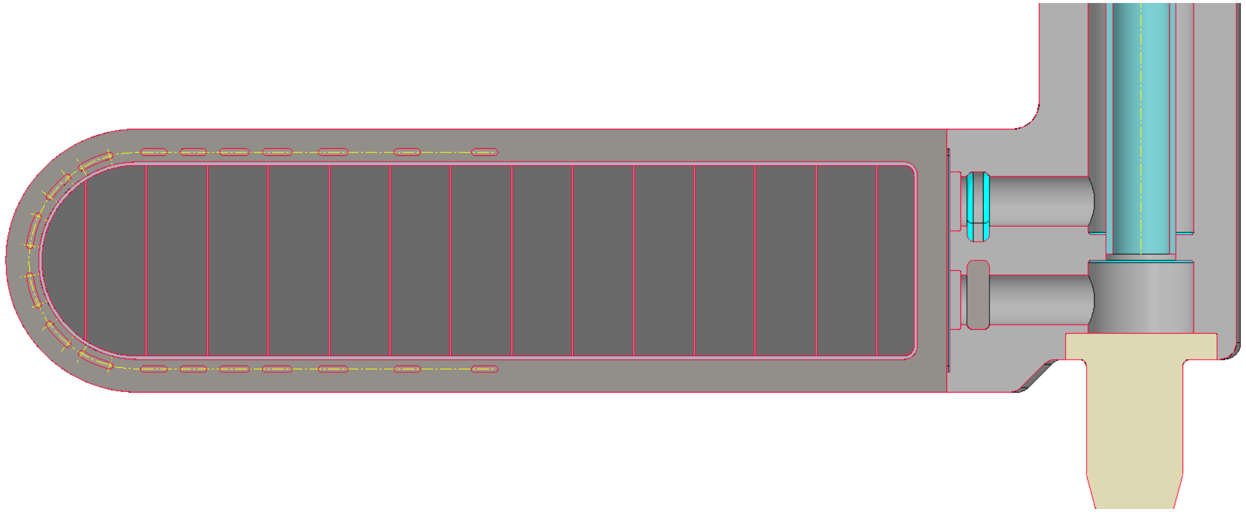
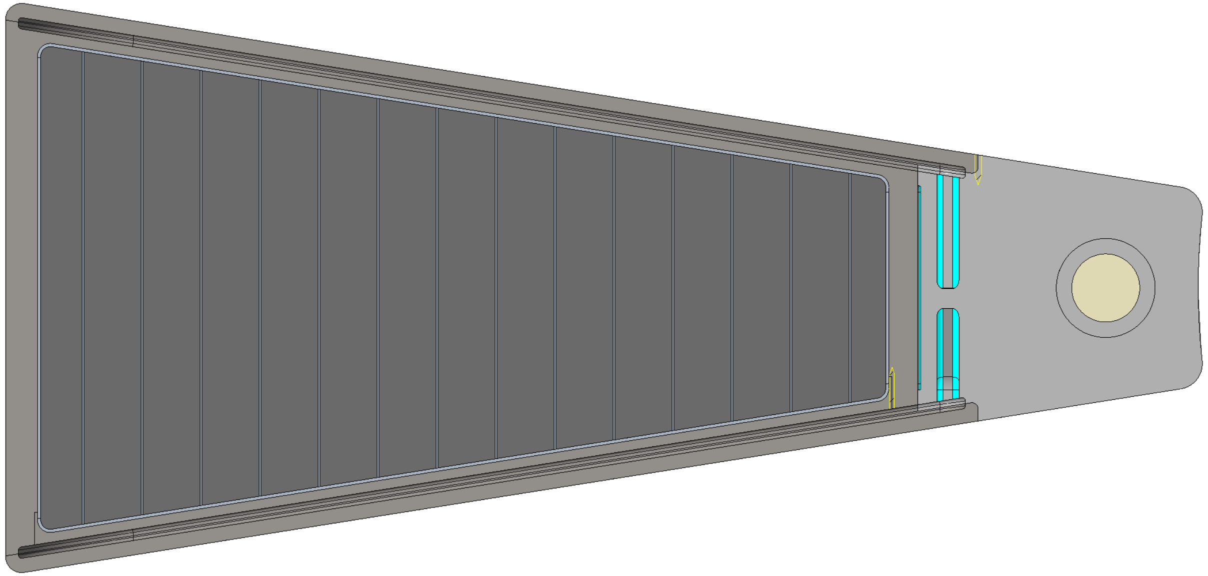
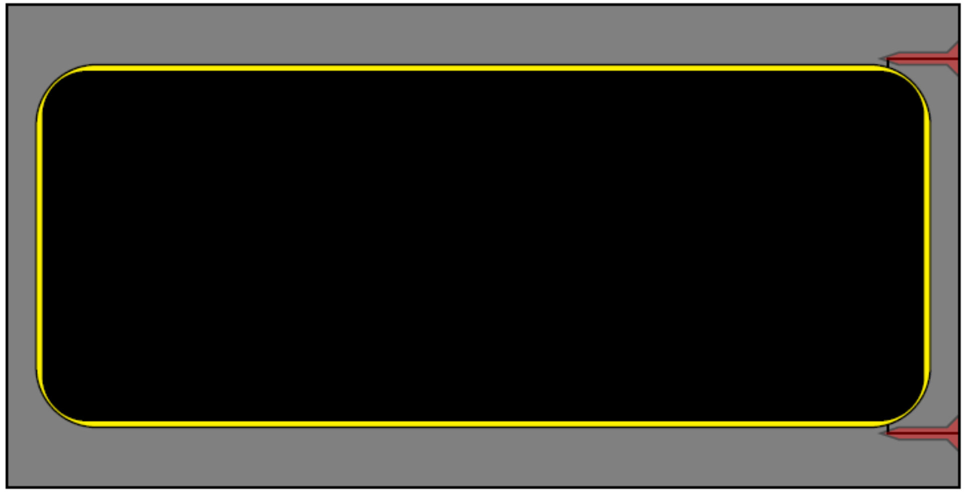
Backup slides – Weld details

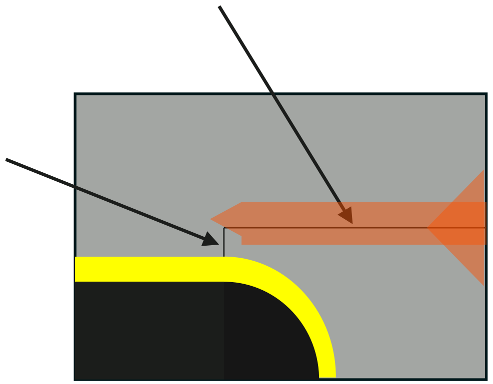
Key Cross Sections

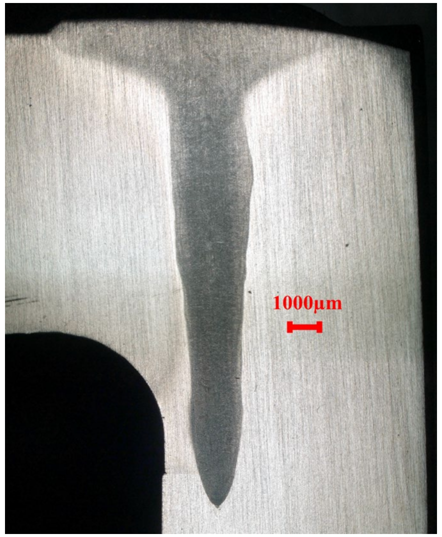


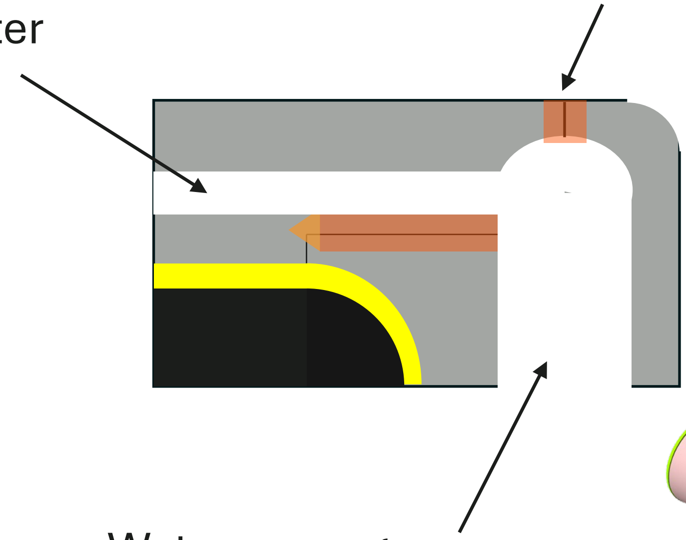


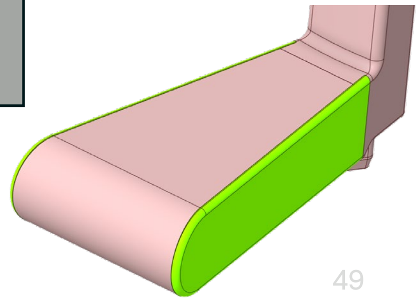
Closure weld details











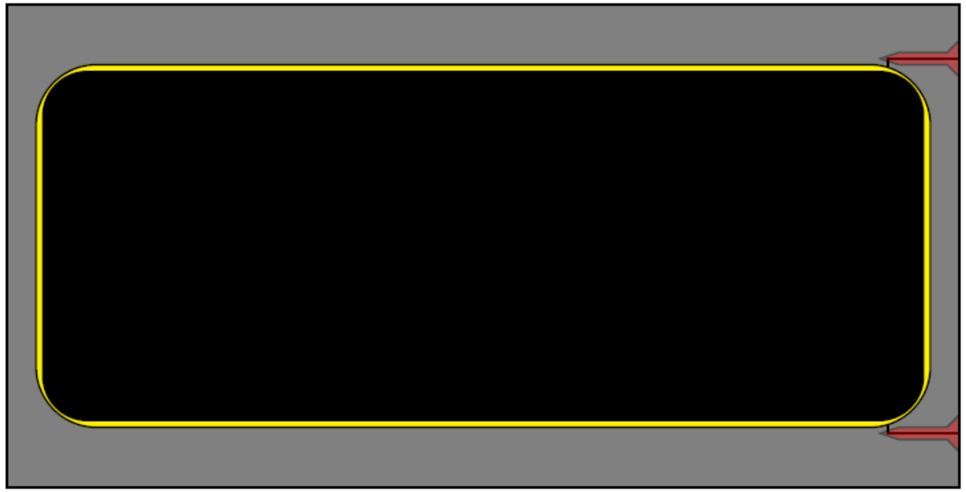
The weld location provides assembly and weld confidence

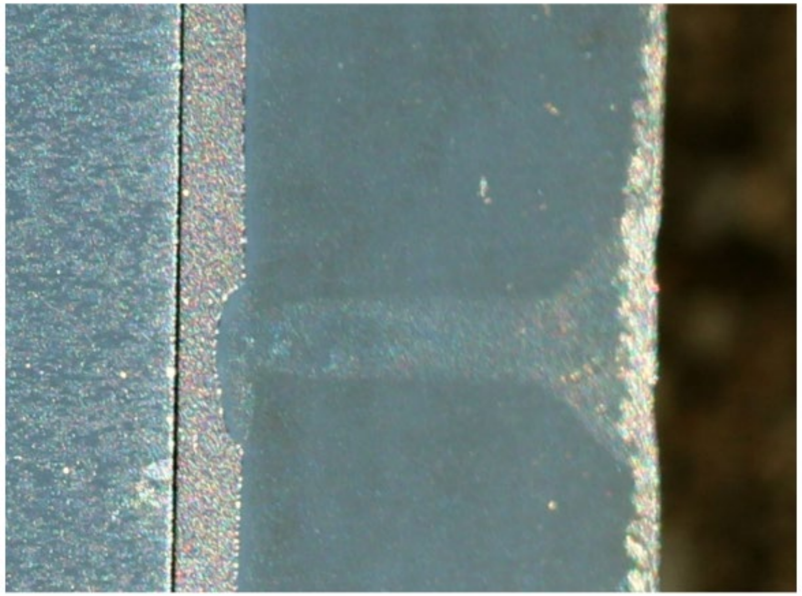
The spallation package must be inserted into the Inconel and then sealed

No "Crack tips" from welding

Welding should not inhibit bonding

Maintain parent material properties as much as possible





Heel weld details (TIG)