Updates on High Performance He-cooled W Divertor Concepts

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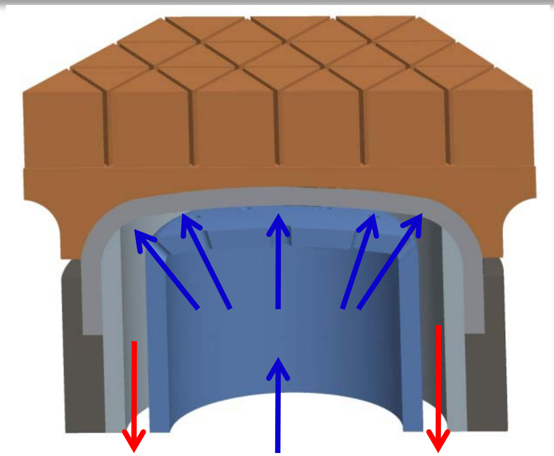
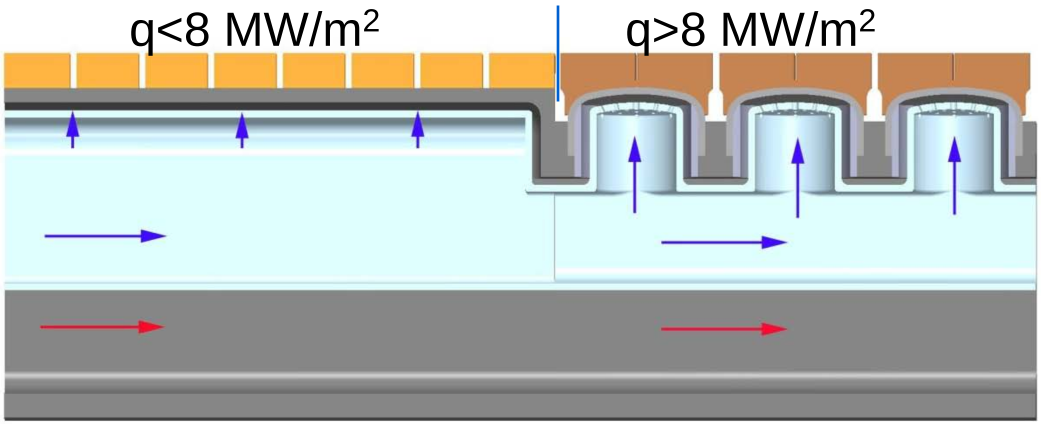
1. Updates on The Combined Finger-Plate Divertor Concepts

- Design optimizations for pushing higher heat flux
  - ✓ Layout of the jets (sizes and numbers of jets)
  - ✓ Thermo-fluid analyses for maximizing heat flux
  - ✓ Elasto-plastic structural analyses

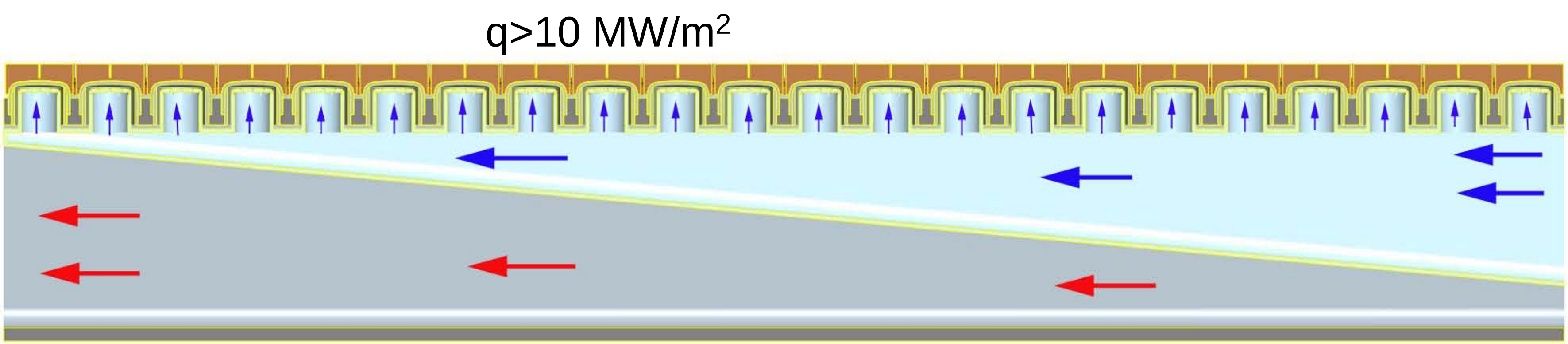
Combined Finger-Plate Divertor Concepts



Finger unit (1/2 module)



Two zone divertor concept



Small finger modules at the plasma-facing side covered over the entire plate

✓Employing the jet-cooling (like EU-finger) at the back side of the plasma facing surface

✓Adjusting the cooling conditions to the local heat flux by changing the number of cooling jets and their diameter

MATERIAL CONSIDERATIONS

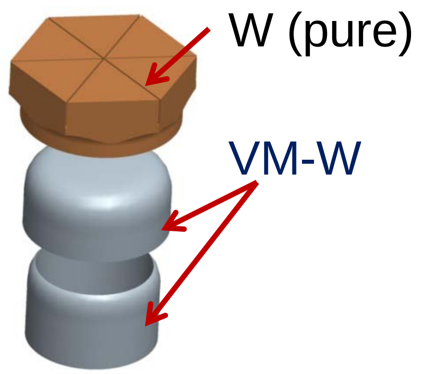
- **Plasma facing surface (Armor or Tile)-Pure Tungsten**

✓These tiles operate in a temperature range of roughly 1000 ºC to 2000 ºC, and there are no high requirements on the mechanical strength.

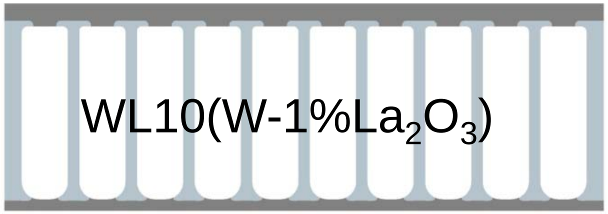
✓Probably the most economic way to fabricate these tiles by hipping of tungsten powder or injection molding.

- **The cup-shape thimbles-VMW**
  - ✓ Vacuum metalized W (VM-W) is pure W doped with 0.005 wt. % K, offering excellent mechanical properties and a high re-crystallization temperature, the thinner the better.
  - ✓ Since the wall thickness of the thimbles is 1 mm, we can take the benefit of the VMW and fabricate them by deep drawing of a thin sheet, rolled in two dirctions, and obtain excellent material properties.

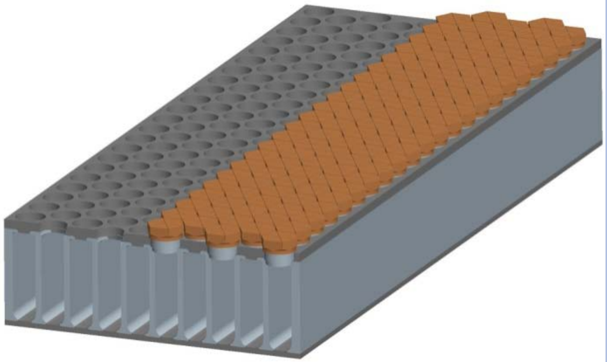
- **The front, side and back plates-WL10 (W-1%La_2O_3)**
  - ✓ The plates are constructed by brazing together the front und back plates with the side plates between the parallel helium channels.
  - ✓ All the plates have a thickness of < 10 mm and operate in a small temperature range between 750 ºC and 850 ºC. The material requirements are relatively moderate, and it should be possible to fabricate them from standard Tungsten plates.



Finger unit

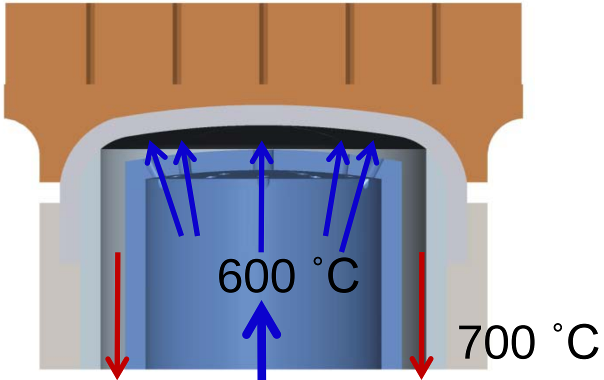


Front/Side/Back Plates

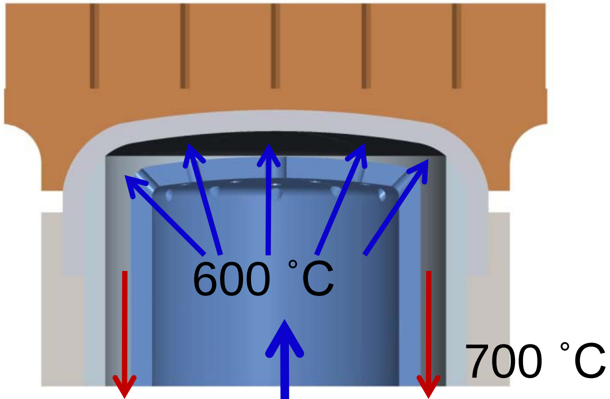


PUSHING TO HIGHER PERFORMANCE

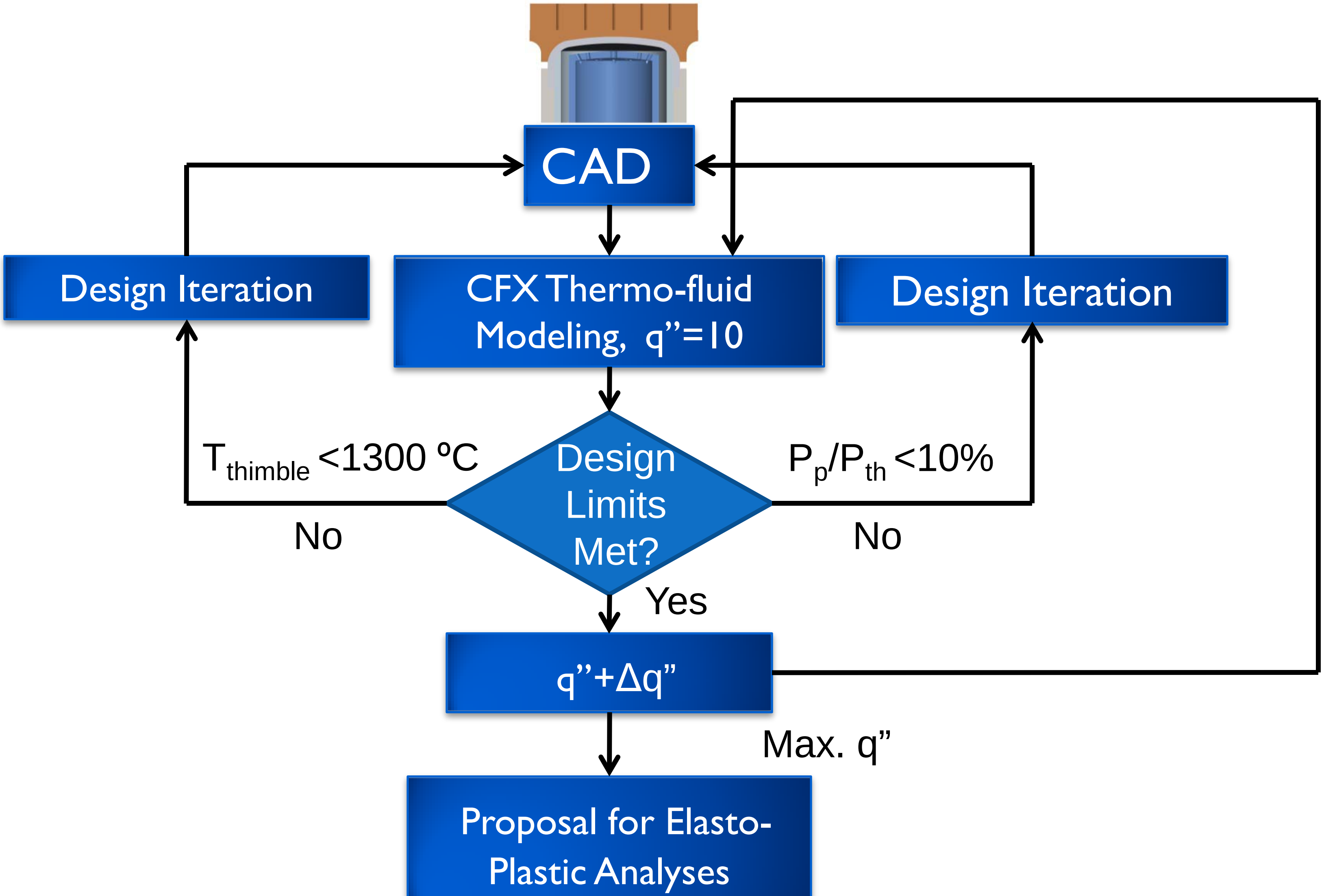
- Previous thermo-fluid and elastic structural analyses indicated that the finger unit could handle a surface heat flux up to 10 MW/m^2,
- Temperature, pumping power and stress limits are the major reason for heat flux limits on plasma-facing components
- **Temperature is the most limiting constraint**
- The approaches for pushing to higher surface heat flux for higher divertor performance:
  - ✓ by optimizing the layout of the jets (jet sizes, number of the cooling jets) to improve heat transfer with acceptable pressure drop
  - ✓ by allowing "yielding" for pushing the limits beyond $3S_m$ and considering plastic deformation



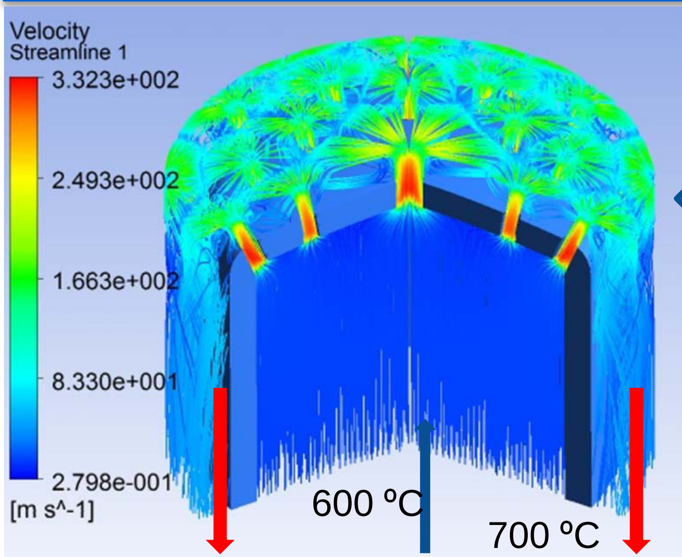
Example of changing the jet-layout



Design Iteration

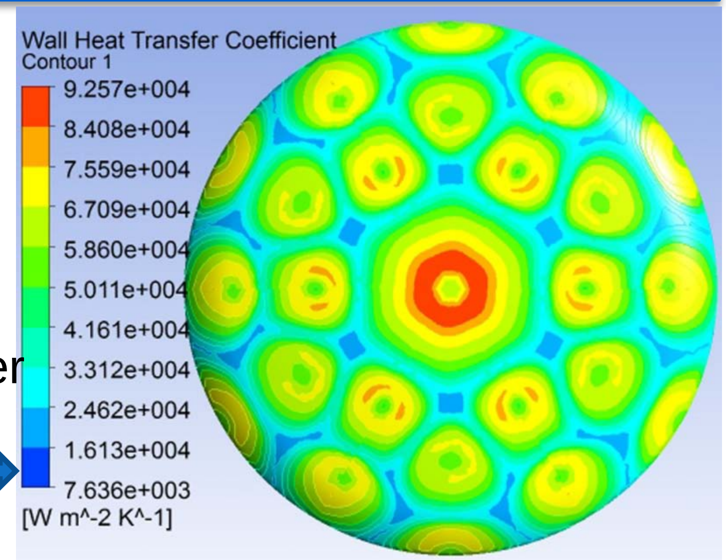


ARIES Finger Divertor Can Handle a Heat Flux up to 15 MW/m² without Exceeding Temperature or Pumping Limits

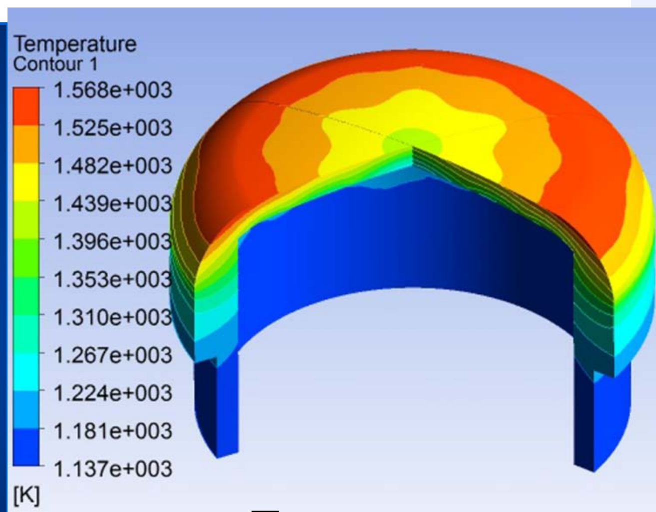


Velocity

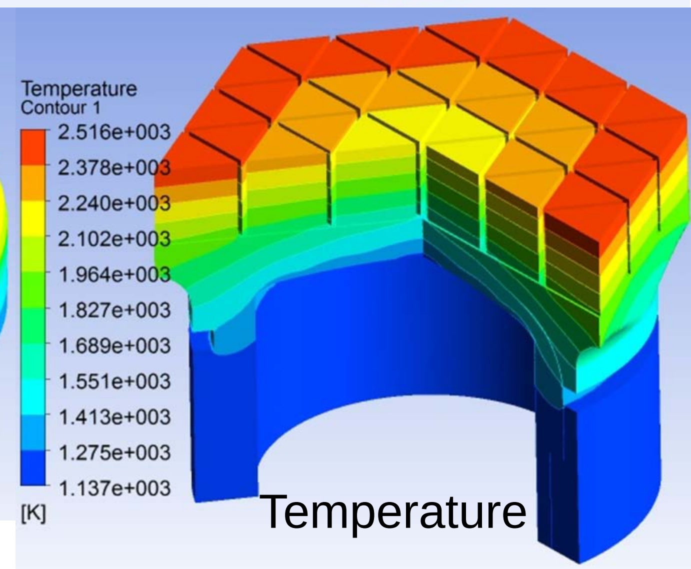
Wall heat transfer coefficient



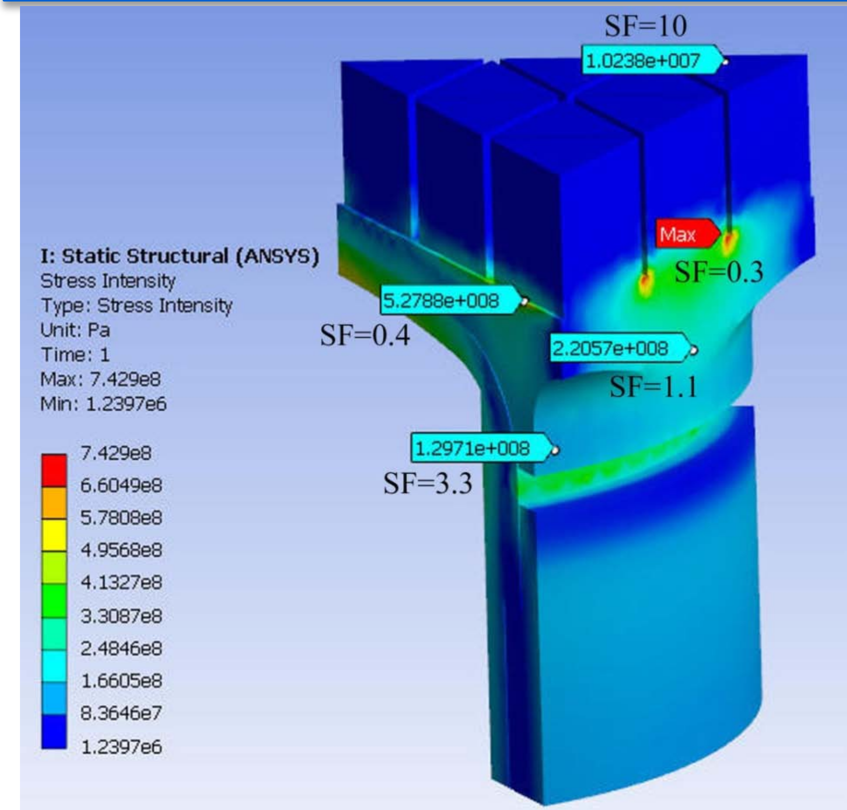
- $q'' = 15\ \mathrm{MW/m^2}$
- $q_v = 17.5\ \mathrm{MW/m^3}$
- $T_{in}/T_{out} = 600/700\ ^{\circ}\mathrm{C}$
- $P = 10\ \mathrm{MPa}$
- $V_{jet} = 332\ \mathrm{m/s}$
- $\mathrm{H.T.C} = 9.257 \times 10^4\ \mathrm{W/m^2K}$
- $P_p/P_{th} = 9.9\%$
- $\mathrm{Max.}T_{armor} = 2243\ ^{\circ}\mathrm{C}$
- $\mathrm{Max.}T_{thimble} = 1295\ ^{\circ}\mathrm{C}$
- $\mathrm{Min.}T_{thimble} = 864\ ^{\circ}\mathrm{C}$

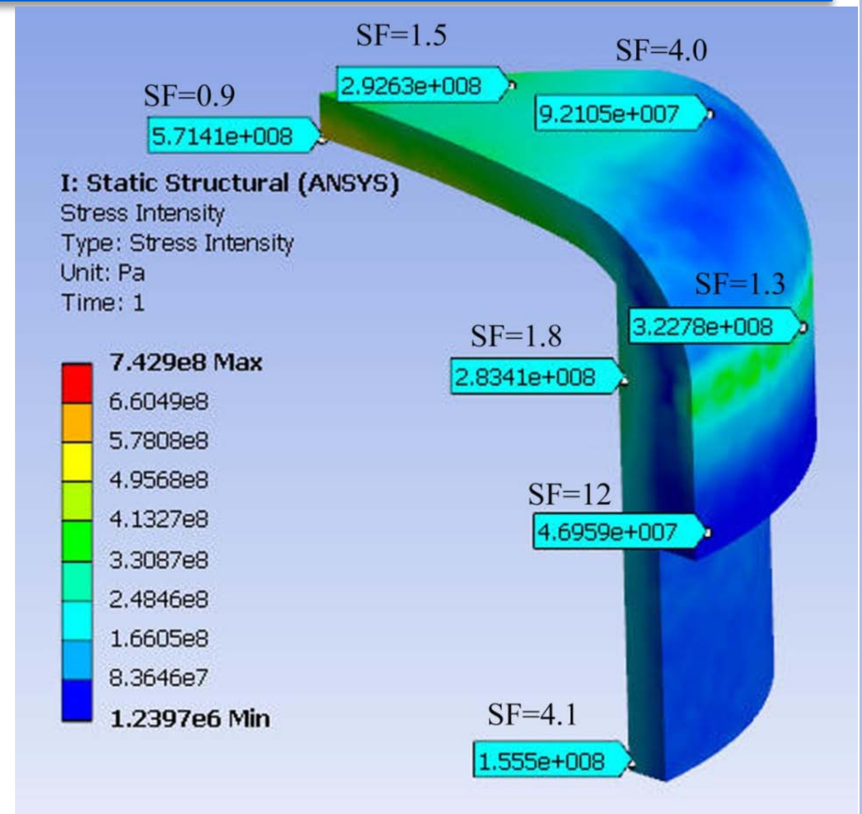


Temperature



Structural Analysis Without Including the Material Plasticity

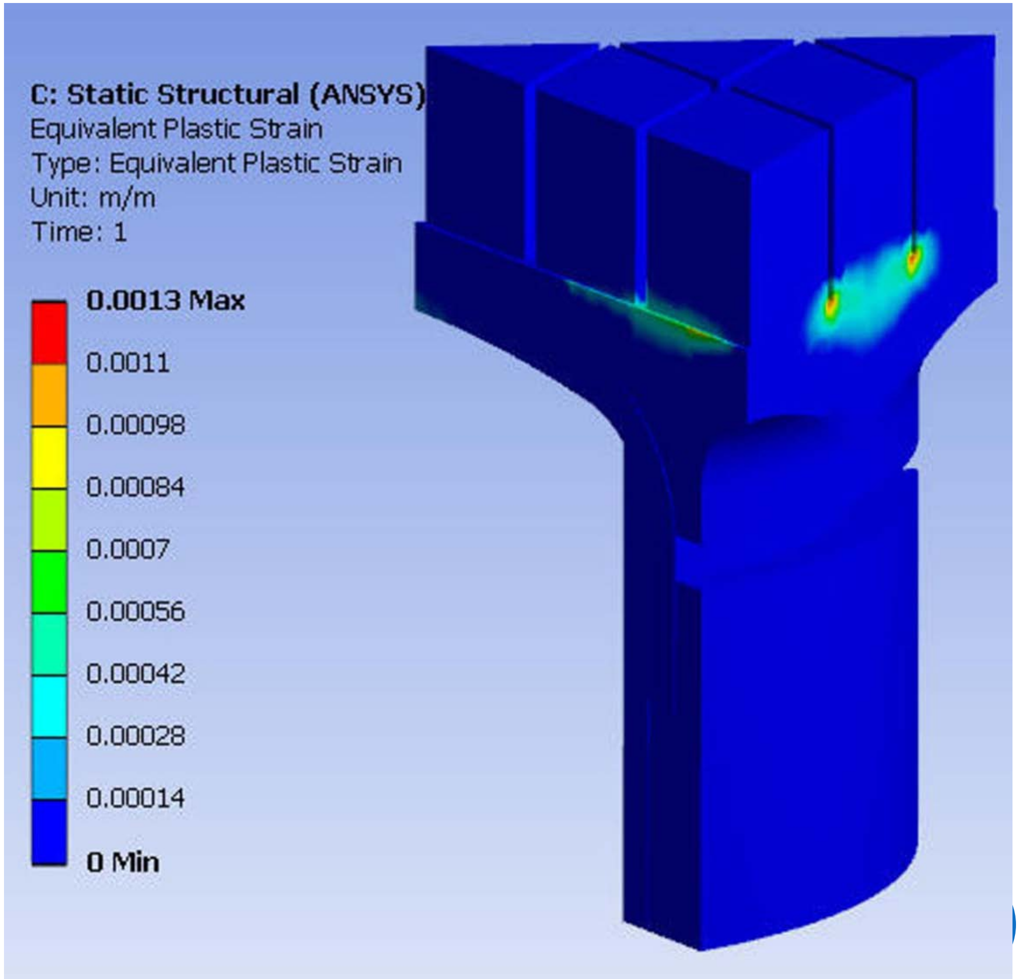




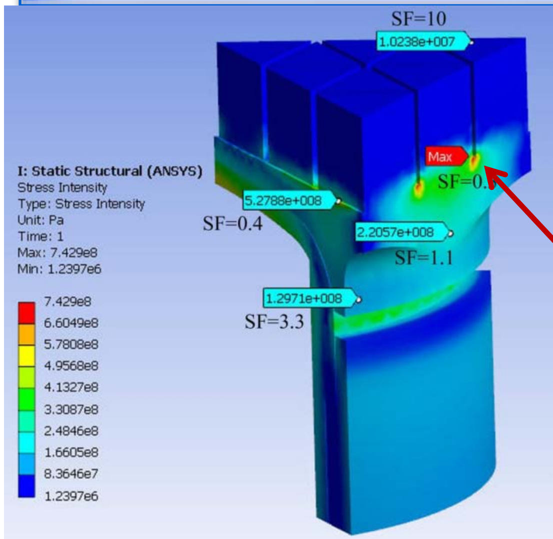
- Thermal loads were used: q"=15 MW/m^2, q_v=17.5 MW/m^3
- Safety factor=Allowable stress(3Sm)/Maximum nodal stress (combined primary and secondary stresses)
- The safety factor must be > 1 (to meet the ASME 3Sm code)
- The minimum safety factor is 0.3 in the armor and 0.9 in the thimble

RESULTS OF NON-LINEAR STRUCTURAL ANALYSES INDICATES THE DESIGN CRITERIA MET

- Bilinear isotropic hardening material model is utilized
- **Allowable plastic strain (50% of uniform elongation) for the pure W is 0.8% at 270 ºC and 1.0% at ~1200 ºC.**
- Operation temperature for the heat flux up to 15 MW/m^2:
  - ✓VM-W (thimble and cylindrical ring): 800 <T<1300 ºC
  - ✓Standard W(armor): 1000<T<2300 ºC
  - ✓WL10(Front plate): 800<T<1300 ºC)
- **The maximum plastic strain is ~0.13% in the armor and 0.04% in the thimble.**
- Plastic design criteria met.

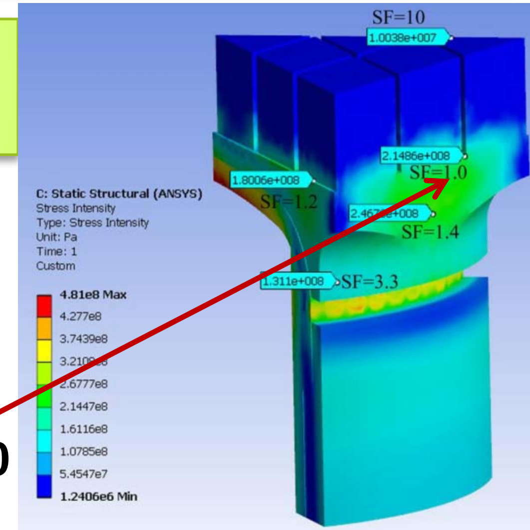


Comparing Results Between Elastic and Plastic Analyses

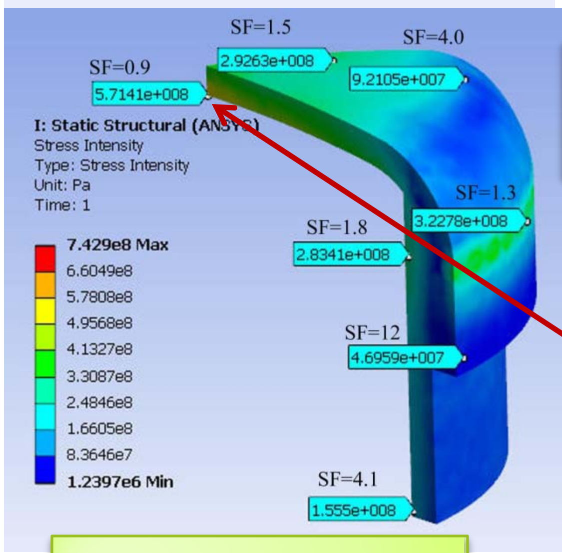


The Minimum Safety Factor in W-armor

SF_{min}=0.3

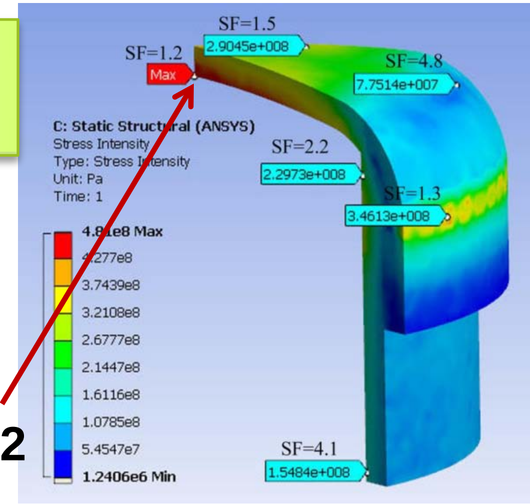


SF_{min}=1.0



The Minimum Safety Factor in W-thimble

SF_{min}=0.9



SF_{min}=1.2

Elastic Analysis

Plastic Analysis

Summary of the Combined Finger-Plate Divertor

- **EU- finger concept has been improved:**
  - ✓ by avoiding the transition joints between W and steel manifolds
  - ✓ by adding a cylindrical ring for double containment in the critical region for decreasing the potential for coolant leaks

- **The layout of jets for the finger unit have been optimized based on the thermal-fluid analysis for higher heat flux and performance.**

- **Design iteration indicates that the finger units can handle a surface heat flux up to 15 MW/m^2 without exceeding the high temperature limit and pumping power limit.**

- **With consideration of the material plasticity, the finger module meets the plastic strain criteria. After stress relaxation by plastic deformation, it also meets the ASME Code (3 Sm).**

2. Updates on The Non-linear Structural Analyses of the ODS-Ta-W Joints

- 2D Nonlinear Structural Analyses Have Been Performed Under Fabrication Steps and Transient Operations
  - ✓ Sub-assembly 1 for the ODS-ODS diffusion welding
  - ✓ Sub-assembly 2 for the Ta-W brazing welding
  - ✓ Whole Assembly for the operations

- 3D Non-linear Structural Analyses Are Underway

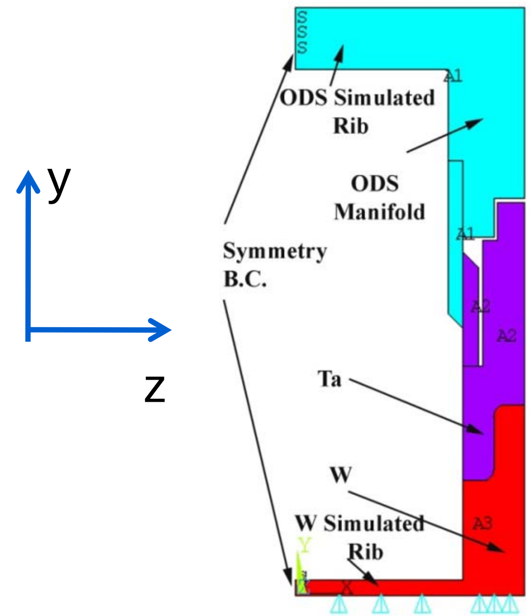
Non-linear Structural Analyses for the Transition Joints

➢A 2D model of the ODS-Ta-W joints are utilized for purpose of scoping, parametric studies and design improvement.

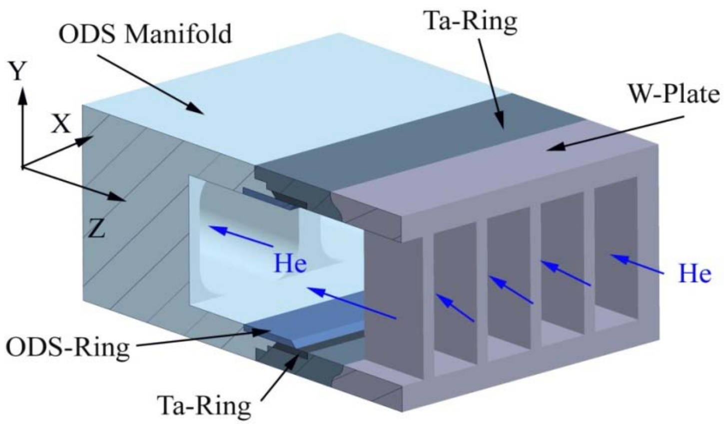
1. *ANSYS Generalized Plane Strain Element Model is used to include both Elasticity and plasticity*
2. *Bilinear Isotropic Material Model is utilized*
3. *Stress –free-temperature is assumed to be 1050 C(brazing and diffusion temperature*

➢The transition joints during fabrication steps and transient operations will be simulated

➢A full 3D model including the elasticity and plasticity is performed to confirm the joint design .

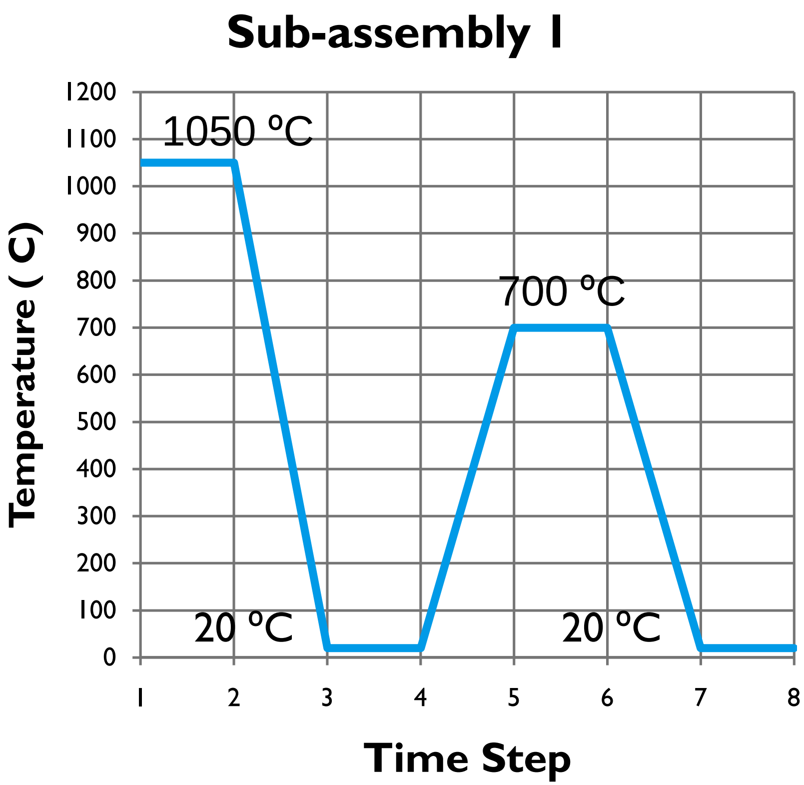


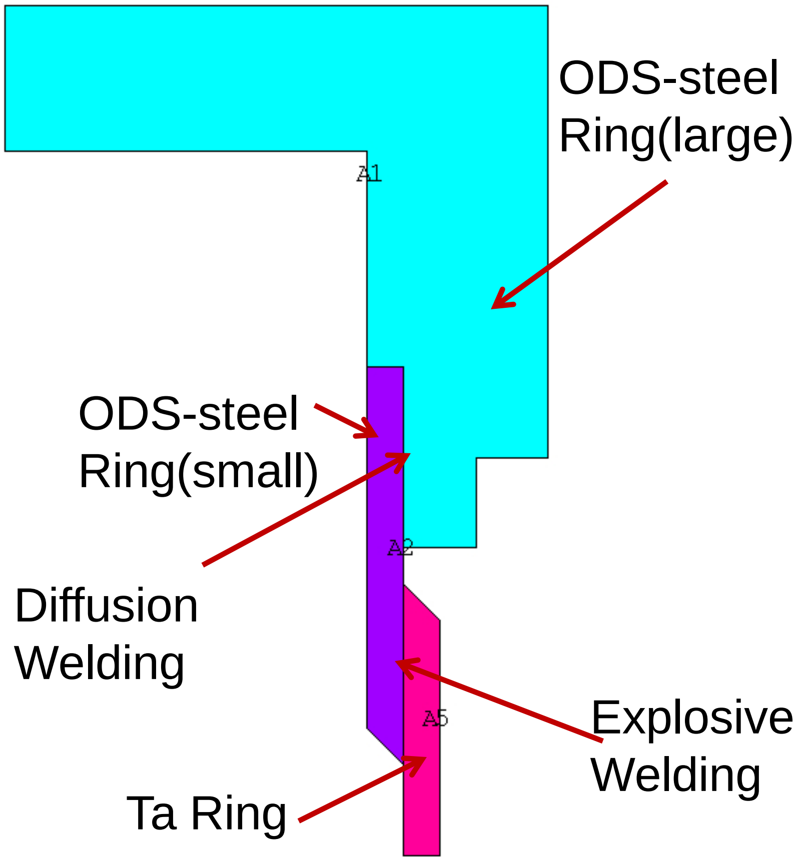
ANSYS Model



Cut-away view showing the transition zone

Thermal Loading for the Proposed Fabrication Step 2

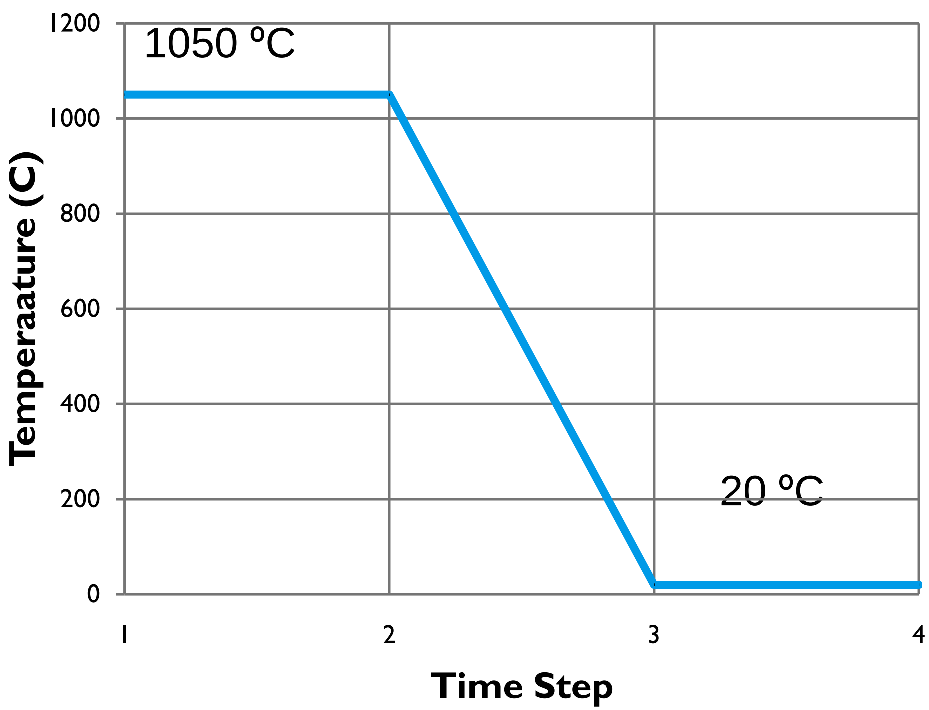


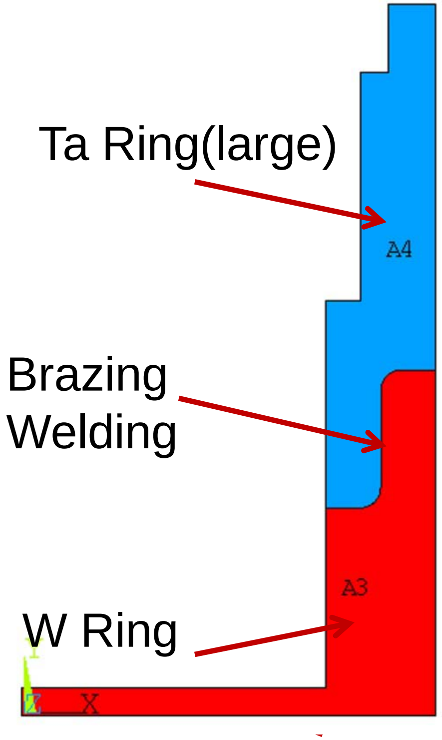


Step 1: Explosive welding between small ODS-steel Ring and Tantalum Ring(this process happens in micron seconds, and residual stress is small)

Step 2: Diffusion welding between large and small ODS-steel rings at a HIP chamber

Thermal Loading for the Proposed Fabrication Step 3





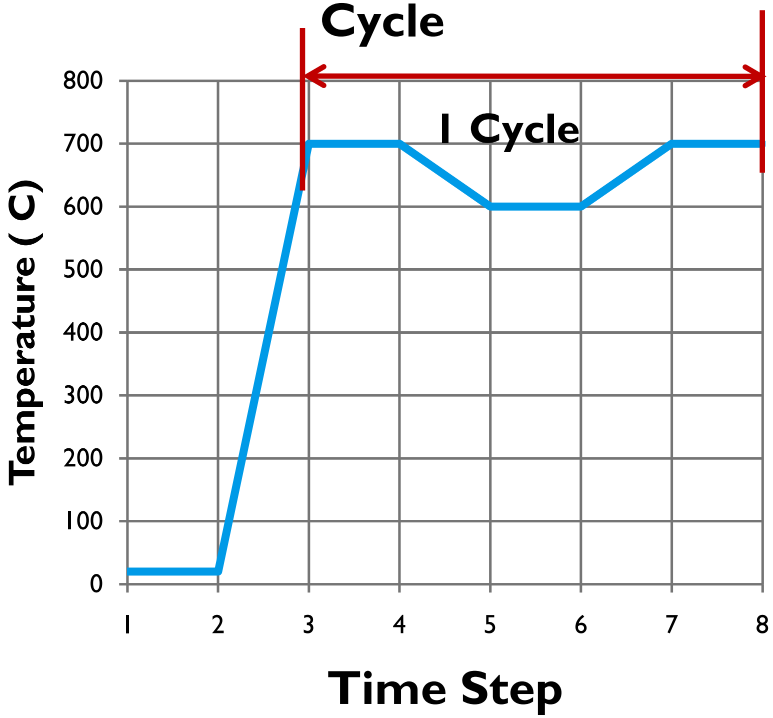
Sub-assembly 2

Step 3: Brazing between the Ta Ring and Tungsten Ring

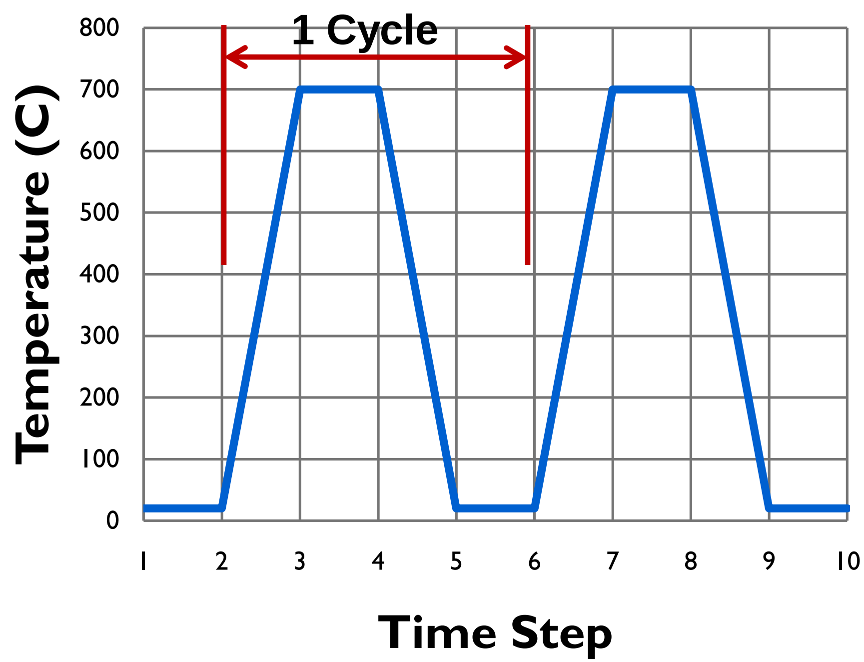
Step 4: Tig or Laser beam welding between large and small Ta rings (Both rings will be cold, and the heat affected zone will be small)

Loading Conditions for Operations

Warm Shutdown Loading Cycle



Cold Shutdown Loading Cycle



- Pressure load (P=10 MPa) is applied at the step 2 and maintain it all the time during the operation with warm shutdown, repeating Step 2-8 for additional cycles
- Pressure load applied at the time step 2 and removed at the time step 5 for cold shut down, repeating Steps 2-6 for additional cycles.

Design Criteria for the W-Ta-ODS Transition Joints

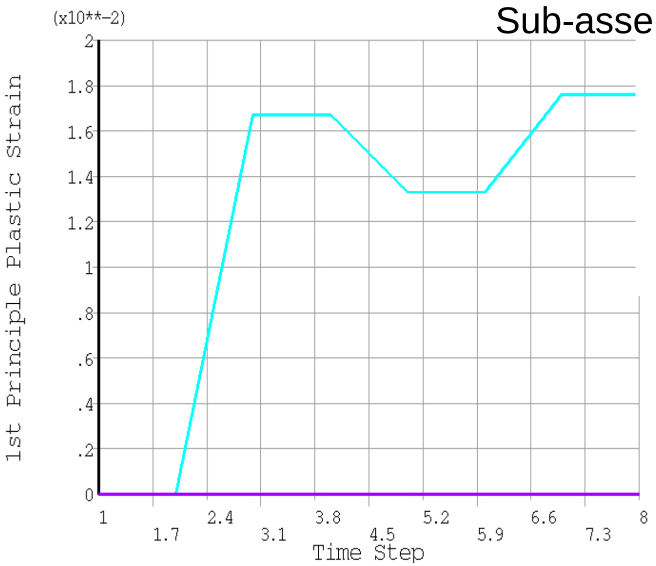
➢Allowable plastic strain for ODS-EUROFER is ~2.3% at RT and 1.9% at 550 ºC, and 2.4% at 700 ºC.

➢Allowable plastic strain for the Ta is >15% at the room temperature and >5% at 700 ºC (based on Steven Zinkle's information).

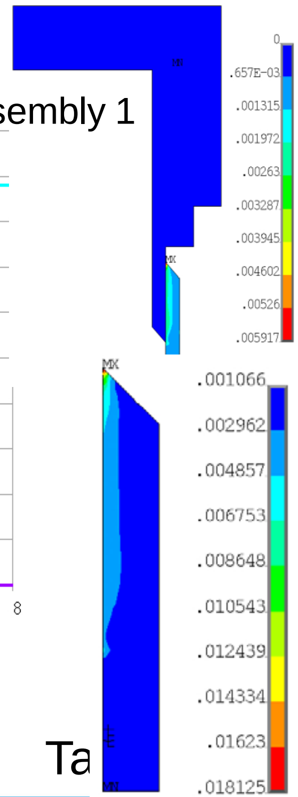
➢Allowable plastic strain for the W is 0.8% at 270 ºC and ~1.0% at ~1200 ºC.

Results Indicate the Joints Can Survival During Fabrication Steps

➢**The max. plastic strains of the ODS/Ta/W joints during fabrications are under design criteria.**



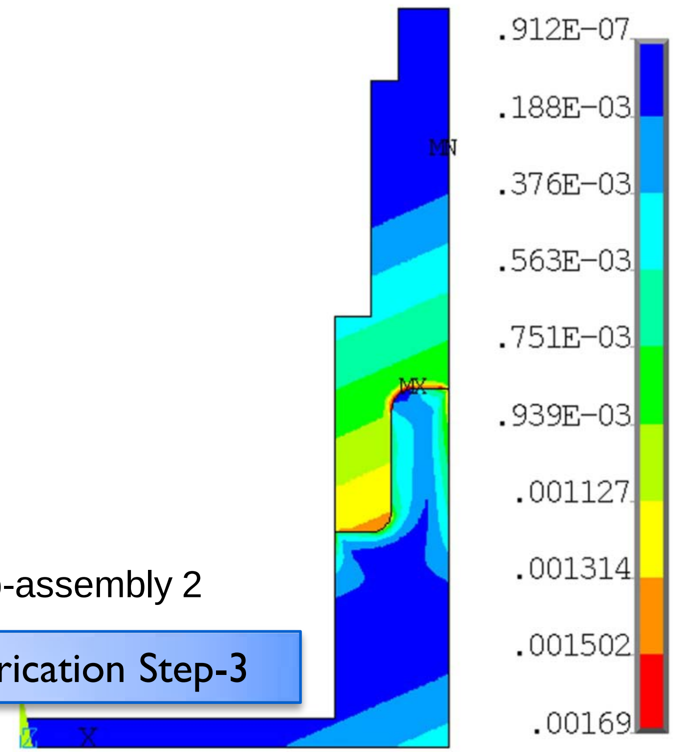
Sub-assembly 1



Ta

Fabrication Step-2

Sub-assembly 2

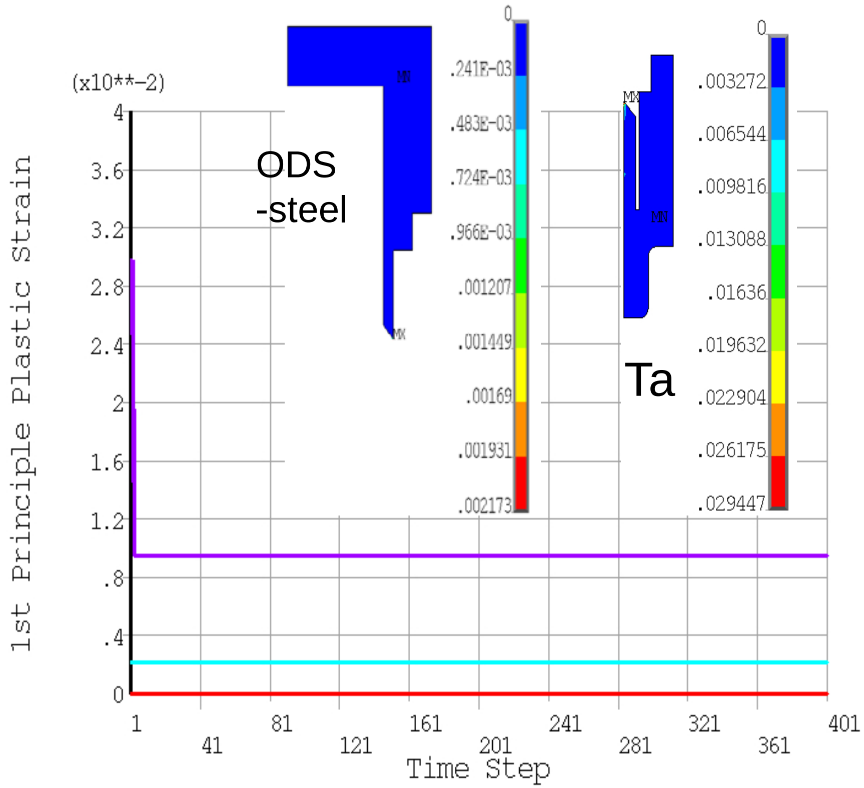


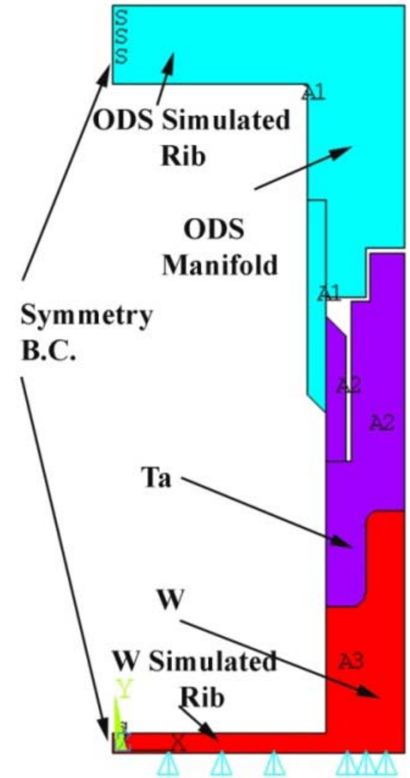
Fabrication Step-3

✓Max. Plastic strain at Ta is ~1.8% (ε_{allow}=~15%)
✓Max. Plastic strain at W and ODS steel is 0.0

✓There is no plastic strain in the sub-assembly 2 for the Step-3, and the max. elastic strain is ~0.2% for Ta and ~0.1% for W

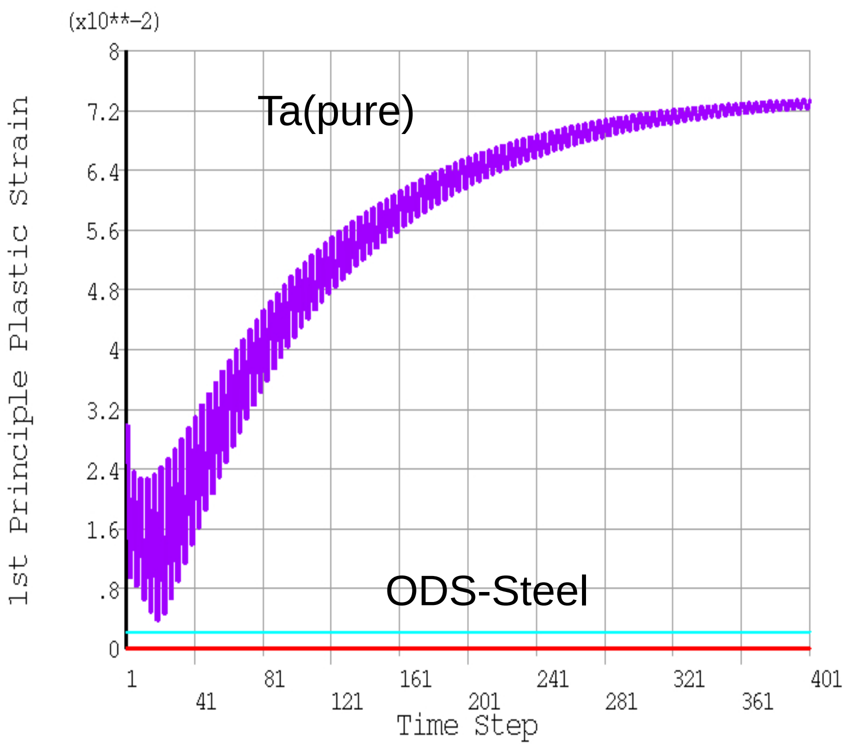
The Joints Met Design Criteria During Operation Cycles with Warm Shutdown

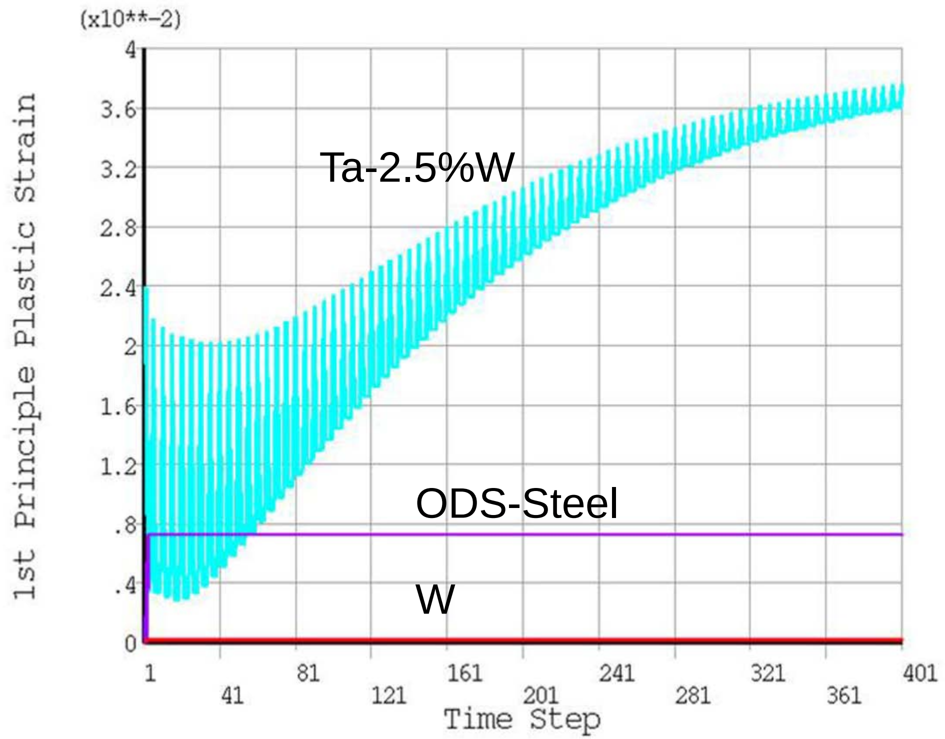




- ➢Max. Plastic strain at Ta increases from 1.8% (after fabrication) to ~2.9% when the 10 MPa pressure is applied for the first time, but remains at ~0.9% for entire cycles (<ε_{allow} =15% at RT).
- ➢Max. Plastic strain at ODS steel is ~0.2% ((<ε_{allow} =2.3% at RT) and 0 at W.

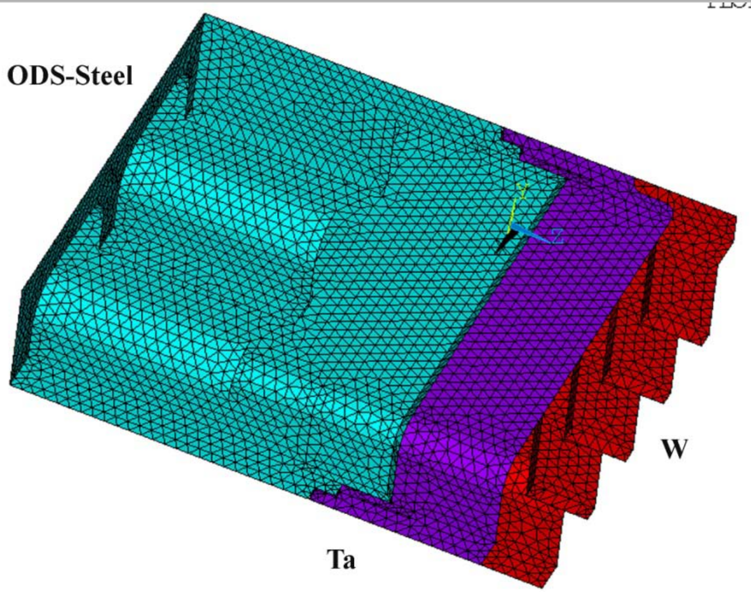
RATCHETING IS OBSERVED DURING OPERATION WITH COLD SHUTDOWN



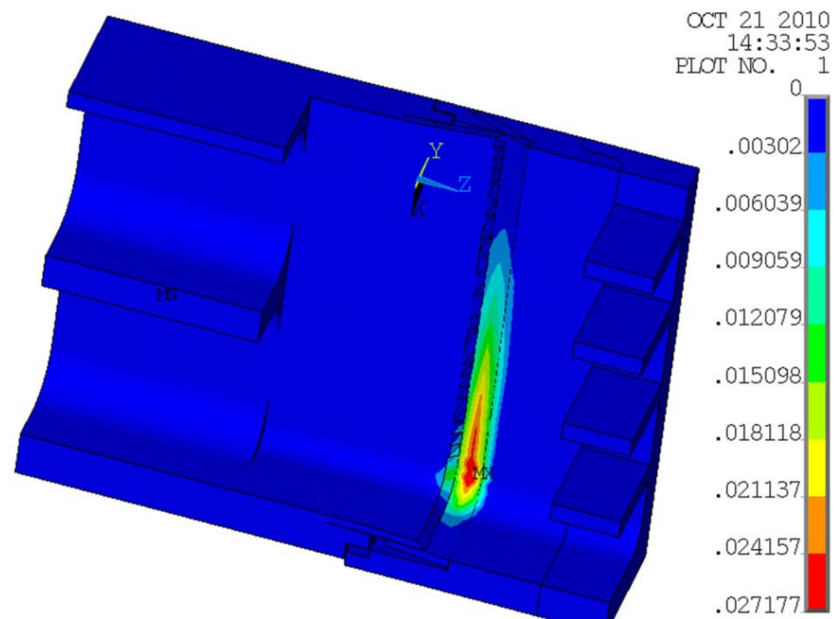


- ➢Ratcheting occurs at the interface of Ta during operation with cold shut down.
- ➢The max. plastic strain of the Ta Ring is ~7.2% in very small region close to the sharp tip of the ring, however it is still under the allowable value(< ε_{allow}=15%) after 100 cycles.
- ➢Ta-2.5%W has higher yield strength and uniform elongation, and the max. strain can be reduced by a factor of 2.

3D Non-linear Structural Analysis



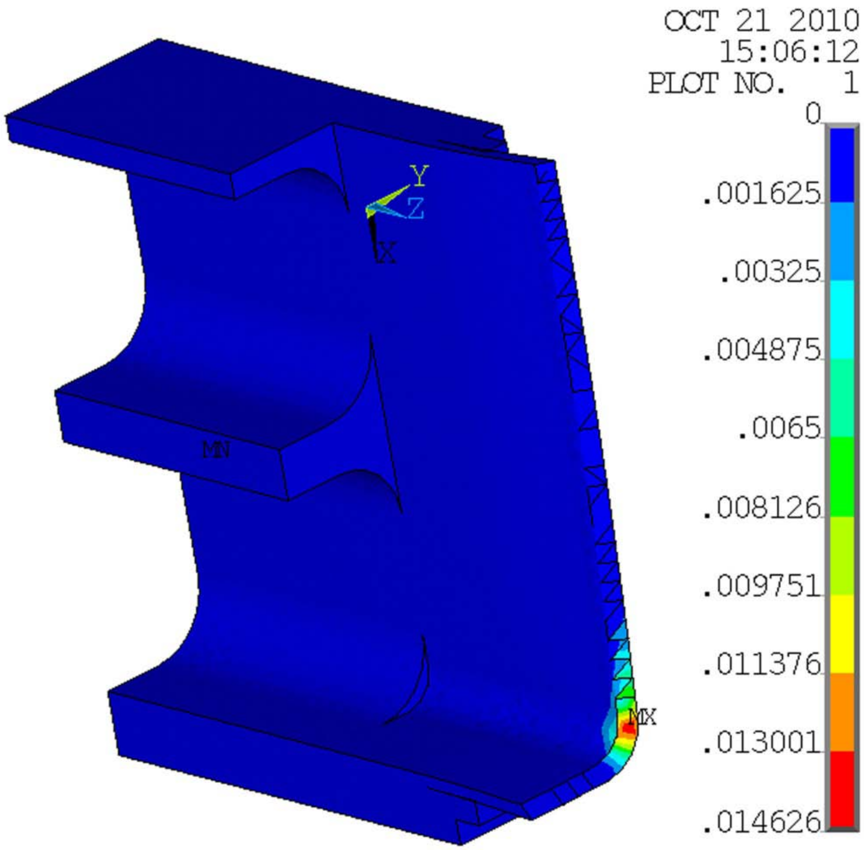
3D Element model



Distribution of the plastic strain

- 3D non-linear structural analysis is performed for validation of the 2D results at the load conditions of 20 ºC and 10 MPa.
- The max. plastic strain in the thinner Ta-Ring is 2.7% (2.9% for the 2D result at the same load conditions).
- However, the max. plastic strain in the ODS-steel is ~7 times higher than the result obtained from 2D (1.5% from 3D analysis and 0.2% from 2D, ε_{allow}=2.3%). Element refinements are needed for the ODS-steel ring because of its sharp tip.

3D Non-linear Structural Analysis (extra)



The plastic strain in the ODS-steel

SUMMARY AND CONCLUSIONS FOR TRANSITION JOINT DESIGN

- **Non-linear structural analyses were performed to investigate the responses of the divertor transition joints between W and steel manifold.**

- **The results indicate that the Ta Rings provide a mitigation of CTE mismatch between W and ODS during fabrication and operations**
  - ✓ Max. plastic deformation is ~1.8% for Ta, 0% for ODS-steel and W (fabrication)
  - ✓ Max. plastic deformation is ~2.9% for Ta, 0.2% for ODS-steel, and 0% for W (warm shutdown)
  - ✓ Max. plastic deformation is ~7.2% for Ta, 0.2% for ODS-steel, and 0% for W (cold shutdown)

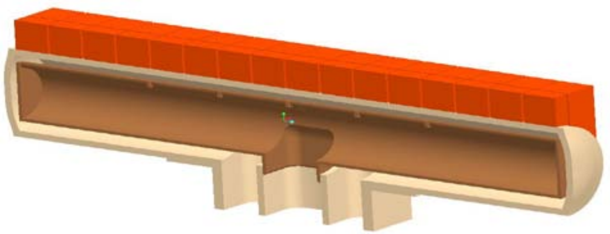
- **Ratcheting occurs at the interface of Ta during operation with cold shut down, but maximum strain value below the given limit is reached asymptotically after 100 cycles.**

- **Ta-2.5%W is a better material to be used for the divertor joints, and the plastic strain could be reduced by a factor of 2 comparing to the pure Ta.**

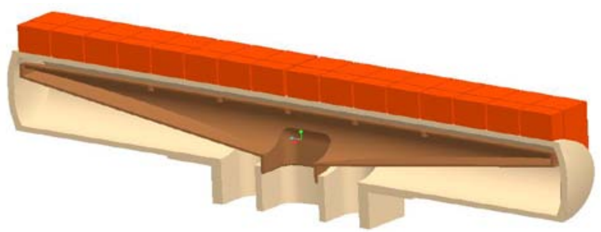
3. Updates on The T-Tube Divertor Concept

- Design optimizations for pushing higher heat flux
- Transition joint concept for T-Tube

Design Window Based on High Temperature Limits

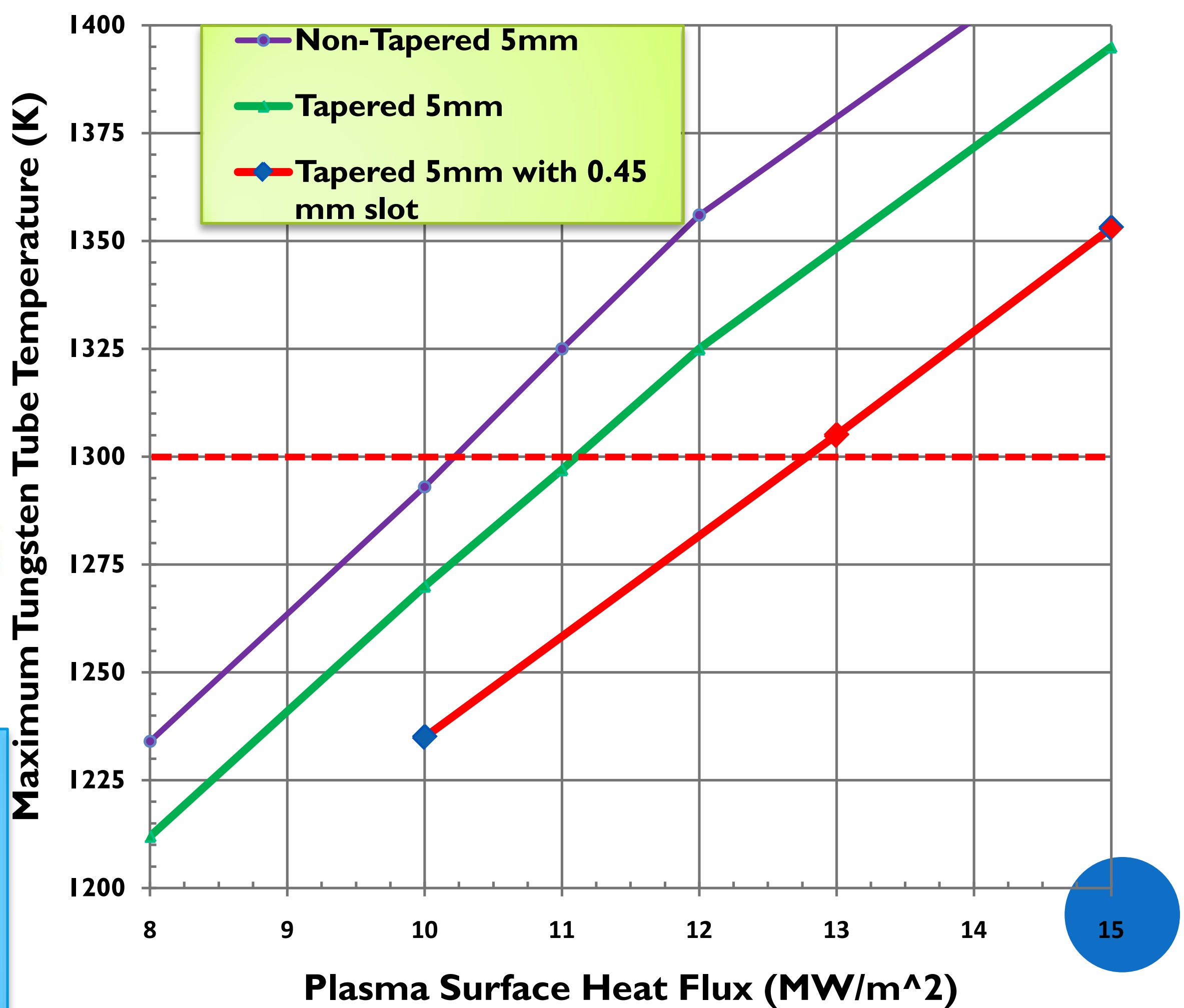


Non-Tapered T-Tube

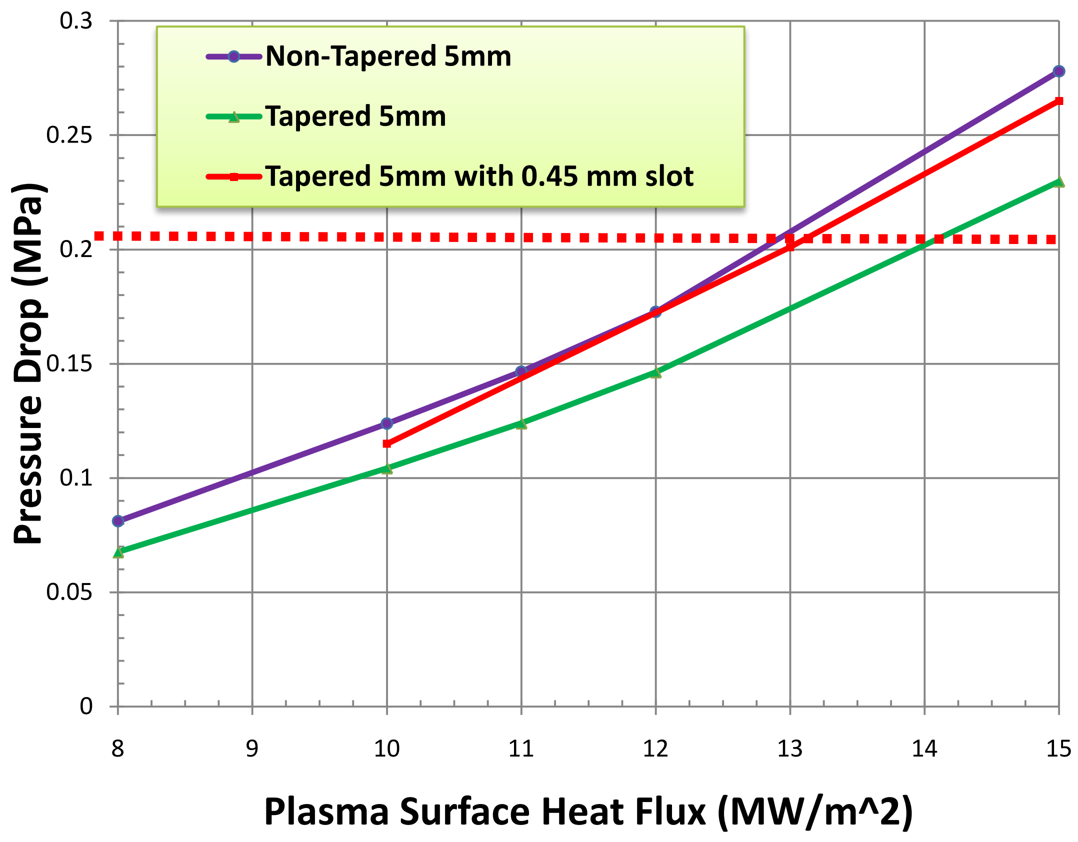


Tapered T-Tube

➢ **By reducing the slot size from 0.5mm to 0.45mm the heat flux limit increases from 11 to 13 MW/m²**



Design Window Based on High Pumping Power Limits



- with this optimal slot size the pressure drop limit is also reached at 13 MW/m^2

Transition Joints Design For the T-Tube Divertor

- A design for a W to steel joint is currently being worked on.
- It will use the same design principle as the joint for the plate and ARIES finger design.
- The same configuration will be used but now it will be three separate channels