Update on High Performance Divertor Design and Analyses

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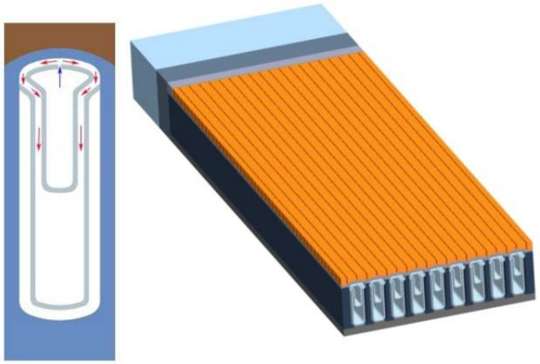
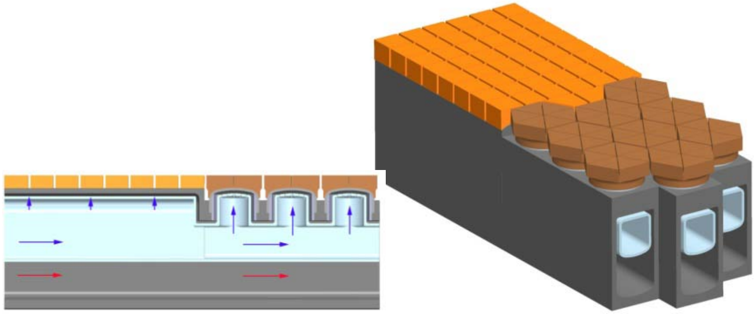
High Performance Plate-Type Divertor Concepts

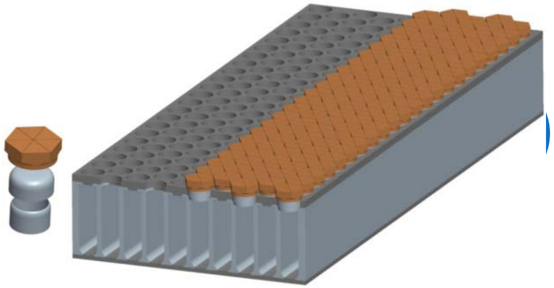
- Three plate-type divertor concepts have been investigated in order to take advantages of large scale and reduce the number of units, fabrication complexity and possibly cost of the divertor.



- Plate divertor: 20 cm x 100 cm
- Impinging-jet cooling
- Allowable heat flux q<~10 MW/m^2
- ~750 units for a power plant, and 2x750 joints between W and ODS steel, two materials with largely different thermal expansion



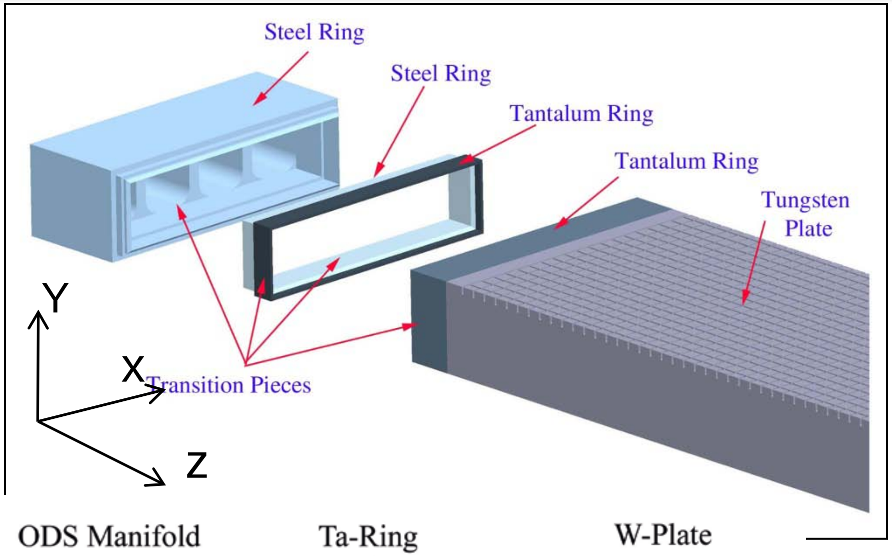
- Combination of the plate and finger divertor
- Fingers for q>8 MW/m^2, plate for q<8 MW/m^2
- Decreased number of finger units compared to the EU design

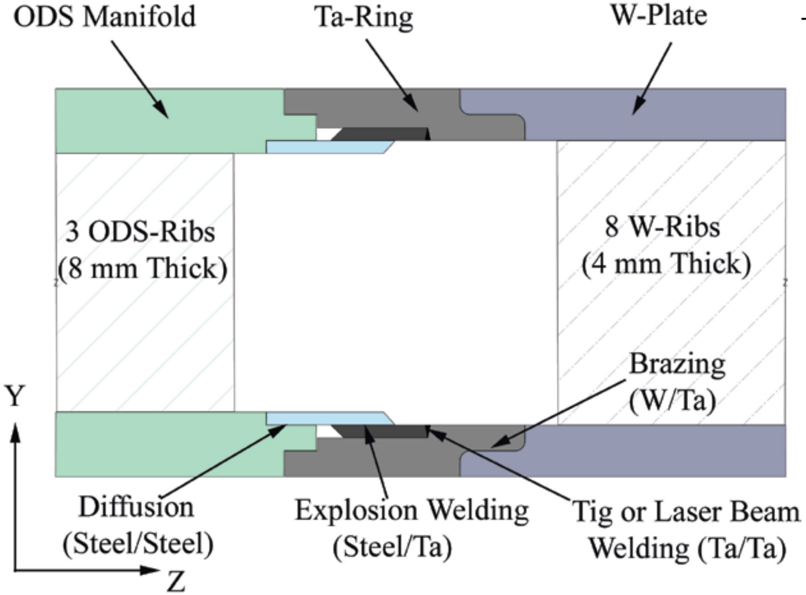


- Small modules arranged over the entire plate
- Allowable heat flux q>10 MW/m^2
- Avoiding joints between W and ODS steel at the high heat flux region

Transition Joints were Designed for All Three plate-type Concepts

- Design robust transition joints between W and steel manifold is a key for all the W divertor concepts.
- The transition joints have been designed and proposed to be arranged at both ends of the plate (q''=0) with a Ta transition piece between W and ODS steel.
- The transition joints are used for all three plate-type concept.
- Steps for the assembly of the transition region at the both ends of the plate:
  - ✓ Step 1: Explosion welding between ODS Ring and Ta-Ring
  - ✓ Step 2: Diffusion welding between thick ODS-Ring and thin ODS-Ring in a HIP chamber.
  - ✓ Step 3: Brazing Ta-Ring to W-Plate in a furnace at T=1050 °C
  - ✓ Step 4: Tig or Laser beam welding between thick and thin Ta-Rings





Thermo-Mechanical Analyses Performed by UCLA

➢Thermo-mechanical analyses including both elasticity and plasticity were performed by UCLA:

- ✓ 2D axis-symmetry model (primary stress depends on the radius of cylinder)
- ✓ Bilinear Kinematic Hardening(BKIN)
- ✓ Thermal cycle between 20 to 800 ºC, and P=10 MPa

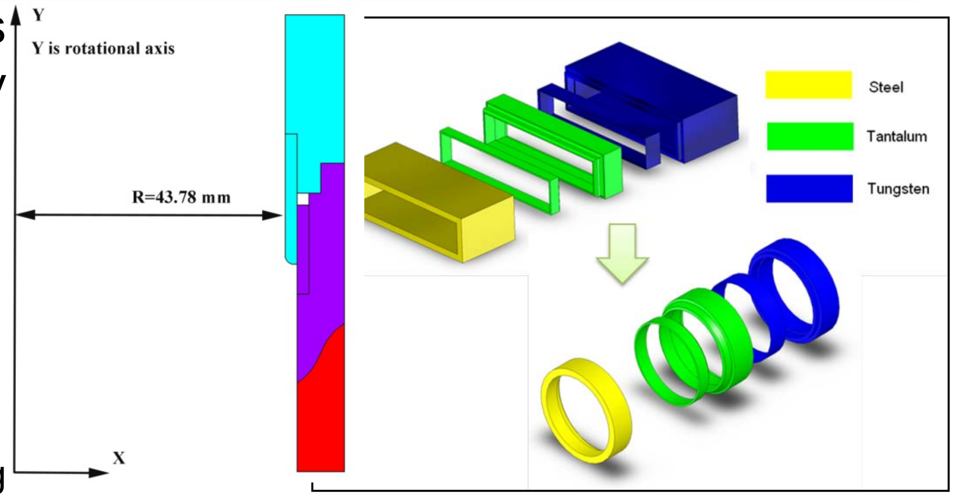
➢Results published:

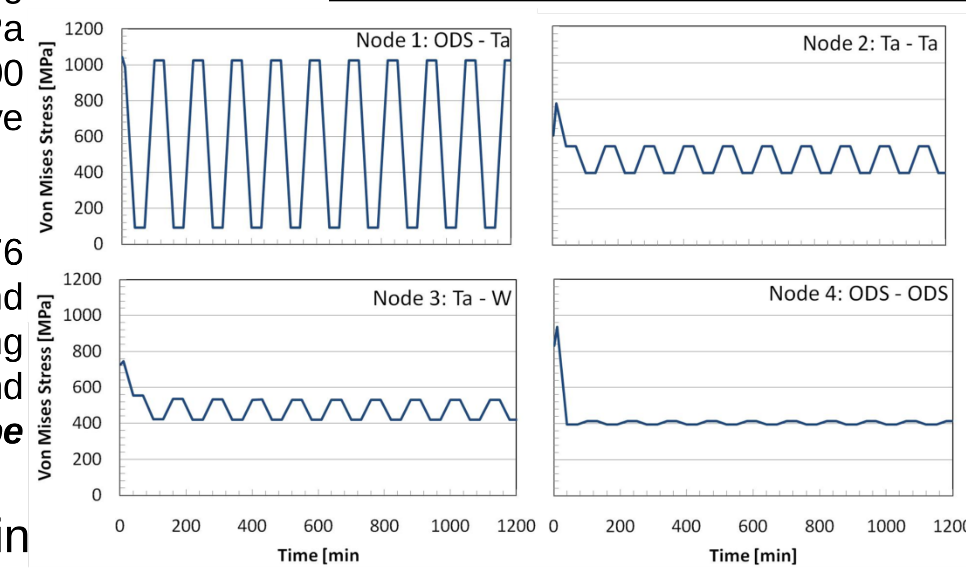
✓The ODS experiences the largest swing in stress between 1000 and 100 MPa (Yield strength: 1200 MPa at RT and ~300 MPa at 800 ºC). The ODS might survive the cyclic loading.

✓W material might survive

✓The max. residual stress in Ta is 776 MPa at RT, and swing between 542 and 400 MPa during loading cycles, exceeding the yield strength of 500 MPa at RT and 180 MPa at 800 ºC, and ***it needs to be replaced by other material.***

➢The plastic strains were not given in the published paper.





IMPROVED JOINT DESIGN AND THERMO-MECHANICAL ANALYSES AT UCSD

➢We start from a 2D model for purpose of scoping, parametric studies and design improvement.

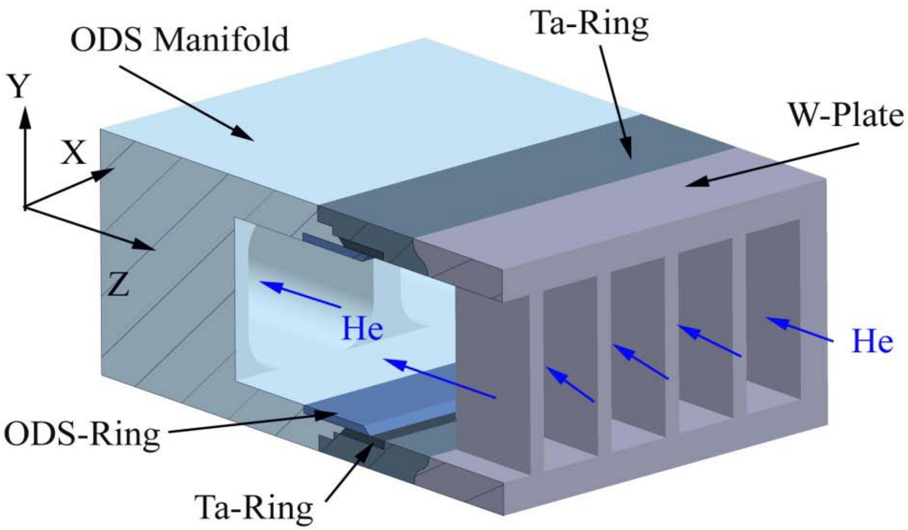
➢ANSYS 2D linear or non-linear structural models:

- ✓ plane stress
- ✓ plane stress with input of thickness
- ✓ plane strain or generalized plane strain
- ✓ axis-symmetry

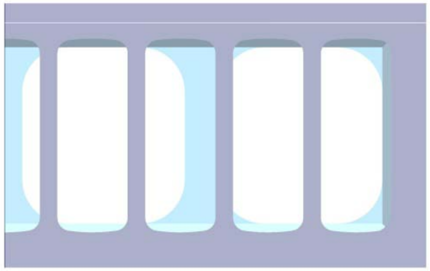
➢The 2D plane strain model is the most conservative.

➢All the 2D models may not accurately simulate the structural behaviors of the ODS-Ta-W joints. However, it can help for geometry optimization and design improvement.

➢A full 3D model including the elasticity and plasticity is needed.



Cut-away view showing the transition zone

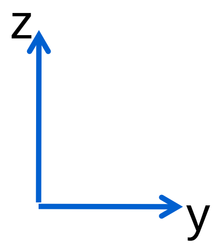


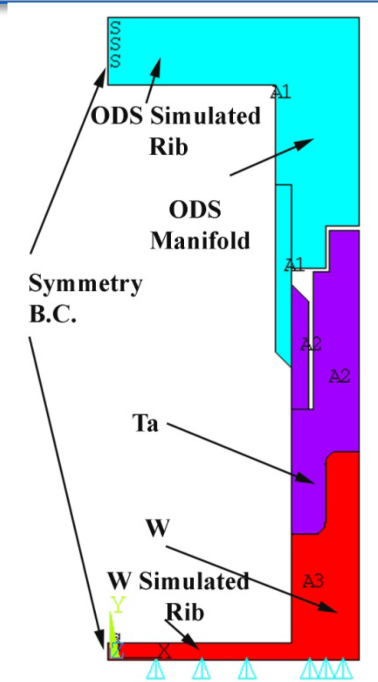
Front view

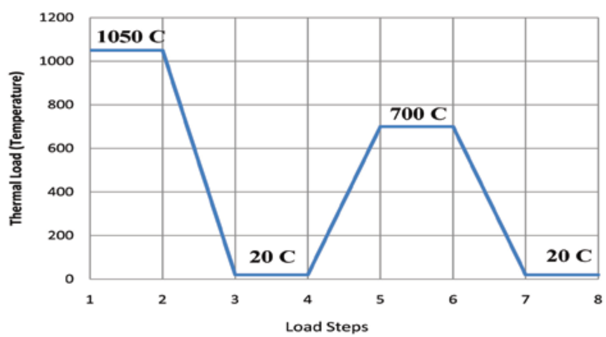
ANSYS 2D Plane Strain Model

- An effective W-rib is added to the ANSYS structural model for convergence and against bending.
- ANSYS Plane182 is used to include both elasticity and plasticity, and Bilinear Isotropic Hardening Material Model is utilized.
- Stress-free-temperature is assumed to be 1050 °C (brazing and diffusion welding temperature), and the assembly is free to expand.
- Three thermal and structural loading cycles will be investigated:
  - ✓ Fabrication
  - ✓ Operation with warm shutdown
  - ✓ Operation with cold shutdown

ANSYS Model







Fabrication steps

Plastic Deformations of the ODS-Ta-W Joints at Room Temperature

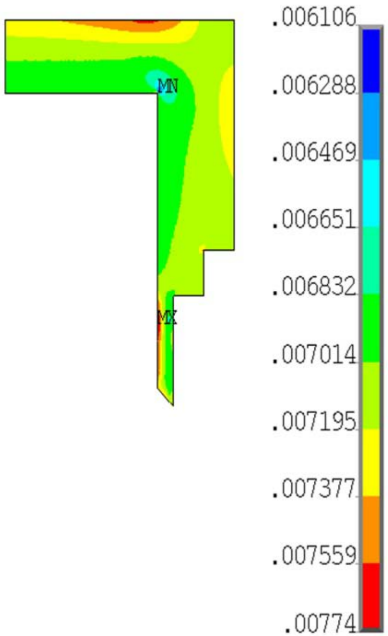
- ➢Allowable plastic strain for ODS-EUROFER is ~2.3% at RT and 1.9% at 550 ºC, and 2.4% at 700 ºC.

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

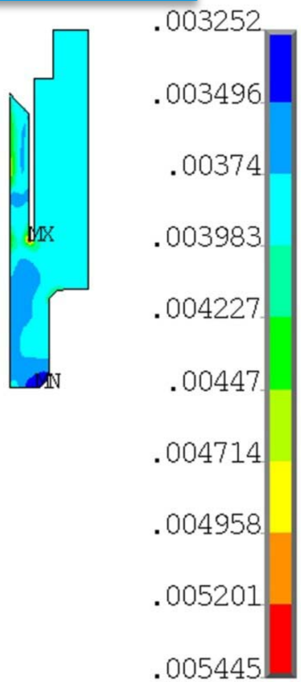
- ➢Allowable plastic strain for the W is 0.8% at 270 ºC and ~1.0% at ~1200 ºC.

- ➢The max. plastic strains of the ODS/Ta/W joints with 2 mm W-rib at room temperature are less than allowable limit.
  - ✓ODS steel: ε_{pl}= 0.77% (ε_{allow} =2.3% at RT)
  - ✓Ta: ε_{pl}= 0.54% (ε_{allow} =15% at RT)
  - ✓W: ε_{pl}= 0.0

Plastic strains at RT

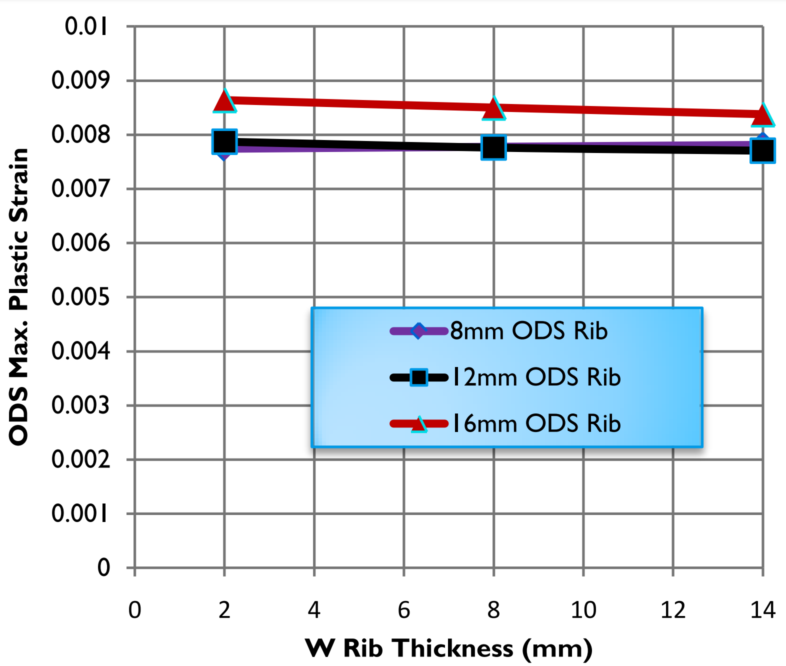


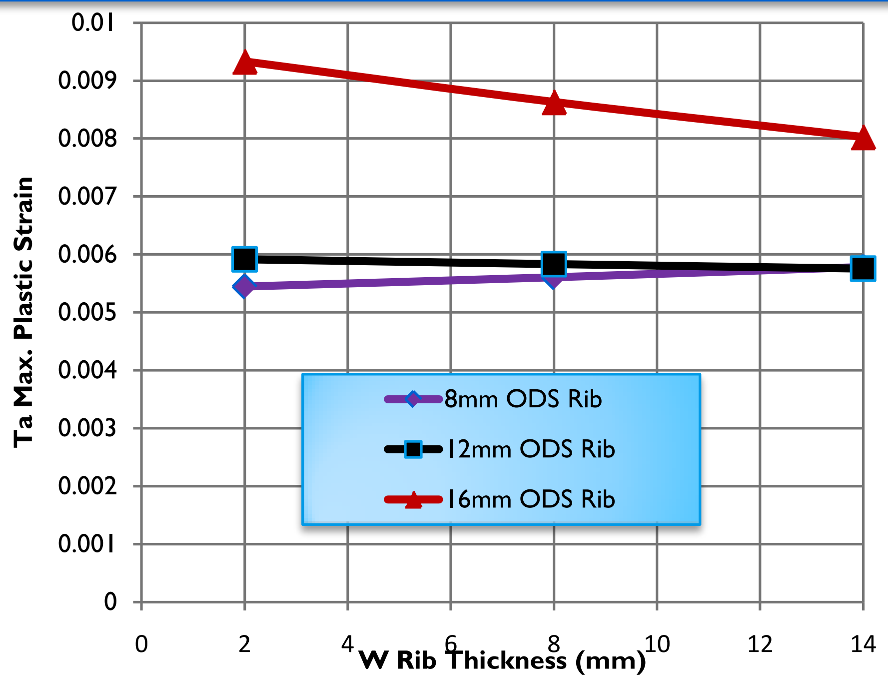
Plastic strain in ODS steel



Plastic strain in Ta

EFFECTS OF THE ODS AND W RIB THICKNESS ON THE PLASTIC DEFORMATIONS

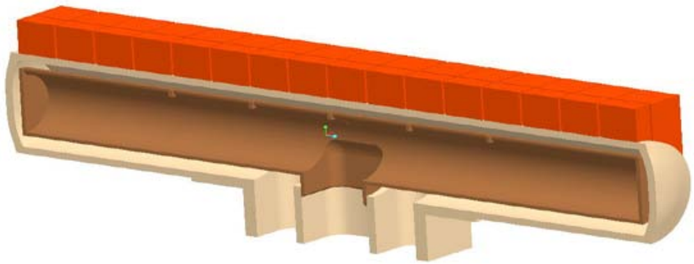




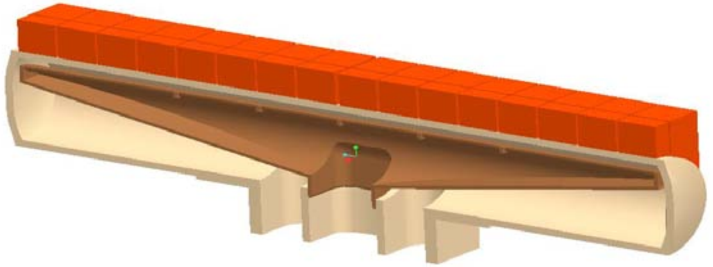
- Initial results indicate that increasing the W-rib thickness in ANSYS model will result in slightly reducing the plastic strains in both ODS-steel manifold and Ta-Ring.
- Increasing the ODS-steel thickness will slightly rise the plastic strains in both the ODS-steel manifold and Ta-Ring. However, all the plastic strains are far below the allowable plastic strain.
- **In a real design, we are not going to increase the thickness of the simulated rib in the 2D model.**
- A full 3D non-linear structural analysis will be performed.

UPDATE ON THE T-TUBE DIVERTOR CONCEPT

- Very little information is available on the mechanical properties of irradiated W alloy.
- Considering uncertainty of the irradiation effects on the thermal conductivity and operating temperature.
  - ✓ Degradation in thermal conductivity of ~5 to 10% is assumed.
  - ✓ OTL(Operation temperature limit) of the W depends strongly on alloy and degree of rolling,
    1. OTL~1200 ^{o}C with damage levels of 10 to 50 dpa for "standard "W (Steven Zinkle)
    2. OTL>1300 ^{o}C for the VM-W without irradiation. The re-crystallization starts at1500 ^{o}C for a 1 mm wire and 1800 ^{o}C for a 0.6 mm wire.
    3. OTL~1300 $^{\circ}$C for WL10 (FZK)
- VM-W will be used for fabricating the 1 mm W-tube, and 1300 ^{o}C is considered as the OTL.
- The effects of the W armor thickness are also considered.
  - ✓ 5 mm armor
  - ✓ 1 mm armor



Non-Tapered T-Tube



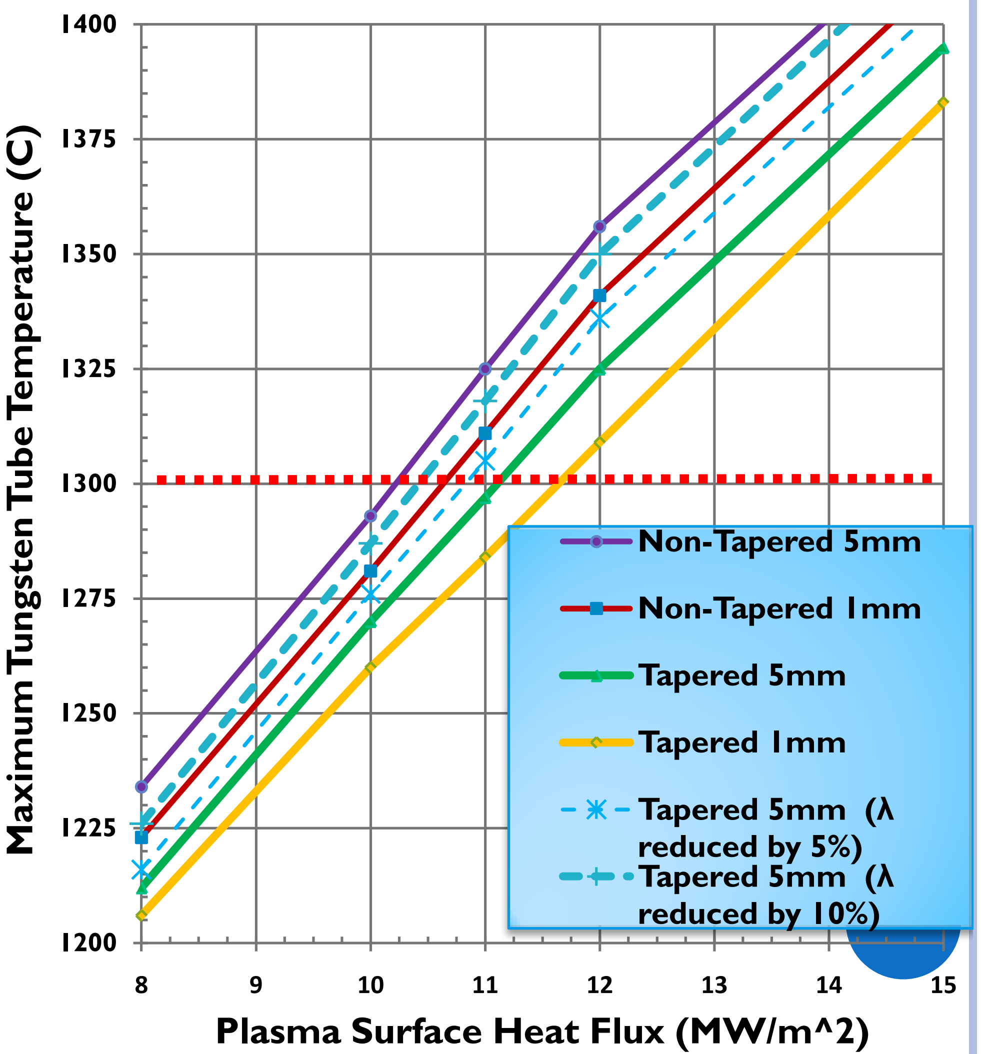
Tapered T-Tube

Design Window Based on High Temperature Limits

➢Without considering irradiation effects on thermal conductivity, the Tapered-Tube can accommodate a surface heat flux of ~11 MW/m^2, and ~10 MW/m^2 for the No-tapered T-Tube.

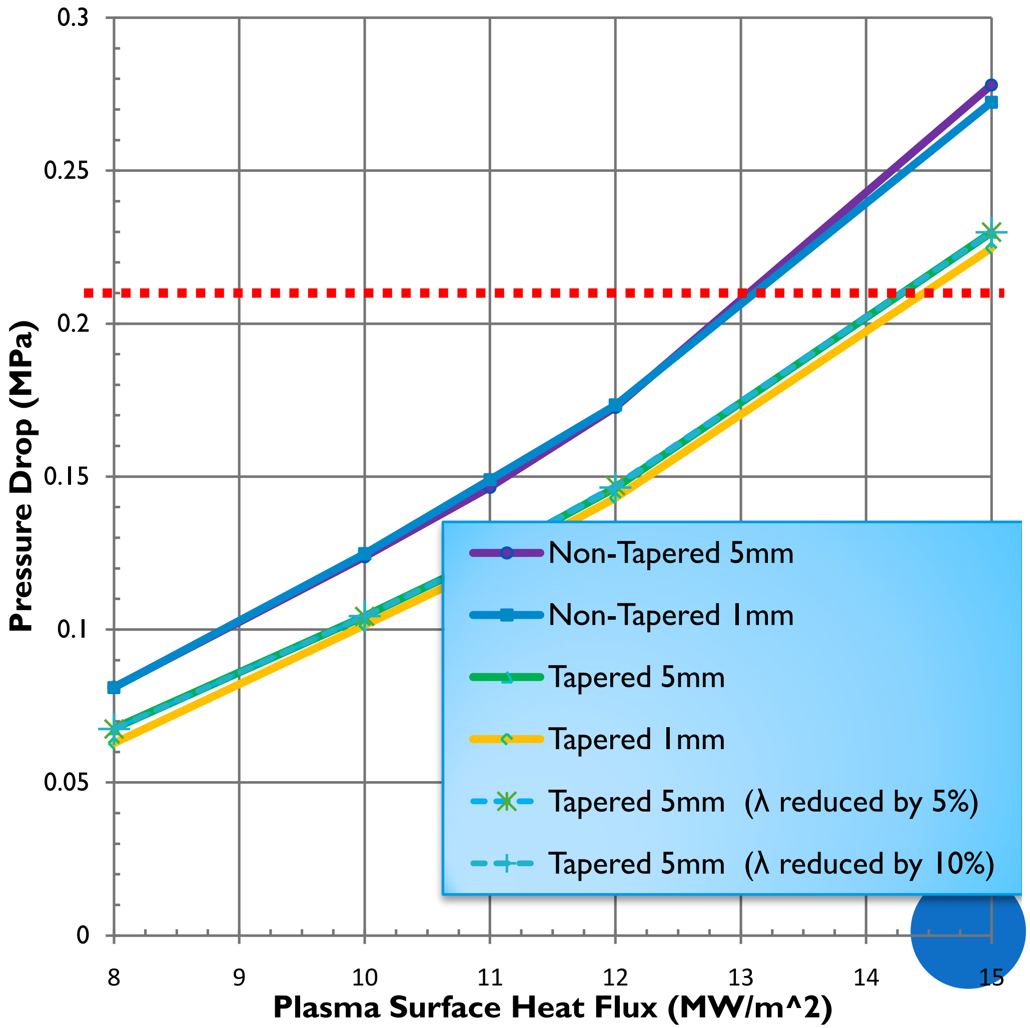
➢The thickness of the armor has small effects on the temperature, ΔT~10 K.

➢With consideration of the 5% and 10% irradiation degradation in thermal conductivity, the temperature roughly rises ~10 K for 5% degradation and ~20 K for 10% degradation in thermal conductivity.



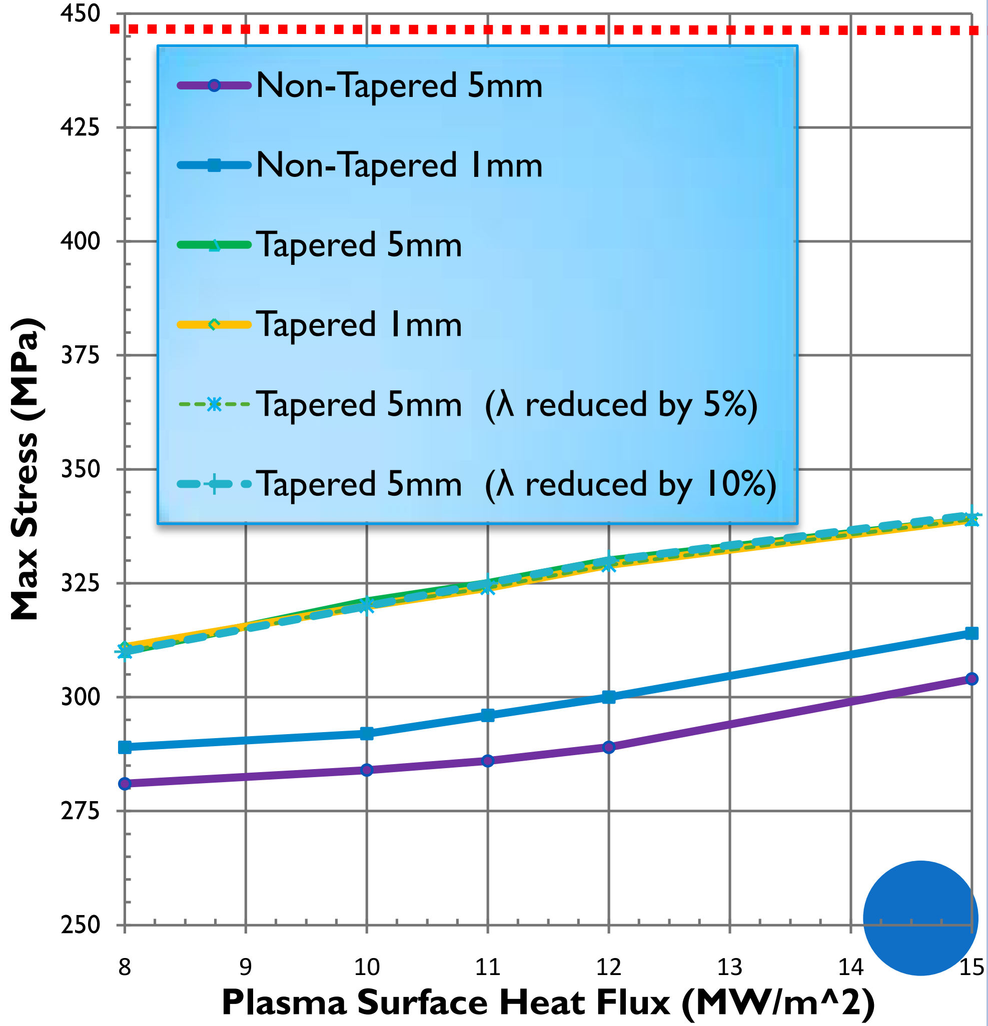
Design Window Based on the Pumping Power Limit

- ➢Pumping power is assumed to be less than 10% of the total removed thermal power (corresponding pressure drop of 0.21 MPa).
- ➢Thickness of the armor has no impacts on the pumping power design window.
- ➢The irradiation degradation in the thermal conductivity has no impacts on the pumping power.
- ➢There is a large room to increase the heat transfer coefficient by reducing the size of the slot jet to improve thermal performance.



DESIGN WINDOWS BASED ON THE STRESS LIMITS

- The stresses of all the tapered and non-tapered are below the 3 Sm limit (3Sm=~447 MPa at the corresponding temperature of ~700 ºC).
- There is a large margin for the stress design window, however, the thermal results of the T-Tube indicate that the temperature is the most limiting constraint.
- As the pumping power has a large room to push a higher heat transfer coefficient by using smaller slot-jet, we need to explore the temperature design window further.
- Creep date will be sought and analyses performed once we have it.



Summary and Future Work on He-cooled W Divertor

- Progress on the elastic-plastic analysis has been made for the ODS-Ta-W joints.

- Initial results indicate that the maximum plastic deformations stay within limits.

- Analyses for the joint assembly under loading cycles, including the fabrication steps, and operations with warm and cold shutdowns, are underway, and a full 3D modeling for the joints will be performed.

- Results of the T-Tube indicate that the tapered T-Tube has a room for pushing higher heat transfer coefficient to explore the temperature design window further.

- The plate-type divertor covered by small fingers will be re-investigated by using models including the plastic deformations (allow yielding) to determine how high heat flux can be without failure.