Technical Approach for Improved First Wall Protection

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Problems

- In power plant studies, the FW is usually designed for a steady-state heat flux up to 1 MW/m^2. In case of He-cooling with a pressure of ~ 8 MPa, temperature and stresses are close to the limits for the selected RAFS.
- However, there are indications, that at some locations a fast increase of the surface heat flux up to ~ 2 MW/m^2 can occur, accompanied by much higher erosions.
- As a first approach to be discussed, we assume the following transient:
  - ✓ Increase of the surface heat flux to 2 MW/m^2 in the order of milli seconds.
  - ✓ Heat flux remains constant at this value for up to 1 minute.
  - ✓ Such transients can occur on a fraction of the total FW area at anticipated locations.

  To protect the FW during such transients, some additional armor (W!) is required
- It is mandatory, that such transients do not require a FW exchange, because this could lower the availability of the plant to intolerable values.

Suggested Concept for FW Armor

- Arrange at the anticipated locations of large transient heat fluxes an additional armor, composed of brush-like W-pins embedded in a thin plate of ODS-steel.
- A similar solution had been developed for the ITER divertor target plates, where W-pins are embedded in a copper heat sink. These pins with a diameter of ~ 4 mm ("macro brush") or < 1 mm ("micro brush") are connected to the water cooled heat sink by casting Cu around them. The large interface area between heat sink and W-pins together with the small pin dimensions facilitates a reliable fixture of the pins after extensive thermal cycles in spite of the rather different thermal expansion coefficients.
- We are trying to extrapolate these ideas to the conditions at the FW, requiring a combination of W and ODS-steel for transient heat fluxes up to 2 MW/m^2.
- Suggested fabrication method for such a composite is to braze the different elements

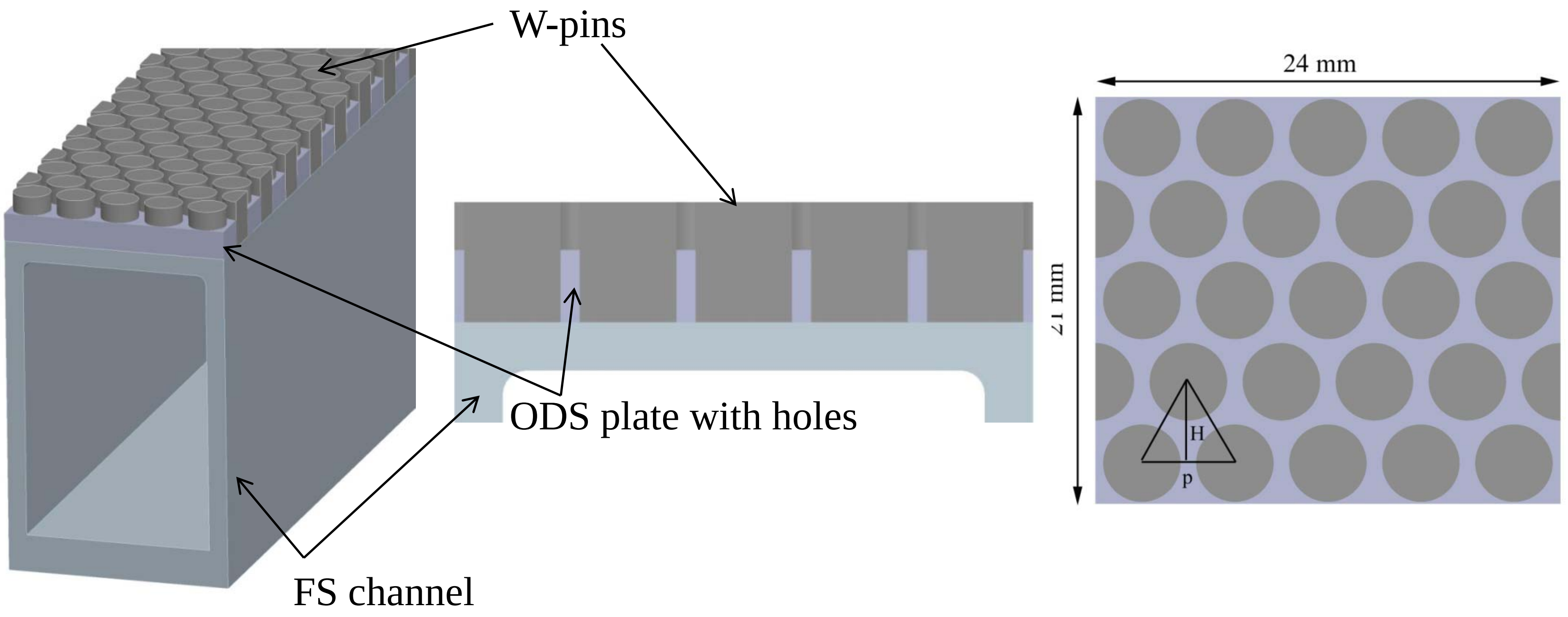
  - FS layer, ODS steel layer, W pins- together in a furnace. This can be done in a one step operation.

Macrobrush

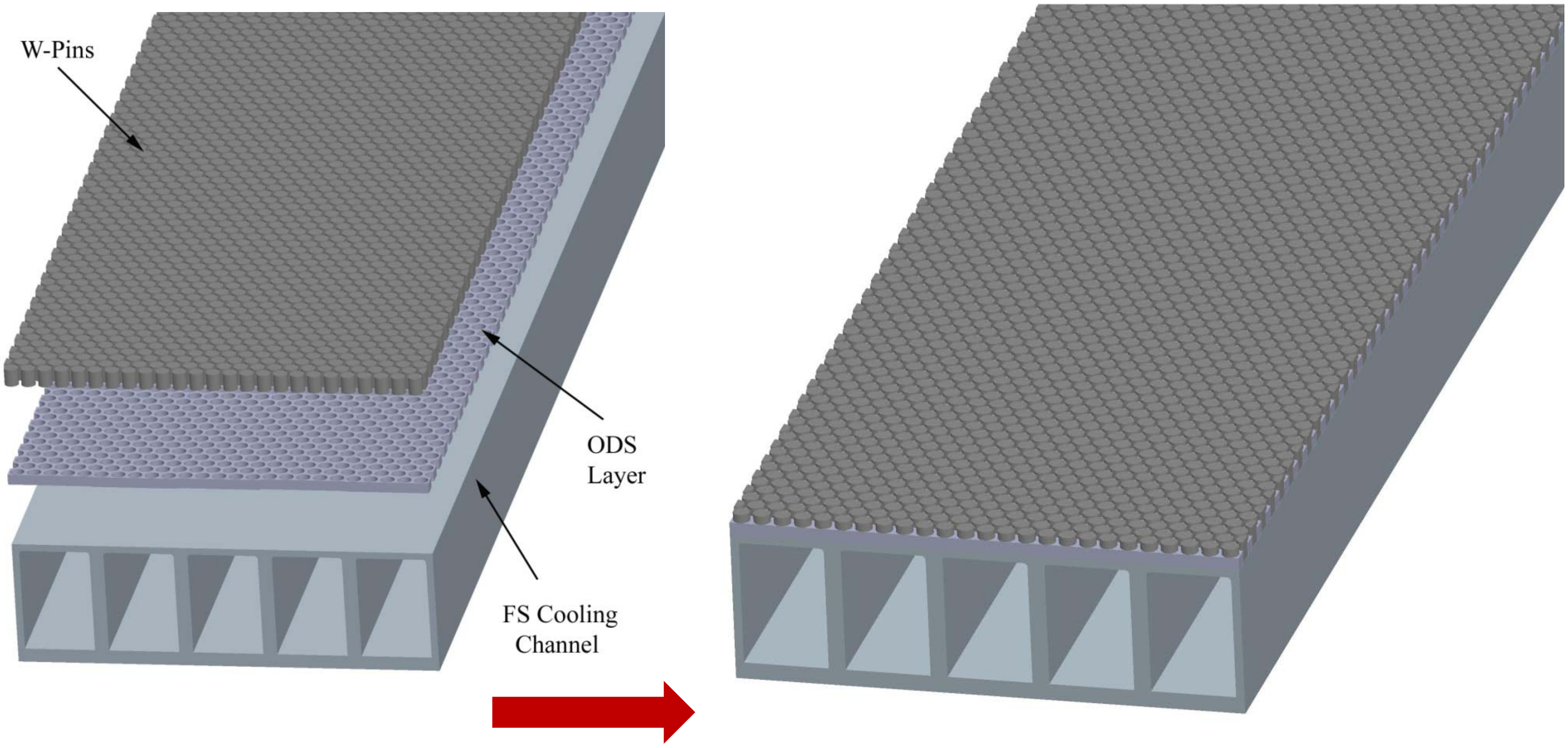
Lamellar

Rod

First Wall Armor Design



Suggested Fabrication Method



Bracing the W-pins, ODS plate and FS cooling channel together.

Main Issues to be Considered for the Design of such a FW Armor

- Issues
  - Decrease of the tritium breeding rate by the additional material
  - Increase of the FW temperature
  - Increase of the FW thermal stresses
- Clearly, TBR must not be reduced by more than 1 %.
- Temperature limits to be considered for Reduced Activation Ferritc Steels (RAFS) of the class F82H and EUROFER:
  - T_{min} > 350 °C
  - T_{max} < 550 °C
- Stress limits allowing a simple analysis based on elastic deformation only:
  - Primary (pressure) stresses < Sm=Min(1/3 of rupture strength, 2/3 of yield strength)
  - Sum of primary+ secondary (thermal) stresses < 3 Sm

Reduction of TBR

- First check performed by Mohamed Sawan (UW Madison):

  Demo power plant with DCLL blankets at IB and OB region, FW thickness 4 mm (RAFS), Reduction of TBR by added armor to the normal FW:
  - ✓ 10 mm RAFS: TBR reduced by 5 %
  - ✓ 10 mm W: TBR reduced by 1 %
- Interesting observation:
  - ✓ If the additional amount of armor would be distributed over the entire blanket depth, the resulting reduction of TBR would be 0.5 % (RAFS) and 3 % (W) respectively.
- Conclusion: We can easily afford an additional armor up to 10 mm thickness, composed of W and ODS steel, since this armor covers a fraction of the FW surface area only.

Limits for the FW Temperature

- Temperature limits
  - ✓Minimum irradiation temperature > 350 ºC to avoid embrittlement
  - ✓Maximum temperature < 550 ºC for creep strength reasons.

    This limit can be raised by ~ 100 K for "normal" Oxide Dispersion Strengthened (ODS) steels, and by ~ 200 K by advanced ODS steels with nano-sized particles.

- Problem: A heat flux of 2 MW/m^2 leads in ferritic steel to a temperature gradient of ~ 70 K/mm. Since the thickness of the FW has to be at least ~ 4 mm for strength reason, the resulting FW temperature would become too high.
- Suggested solution: Compose at the anticipated locations the FW of ~ 2 mm RAFS and a sieve-like plate of ODS-steel with W-pins embedded in the 2-3 mm thick plate. The average conductivity of this ODS+W plate is decisively increased by the high conductivity of W. In addition to this increased thermal conductivity, the heat transfer coefficient between the He-coolant and the FW has to be increased. Such an increase must be permanently at the selected locations since the heat flux can rise in milli seconds. This is tolerable without excessive reduction of thermal efficiency since the larger pressure drop is limited to a small fraction of the FW.

Limits for the FW Stresses

- Thermal stresses are a crucial issue for any FW design. In order to keep the primary stresses caused by the high pressure of the He-coolant (~ 8 MPa) in a tolerable range, a wall thickness of ~ 4 mm is required. The thermal stresses in such a steel wall limit in general the allowable heat flux to values $< 1\ MW/m^2$.
- This limit is usually determined with FE calculations, assuming that stresses and strains remain in the elastic region.
- With this assumption, the ASME code requires that the sum of primary +secondary stresses are < 3 Sm, which at the maximum wall temperature.
- However, there are provisions in the ASME codes allowing more sophisticated designs of highly loaded high temperature components in case the 3 Sm limit is exceeded.
- Since most of the FW designs are at or above this limit, the different approaches are described briefly in the followings.

Design Methods for High Temperature Components as Allowed by the ASME Code

- The simplest method which is always the first step is to limit the analysis to the elastic behavior of the structural material. If the calculated sum of primary and secondary stresses remains < 3 Sm, the design is fine. However, it is not always possible to avoid plastic strain caused by exceeding the yield strength or by thermal creep. In such cases, the analysis has to show that the strain does not continuously increase with the number of temperature cycles ("ratcheting") but reaches its final value after a few cycles ("shake down").
- As a last resort, it is possible to “design by experiments”, requiring an extensive test program to prove that the component will survive all anticipated transients.
- With our suggested FW armor, we have probably to go to method 2, requiring sophisticated analyses of plastic strains.

Design Methods for High Temperature Components as Allowed by the ASME Code

a) Strains during the fabrication steps

- There are three elements to be braced together:
  - 2 mm feritic steel plate of the FW box
  - 2-3 mm ODS steel plate with multiple holes (“sieve plate”)
  - W-pins with a diameter of ~ 4 mm to be inserted as a pin-array into the ODS sieve plate.
- All these elements are braced together in a one-step furnace operation at a temperature of ~ 1000 ºC. This is the same temperature as required for austenicing the ferrite steel. All the material will be stress-free annealed at this temperature.
- The assembly is cooled down slowly to room temperature. The different thermal expansion coefficients of W and steel lead to tensile stresses in the steel and to compression stresses in the W-pins. The yield strength of the steel will be exceeded during this transient, resulting in plastic strain of the steel.
- As standard post weld heat treatment required for this class of steel, the assembly is heated up to ~ 750 °C for ~ 1 hour. This leads again to a relaxation of the stresses in the different elements by plastic deformation. Therefore it can be assumed, that the assembly is at “stress free” condition at this temperature.
- There may be some plastic deformations if the assembly is cooled down after this tempering, which will be the starting condition for the FW operation.

Design Methods for High Temperature Components as Allowed by the ASME Code

b) Strains during the operation of the plant

- During the start-up of the plant, the FW is heated up slowly to ~ 500 °C. With this uniform temperature field, all elements may remain in elastic conditions.
- However, if the surface heat flux rises to its normal operation value, the temperature gradient in the FW assembly may result in some plastic strain.
- Cooling the assembly down during off-power situation, the FW stresses will reverse, causing perhaps plastic strains in opposite direction.
- In such cases, the analysis has to show that the strain does not continuously increase with the number of temperature cycles ("ratcheting") but reaches its final value after a few cycles ("shake down"). The crucial issue is if all materials will remain in the elastic region after a few cycles.

Design Methods for High Temperature Components as Allowed by the ASME Code

c) Cooling and strains during anticipated short transients, resulting in heat fluxes up to 2 MW/m^2

- Such transients can raise the heat flux at some anticipated regions of the FW surface to more than twice the normal operational value in milli seconds. This means that the cooling at those locations has to be adequate for the high heat load all the time.
- Assuming that those regions to not cover more than about 20 % of the entire FW surface, it is possible to design the coolant channels in such regions for much higher helium velocities than in the major part of the FW, resulting in a local heat transfer coefficient up to twice as large than in the "normal" region with a tolerable increase of the entire pressure drop.
- This means, that temperatures and strains in such regions can be maintained at lower values during normal operation than in the normal FW, and there is hope that the design survives the fast transients without damages. This, however, has to be verified by detailed analysis.

Conclusions and Outlook

- It is an ambitious task to design an additional protection of the FW, allowing a fast increase of the surface heat flux up to 2 MW/m^2.
- A suggestion for such a FW armor, based on the successful development of the ITER brush divertor concept, has been presented.
- This concept is described briefly including design, suggested fabrication steps and the investigation of the transient behavior.
- However, sophisticated FE analyses including the description of the plastic deformations during fabrication and operation are necessary to optimize the design and to prove its viability.
- A first step in that direction is the subject of the following presentation .