Design Improvements of the W-Based Divertor Concepts

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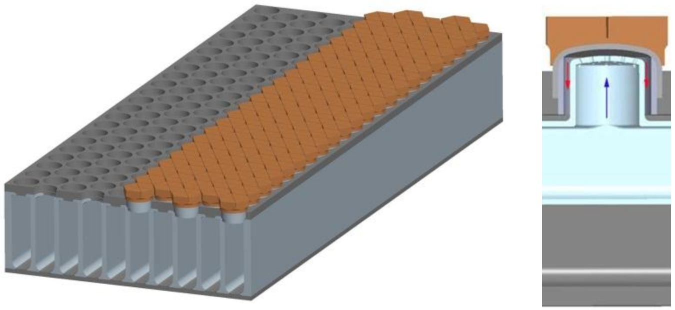
Status of the He-cooled W Divertor Concepts

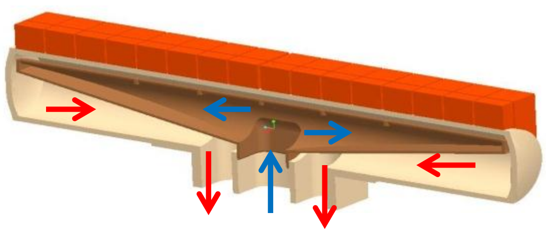
1. HCPF(He-cooled Combined Plate and Finger)

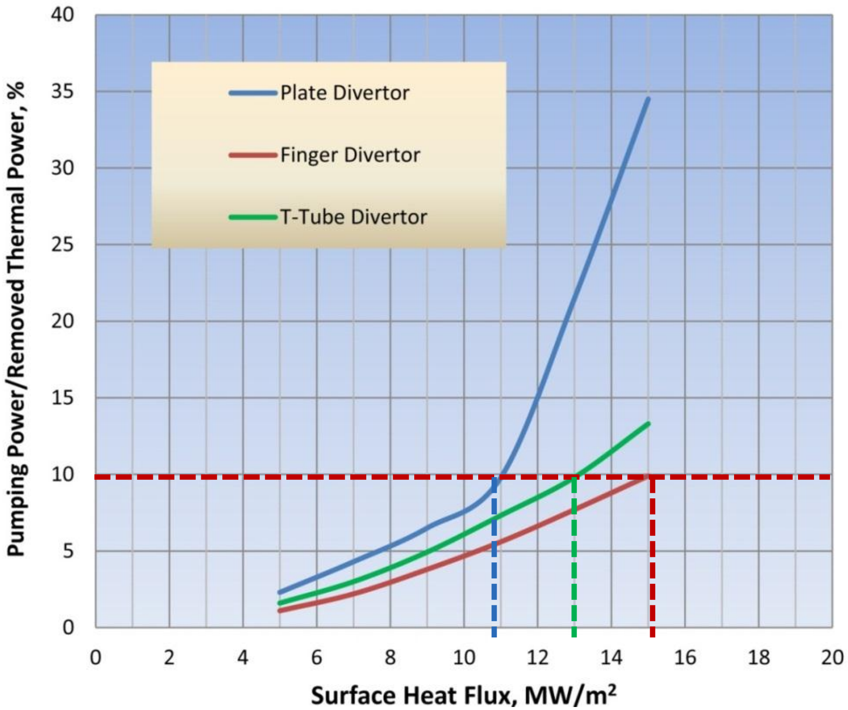


Design limits :

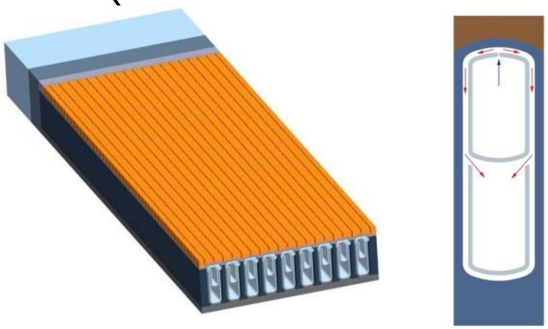
- ✓ Minimum temperature of the W structure 700 °C (embrittlement)
- ✓ Maximum temperature of the W structure 1300 °C (recrystallization)
- ✓ Pumping power 10% of thermal power removed.

2. HCTT(He-Cooled T-Tube)





3. HCFP(Helium-cooled Flat Plate) divertor

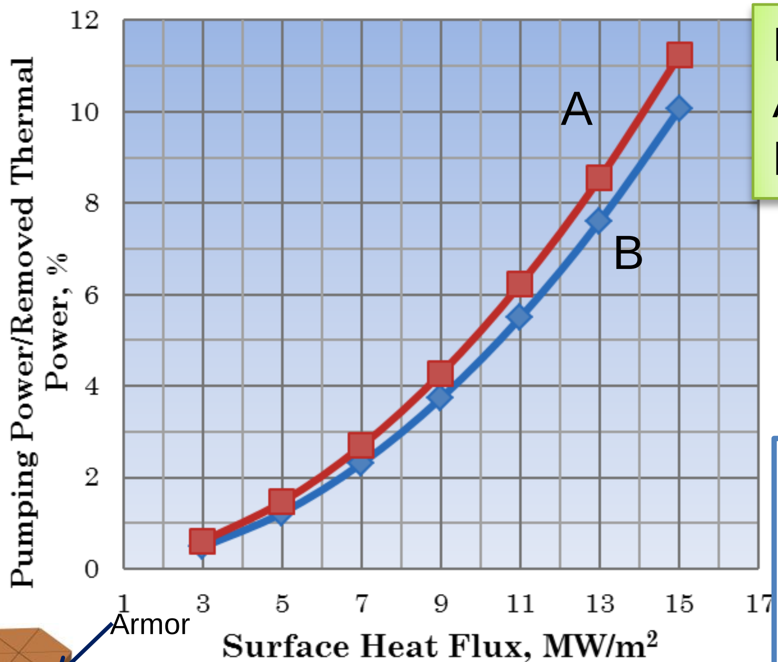


MODIFICATIONS

- Since fracture toughness of the W alloy is reduced by low temperature irradiation, the lower temperature limit (~700 °C) must probably be raised to ~ 800 °C to avoid the embrittlemeent of the W structure.
- To achieve this, the He coolant exit temperature has to be raised to a range of 750~800 °C (previous cooling conditions: T_{exit}=650~700 °C, T_{Inlet}=600 °C).
- Advanced ODS steel (such as 12CrYWTi) would be one option for the manifold. Creep tests of the 12CrYWTi at 800 °C and 138 MPa showed the specimen is in the steady-state stage at ~5000 h and ruptured at ~14500 h.*
- Such a higher He exit temperature require a reduction in the maximum heat flux in order to keep the maximum temperature of the W structure under the upper operating limit of 1300 °C.
- We should make new optimizations to the divertor concepts with a goal to find the maximum allowable heat flux with obeying the 1300 °C limit for the W structure and 10% limits for pumping power.
  - ✓ HCPF(Finger)
  - ✓ HCFP(Plate)
  - ✓ HCTT(T-Tube)

**R.L. Klueh et al./J. of Nuclear Materials 307-311 (2002) 455-465.*

Reevaluation of the HCPF Concept

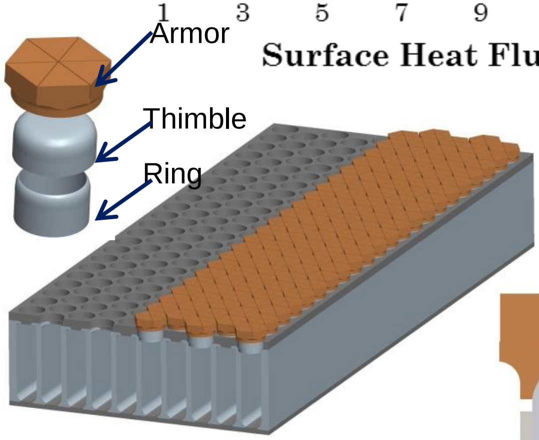


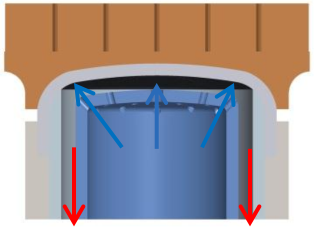
$P_{pumping\ power}/P_{removed\ power}$ <10%

A: **800** <T_s<1300 °C, T_{exit}=800 °C, T_{in}=700 °C

B: **700** <T_s<**1300** °C, T_{exit}=700 °C, T_{in}=600 °C

- ➢ The allowable heat flux calculated by CFX
- ✓ **Case A, ~14 MW/m²**
- ✓ **Case B, ~15 MW/m²**





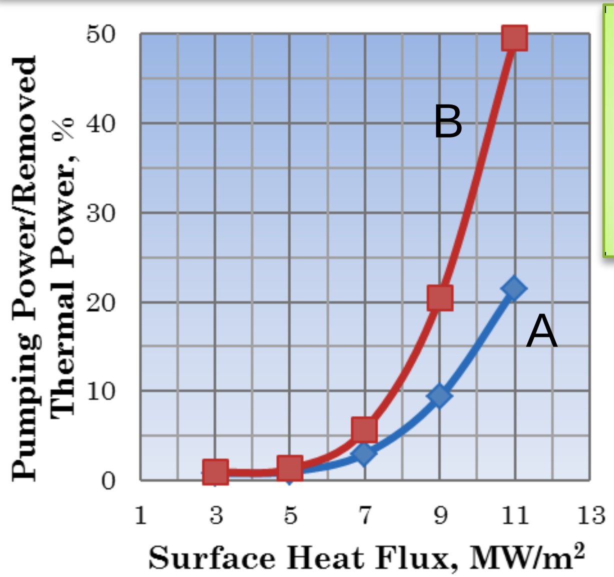
Material applications:

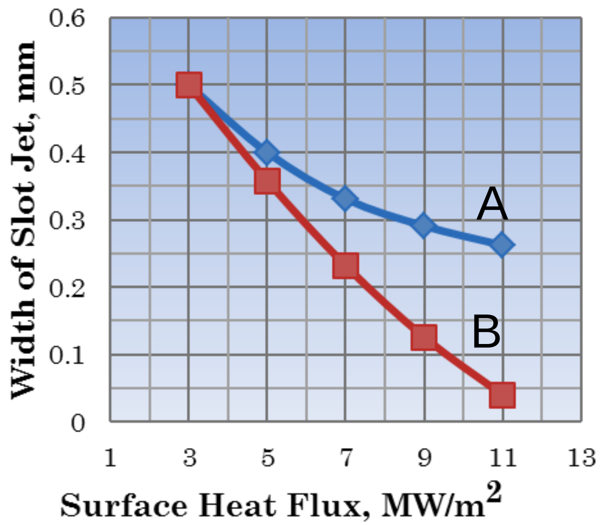
- ✓ Armor: pure W
- ✓ Cup-shaped thimbles: VM-W doped with ppm of $Al_2(SiO_3)_3$ or K_2SiO_3
- ✓ Front, side and back plates: WL10 (W-1%La_2O_3)

Fabrication:

- ✓ Armor: powder HIPing(hot isostatic pressing)
- ✓ Thimbles: Drawn and rolled from sheet (up to 1 mm)
- ✓ All the plates: HIP

REEVALUATION OF THE HCFP DIVERTOR



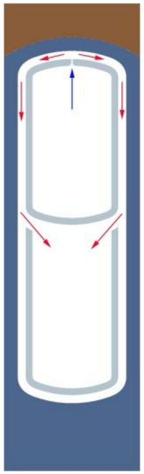


$P_{pumping\ power}/P_{removed\ power}$ <10%

A: **800** <T_s< 1300 °C, T_{exit}=800 °C, T_{in}=700 °C

B: **800** <T_s< **1200** °C, T_{exit}=800 °C, T_{in}=700 °C

C: 700 <Ts< 1300 °C, T_{exit}=677 °C, T_{in}=600 °C



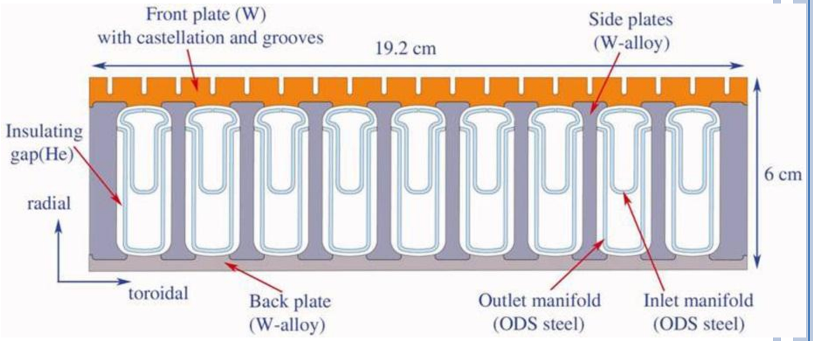
- ➢ The allowable heat flux calculated by CFX
- ✓ **Case A, ~9 MW/m²**
- ✓ **Case B, ~7.8 MW/m²**
- ✓ **Case C, ~11 MW/m²**

Material applications:

- ✓ Armor: pure W
- ✓ Front, side and back plates (thickness> 2mm)
  Pure W or WL10 (W-1%La_2O_3)

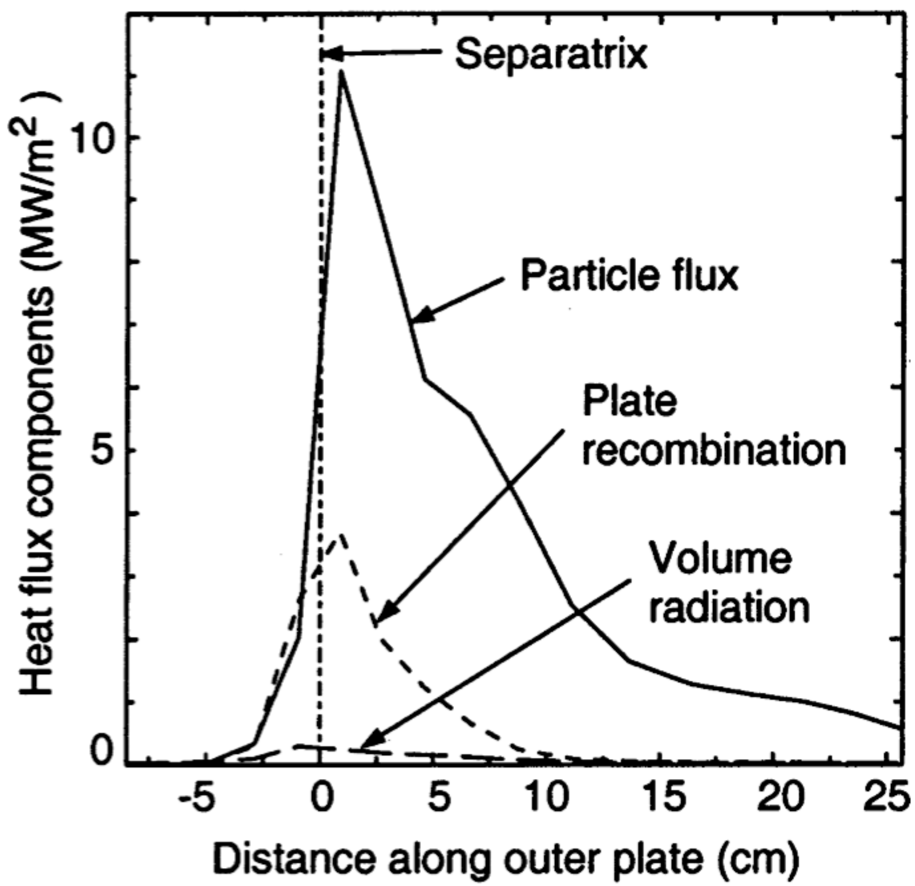
Fabrication:

- ✓ All plates: HIP



How Can A Non-uniform Heat Flux Profile be Handled in Divertor Design

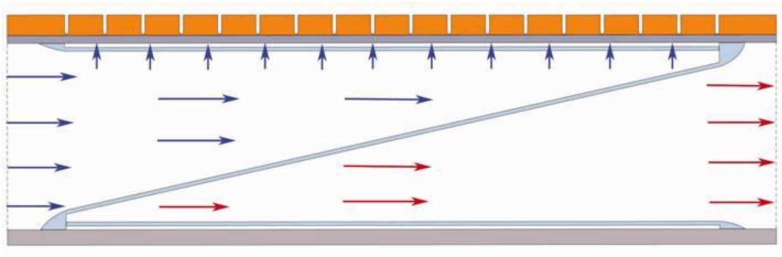
- In previous studies, all evaluations until now were concerned with the layout of the finger and plate concepts for the maximum allowable heat flux.
- However, there is a rather steep profile in the plate direction with a ratio between the maximum (11 MW/m^2) and average heat flux (3.5 MW/m^2) of 2~3.
- How can the localized HHF be accommodated for in our divertor design?



Example of the ARIES-AT or RS Design
*T.D. Rognlien, presented at the ARIES Town Meeting

Adjustment of the Cooling to a Power Profile in Plate Direction

- With the finger, plate and T-Tube design, the coolant flows in poloidal direction in parallel channel. The heat flux, cooling condition, and the temperatures are equal in these parallel channels.
- The helium enters at one side of the plate and leaves at the other side, and the heat flux into the plate is low at the channel inlet, rises to a maximum value, and goes down again in the direction to the exit.
- Inside the channel there is an inlet manifold with decreasing cross-section, and an outlet manifold with increasing cross-section. With this arrangement, the He velocity in the inlet and outlet manifold remains constant over entire length of the plate.
- The **design method** for adjusting the cooling to a power profile in the plate direction is to maintain the He velocity through the nozzles (jets) as well as the coolant temperature rise (T_{exit}-T_{inlet}) as constant over the entire length of the plate. In this way, the pressure drop (ΔP) will remains constant.



Design Method of Accommodating to a Power Profile in Plate Direction

To maintain the jet velocity $\mathbf{v}_{jet}$, coolant temperate rise $\Delta\mathbf{T}$ and the $\Delta\mathbf{P}$ as the constant:

- We have to adjust the local coolant mass flow rate to the local divertor heat flux, and this requires **the ratio of the mass flow rate to surface heat flux should be constant**. This means we have to adjust the **flow cross-sections** to the local divertor heat flux.
- The ratio of the local cross-section area of the nozzle to the cross-section area of the nozzles at the location of the maximum heat flux has to the same ratio of the local heat flux to the maximum heat flux:

  $$S_{\text{nozzle at local}} / S_{\text{nozzle at max}} = q''_{local} / q''_{max} \quad (S_{nozzle}\text{: CS area of the nozzles})$$

- The slot should not become too small for practical reason, the continuous slot should be replaced by an interrupted slot with ratio

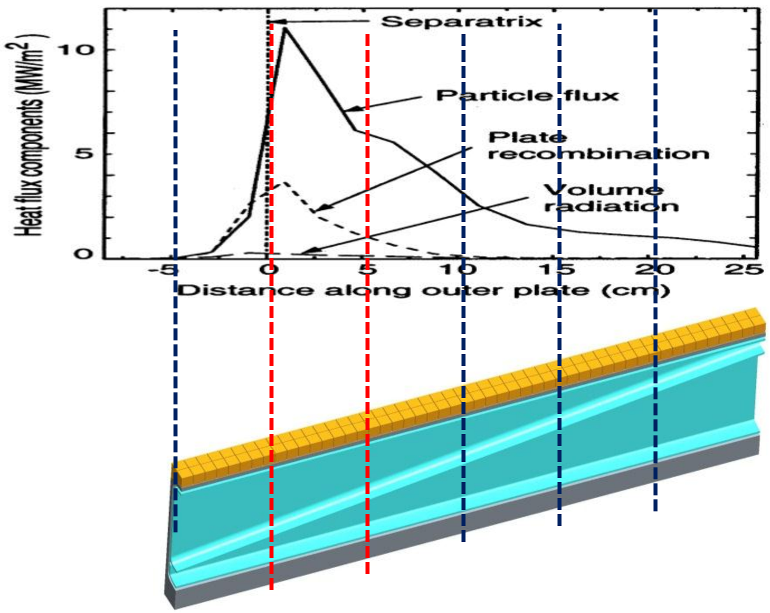
  $$L_{\text{slot at local}} / L_{\text{slot at max}} = q''_{local} / q''_{max} \quad (L_{slot}\text{: length of the slot})$$

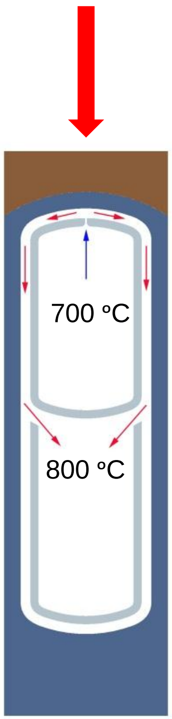
- **Examples:**

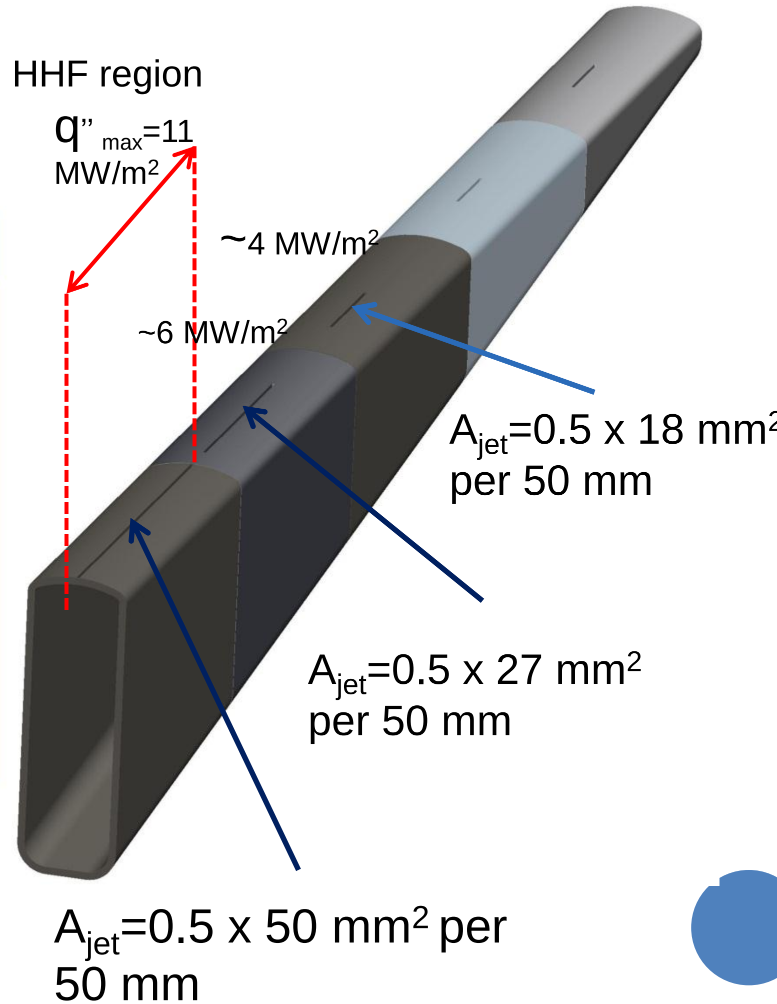
Plate design with jet cooling through a slot

Heat flux (MW/m^2)	**10**	**5**	**2**
Slot length (mm per 5 mm unit)	**5**	**2.5**	**1**

Example of the HCFP Divertor to Accommodate a HF Like ARIES-AT







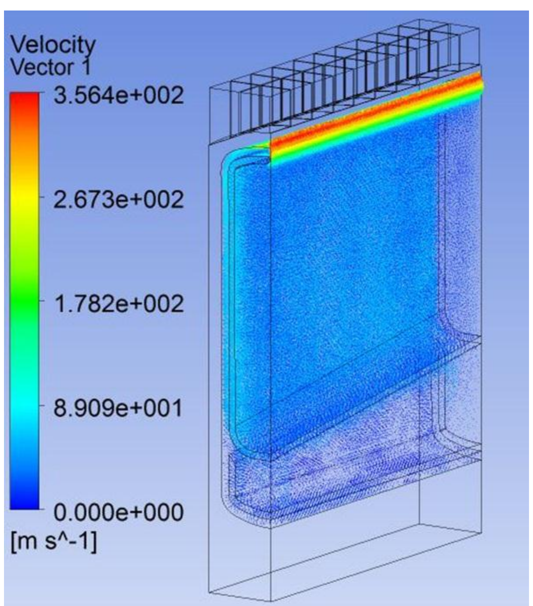
- HCFP: poloidal length ~30 cm
- High heat flux region ~5 cm in the poloidal direction
- V_{jet}, ΔT and ΔP remain constant

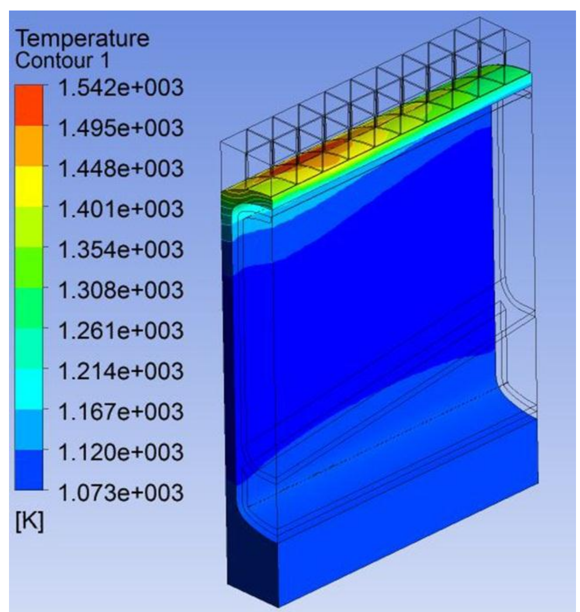
CFD Results Indicated the Plate can Handle the ARIES-AT Like Power Profile

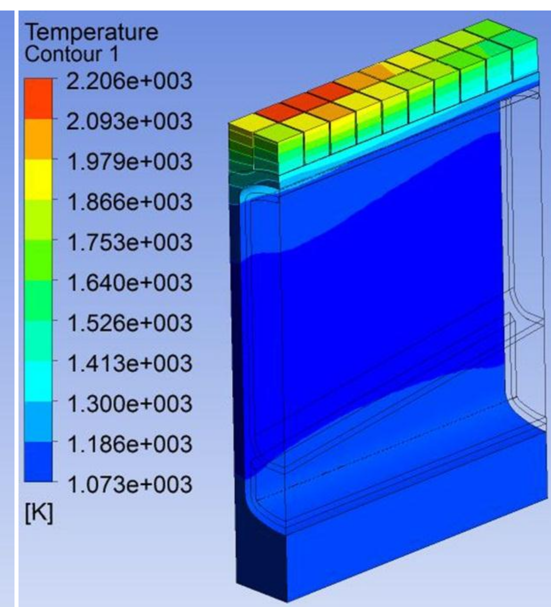
- Only high heat flux region(L=50 mm) with the maximum heat flux of 11 MW/m^2 is simulated by CFD code in order to reduce the elements and nodes.
- Total number of the nodes is ~4.1 million for the high heat flux region.
- CFD results are based on T_{exit}/T_{inlet}=800/700 °C and W structure operating temperature of 800 $<T_s<$1300 °C

  V_{jet}=356 m/s, $T_{s,max}$ =1296 °C, $T_{s,min}$ =800 °C, $T_{armor,max}$ =1933 °C

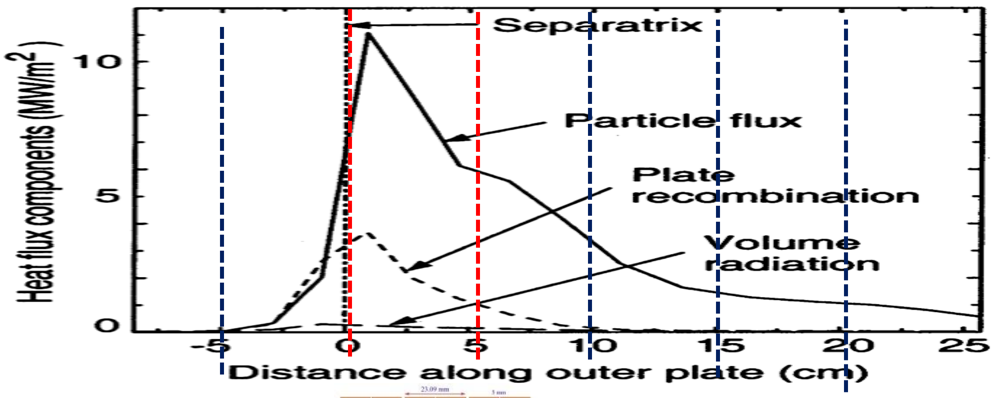
  $P_{pumping}/P_{removed\ thermal}$=9.6%

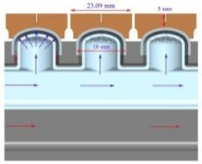


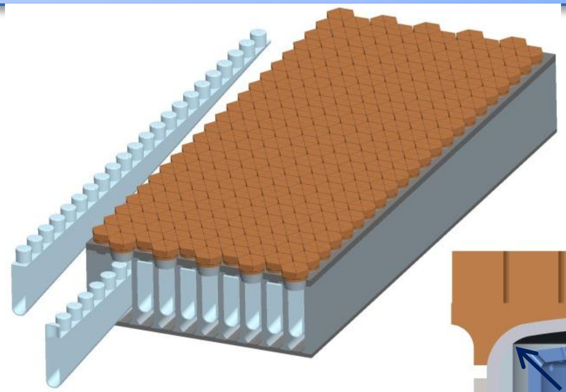


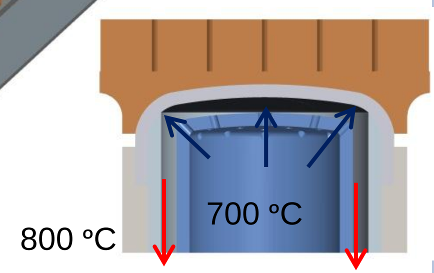


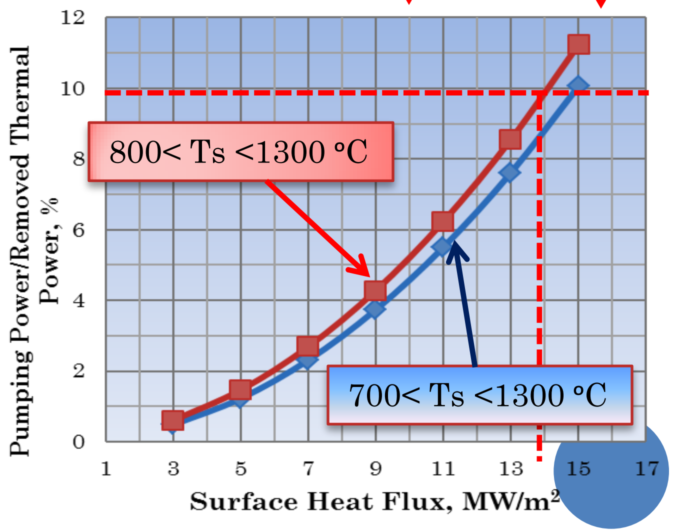
Example of the HCPF to Accommodate a Power Profile Like ARIES-AT









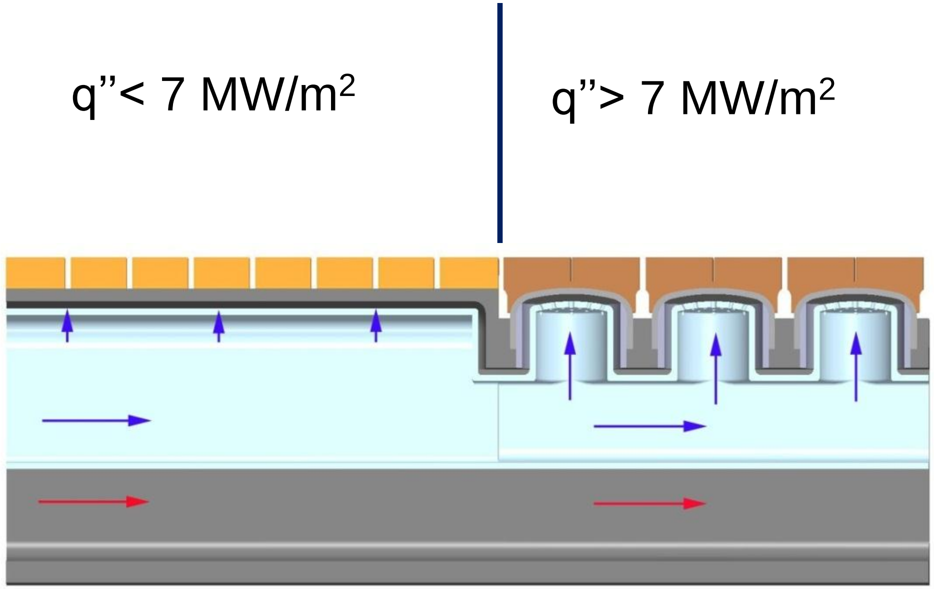


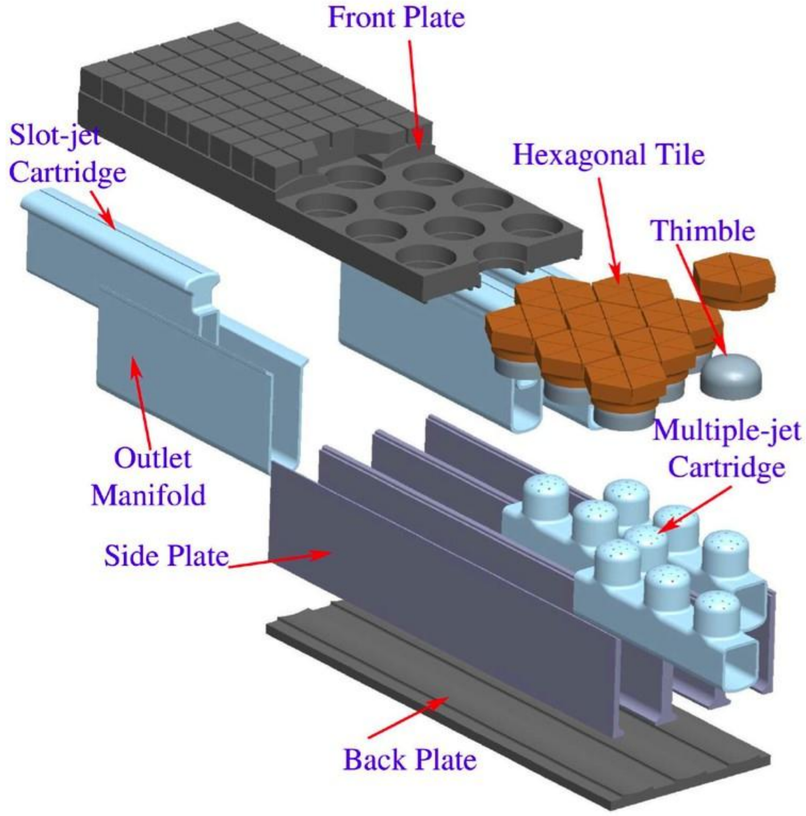
Uniform heat flux

- HCPF: poloidal length ~30 cm
- ~2 to 3 fingers in the high heat flux region,
- Maintaining the V_{jet}, ΔT and ΔP as constant over whole poloidal length
- Keeping the nozzle diameter constant and decrease the number of nozzles in the same ratio as the local heat flux
- Accommodating much higher localized heat flux (about 6% only for q''=11MW/m^2)
- No analysis been done.

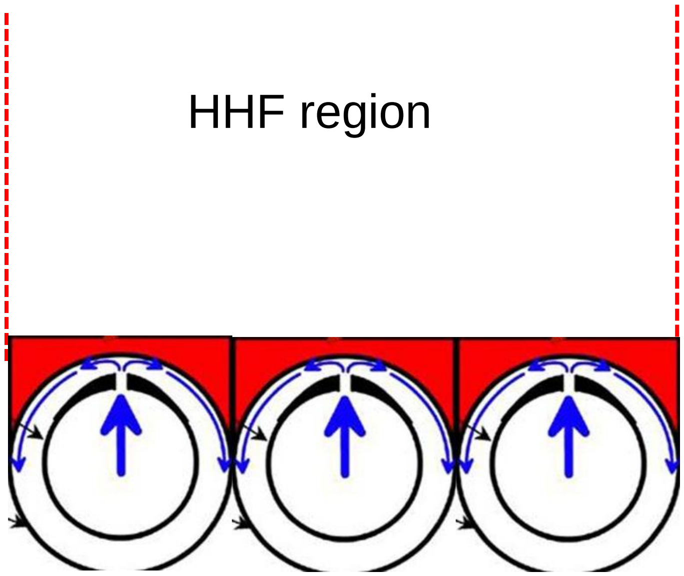
FINGERS CAN BE COMBINED WITH SLOT JETS FOR LOCALIZED HHF HANDLING CAPABILITY AND MINIMUM UNITS

- Cartridges with both slots and fingers can be combined
- Limit fingers to zones with the highest heat flux

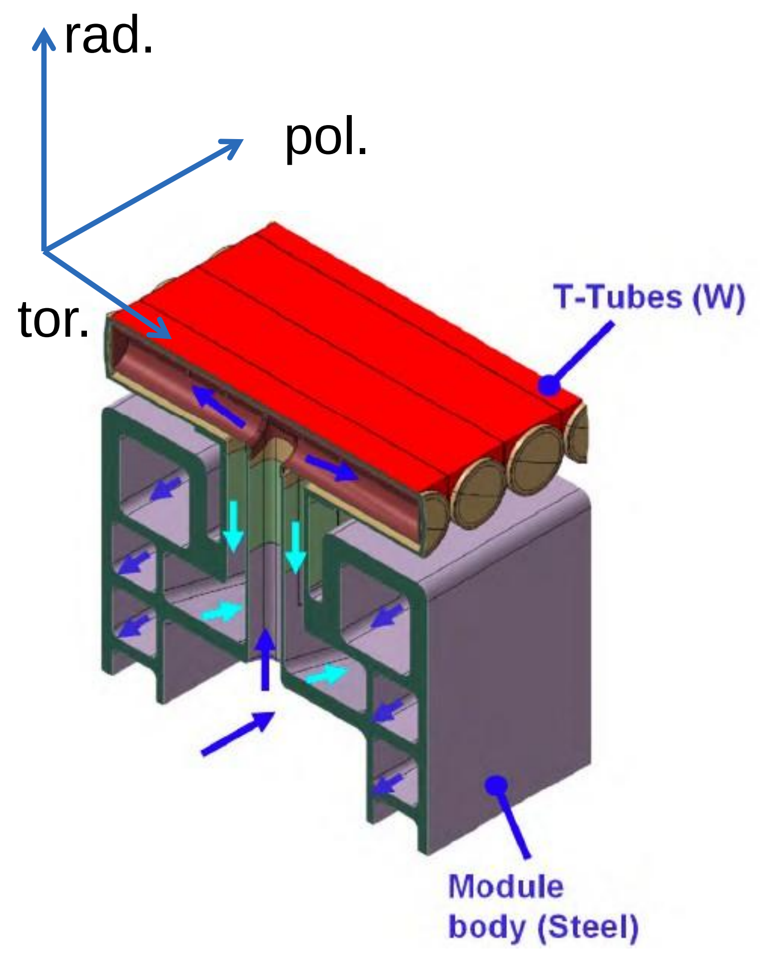




Example of the HCTT to Accommodate a Power Profile Like ARIES-AT (Jeremy)



- V_{jet}, ΔT and ΔP remain constant



SUMMARY AND CONCLUSIONS

- Divertor concepts including the finger, T-Tube and plate-type, have been re-evaluated and optimized based on raising the minimum W temperature from 700 °C to 800 °C in order to avoid enbrittlement under neutron irradiation.
- Allowable heat flux based on the operating temperature limits of 800 °C < Ts <1300 °C
  - ✓ HCPF(Finger), q''_{allow}=14 MW/m^2
  - ✓ HCTT(T-tube), q''_{allow} =???(waiting for results from Jeremy)
  - ✓ HCFP(Plate), q''_{allow}=9 MW/m^2
- Stresses for the adjustment of the W minimum temperature from 700 to 800 °C have not been checked, yet. However, thermal stress should be reduced because of the raising the W minimum temperature.(ΔT=400 °C comparing to ΔT=500 °C).
- Previous studies indicate in all concepts, stress relaxation by plastic deformations reduce the stresses to a degree that the sum of primary and secondary stresses remain below the 3 S_m limit of the ASME code.
- Initial results indicate that the plate-type divertor can accommodate a localized HHF like the ARIES-AT with maximum heat flux of 11 MW/m^2 while meeting the design limits of the W-structure temperature and pumping power.
- **Expecting (without CFD analysis)** the finger can handle much higher localized HHF than the plate.