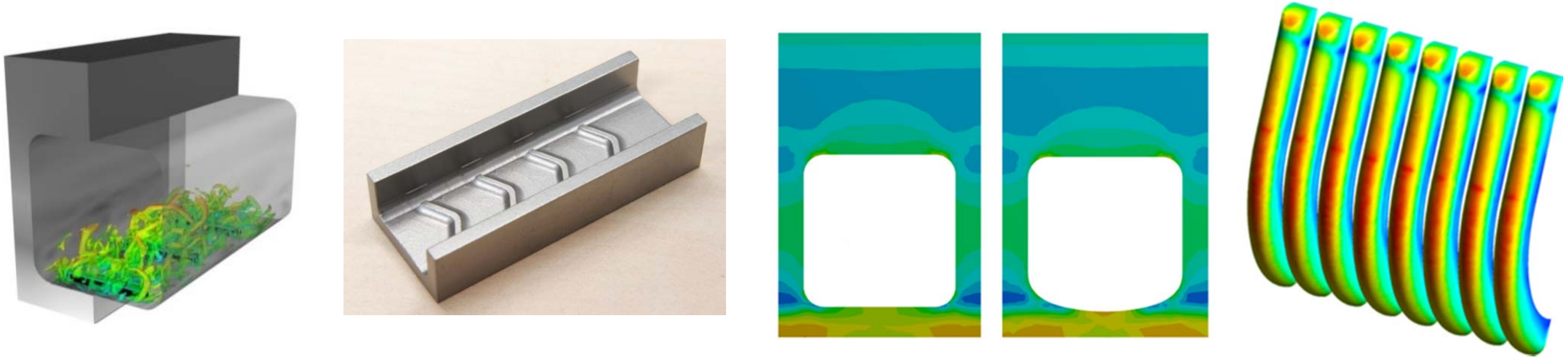
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Options for a high heat flux enabled helium cooled First Wall for DEMO

Frederik Arbeiter, Y. Chen, B.-E. Ghidersa, Ch. Klein, H. Neuberger, S. Ruck, G.Schlindwein, F. Schwab, A. v.d. Weth, 06.09.2016, 29th SOFT 2016, Prague, Czech Republic

Institute for Neutron physics and Reactor technology, Measurements and Experimental Techniques group (INR-MET)



Objective

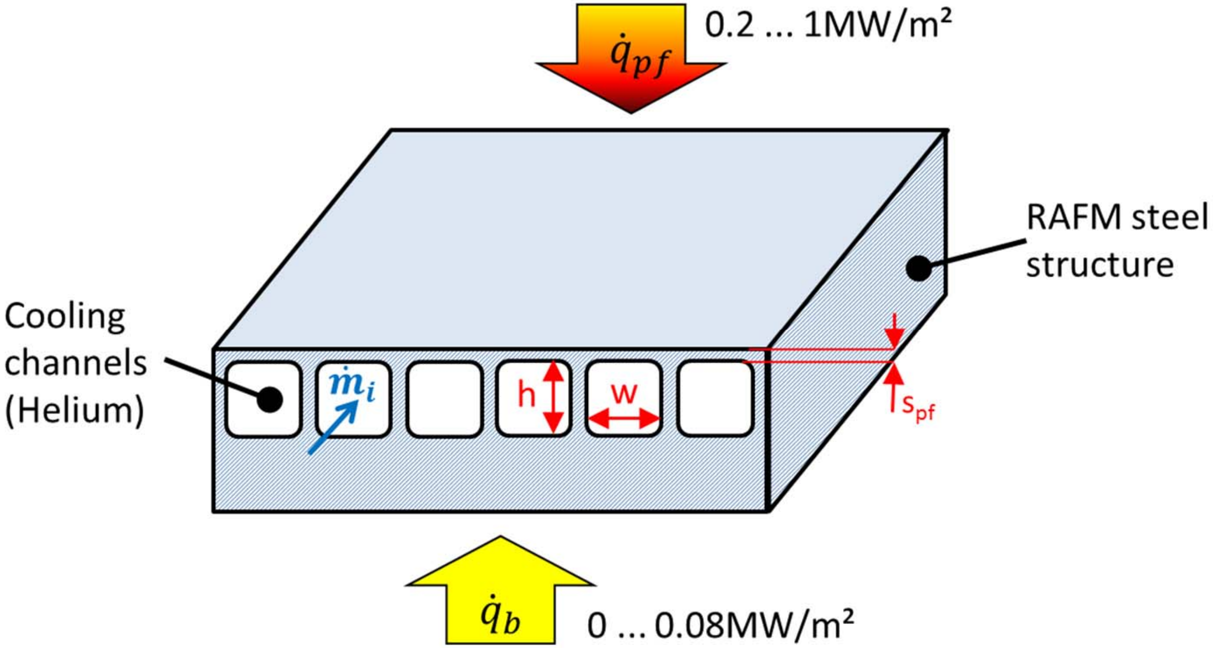
One of the major challenges of the DEMO First Wall (FW) design is to deal with the high heat fluxes from the plasma in the form of radiation and particles:

- Average steady state wall heat flux density from plasma about 0.3MW/m²
- Peak steady state wall heat flux density
  - Depends on FW shape (distance to SOL, angles)
  - Plasma physics conditions such as fraction of radiated power, power-fall-off length λ_q, …
  - **Upper limit definition ongoing**

➔ The objective of the present study is to explore the technical feasibility of an 8MPa-Helium-cooled FW for high heat fluxes in the **1MW/m²** range

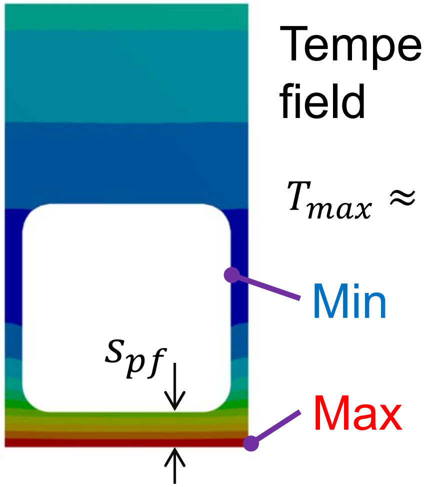
- Investigation and application of heat transfer enhancement methods (Experiments, CFD)
- Thermal-mechanical simulations (FEM)
- Discussion of manufacturing methods

Considered geometry



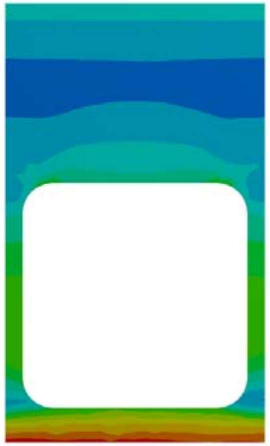
- The considered geometry is based on the classical „integrated FW“ of HCPB / HCLL DEMO blankets
  - Thin wall towards plasma (high heat flux), thick wall towards BZ (low heat flux)
  - „Square“ (w=h) coolant channels (with chamfers)
- Analyses restricted to a single channel
(thermal symmetry, mechanical constraints to maintain flatness)

Typical FW temperature & stress fields



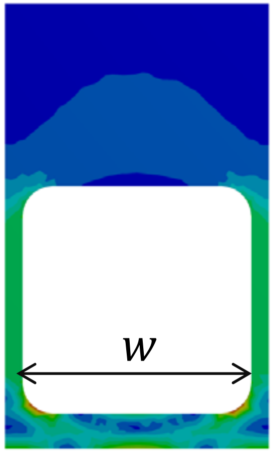
Temperature field

$$T_{max} \approx T_{He} + \underbrace{\dot{q}_{pf}\left(\frac{1}{h_{psc}} + \frac{s_{pf}}{\lambda_{steel}}\right)}_{\Delta T_{max}}$$



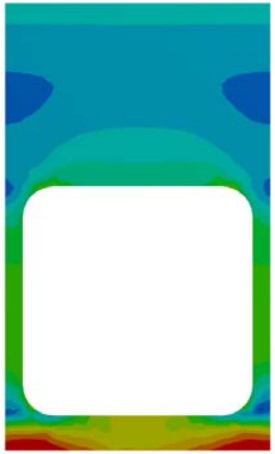
Mises stresses from thermal expansion

$$\sigma_{DT} \propto \Delta T \cdot CTE \cdot E \cdot (1 - \nu)$$



Mises stresses from pressure load

$$\sigma_{pb} \propto p \cdot \frac{\beta \cdot w^2}{s_{pf}^2}$$



Von-Mises stresses from combined thermal & pressure loads

Followed first optimization approaches

- Increasing the plasma-side heat transfer coefficient h_{psc}
  1. Reduces the peak temperature T_{max} / average shell temperature θ_m and thus increases material strength (Yield stress $S_y(\theta_m)$, rupture stress $S_r(\theta_m)$)
  2. Reduces the temperature spread ΔT and thus reduces the stresses from constrained thermal elongation

➔This is achieved by using **structured channel surfaces**, due to much better BoP-economy compared as to increasing the mass flow rate [Arbeiter 2016]

- Adjusting the plasma side wall thickness (steel) s_{pf} to minimize $\sigma_{DT} \propto s_{pf} + \sigma_{pb} \propto 1/s_{pf}^2$

Applied FW design assessment criteria

- Comply with the application temperature range of the structural material Eurofer-97:
  - θ > 330 ... 350°C (tbd.) during irradiation to avoid embrittlement
  - θ < 550°C to maintain strength (Yield stress S_y, Rupture stress S_r)
    For this study: mean temperature over pressure bearing wall $\theta_m \leq 500°C$

- Stress limits
  - Primary stress intensities: $\overline{P_L + P_b} \leq 1.5 \cdot S_m(\theta_m)$
  - Primary+secondary stress intensities: $Max(\overline{P_L + P_b}) + \Delta Q \leq 3 \cdot S_m(\theta_m)$
  - Eurofer-97 $S_m(500°C) = 145\ MPa$

R&D on heat transfer of the He-cooled FW

- **HETRA** FW Heat Transfer Experiment [Ilic et al. 2015]
  - Experiments in the HEBLO loop, 8MPa, up to 250kW/m²
  - Heat transfer in smooth and micro-roughened FW channels
  - Compared to CFD for test of turbulence modelling options

  ➔ Set of experimental data for heat transfer

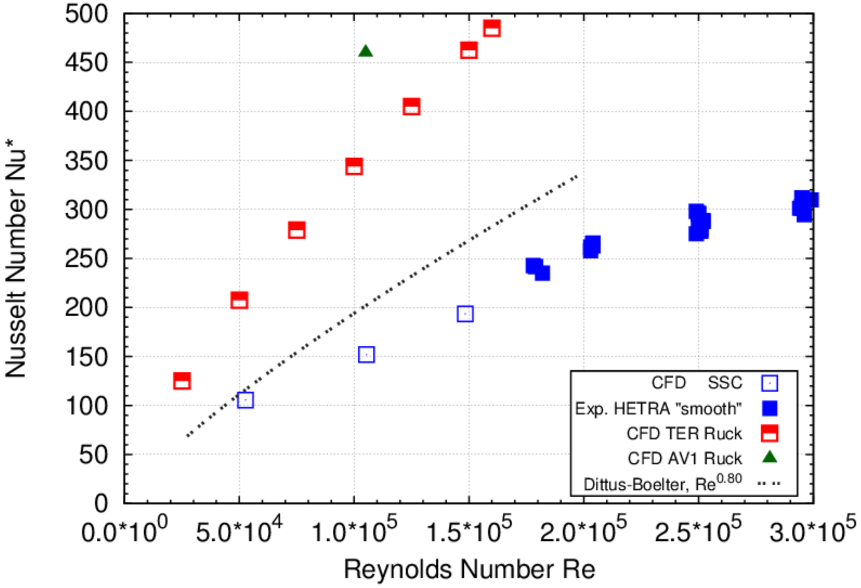
  ➔ Validated CFD method for smooth/micro-rough channels

- **HETREX** FW Heat Transfer *Enhancement* [Ruck et al. 2016, ongoing]
  - Reynolds-scaled experiments with air at 0.4MPa
  - Use of *heat transfer enhancement structures* inside the channels
  - Scale resolving Detached Eddy Simulations
    - With air for validation vs. the experiments
    - With He and high heat flux at FW conditions for engineering

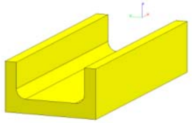
  ➔ Sets of (exp./num.) data for heat transfer and friction, Correlations

  ➔ Validated CFDmethod for *rib-structured* channels

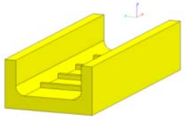
HETRA / HETREX heat transfer data



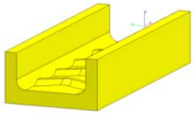
- **CFD SSC** : Smooth channel : data from RANS CFD
- **HETRA** : HETRA experiments He 80bar, w=14.3mm, smooth channel
- **Dittus-Boelter** : Correlation $Nu_{DB} = 0.023\, Pr^{0.4}\, Re^{0.8}$



- **CFD TER** : Transversal edged ribs : data from DDES CFD, validated against HETREX experiments



- **CFD AV1** : V-shaped ribs, upstream pointing, data from DDES CFD



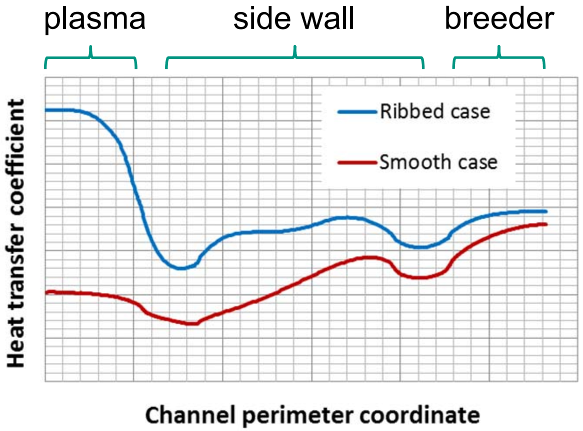
- Transversal edged ribs (TER) increase heat transfer by ~ factor 2 vs. smooth
- V-ribs offer even higher heat transfer gain (but not yet fully investigated)

➔ Transversal edged ribs are used for the current study for high heat fluxes

Remark: The Dittus-Boelter correlation overestimates heat transfer for the smooth FW channels

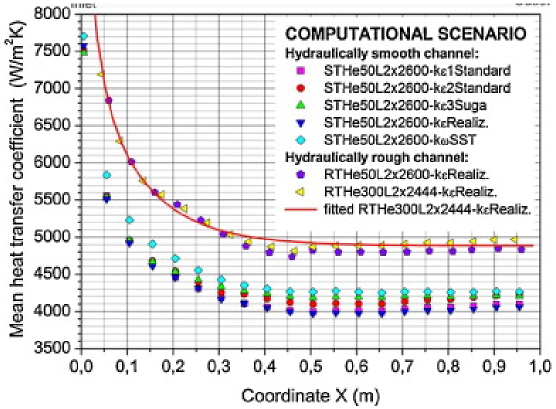
FW heat transfer coefficient spatial distribution

- Plasma-side and BZ-side heat transfer coefficients are not the same:
  - For smooth surfaces: $h_{psc} < h_{bsc}$
  - For structures on the plasma side : $h_{psc} > h_{bsc}$



Circumferential heat transfer coefficient profile

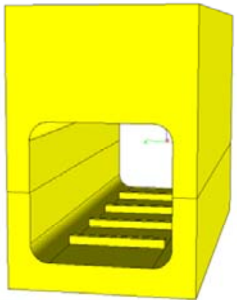
- The heat transfer coefficient is large after the inlet bend
  - For smooth surfaces: decreases asymptotically
  - For structured surfaces: can be taylored to smoothen the temperature field



Axial heat transfer coefficient profile along FW channel [Ilic 2015]

1MW/m² design point study with TER ribs

- Highlighted case: $w = 12.5mm, s_{pf} = 2.1mm$
  - Helium mass flow 60g/s to reach $\theta_m < 500°C$ and $\theta_{max} < 550\ °C$
  - Pumping power: 2.9% of collected thermal heat, $520\ mbar/m$

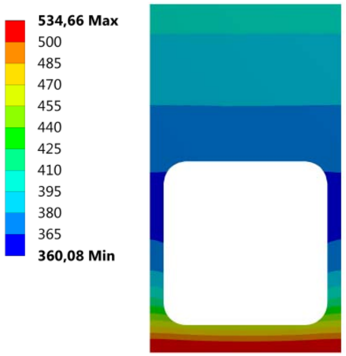


Transversal Edged Ribs

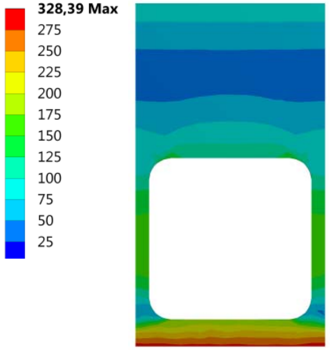
$Max(\overline{P_L + P_b})$	$Max(\overline{P_L + P_b}) + \Delta Q$	θ_m
$72\ MPa$ $< 1.5\ S_m$	$393\ MPa$ $< 3\ S_m$	$493\ °C$ $< 500\ °C_m$

$1.5S_m(500°C) = 231\ MPa$

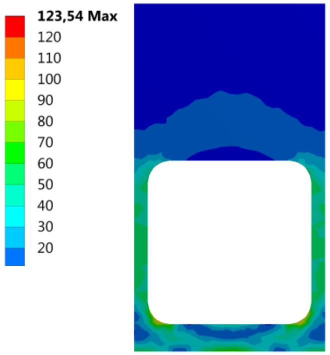
$3\ S_m(500°C) = 435\ MPa$



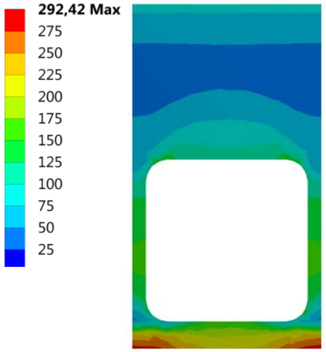
Temperature field



Stresses from thermal loads



Stresses from pressure loads



Stresses from combined loads

➔ Solutions for 1MW/m² can be demonstrated by thermal-mechanical analyses

Manufacturing methods

(1) FW is fabricated from two half-shells + HIP
➔ The channels and surface-attached structures can be conventionally machined with moderate extra effort.

(2) FW fabricated from solid piece by wire-cut EDM

(a) The structures can be added by a die-sink operation - comparatively high cost

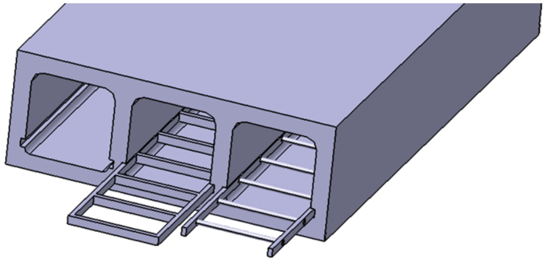
(b) Detached rib geometries can be *very economically* generated by inserting „ladder-like“ structures into side groves

(3) FW fabricated by generative methods (SLS etc.)
➔ Fabrication of surface structures is easily facilitated with low extra effort. Generative methods are under development

➔ Viable fabrication technologies for structured channels were demonstrated.

Conventionally machined half-channel

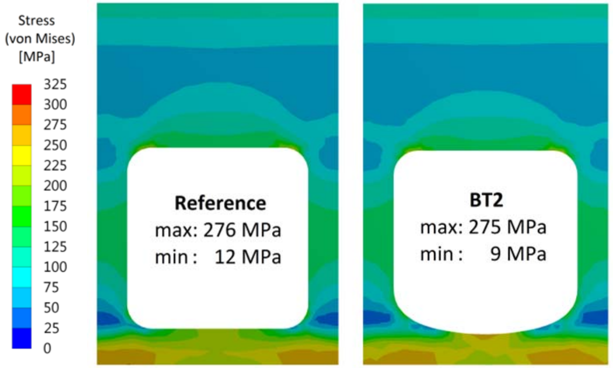
EDM fabricated test piece



CAD concept of „ladder-like“ ribs

Is internal channel cross section shaping useful?

A biomimetically inspired „branch/root"-type arch-shape has been investigated with the aim to better balance the stress distribution.



Mises stresses for combined thermal (0.75MW/m²) and pressure (8MPa) loads.

Case	$s_{pf\,,min}$	$\overline{P_L + P_b}$	ΔQ	θ_m
Reference	3 mm	58 MPa	288 MPa	511°C
"BT2"	2.5 mm	52 MPa	286 MPa	512°C

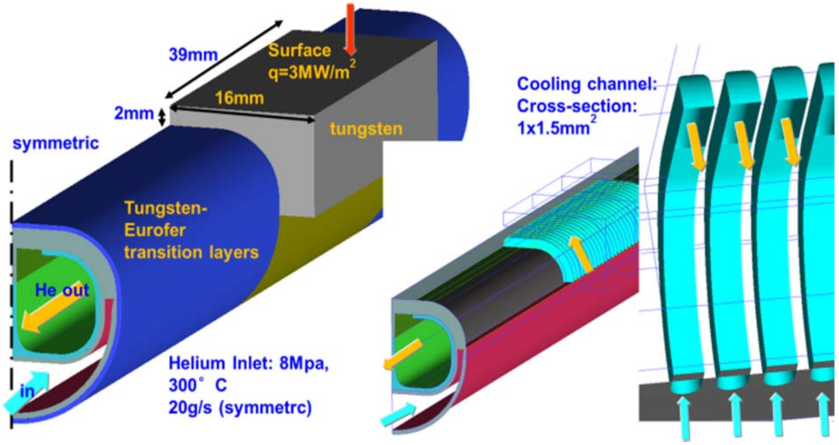
w=15mm, TER-type heat transfer enhancement over full width

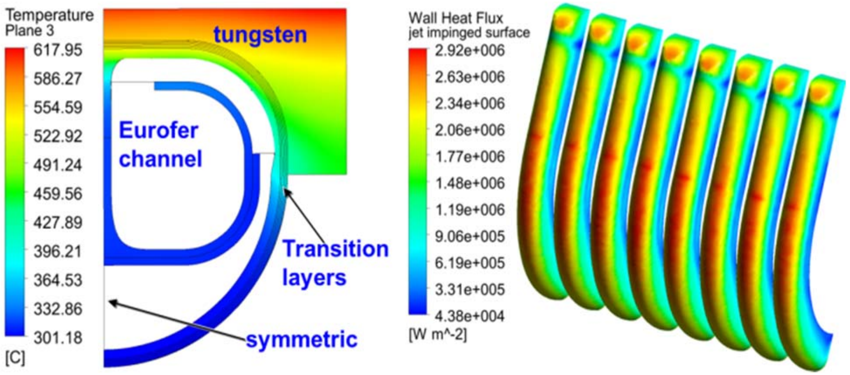
- Primary stresses can be reduced (with less total steel in the arch)
- But: only in conjunction with heat transfer enhancement also near the edges a beneficial effect for combined primary+secondary stresses is obtained

➔ May be beneficial for lifetime improvements of FW components at elevated coolant pressures and moderate heat flux densities

Options for *very* high heat fluxes (~3MW/m²)

Locally (especially near the upper/lower x-points), very high heat fluxes may occur. He-cooled solutions for such extreme cases are also investigated [Ghidersa, Chen]





- „Concentric“ feed/return channels, short parallel minichannels (1x1.5mm²)
- Tungsten blocks / interlayer / Eurofer heat sink
- Eurofer maximum temperature 539°C obtained for 3MW/m² (40g/s, 23.4kW/m²/K, 0.88bar)

➔ Solutions for very high heat fluxes are already emerging

Summary and conclusions:

- Heat transfer enhancement methods were investigated by CFD and experiments and applied to a He-cooled FW channel design
- FEM thermal-mechanical analyses of a FW patch show tolerable temperatures and stresses for a load of 1MW/m² for tolerable pumping power
- Fabrication methods of structured channels compatible with up-to-date FW manufacturing strategies were demonstrated (prototypes and test sections)

Outlook:

- Further investigation of heat transfer enhancement methods
  - Even higher heat transfers / lower pumpuing power
  - Locally optimized heat transfer (chamfers, axial homogenization)
- Application to more complex blanket / FW models
- Test of a high heat flux FW test section in HELOKA/KATHELO He-loop

Contributors and references

- KIT-INR Thermal&mechanical: Sebastian Ruck, Florian Schwab, Christine Klein, Yuming Chen, Bradut-Eugen Ghidersa
- KIT-INR Manufacturing: Heiko Neuberger, Axel von der Weth, Jörg Rey
- EUROFUSION, close collaboration: Ronald Wenninger, Christian Bachman, Tom Barrett

[Ilic 2015] M. Ilić, et al., Experimental and numerical investigations of heat transfer in the first wall of Helium-Cooled-Pebble-Bed Test Blanket Module—Part 2: Presentation of results, Fusion Engineering and Design, 2015

[Ruck 2016] S. Ruck et al., Effects of Rib-Configuration on the Thermal Performance of One-Sided Heated, Rib-Roughened Cooling Channels, Int. Conf. on Heat Transfer, Fluid Mechanics and Thermodynamics, 2016 (See also Poster P3.116, Wednesday 11:00)

[Arbeiter 2016] F. Arbeiter et al. , Thermal-hydraulics of helium cooled First Wall channels and scoping investigations on performance improvement by application of ribs and mixing devices, Fusion Engineering and Design, 2016

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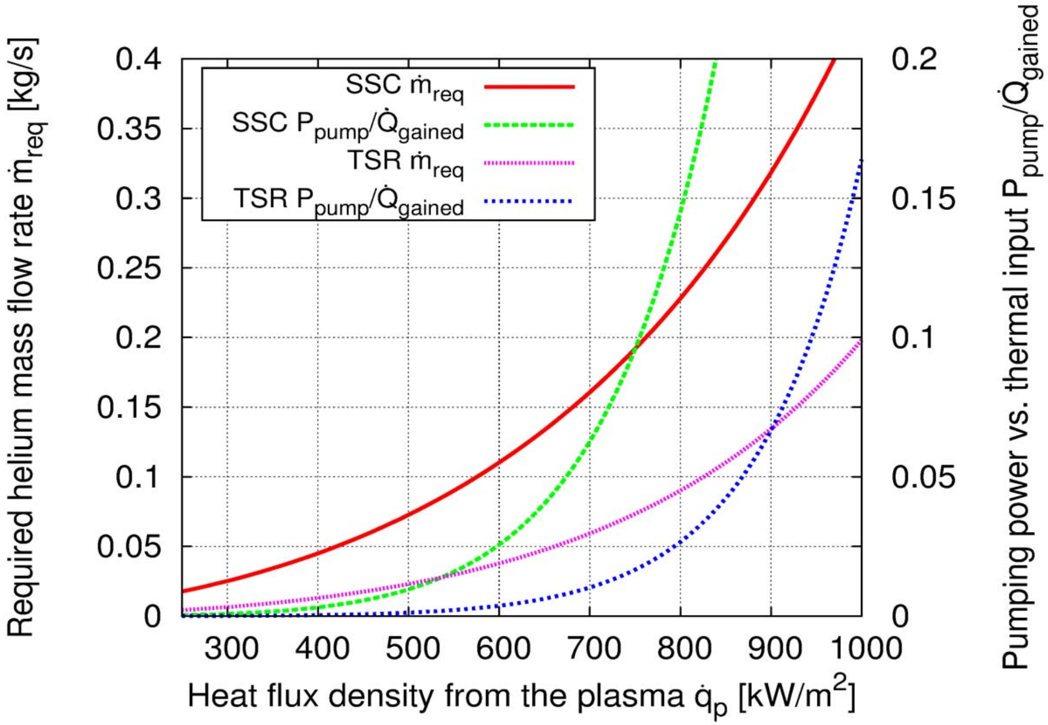
Pumping power

The graph shows mass flow and pumping power rate required to keep the maximum steel temperature of a ***3mm Eurofer*** *FW below* ***550°C****, dependent on the heat flux density from the plasma*



[Arbeiter et al. 2016]

➔At the same mass flow rate, the structured channels create higher pressure drop, but for the same cooling effect, **structured channels require less pumping power!**