Karlsruher Institut für Technologie

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Challenges and Contributions of Numerical Studies of Helium cooled First Wall Channels of DEMO

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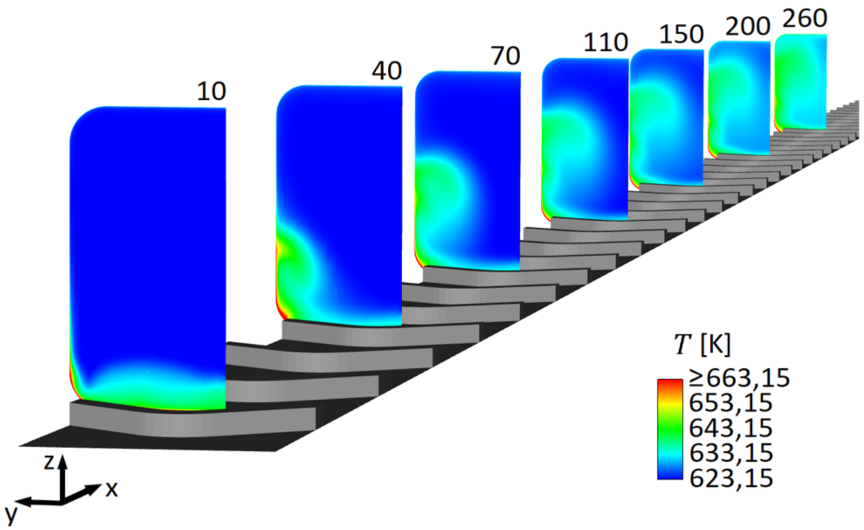
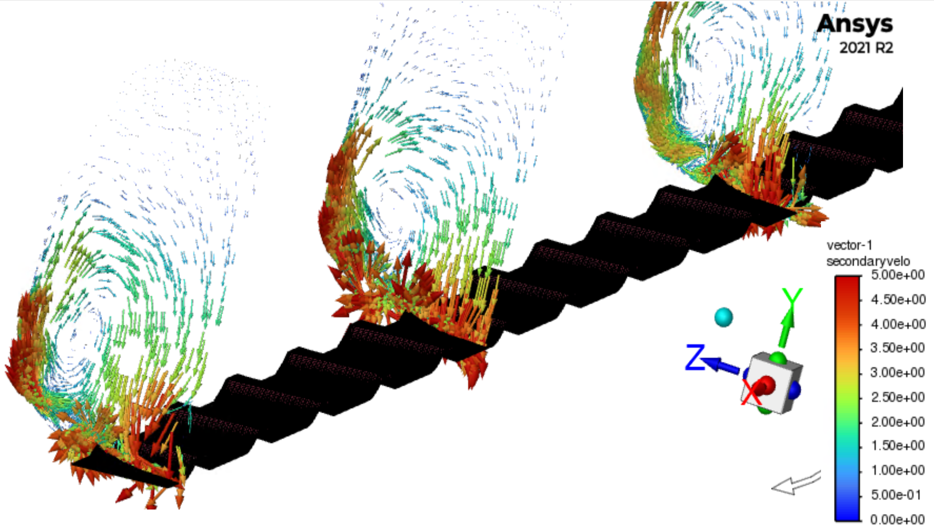
Institute for Neutron physics and Reactor technology, Measurements and Experimental Techniques group (INR-MET)





Long Term Objectives of Numerical Simulations of Helium cooled First Wall Channels of DEMO

- to provide a consistent, fully **validated** and **practically feasible** (in terms of computing cost) **numerical approach** to provide simulations of rib enhanced geometries **FW channels/ full-size blanket component**
- **predict the temperature fields** inside the FW/ blanket component as basis for **thermal-mechanical requirements**
- **provide engineering correlations (for pressure drop**, fluid **outlet temperatures etc.**) i.e. as input for **Balance of plant (BOP)**
- for the **design of thermo hydraulic experiments** to validate numerical codes (determination of suitable measuring positions for sensors, measuring ranges, etc.)
- contribute to **design, build, evaluate, operate, optimize and test demonstrators or Mock ups**

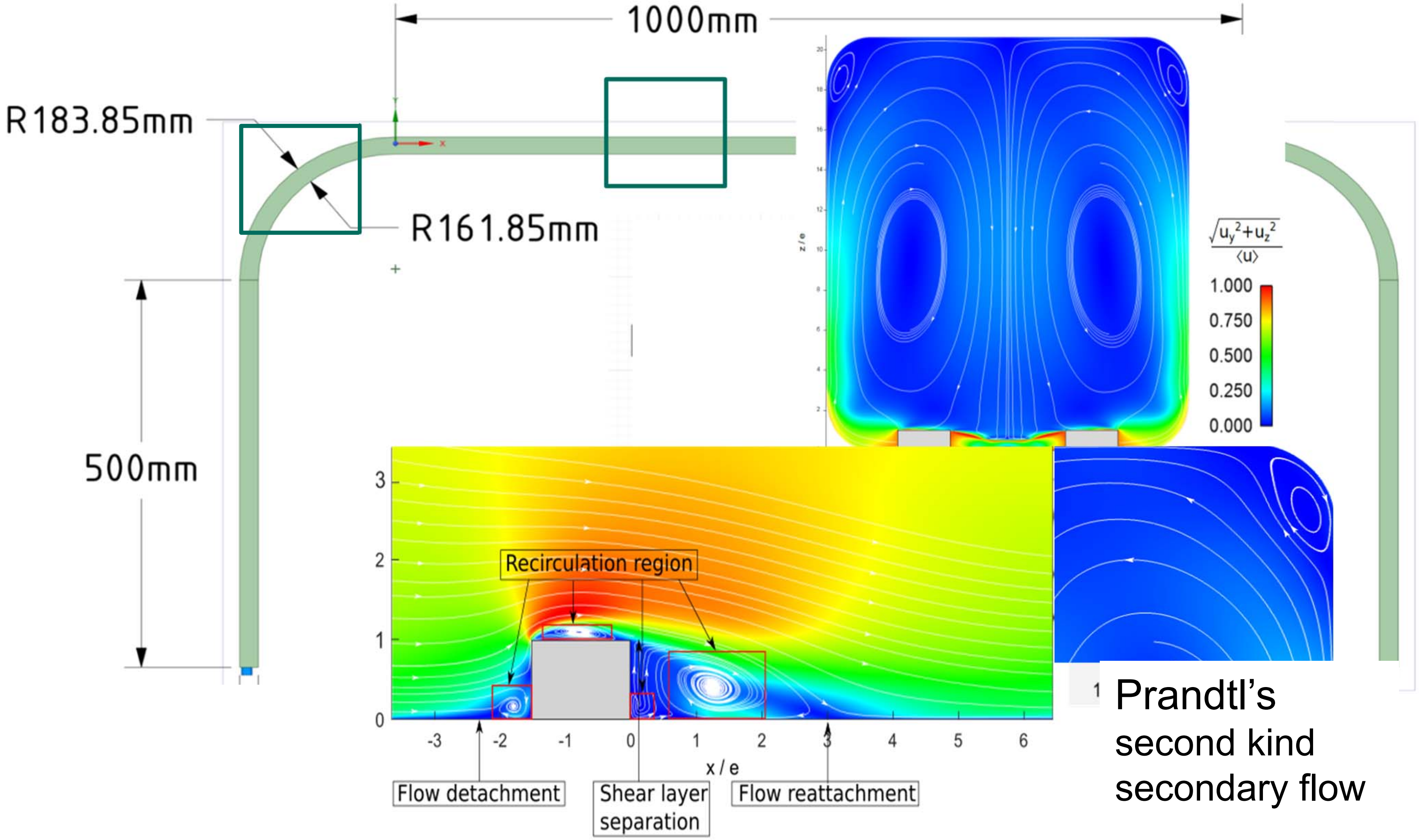
Long Term Objectives of Numerical Simulations of Helium cooled First Wall Channels of DEMO

- To contribute to **high-pressure helium cooling (8 MPa) technology**, which can meet current
- **Heat load specifications for EU-DEMO blanket (Maviglia, F., 2020)**

  - Inboard blanket: the **radiation heat flux** on FW is typically in the range of **0.15 – 0.27 MW/m²**

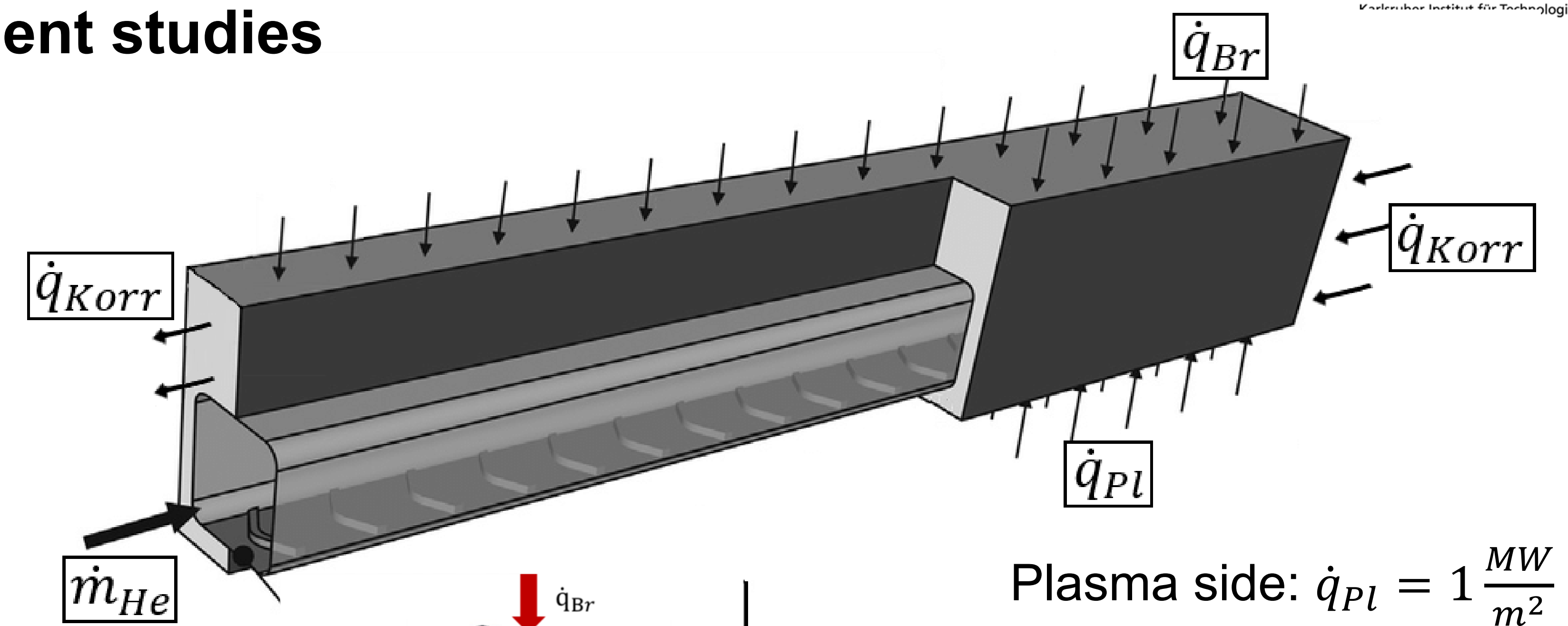
  - Outboard blankets: **radiation heat flux** on FW is typically in the range of **0.23 – 0.31 MW/m²**, with the additional power introduced locally by **charged particles** on the wall being estimated at up to **0.42 MW/m²** , so that approx. **0.73 MW/m²** can occur
- The definition of the **peak values** is ongoing and depends on the chosen - **shape of the first wall, the magnetic configuration** and the assumptions about the **fraction of the radiated** power and the **power decay lengths in the scrape-off layer (SOL)** of the plasma, but higher short-term transient loads are possible

Challenge: Geometry, to capture small and "large scale" flow features

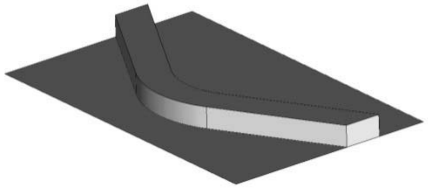


Prandtl's second kind secondary flow

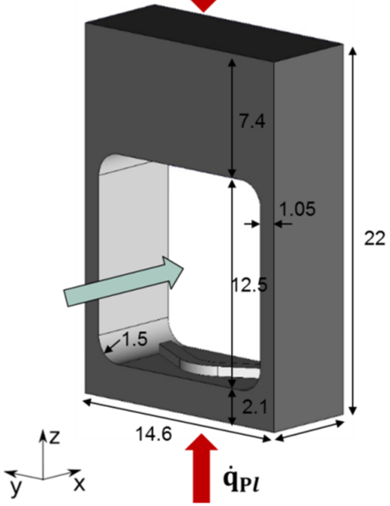
Channel geometry and boundary conditions present studies



$\boldsymbol{p/e = 10}$



$\mathbf{e = 0.2, 0.4, 0.6, 0, 9}$



Plasma side: $\dot{q}_{Pl} = 1\frac{MW}{m^2}$

Breeder side: $\dot{q}_{Br} = 80\frac{kW}{m^2}$

$$\dot{q}_{Korr} = 1612{,}9\frac{W}{m^2}$$

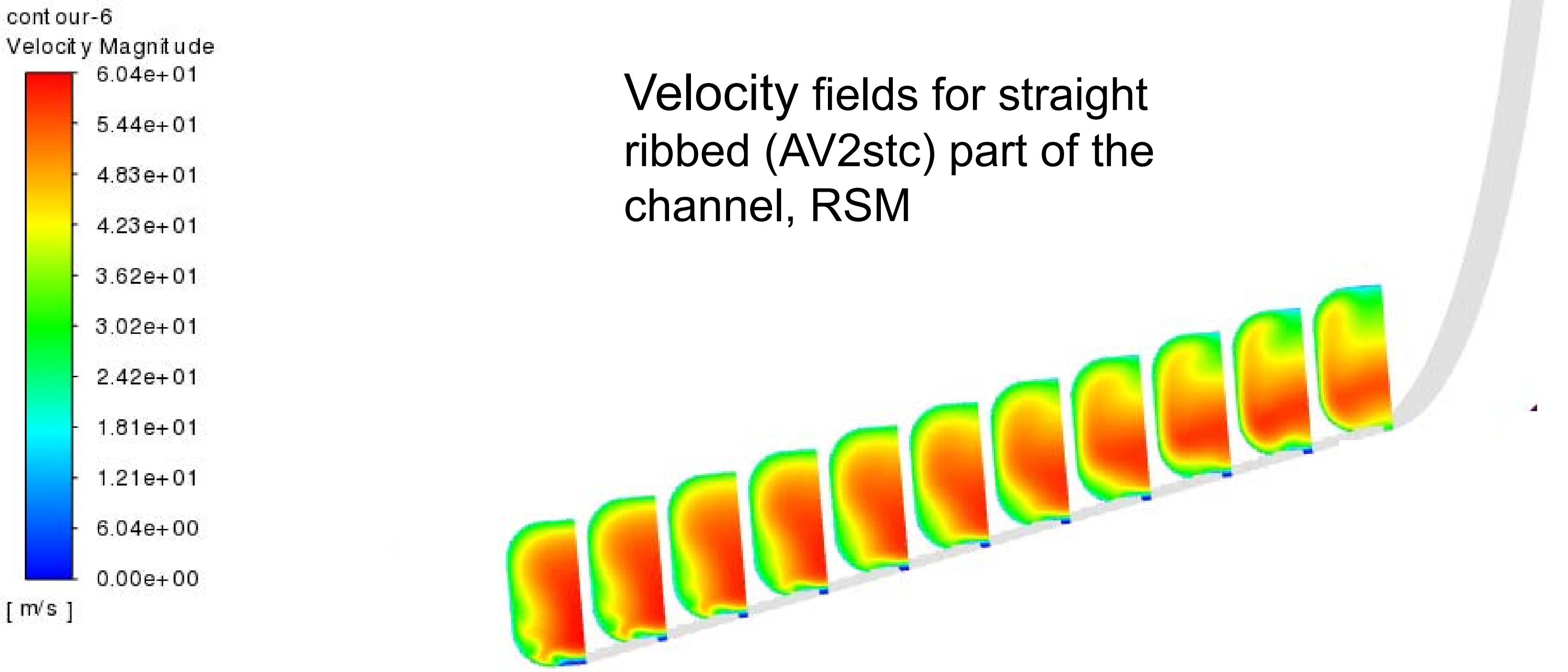
$$\dot{m} = 60\ g/s$$

$$p = 8\ MPa$$

$$T = 623.15\ K$$

Challenge: Geometry FW Cooling Channels, long entrance length

- **hydraulic boundary layer and secondary flow development needs** to be captured along channel > resulting in high mesh count

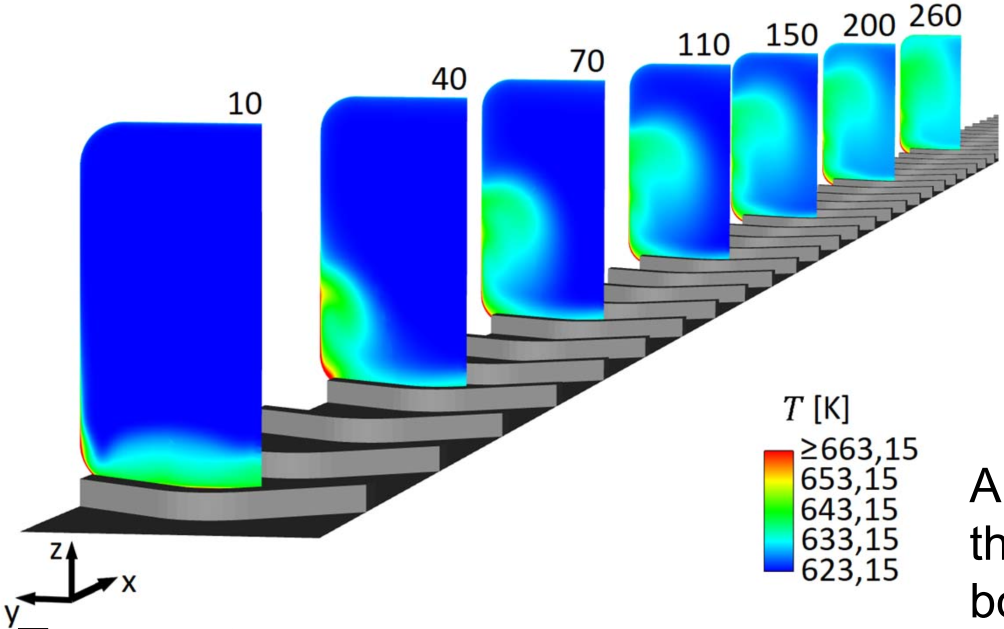


Velocity fields for straight ribbed (AV2stc) part of the channel, RSM

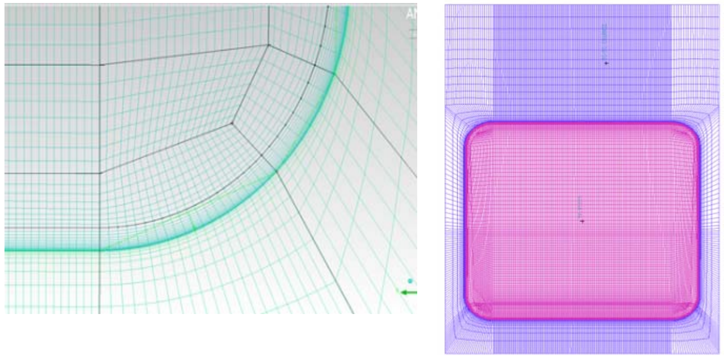
- **Entrance length FW channel** $l_h \sim 38\, d_h$

Challenge: Geometry of Complete Rib enhanced FW Cooling Channels/ full-size Blanket/FW Components

- **thermal boundary layer development needs** to be captured along channel > resulting in high mesh count



Temperature field for the straight part of the channel with 0.9 mm V ribs, RSM

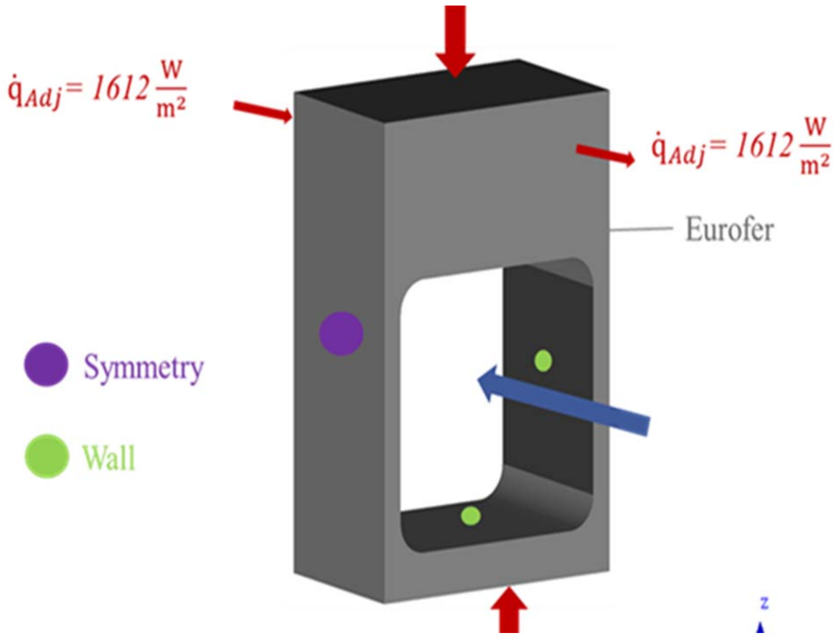


$$y(y^+ = 1) = 1{,}8815 \cdot 10^{-6} m$$

A high-resolution mesh in the vicinity of the wall (i.e. y+ ~ 1) to fully resolve the boundary layer requires > **10 Mill. Hexaeder cells** for 9 mm **one rib channel section**

Challenge: high heat flux > high spatial temperatures and material properties gradients

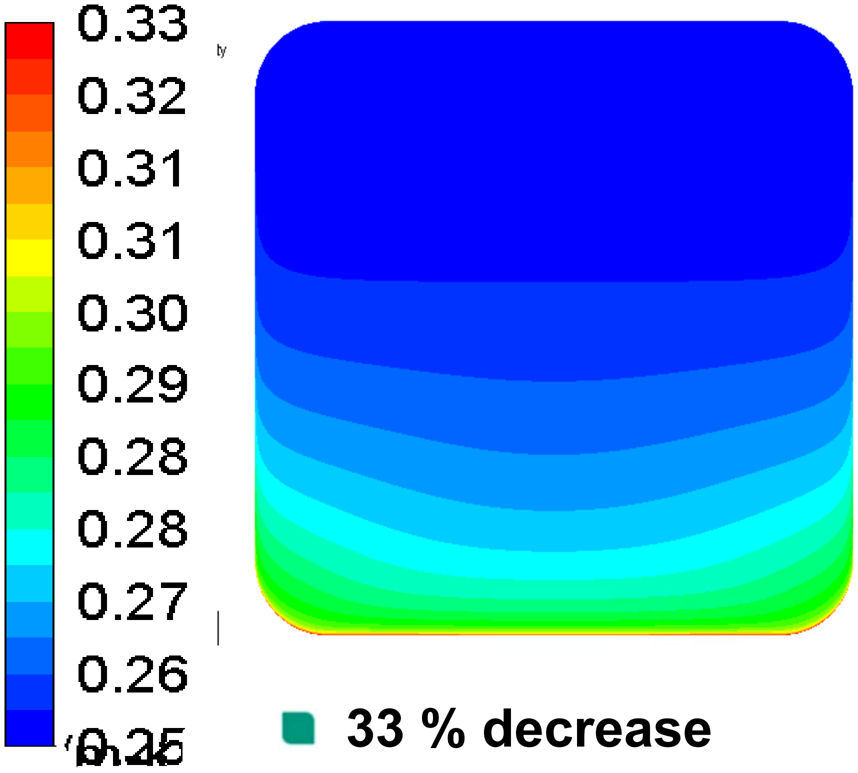
$$\dot{q}_{Br} = 80\,\frac{kW}{m^2}$$



$$\dot{q}_{Pl} = 1\,\frac{MW}{m^2}$$

k-omega SST, flat channel.
periodic boundary condition

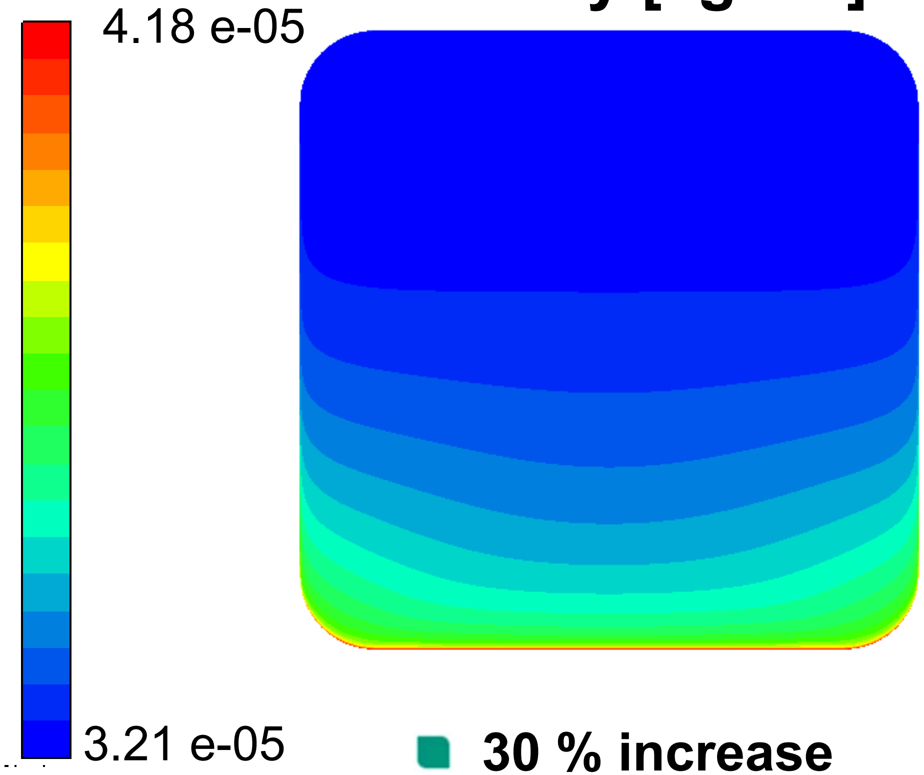
Thermal conductivity [W/mK]



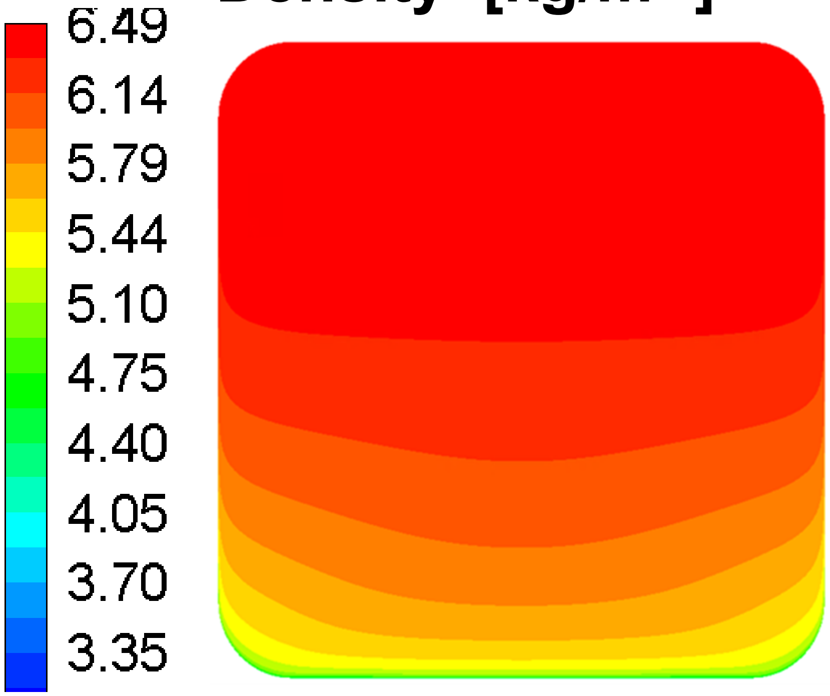
🟩 **33 % decrease**

Challenge: high heat flux > high spatial temperatures and material properties gradients

Viscosity [kg/ms]



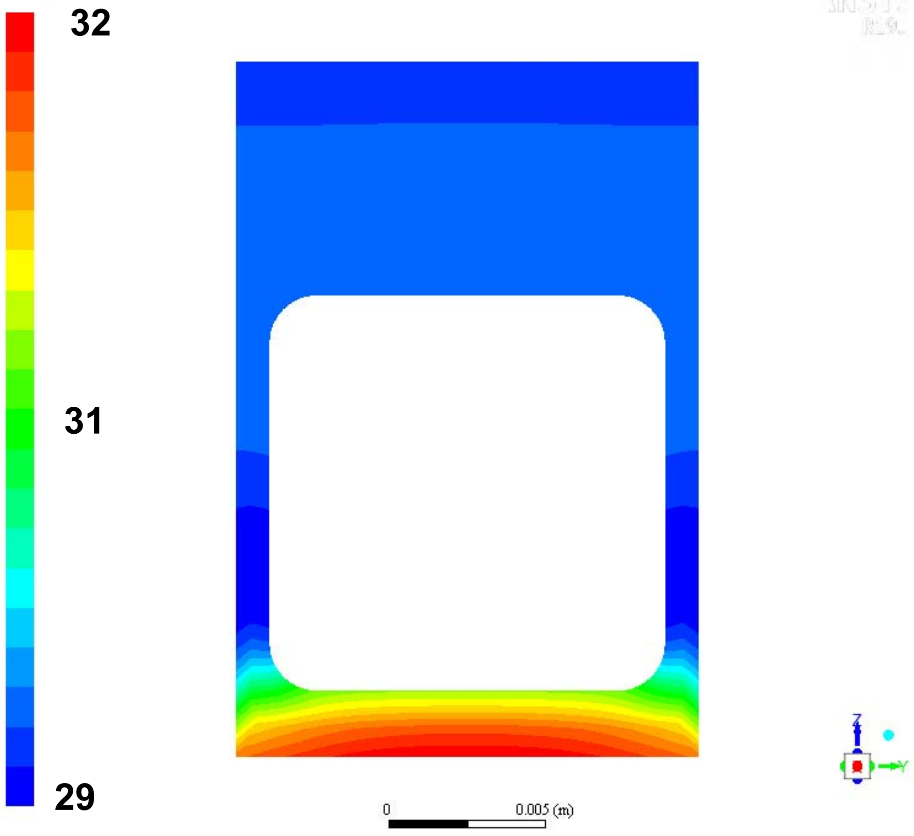
Density [kg/m^3]



- **30 % increase**
- **54 % decrease**

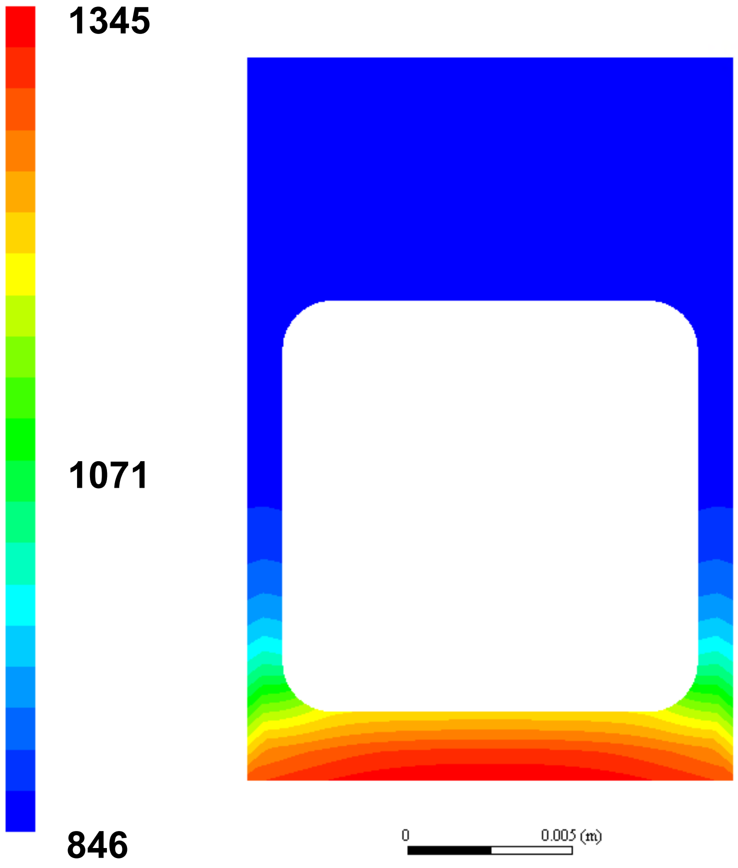
Challenge: High heat flux > high temperatures and material properties gradients

Thermal conductivity [W/mK]



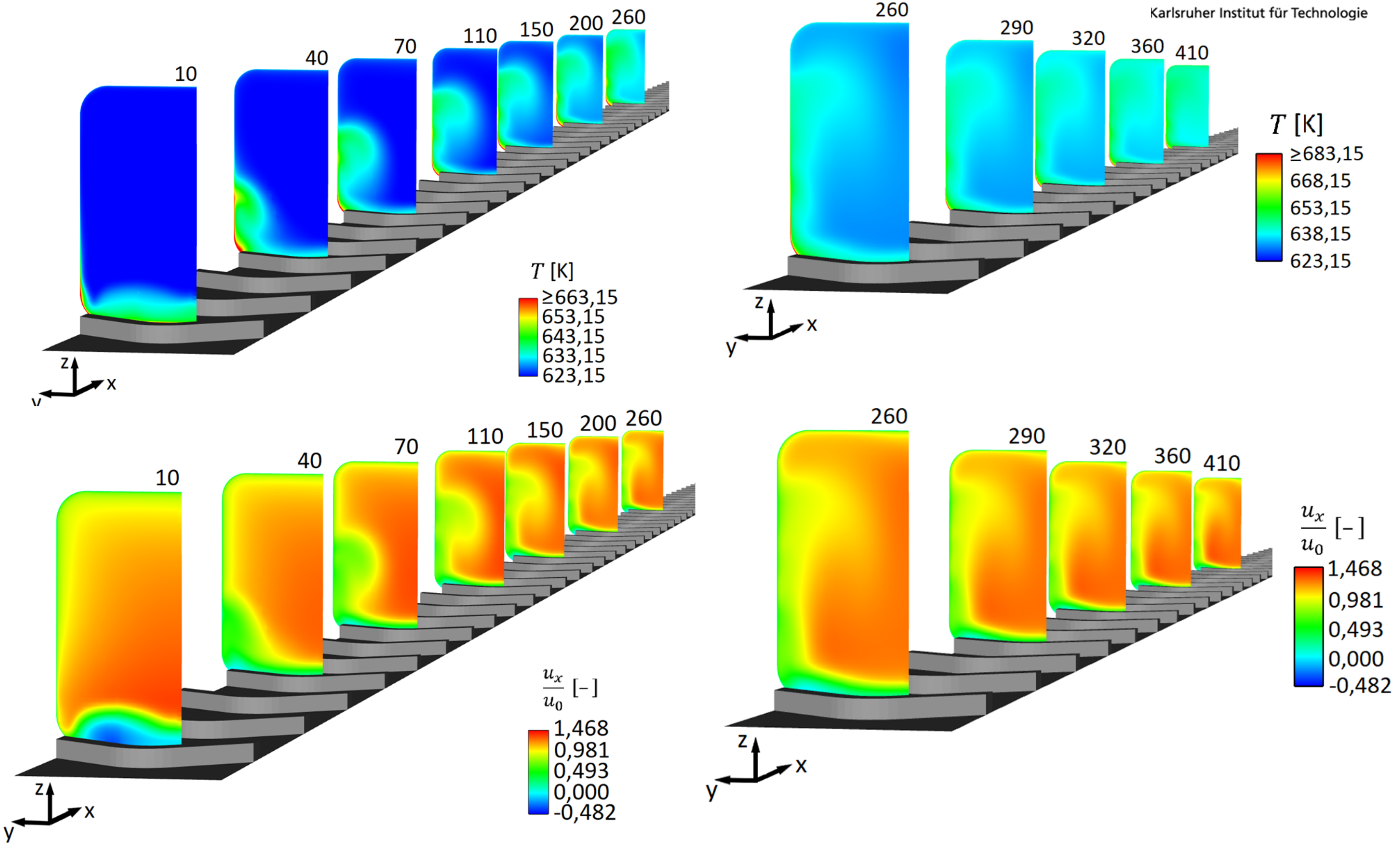
- 10 % decrease

Specific heat capacity cp [J/(kg·K)]



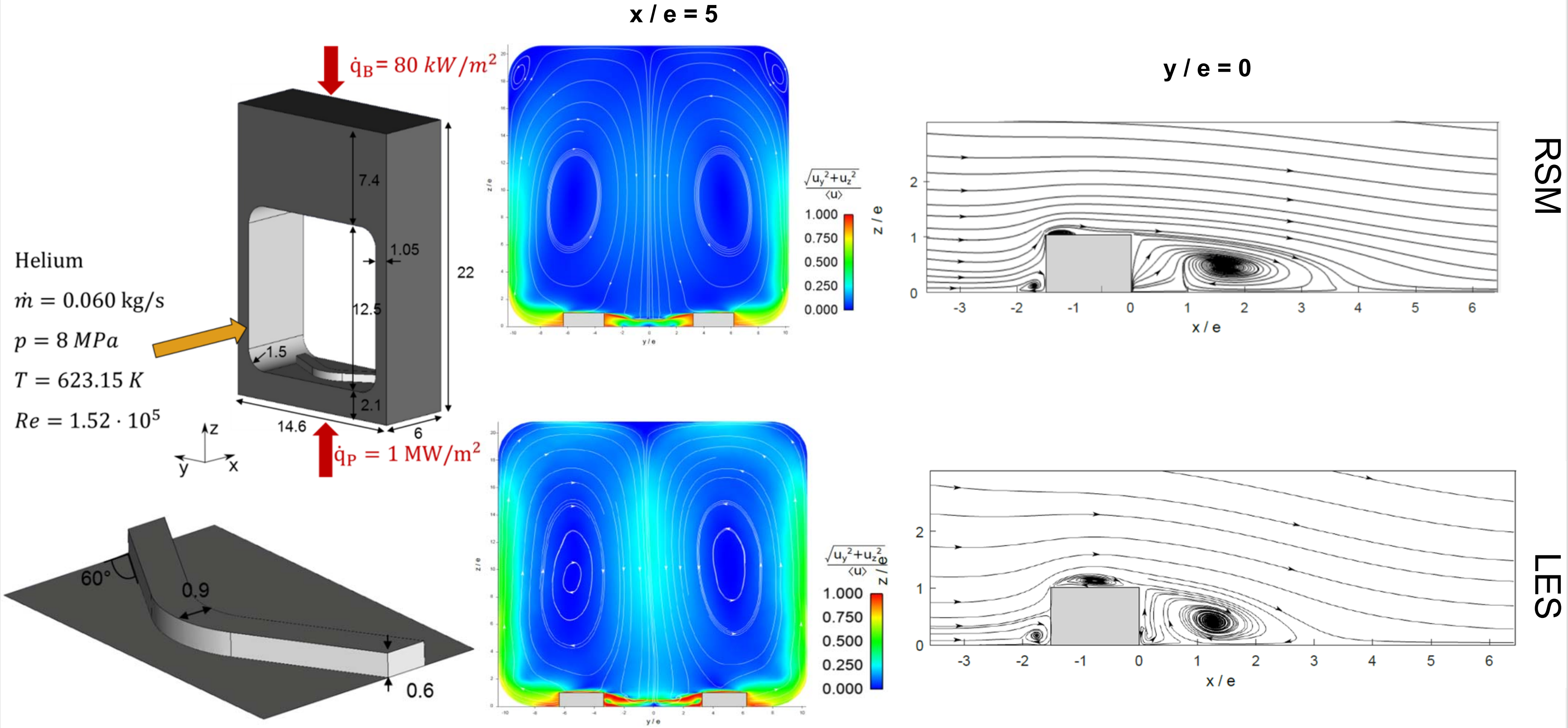
- 58 % increase

RSM (Reynolds stress equation model)



- **Can calculate complete FW Channel**

RSM in **comparison** with **LES** (Large Eddy Simulation) ribbed Channel sections



Helium

$\dot{m} = 0.060$ kg/s

$p = 8\ MPa$

$T = 623.15\ K$

$Re = 1.52 \cdot 10^5$

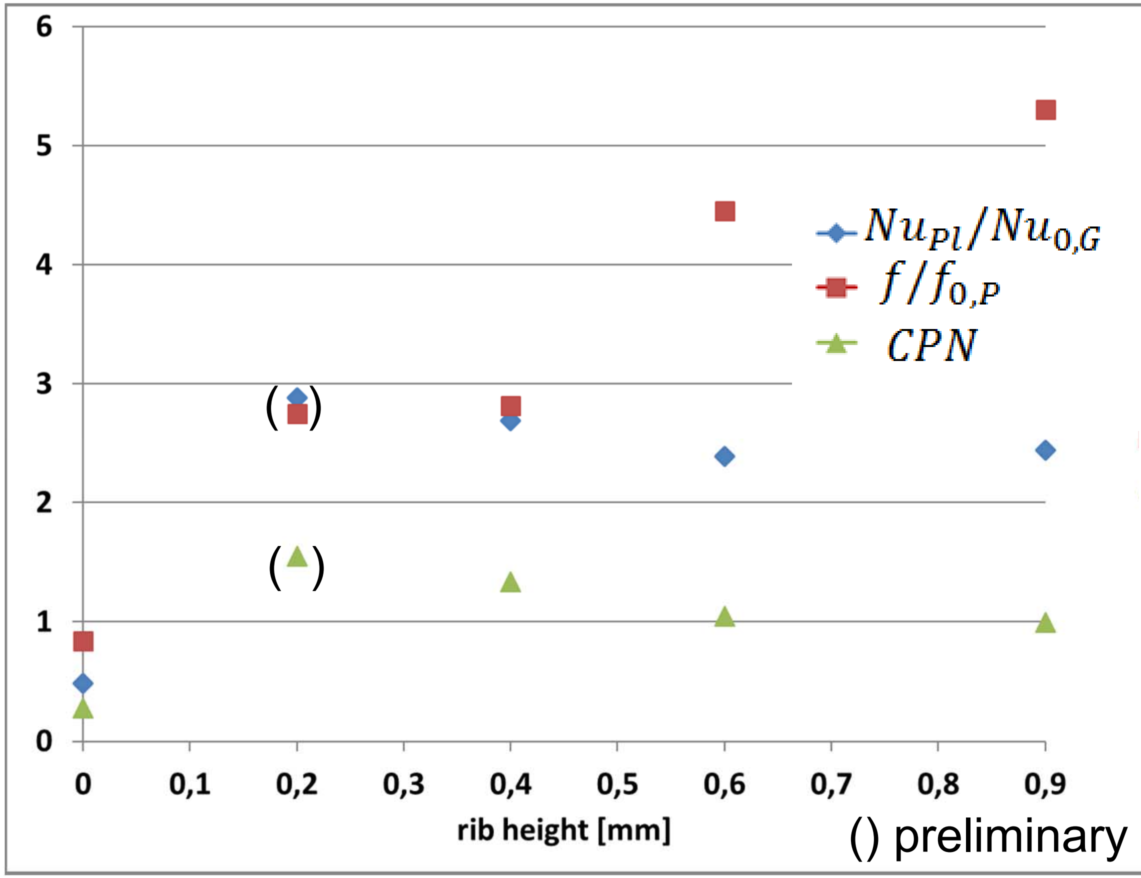
- **RSM redicts friction factor and flow features (flow separation, reattachment, small flow details etc.)**

RSM in comparison with LES

	e = 0.4 mm		e = 0.6 mm		e = 0.9 mm	
	RSM	LES	RSM	LES	RSM	LES
$\overline{Nu_P}/Nu_0$	2.42 / 9.7%	2.69	1.957 / 18.09%	2.389	1.907 / 16 %	2.27
f_D/f_0	3.74/ 32.6%	2.82	4.43 / 0.476%	4.45	5.33/ 5%	5.63
CPN	1.13/ 26%	1.34	0.827 / 20.85%	1.045	1.13 / 16 %	1.34

- **Underestimates heat transfer and overestimates component temperatures**

LES for different rib heights



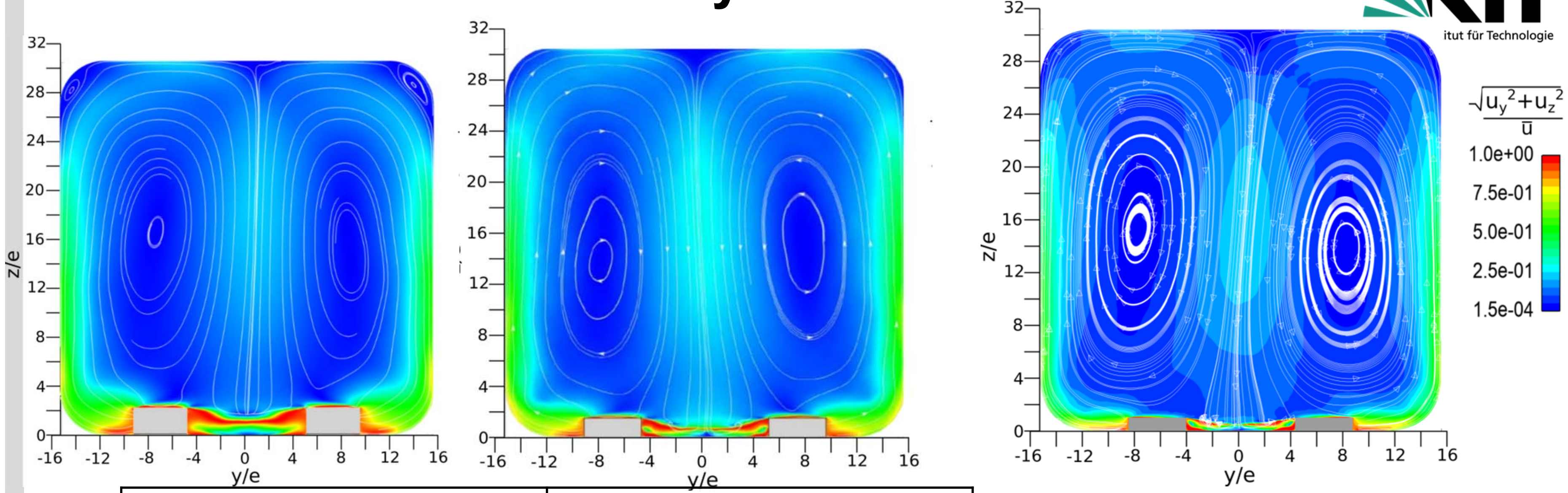
Variation of thermal-hydraulic parameters (Heat transfer: Nu_m/Nu_0; pressure drop: f/f_0) as effect of the rib height
Nu_0 = 238
Gnielinski (1976)
f_0 = 0,016
Petukhov (1970)

$$CPN = \frac{37{,}07 \cdot Nu^{1{,}18}}{Re \cdot f^{1/3}}$$

Ruck und Arbeiter (2018)
Cooling Performance numer

- Impact of **rib height** on **heat transfer** and **pressure drop: increasing friction factor for higher ribs, but heat transfer for smaller ribs**

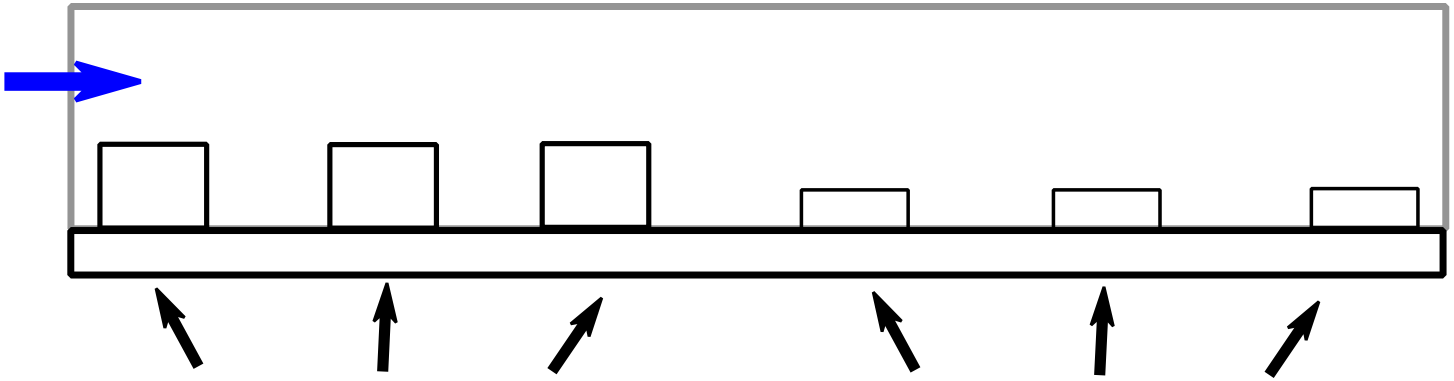
LES Results for Secondary flow



e	$\frac{1}{V}\int\sqrt{u^2{}_y+u^2{}_z}\,dV$
0.4 mm	8.55 m/s
0.6 mm	8.6 m/s
0.9 mm	8.63 m/s

- Impact of **rib height** on **heat transfer** and **pressure drop**
- **Secondary flow**

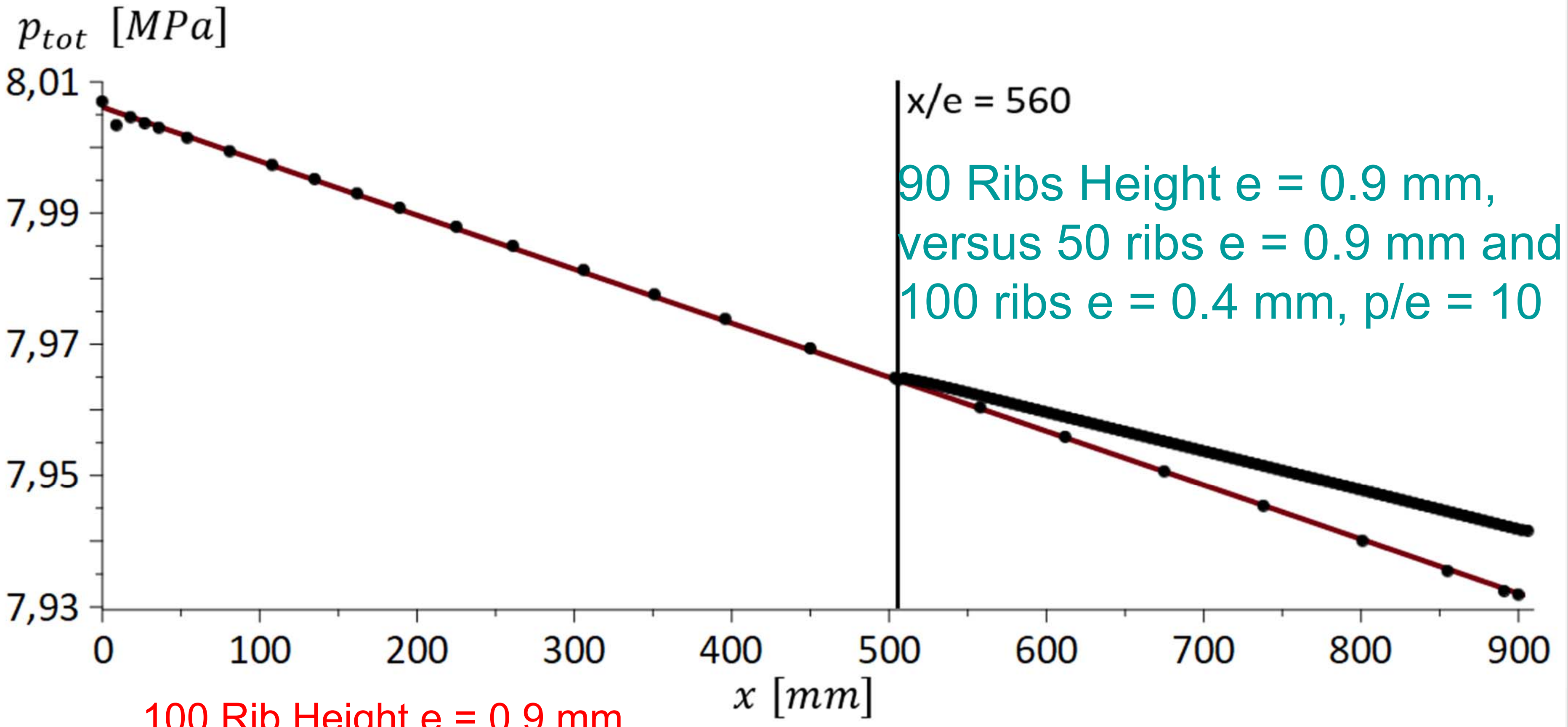
- Impact of **rib height** on **heat transfer** and **pressure drop**
- These finding opens up the opportunity **to decrease the rib height in case of fully developed secondary flow** and using **RSM** to check for complete channel



Higher ribs to induce strong secondary flows

100 Ribs Height e = 0.9 mm,
versus 50 ribs e = 0.9 mm and
100 ribs e = 0.4 mm
p/e = 10

Possibilities RSM: Evolution impact of Rib Secondary Flow along complete channel



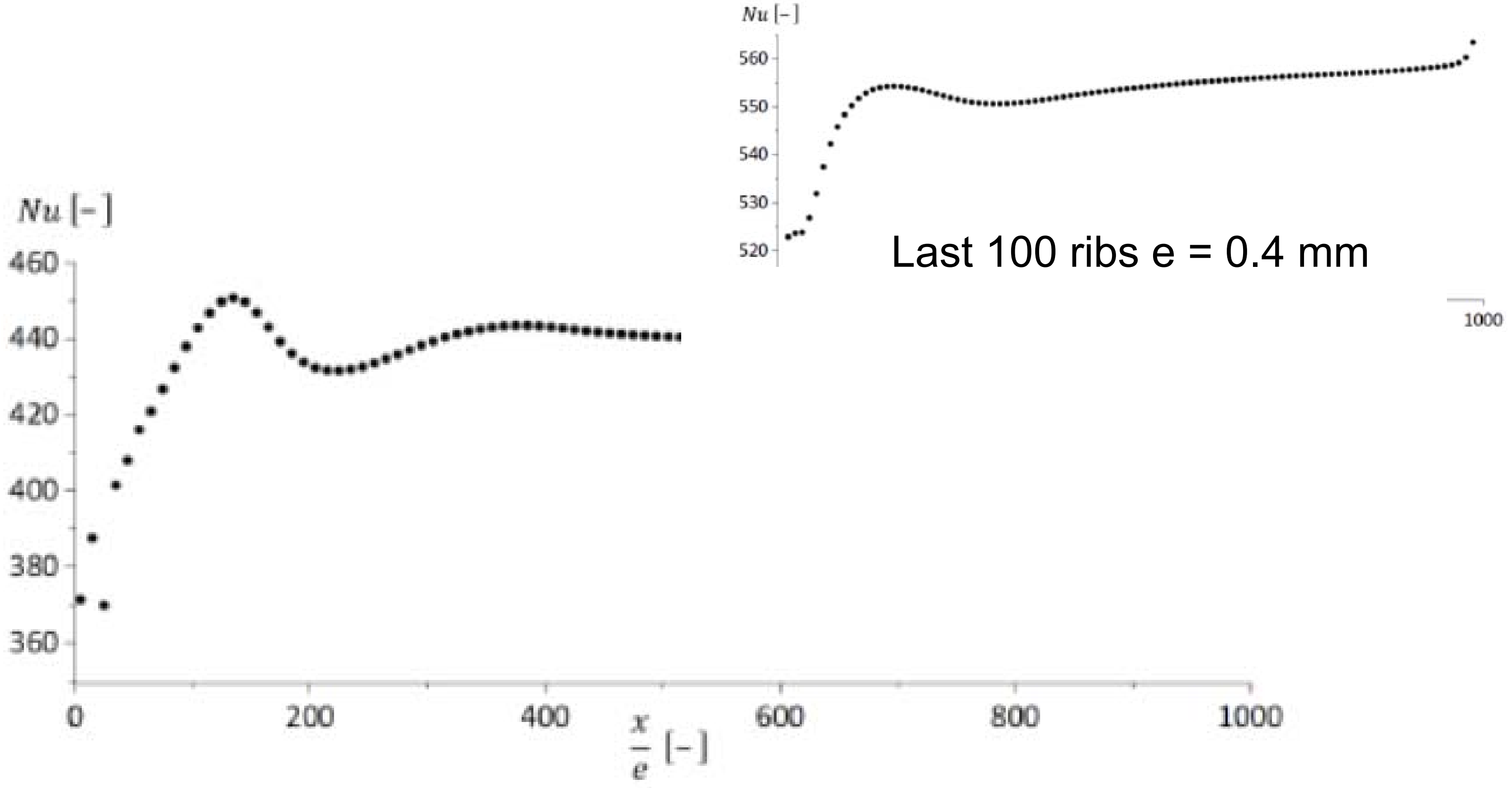
90 Ribs Height e = 0.9 mm, versus 50 ribs e = 0.9 mm and 100 ribs e = 0.4 mm, p/e = 10

100 Rib Height e = 0.9 mm

Last 100 ribs e = 0.4 mm

- **~45% lower pressure gradient** and **pressure drop**

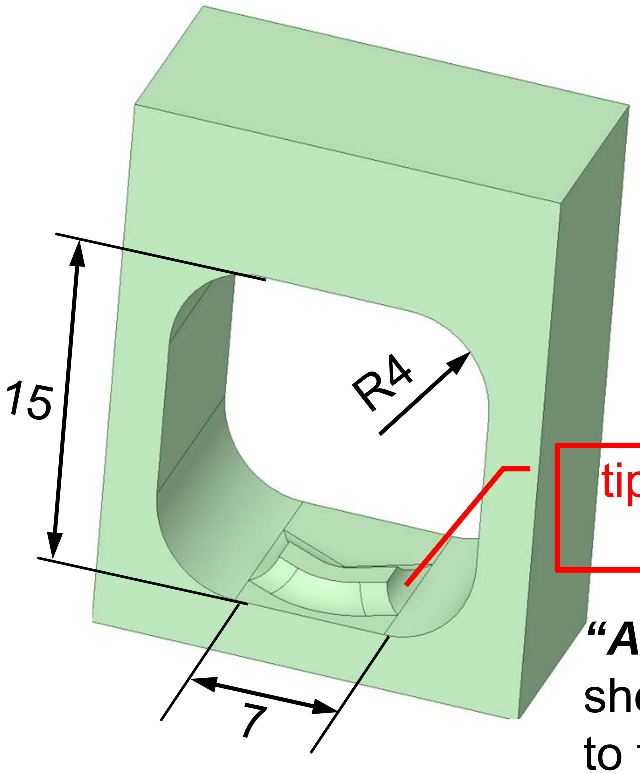
Possibilities RSM: Evolution impact of Rib Secondary Flow along complete channel



Last 100 ribs e = 0.4 mm

- **lower pressure drop and higher heat transfer**

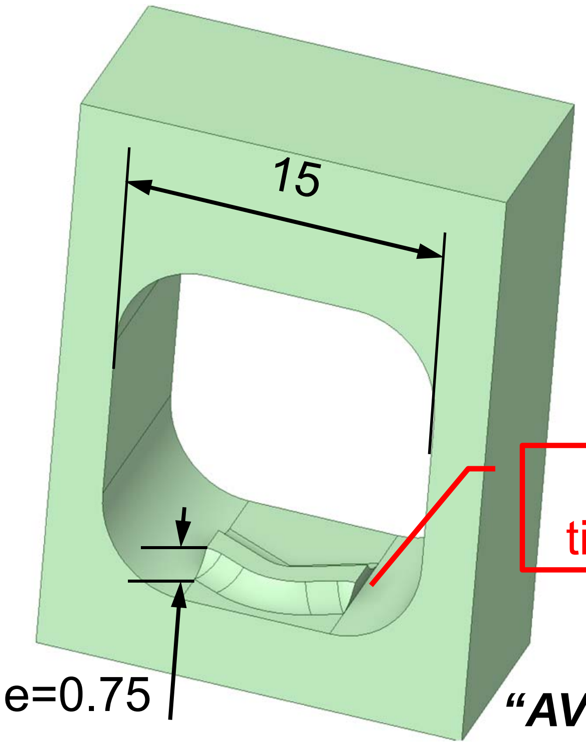
RSM: comparative evaluation of thermal-hydraulic **performance** of **2 "fabrication-friendly"** 120° V-Ribs e=0.75 ribs for for channels L=500mm, 60g/s



tip chamfer
R1

"AV2stc"

shortened rib due to the increase of the channel corner radius with a rounded chamfer R=1mm

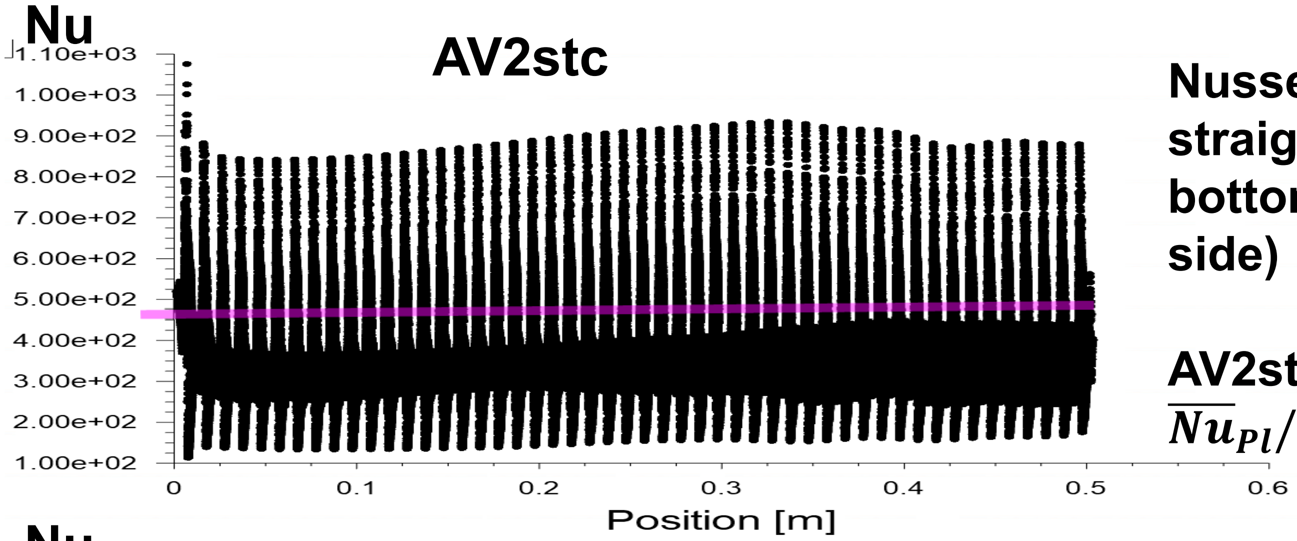


No
tip chamfer

"AV2s"

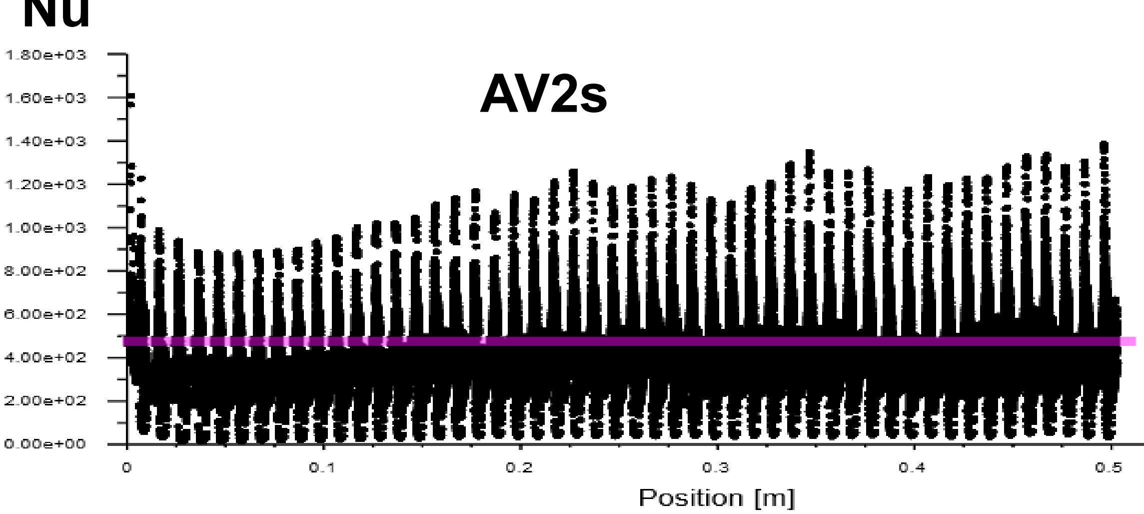
with 90° tip

RSM: Nusselt numbers of "fabrication-friendly" ribs along channel



Nusselt number in the straight channel part on bottom plate (plasma facing side)

AV2stc Ribs: $\overline{Nu}_{Pl}$ = 361
$\overline{Nu}_{Pl}/Nu_0$= 1.39



AV2o Ribs $\overline{Nu}_{Pl}$ = 427
$\overline{Nu}_{Pl}/Nu_0$= 1.64

AV Rib Height e = 0.6
Nu = 480
$\overline{Nu}_{Pl}/Nu_0$= 1.96

CONCLUSIONS/ OUTLOOK

- Temperature dependence of material properties
- Impact of Rib Height for thermal and hydraulic developed flow could be shown
- Simulation show opportunity for rib height reduction with increasing heat transfer and reduction of pressure drop, (already now up to 22 %, more seems possible)
- Tip chamfer reduces heat transfer performance
- Need of improvement of RANS models for heat transfer