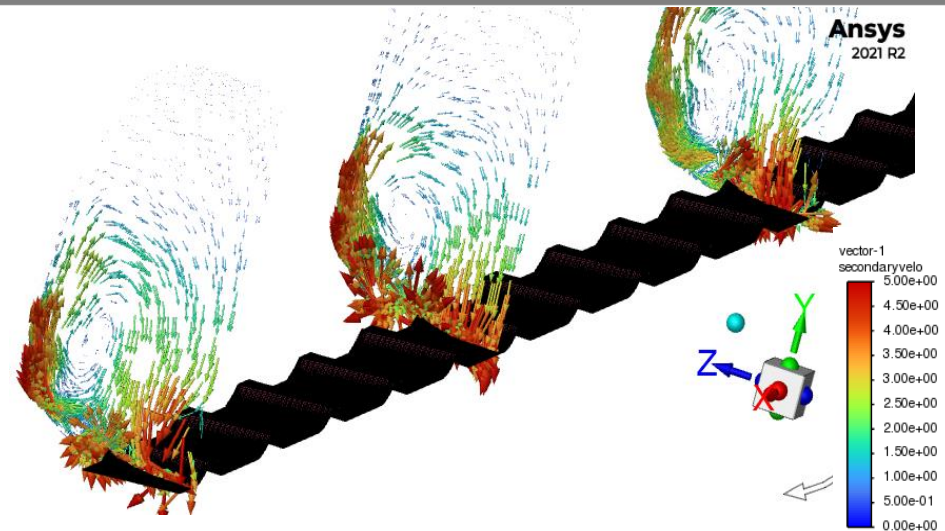
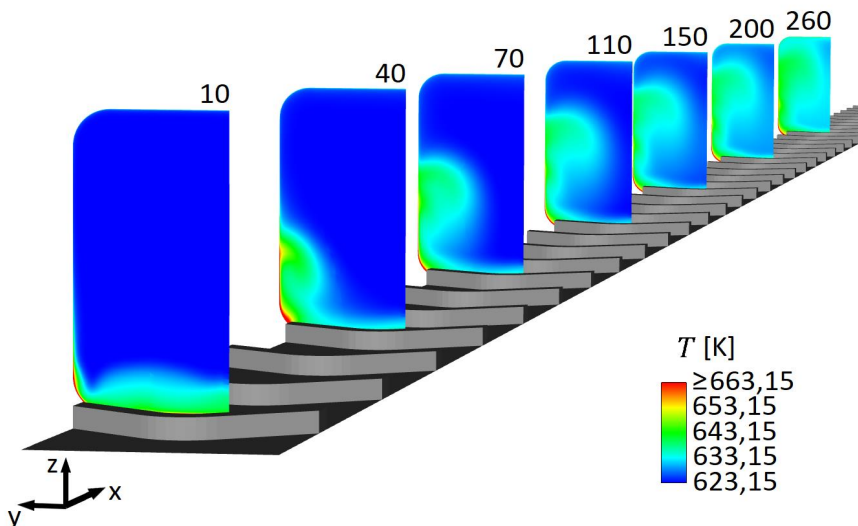


Challenges and Contributions of Numerical Studies of Helium cooled First Wall Channels of DEMO

Christine Klein, Arbeiter F., Enke M. ISFNT 2023, 12.09.2023 Gran Canaria

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



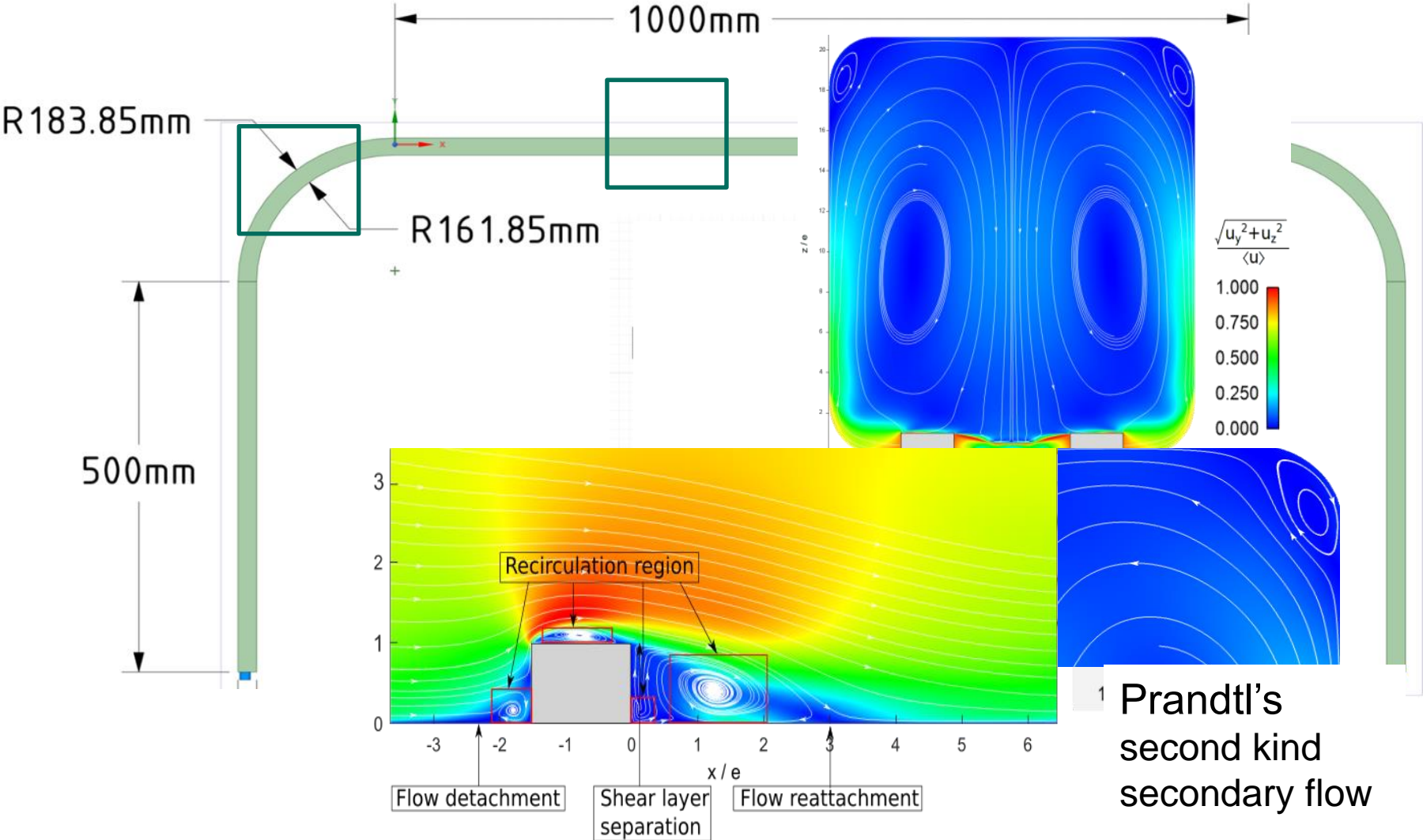
Long Term Objectives of Numerical Simulations of Helium cooled First Wall Channels of DEMO

- To 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
- **60°-V-shaped ribs, 1 MW MW/m² heat load** present studies

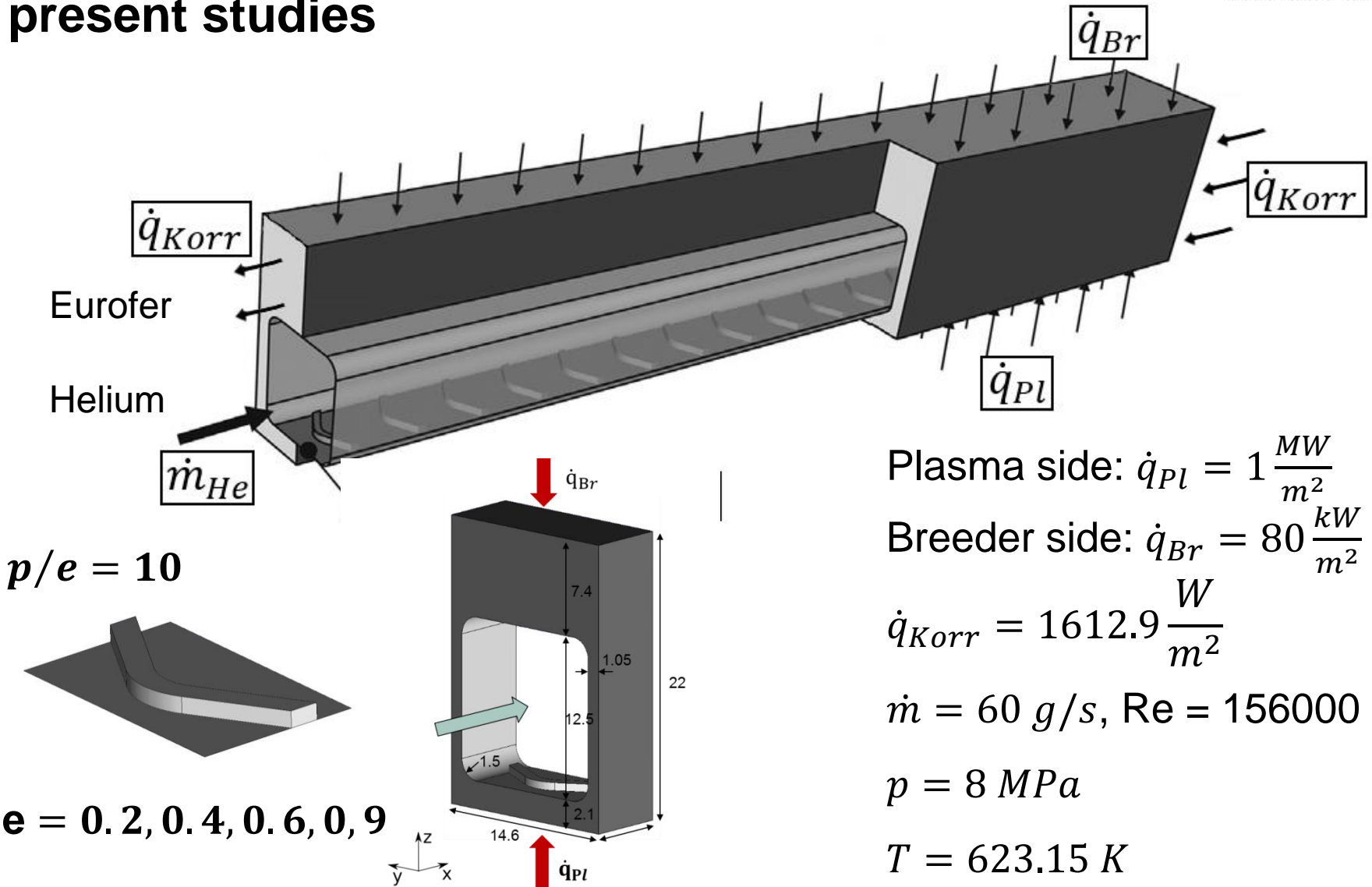
Long Term Objectives of Numerical Simulations of Helium cooled First Wall Channels of DEMO

- To provide a consistent, fully **validated** and **practically feasible** (in terms of computing resources) **numerical approach** to provide simulations of rib enhanced **FW channels/ full-size blanket component**,
- **Predict 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) or codes**
- **Support 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**

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

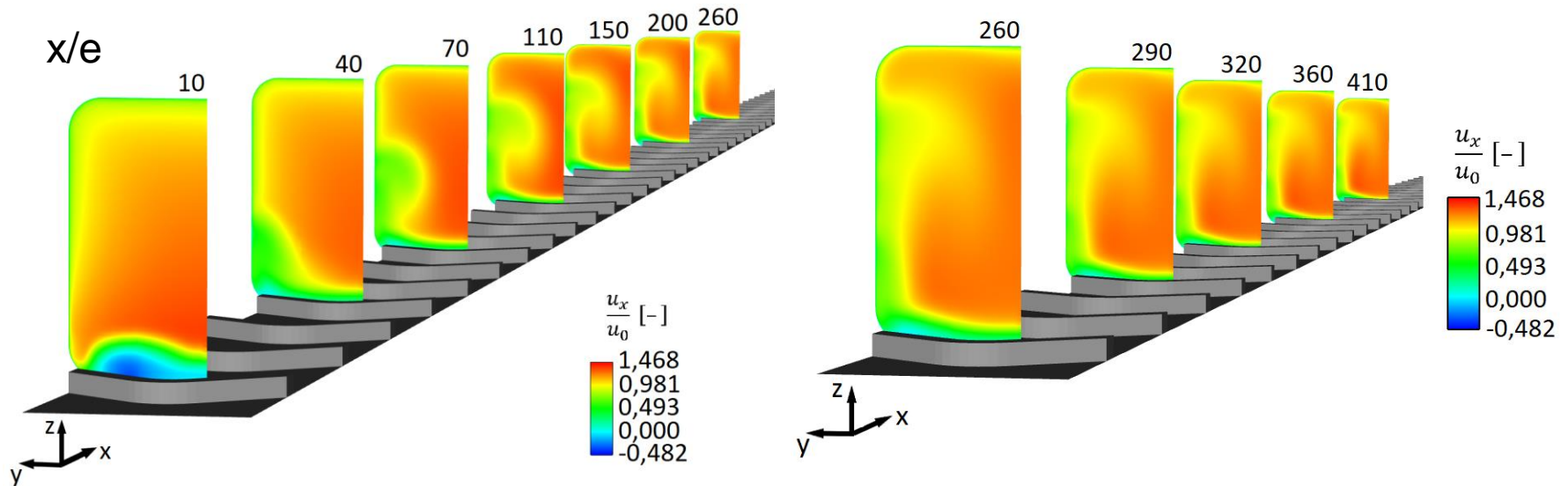


Channel geometry and boundary conditions present studies



Challenge: Geometry FW Cooling Channels, long entrance length

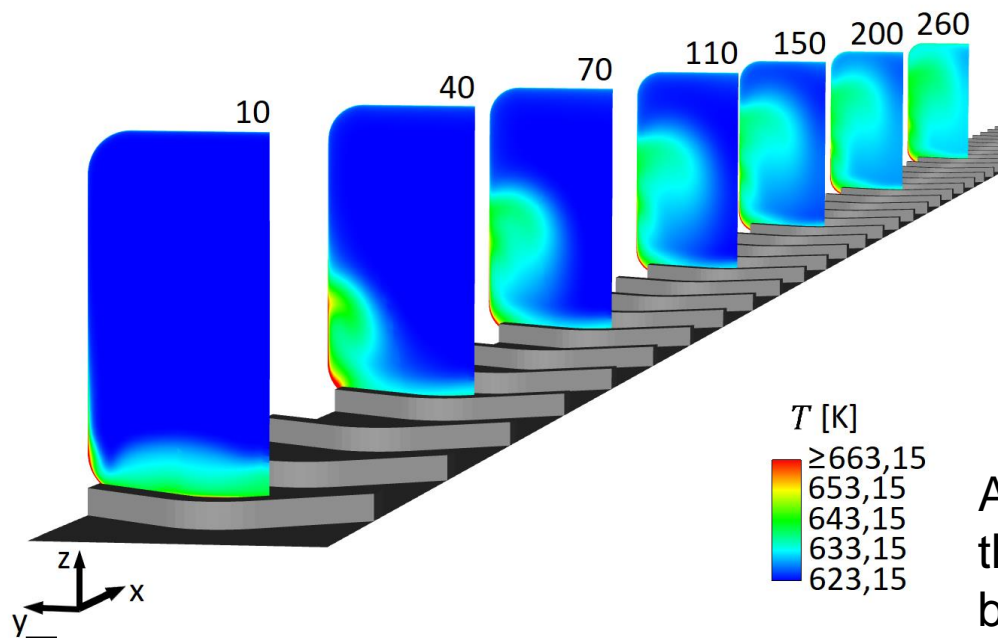
Velocity fields for straight ribbed ($e = 0.9$ mm) part of FW channel, RSM



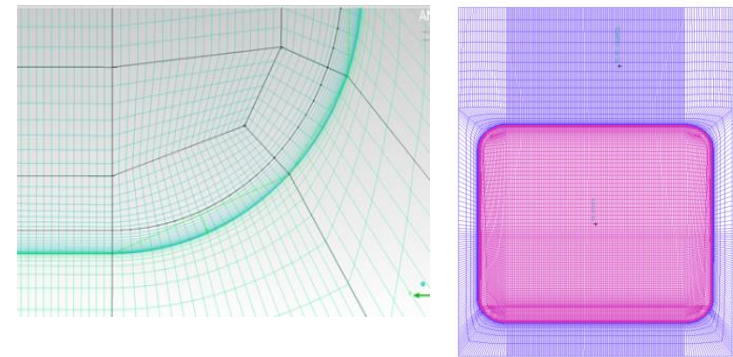
- Hydraulic boundary layer and secondary flow development needs to be captured along channel > resulting in high mesh count
- Entrance length FW channel $l_h \sim 38 d_h$

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



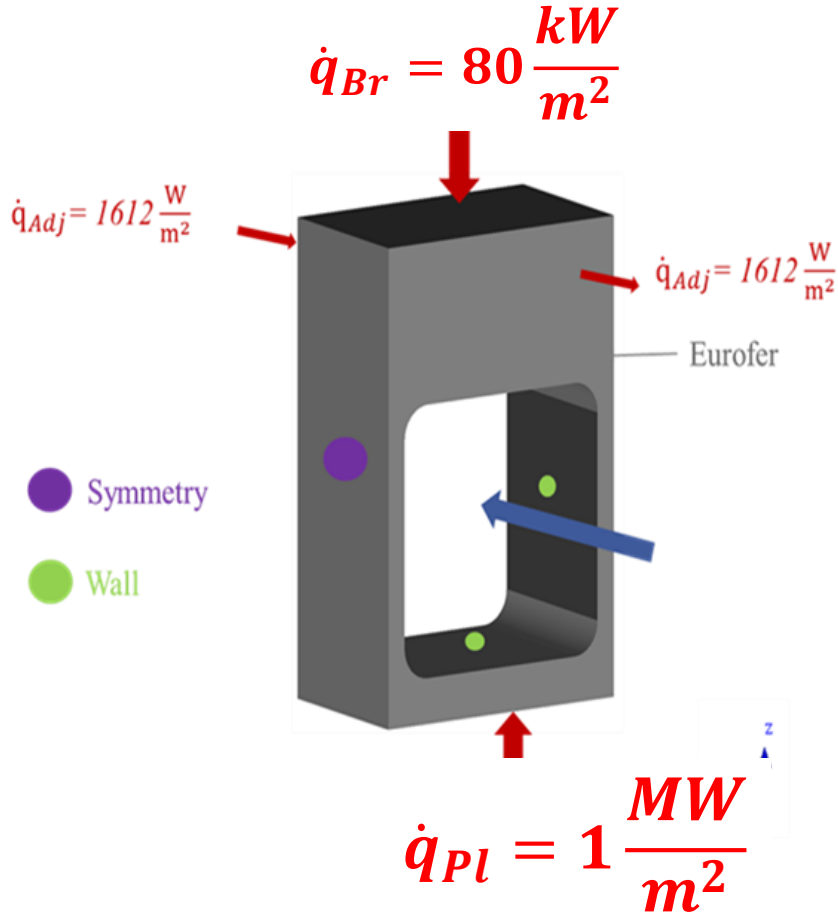
Temperature field for the straight part of the channel with 0.9 mm V ribs, RSM



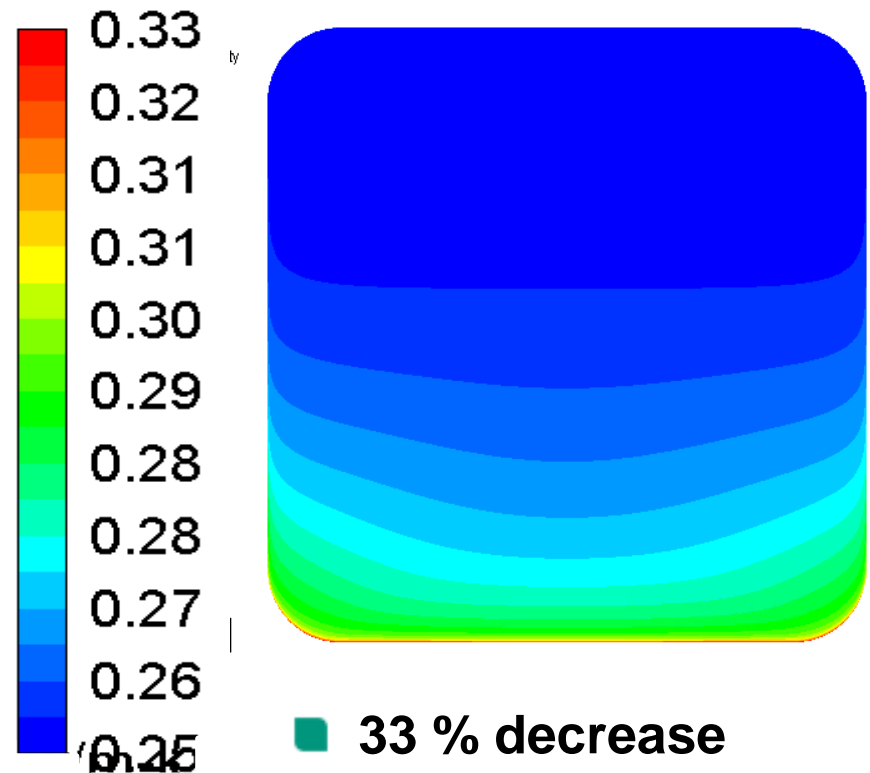
$$y(y^+ = 1) = 1,8815 \cdot 10^{-6} m$$

A high-resolution mesh in the vicinity of the wall (i.e. $y^+ \sim 1$) 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

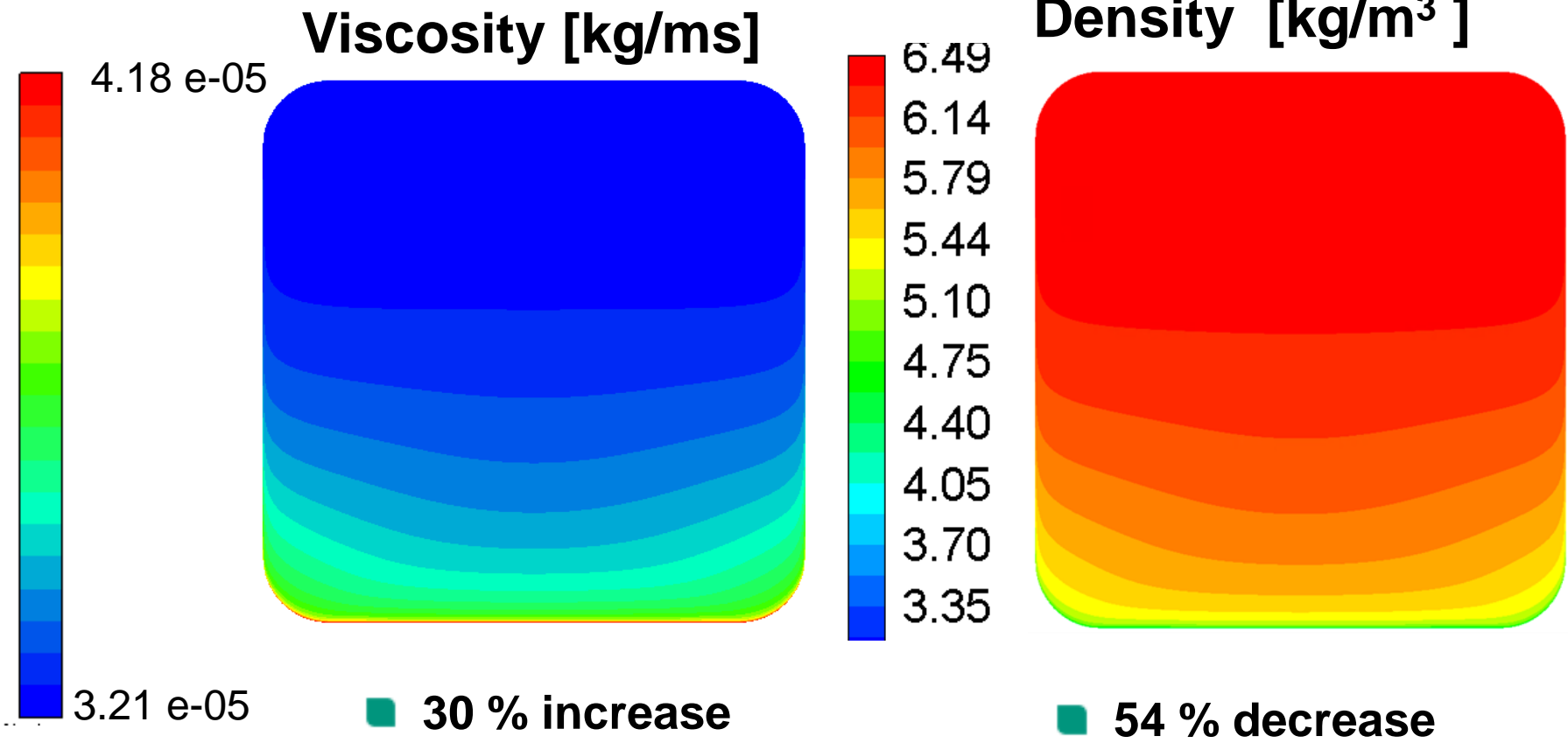


Thermal conductivity [W/mK]



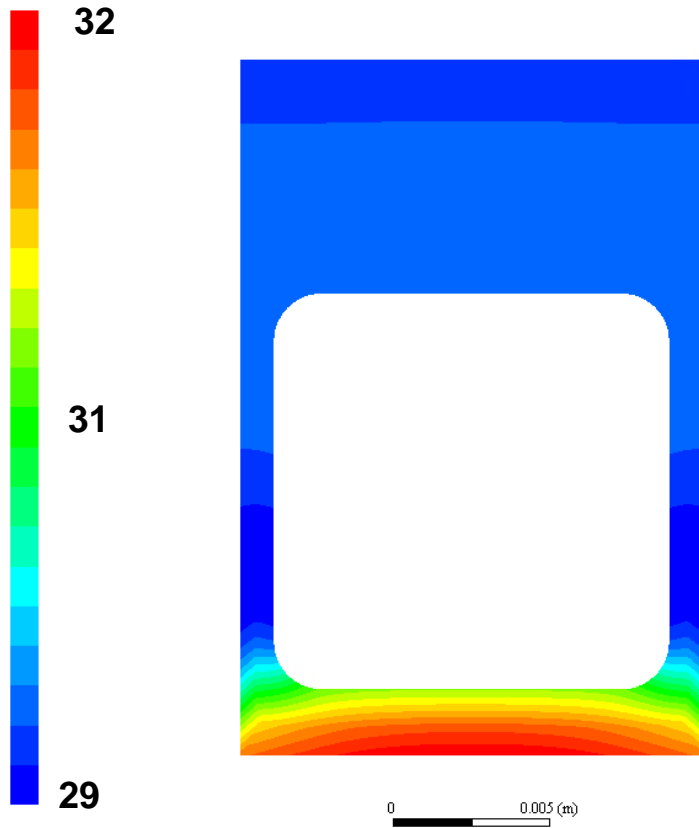
k-omega SST, flat channel.
periodic boundary condition

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

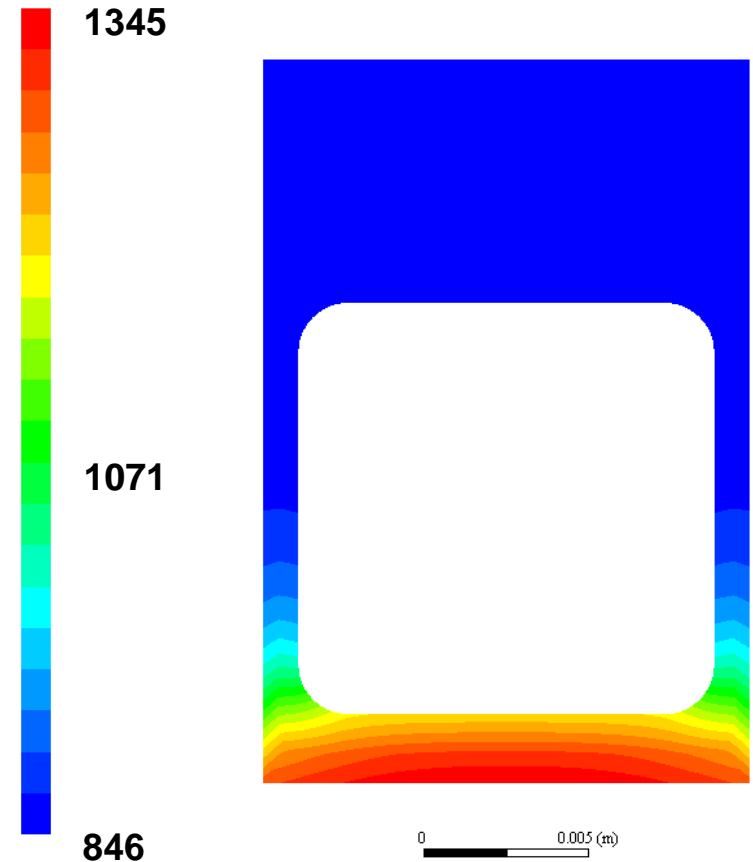


Challenge: High heat flux > high temperatures and material properties gradients

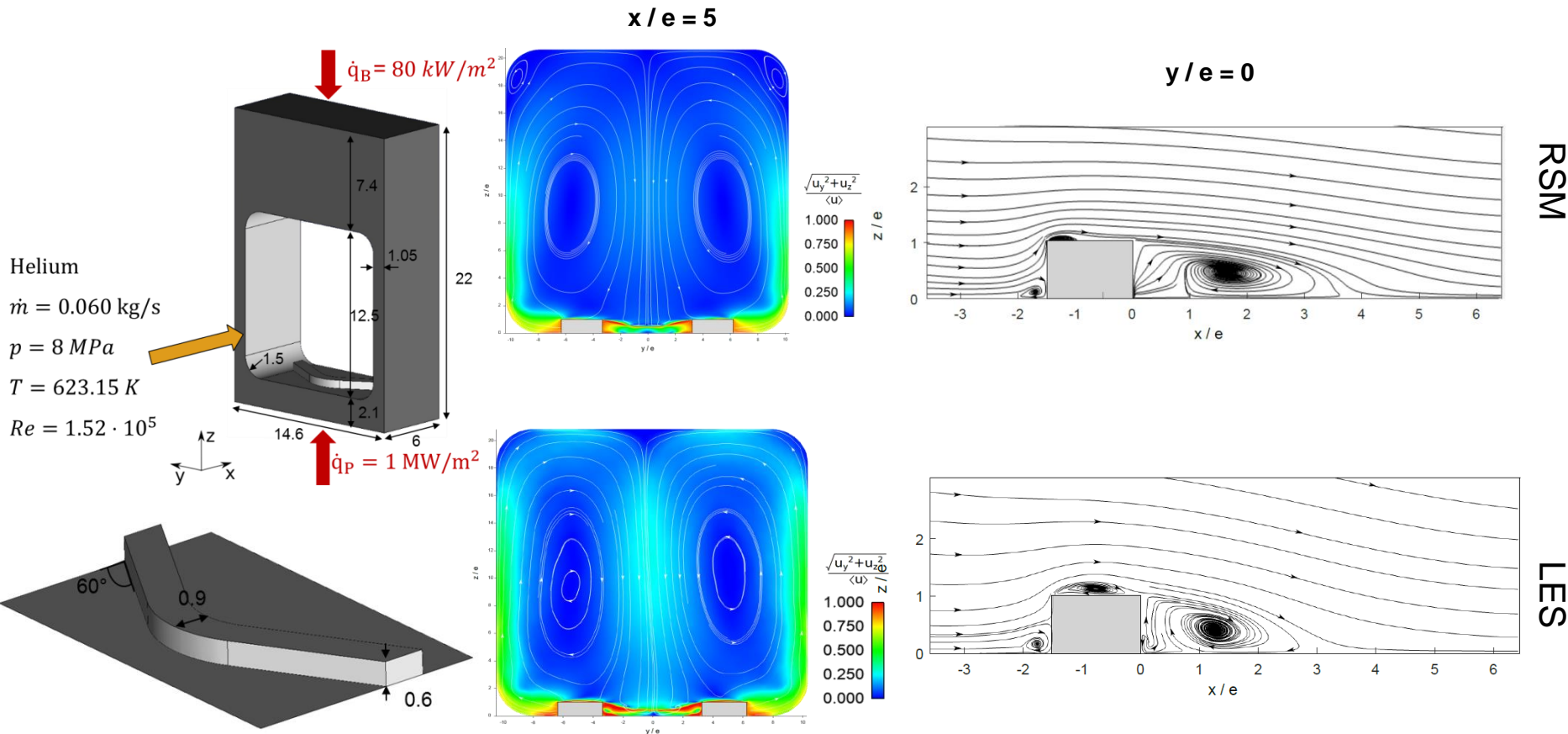
Thermal conductivity [W/mK]



Specific heat capacity c_p [J/(kg·K)]



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



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

RSM in comparison with LES

e = 0.4 mm

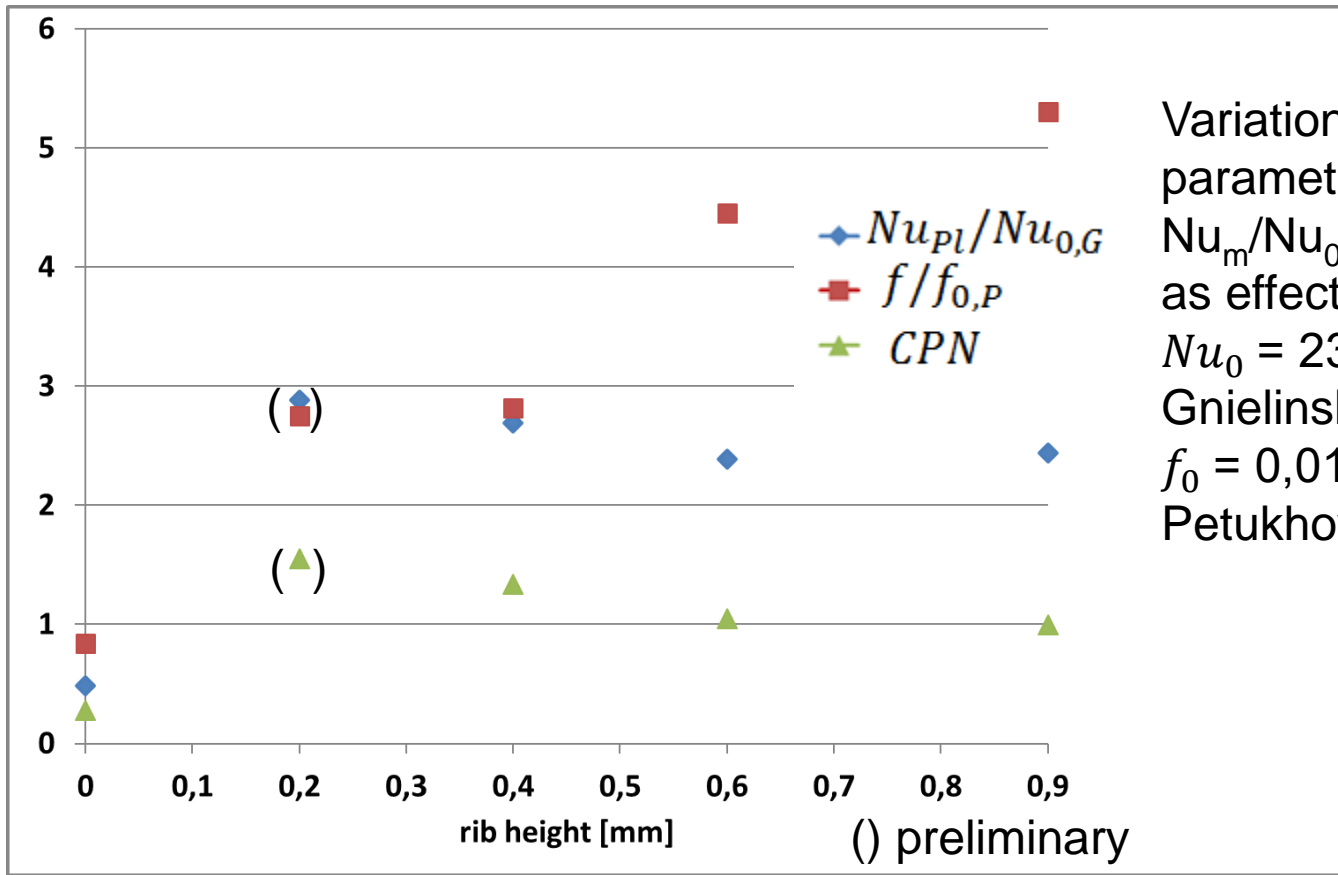
e = 0.6 mm

e = 0.9 mm

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

- Underestimates heat transfer and overestimates component temperatures

LES for different rib heights



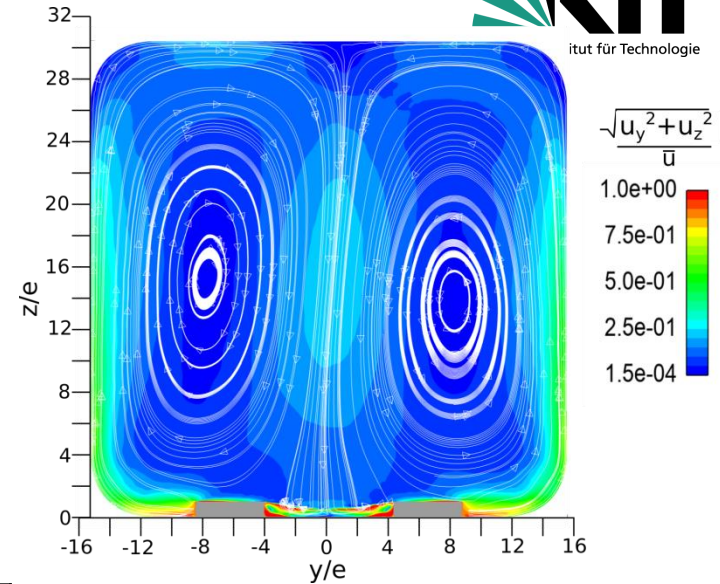
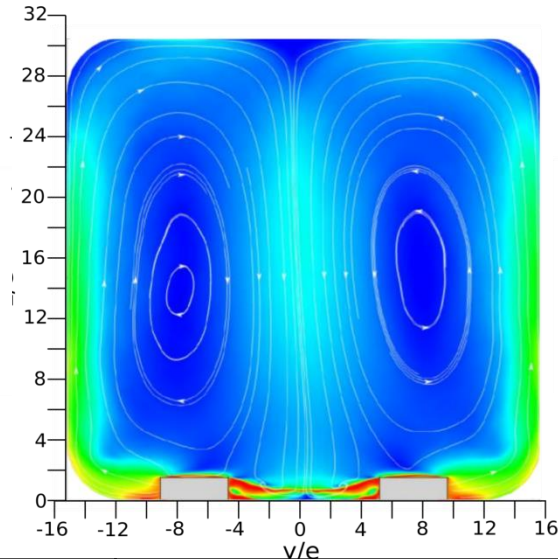
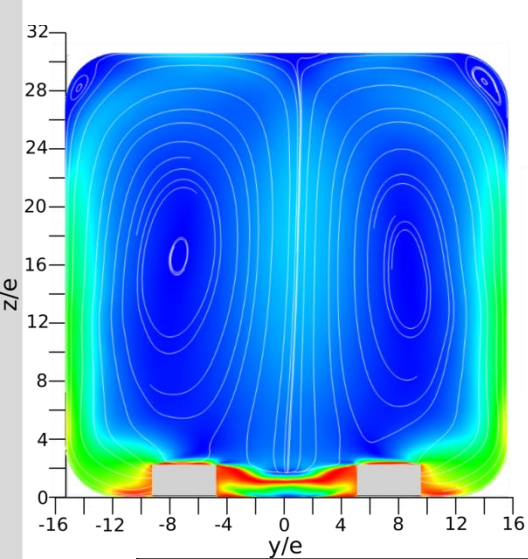
Variation of thermal-hydraulic parameters (Heat transfer: Nu_m/Nu_0 ; pressure drop: f/f_0) as effect of the rib height
 $Nu_0 = 238$
 Gnielinski (1976)
 $f_0 = 0,016$
 Petukhov (1970)

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

Ruck und Arbeiter (2018)
 Cooling Performance number

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

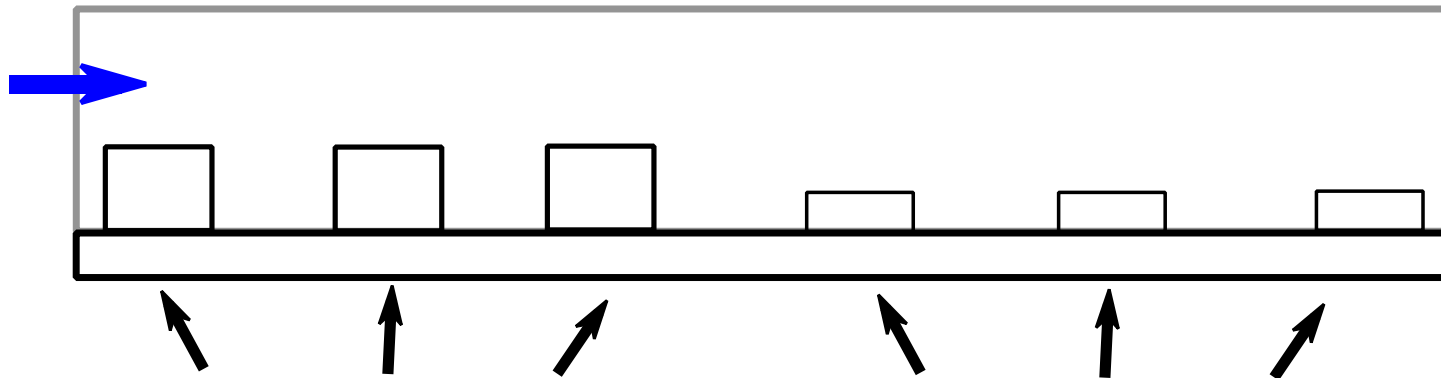
LES Results for Secondary flow



e	$\frac{1}{V} \int \sqrt{u_y^2 + u_z^2} dV$
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

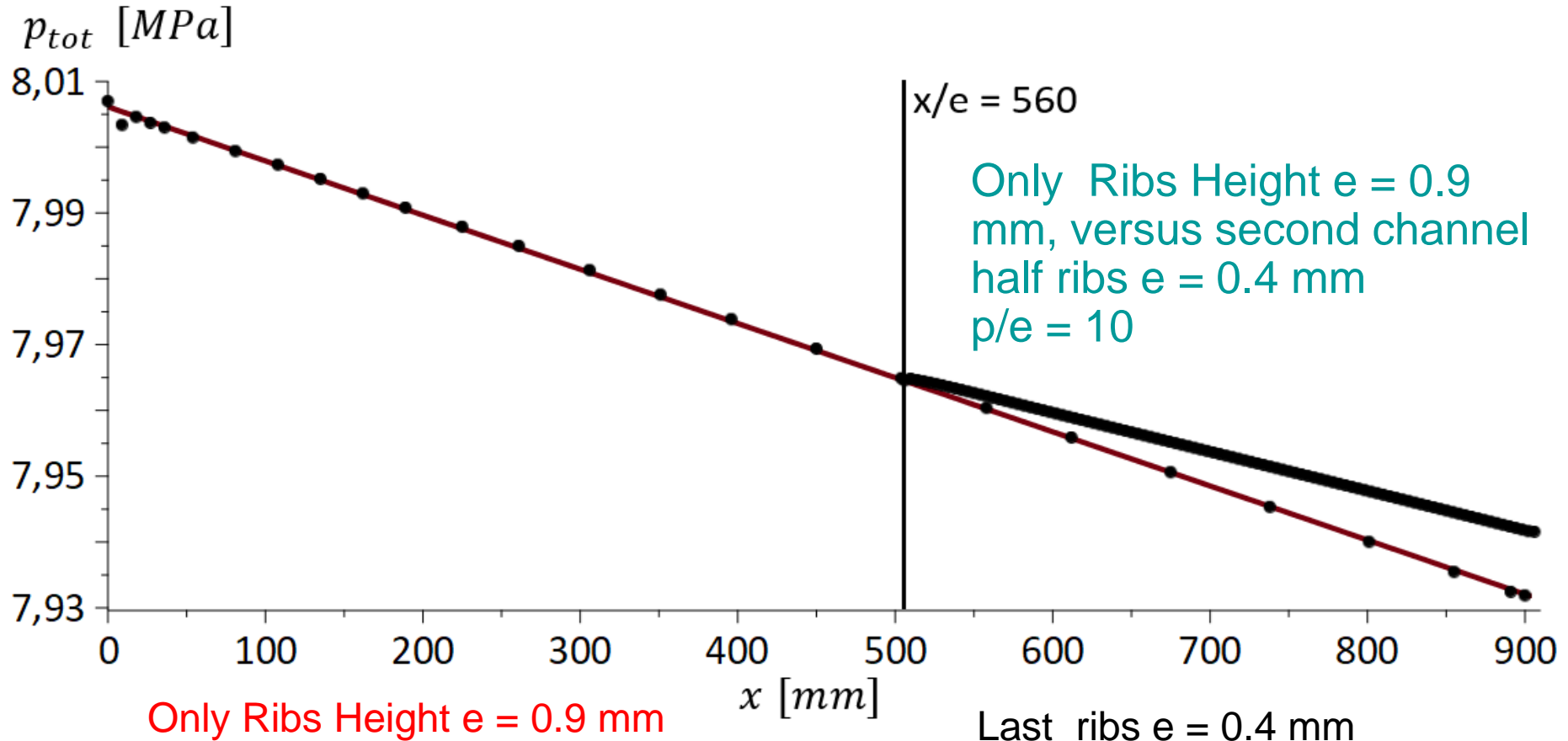
- Impact of **rib height** on **heat transfer** and **pressure drop**
- These finding opens up the opportunity to **decrease the rib height in case of fully developed secondary flow** and using **RSM** to check for complete channel



Higher ribs to induce strong secondary flows

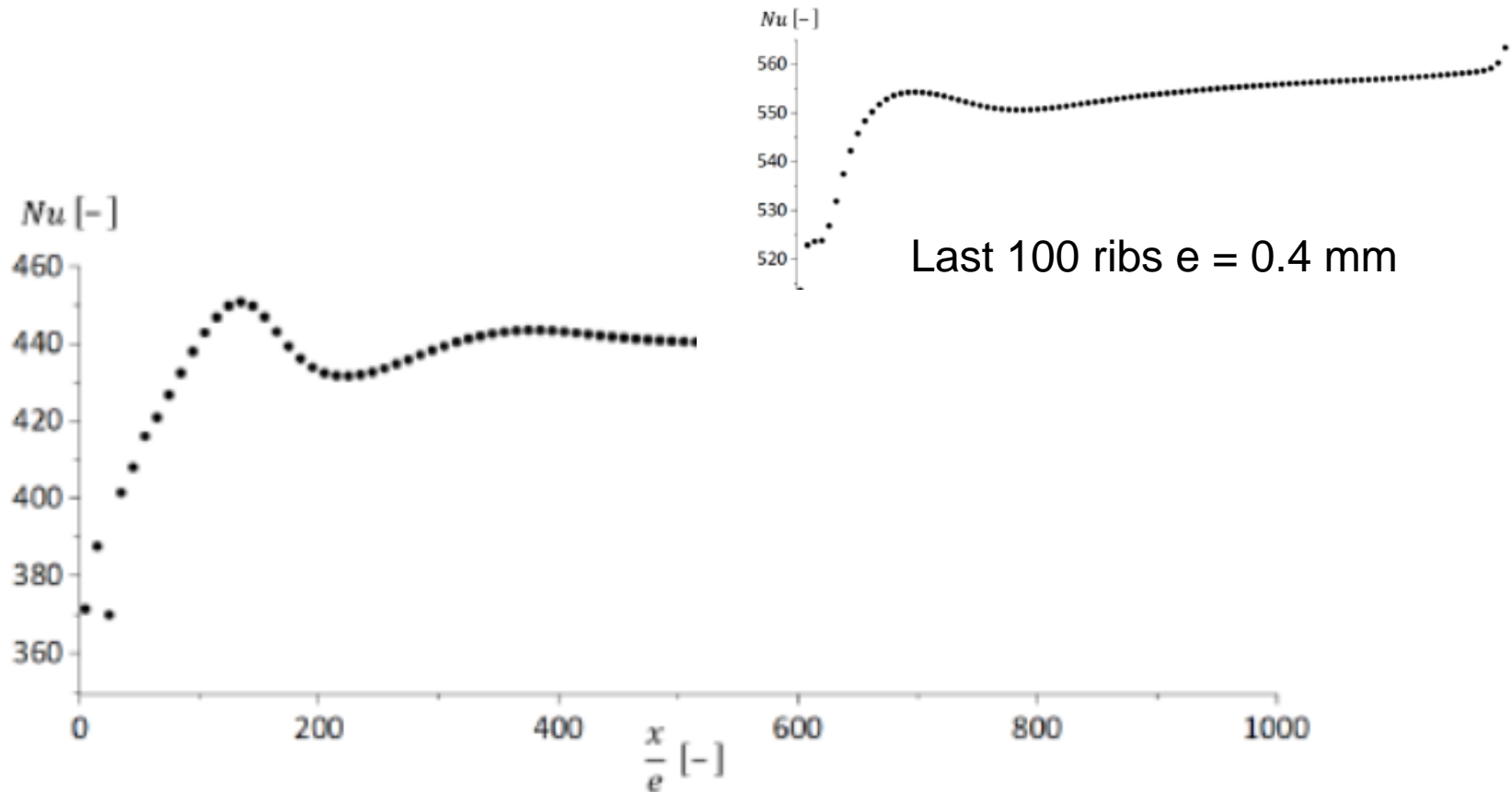
Only Ribs Height $e = 0.9$ mm, versus second channel half \therefore , ribs $e = 0.4$ mm
 $p/e = 10$

Possibilities RSM: Evolution impact of Rib along complete channel



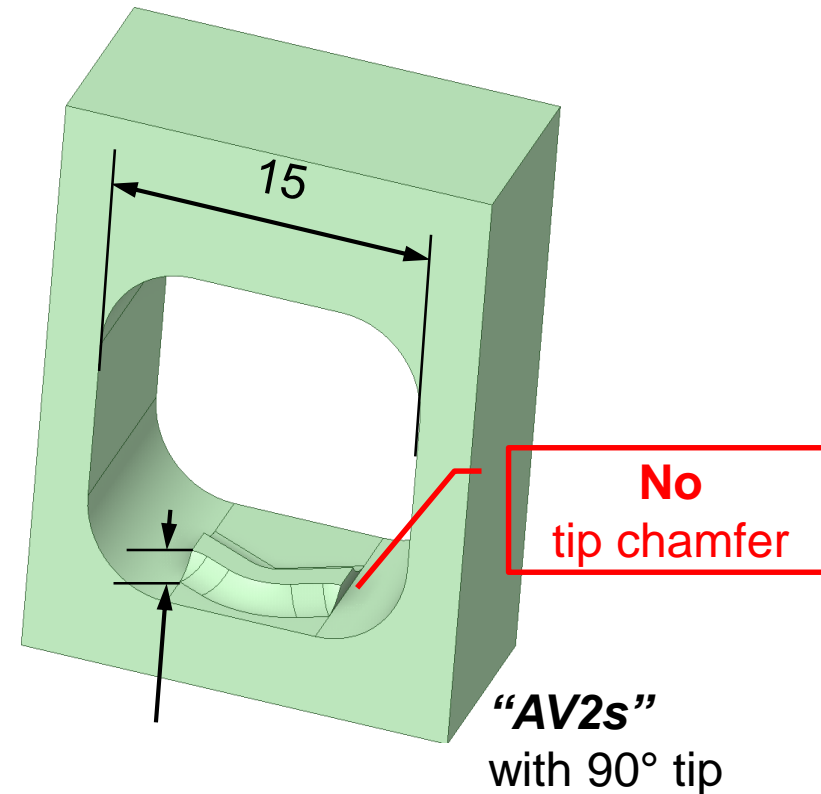
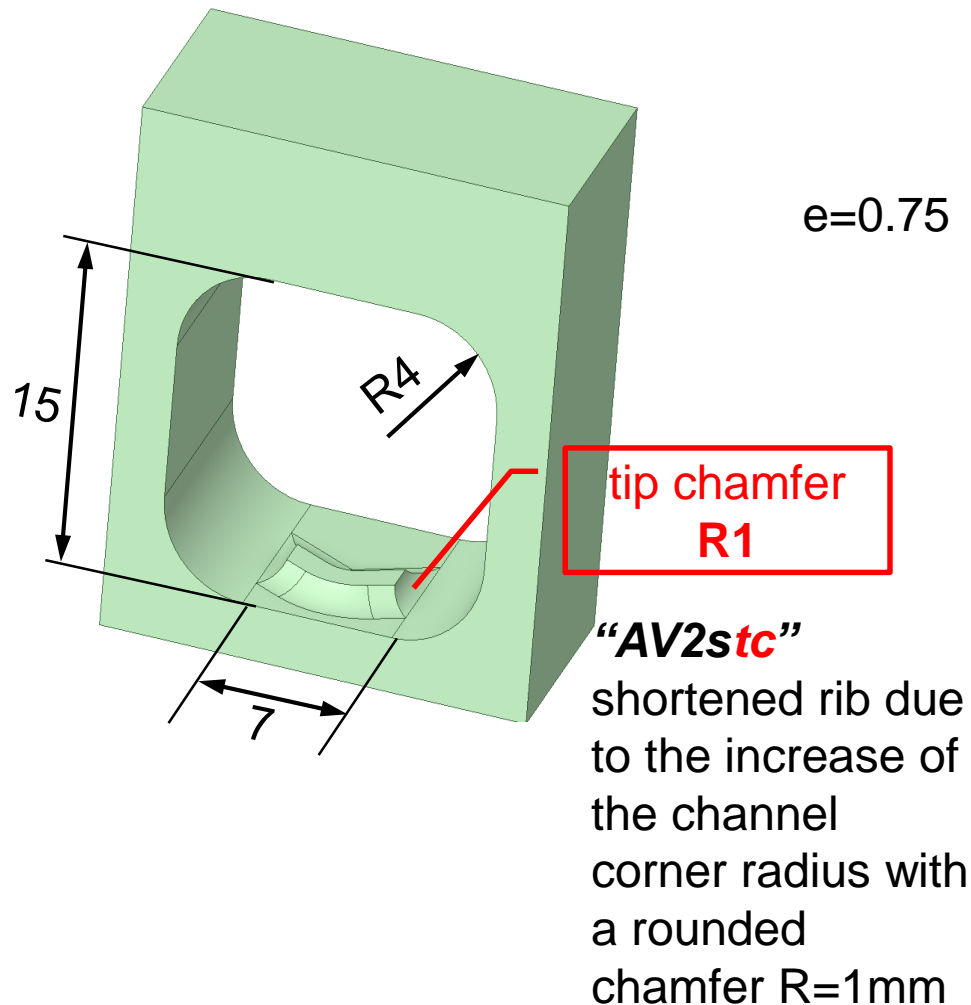
■ ~45% lower pressure gradient and pressure drop

Possibilities RSM: Evolution impact of Rib along complete channel

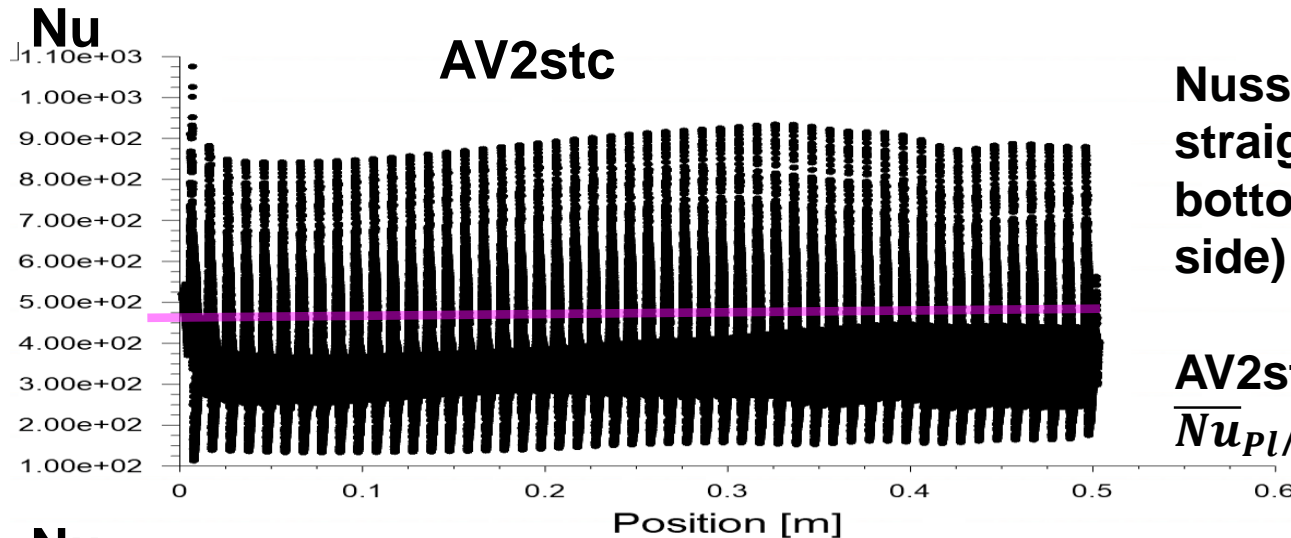


■ lower pressure drop and higher heat transfer

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

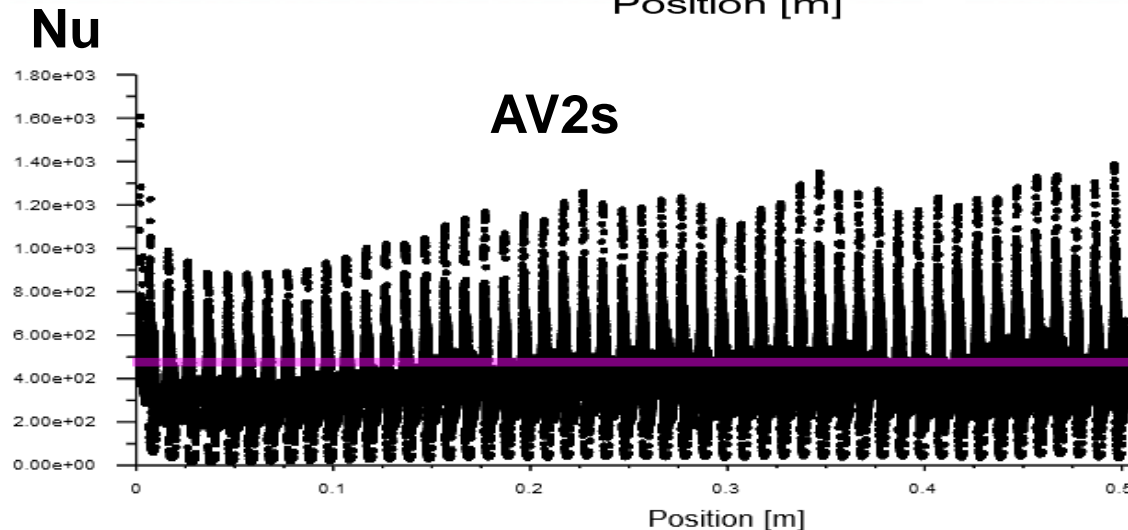


RSM: Nusselt numbers of "fabrication-friendly" ribs along channel



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

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



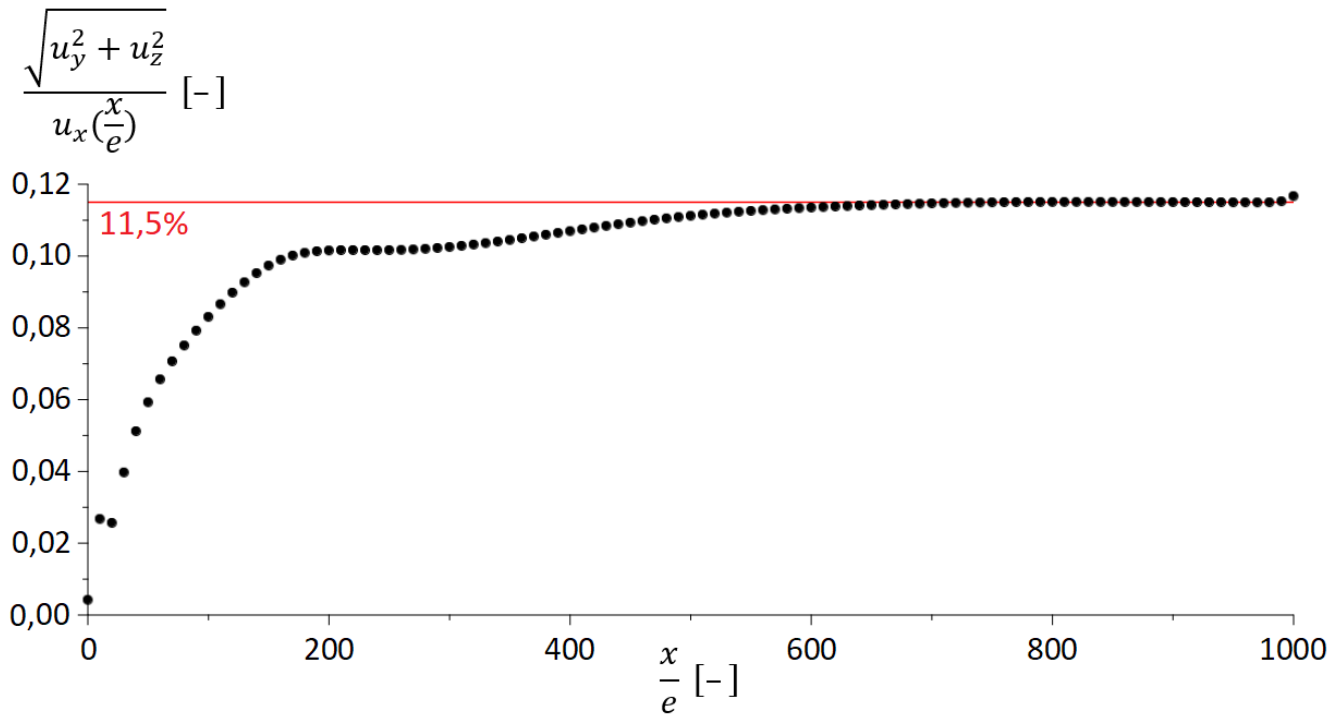
AV2o Ribs $\overline{Nu}_{pl} = 427$
 $\overline{Nu}_{pl}/Nu_0 = 1.64$

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**

Additional Information Entrance length RSM Karlsruher Institut für Technologie



Additional Information Heat Transfer RSM

- possible source of error: modeled equation for **the normal heat flux** is sensitive to **turbulent kinetic energy k** und **dissipation rate ϵ** especially near wall (Reynolds analogy)

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i} [u_i(\rho E + p)] = \frac{\partial}{\partial x_j} \left[\left(k + \frac{c_p \mu_t}{Pr_t} \right) \frac{\partial T}{\partial x_j} + u_i (\tau_{ij})_{eff} \right] + S_h \quad \mu_t = \rho C_\mu \frac{k^2}{\epsilon}$$

where $C_\mu = 0.09$.

- Reynolds analogy** is only valid for developed flows with low gradients
- $Pr_t = 0.85 = \text{const.}$** is used as standard
- unsteady effects** (LES shows vortices detaching irregular from the edge and hitting the cooled surface) cannot be represented by RSM and all other non-time-resolved methods
- URANS RSM calculation should be tested

- Diffusion rate in the
...*TKE* transport equation and ...

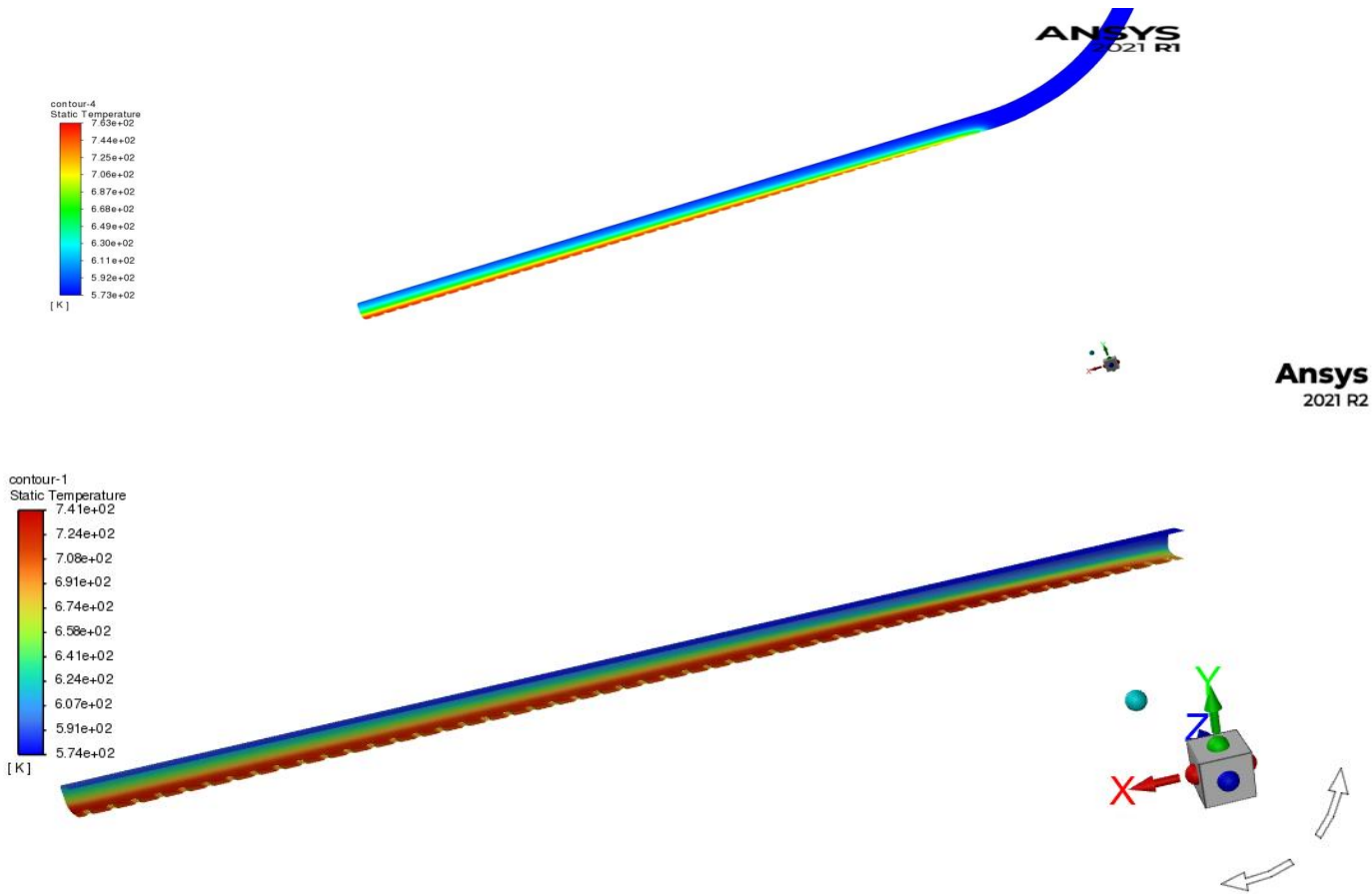
$$-\frac{\partial}{\partial x_j} \left\langle \left(\frac{p'}{\rho} + \frac{1}{2} \cdot u_i'^2 \right) \cdot u_j' \right\rangle \Rightarrow \frac{\partial}{\partial x_j} \left(\frac{\nu_t}{\sigma} \cdot \frac{\partial TKE}{\partial x_j} \right)$$

... $\langle u_i' \cdot u_j' \rangle$ transport equation modelled by **simple gradient-diffusion** model

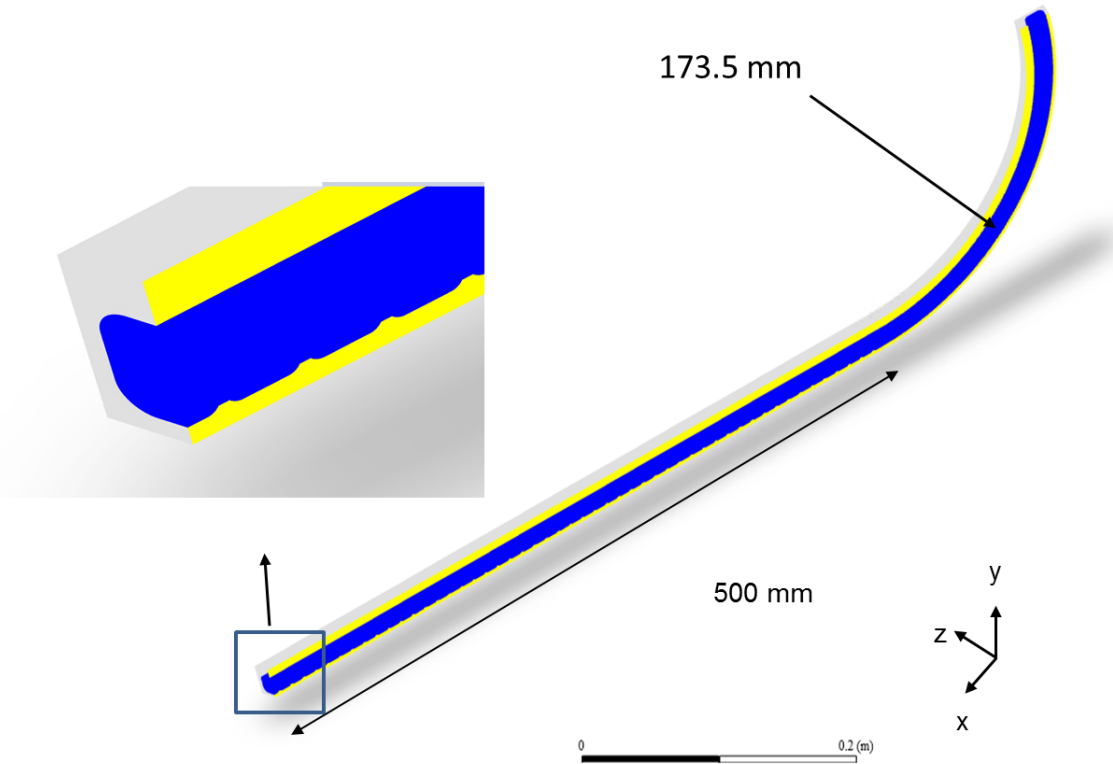
$$-\frac{\partial}{\partial x_j} \left\langle \frac{1}{\rho} \cdot (\langle u_i' \cdot p' \rangle \cdot \delta_{jk} + \langle u_j' \cdot p' \rangle \cdot \delta_{ik}) + \langle u_i' \cdot u_j' \cdot u_k' \rangle \right\rangle \Rightarrow \frac{\partial}{\partial x_k} \left(\frac{\nu_t}{\sigma} \cdot \frac{\partial \langle u_i' \cdot u_j' \rangle}{\partial x_k} \right)$$

Gradient diffusion model for turbulent transport of heat and Impulse

RSM: comparative evaluation of thermal-hydraulic performance of AV2stc and AV2s ribs, temperature field



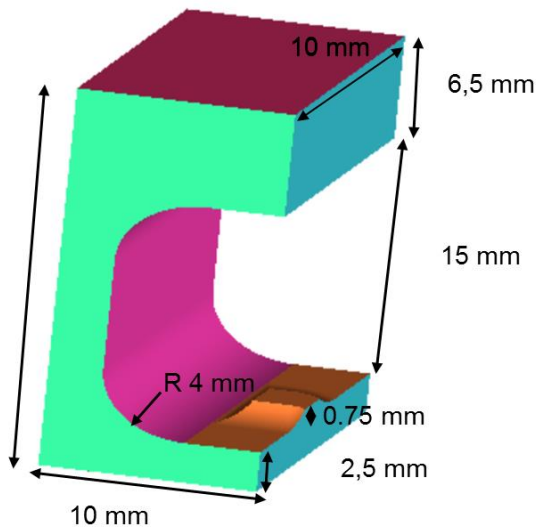
RSM: comparative evaluation of thermal-hydraulic performance of "fabrication-friendly" ribs



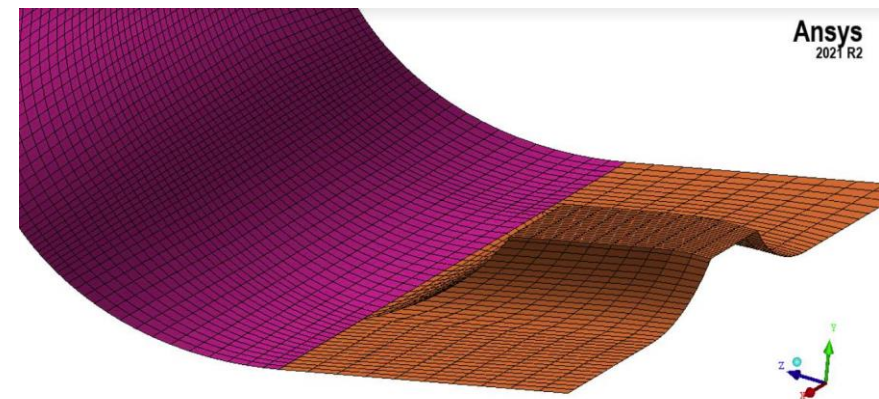
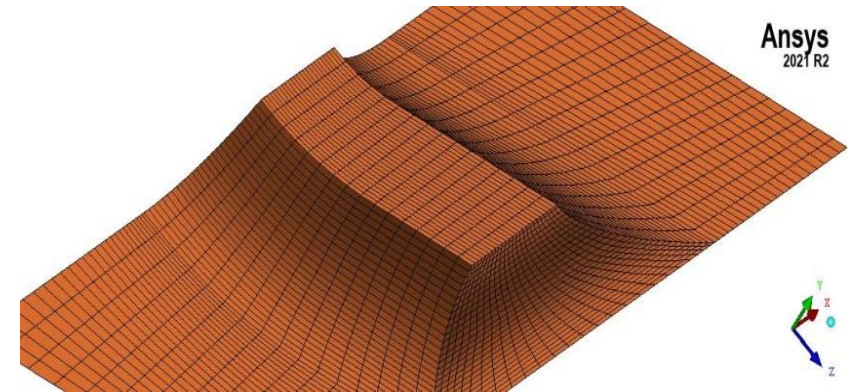
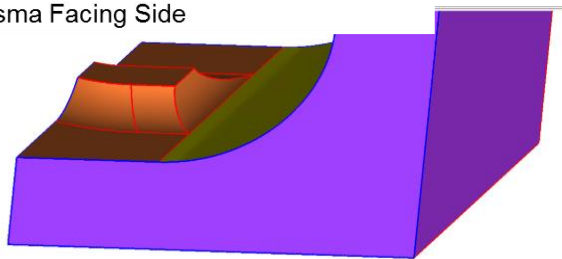
- Mass flow rate of helium 60 g/s
- Inlet temperature of 300 °C
- Reference pressure 8 MPa
- Applied heat flux density on the FW side on the straight part 750 kW/m², all other surfaces are simulated adiabatic

RSM: comparative evaluation of thermal-hydraulic performance of "fabrication-friendly" ribs AV2stc

Breeding Zone Facing Side

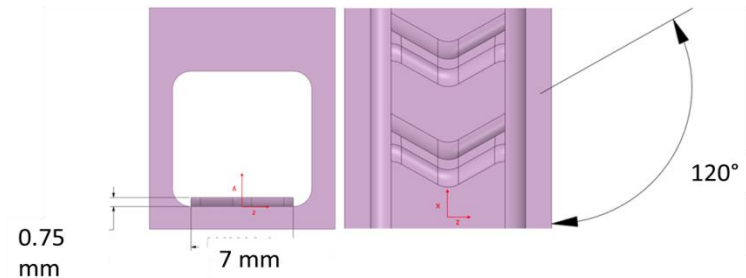
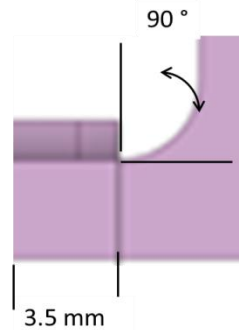
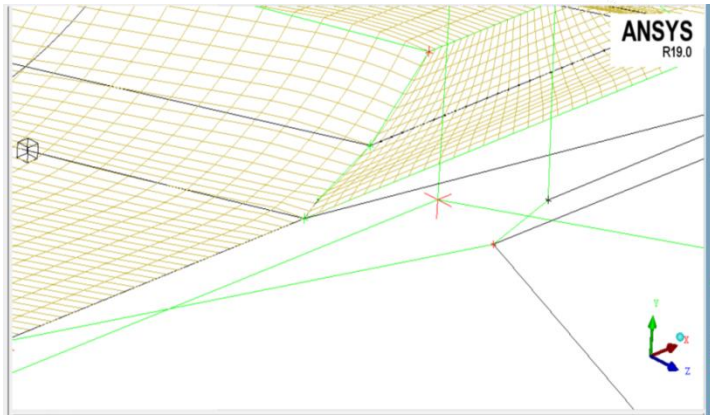
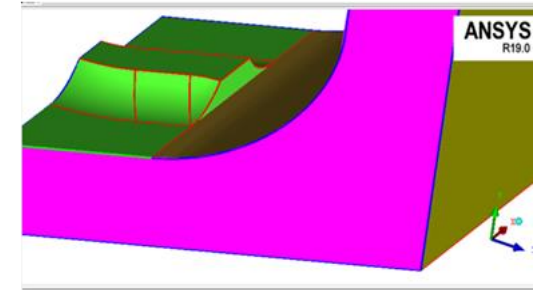
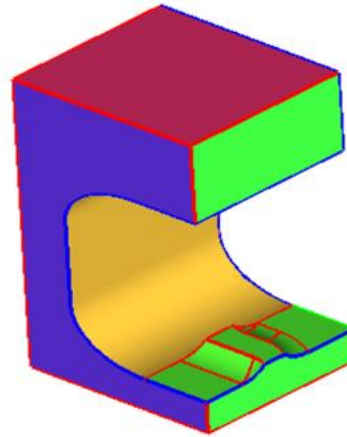
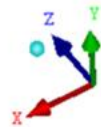
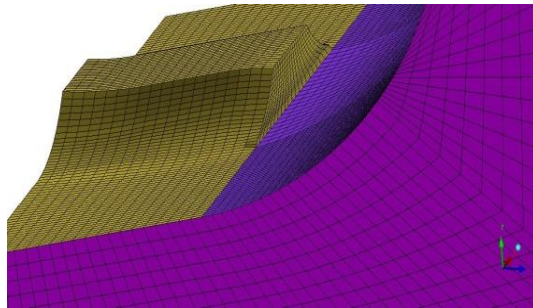


Plasma Facing Side



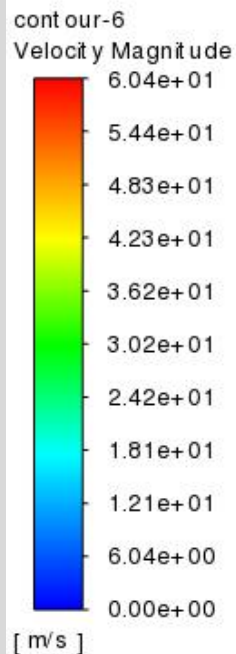
RSM: comparative evaluation of thermal-hydraulic performance of "fabrication-friendly" ribs

AV2s rib

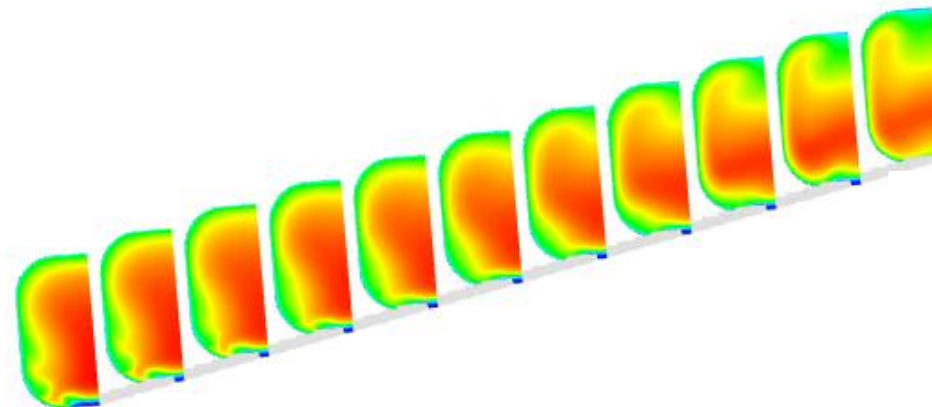


Challenge: Geometry FW Cooling Channels, long entrance length

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

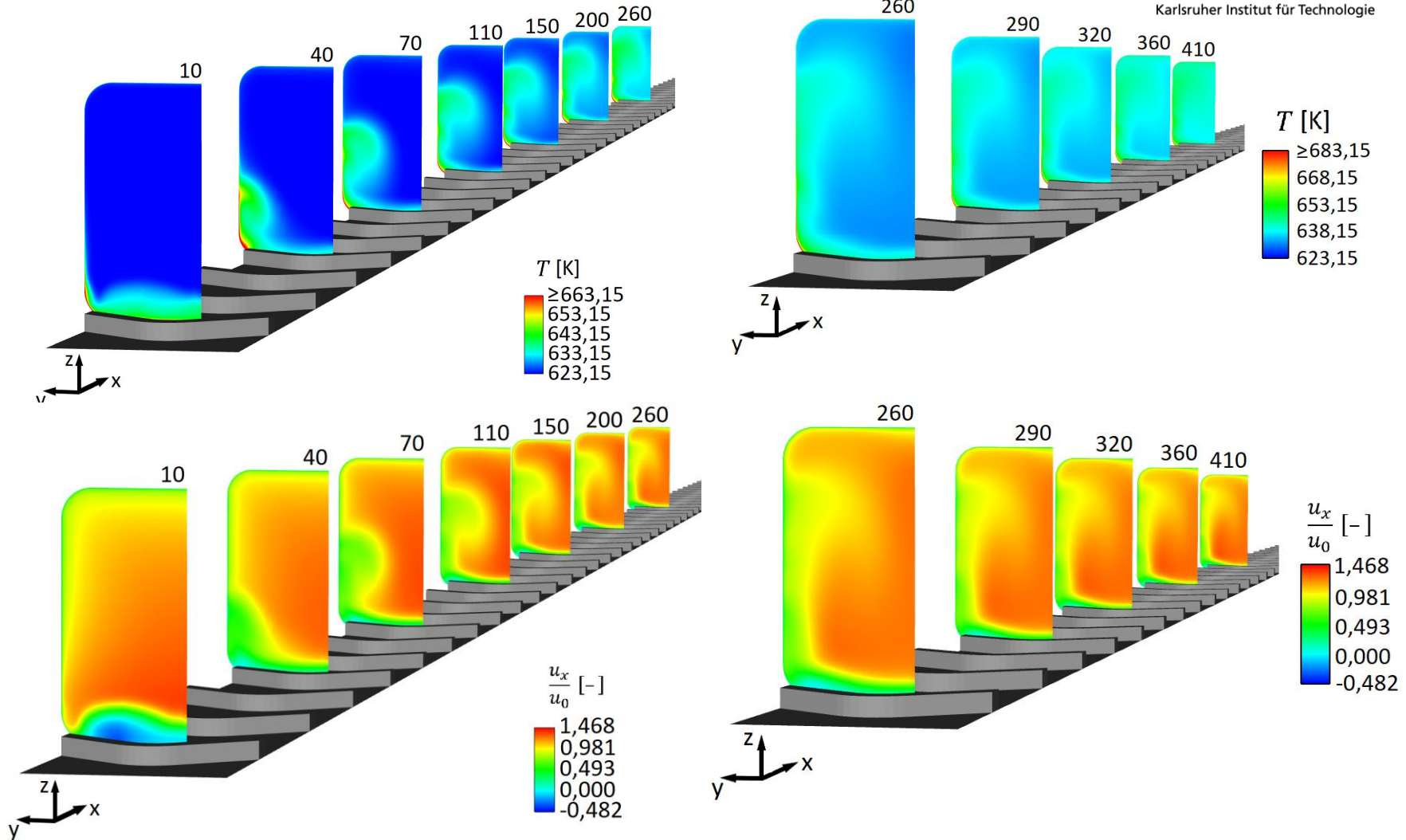


Velocity fields for straight ribbed (AV2stc) part of the channel, RSM



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

RSM (Reynolds stress equation model)



■ Can calculate complete FW Channel