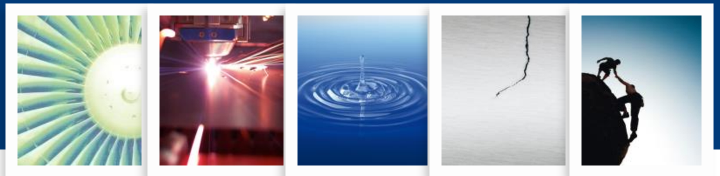

High-Fidelity Simulations of Adverse Pressure Gradient Flow over a Rounded Step for Turbulence Model Improvement via Database Generation

ETMM-15

Dubrovnik,Croatia – 24 September 2025

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Motivation

Predicting **turbulent** flows with **separation**

Remains a **major challenge** in fluid dynamics and engineering

Industry relies on **low-fidelity methods** (RANS, WMLES)

Limited reliability for **separated** or **secondary** flows

Improved turbulence models can strongly impact

Energy efficiency

Noise reduction

Emission

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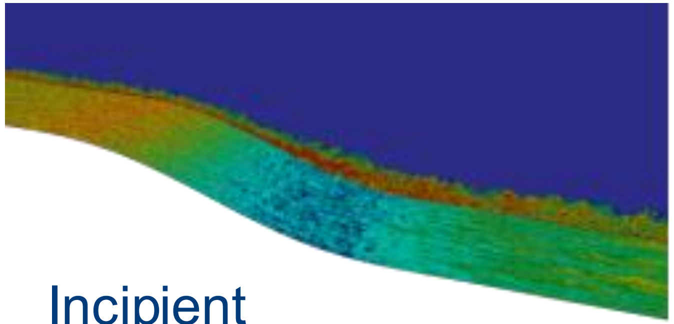
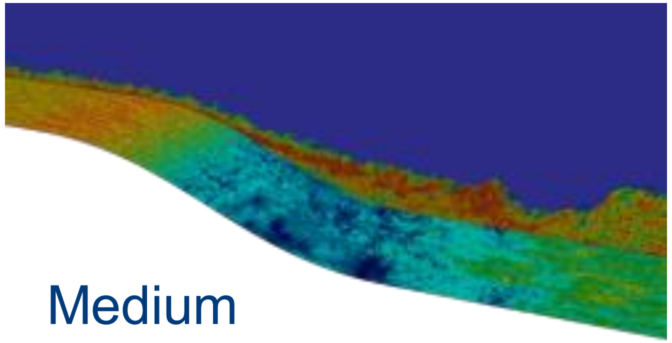
Approach and objectives

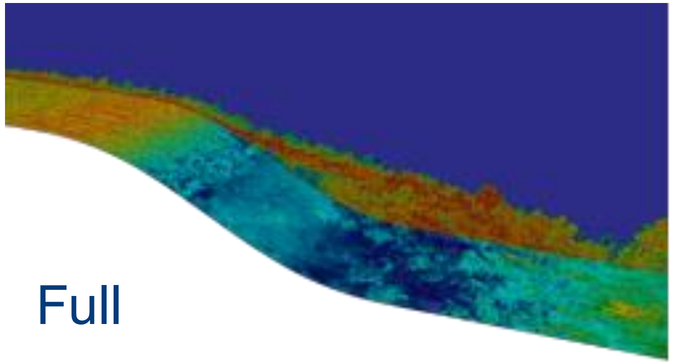
- **Generate** a **high-fidelity database** for a representative configuration
  - **HiFi-Turb DLR rounded step** (ERCOFTAC KB Wiki)



Incipient



Medium



Full

- **Gather**
  - **Statistical quantities:** Flow quantities, Favre-averaged Navier-Stokes, Reynold stress and dissipation
  - **Instantaneous fields** (solution and its gradients)

→ ERCOFTAC KB Wiki

- **Improve RANS and WMLES** using **data-driven** and **ML** approaches

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Statistical data sets

- **Definition of common set of 180 statistics that allow reconstructing all RANS models**
  - **Level 1 – Favre-averaged Navier-Stokes eq. + flow field and QoI**
  - **Level 2 – Favre-averaged Reynolds stress eq.**
    - Several variants considered (Gerolymos and Vallet, Knight, Grigoriev, etc)

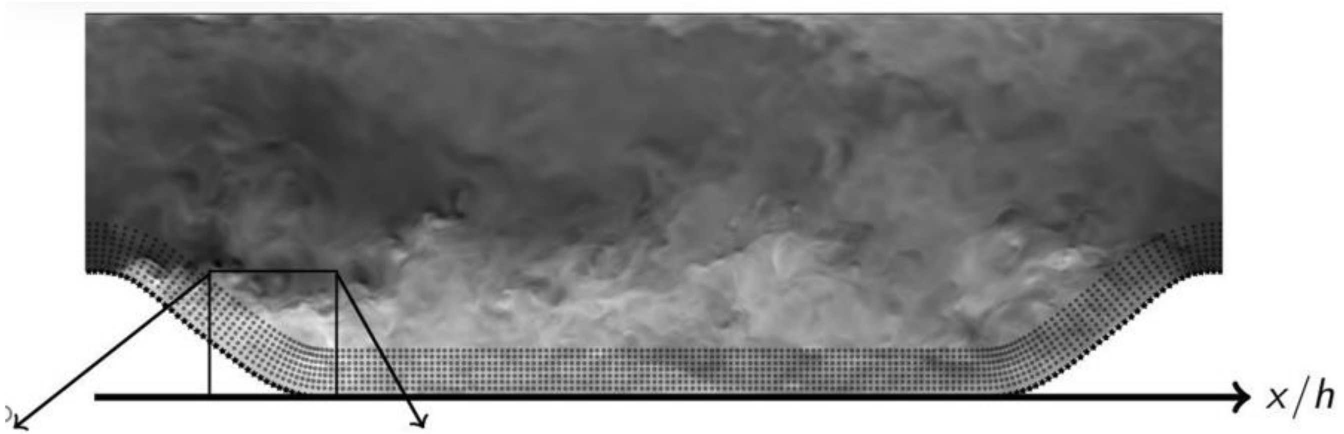
$$\mathcal{R}_{ij,t} + (\mathcal{R}_{ij}\widetilde{u}_k)_{,k} = P_{ij} + D_{ij} + \Phi_{ij} + \Phi'_{ij} - \epsilon_{ij} + K_{ij} \qquad \mathcal{R}_{ij} = \overline{\rho u''_i u''_j}$$

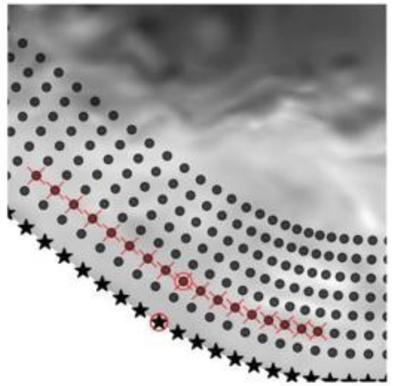
  - **Level 3 – Solenoidal dissipation eq. (Kreuzinger et al.)**
    - Includes third order derivative of velocity

$$\frac{D\epsilon_s}{Dt} = P^1_\epsilon + P^2_\epsilon + P^3_\epsilon + P^4_\epsilon + T_\epsilon + D_\epsilon - \Upsilon + F_\epsilon + T^C_\epsilon + B_\epsilon + \frac{\epsilon_s}{\widetilde{\nu}}\frac{D\nu}{Dt} \qquad \epsilon_s = \widetilde{\nu}\,\overline{\omega'_k \omega'_k}$$

  - **All intermediate terms are also stored**
    - Strain rate and rotation tensors, velocity correlations, etc
  - **If homogeneous direction (e.g. cascade): spanwise + temporal average**
    - Resulting quantities represented by 2D polynomials functions in a plane (ParaView format)
    - Low memory footprint during computation, low disk storage and reduced post-processing burden

Instantaneous data at probes along the surface





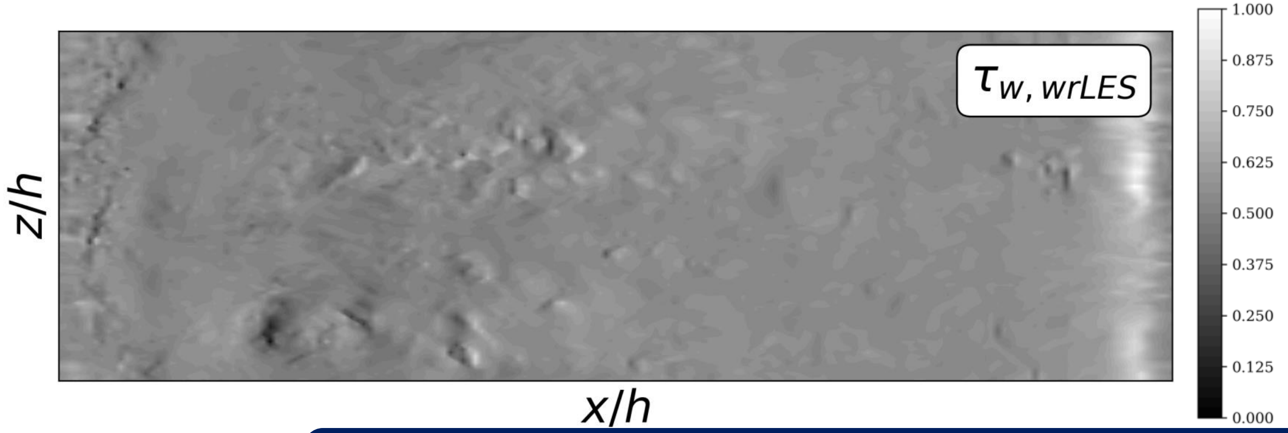
Solution and its gradients

- Boxho *et al.* (2022)

https://doi.org/10.1007/s10494-022-00365-3

- Boxho *et al.* (2025)

https://doi.org/10.1007/s10494-025-00641-y



Instantaneous wall shear stress on the surface

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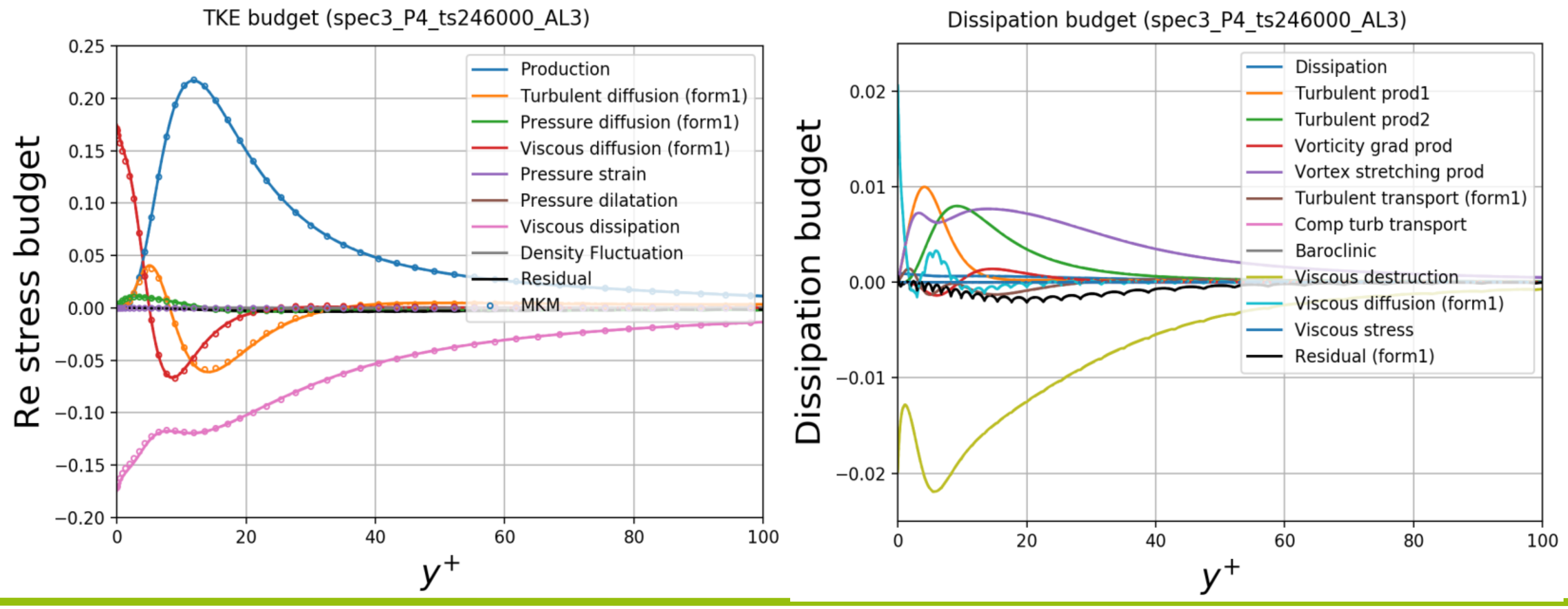
TKE and dissipation budget closure

- Channel flow test case at $Re_\tau = 180$
- TKE: validation against KMM

	Δx^+	Δy_1^+	max $\Delta y^+ = \Delta z^+$	Δz^+	DoFs (M)	t^+
spec1 DG-P3	10	0.5	5	5	16.8	28
spec1 DG-P4	10	0.5	5	5	14.6	22.5
spec3 DG-P4	6	0.25	4	4	39.8	28



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spec3 DG-P4	6	0.25	4	4	39.8	28

	TKE (max res/max prod)	Dissipation (max res/max viscous destruction)
spec1 DG-P3	0.051	0.208
spec1 DG-P4	0.033	0.117
spec3 DG-P4	0.015	0.078

Budget mathematically **closed**→must tend to **zero** with increased **resolution**

Solenoidal assumption→**budget** mathematically **not closed**

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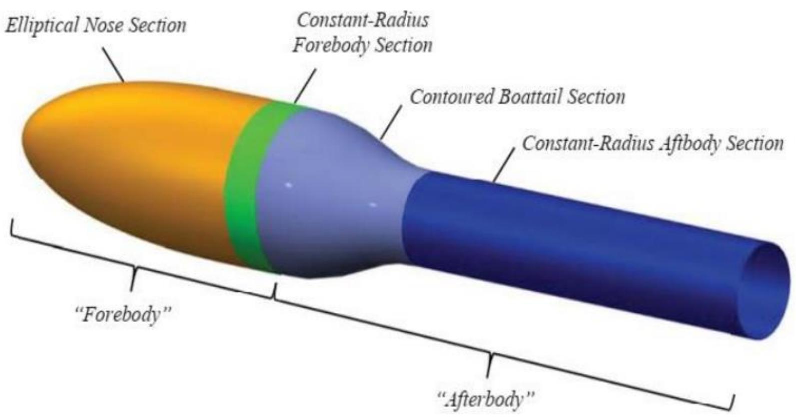
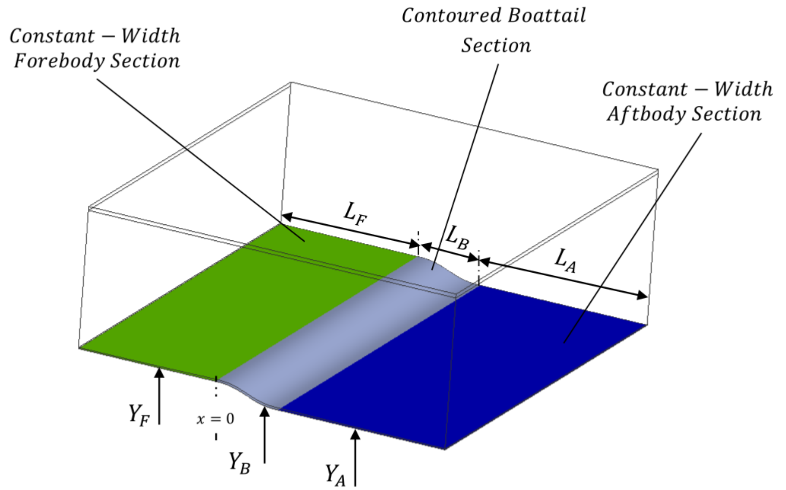
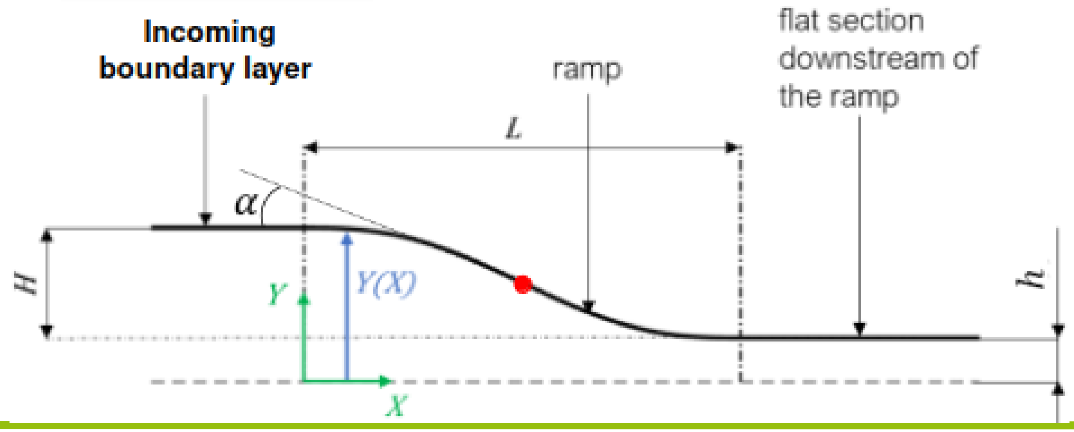
HiFi-Turb DLR rounded step
Ercoftac KB Wiki



Disodell and Rumsey (2017)
Simmons et al (2018)



HiFi-Turb DLR rounded step



Ramp: 5th order polynomial with zero 1st and 2nd derivatives at both ends

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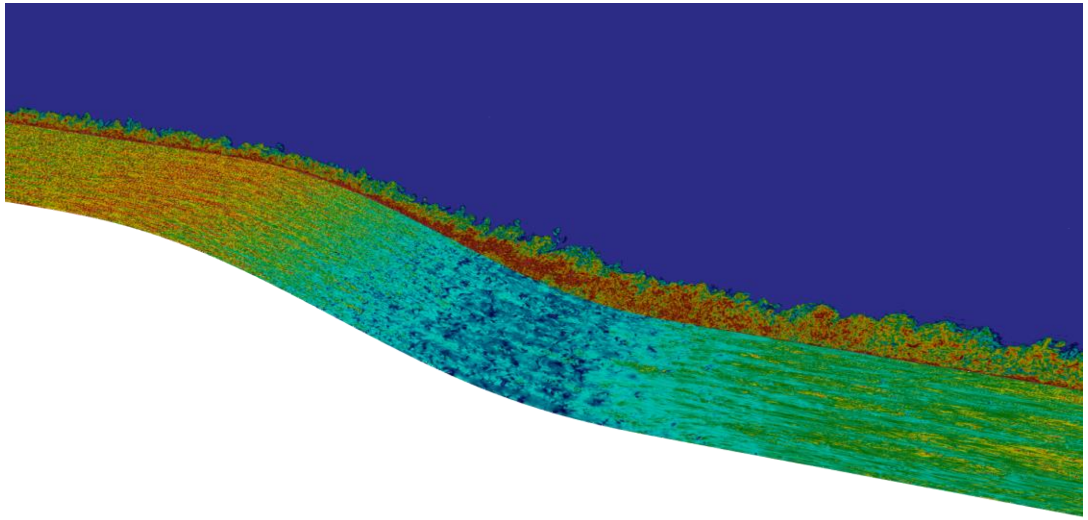
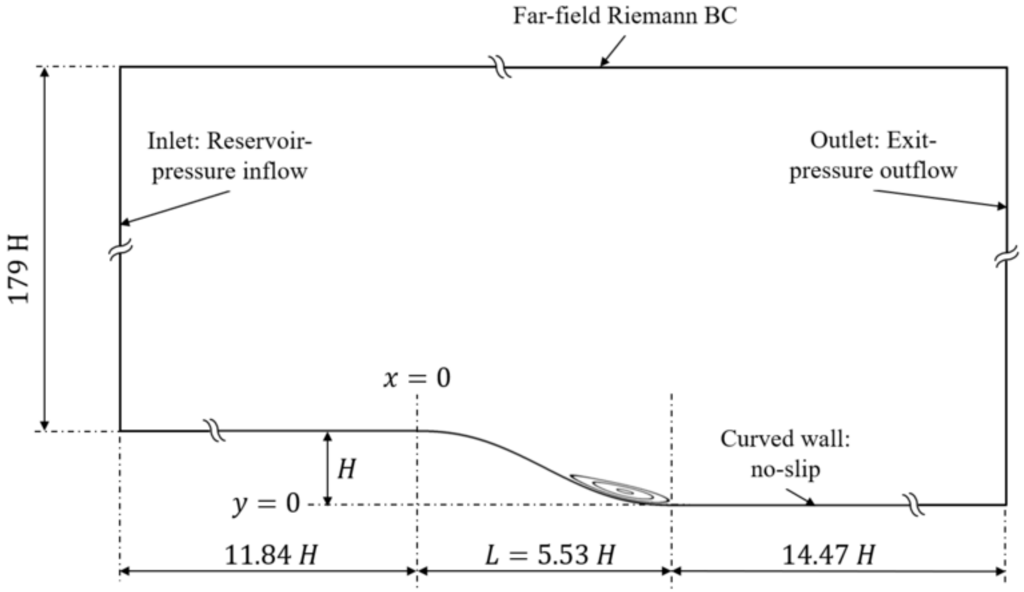
HiFi-Turb DLR rounded step

Ercoftac KB Wiki





Upstream flat plate	Blasius BL profile ($Re_{x,inlet}$ = 650 000)
Transition	Numerical tripping based on a source term proposed by Schlatter et al. (2012) -> harmonics in time and space (span)
Re_τ at the step	~700
Ma	~0.13
L, H and inlet U_∞	L fixed, 3 values for H, U_∞ fixed
H/L	0.181 (incipient separation) 0.226 (medium separation) 0.274 (full separation)
$Re_{\infty,L}$	434k
$Re_{\infty,H}$	78k (incipient), 98k (moderate), 119k (full)
Span length / H	3

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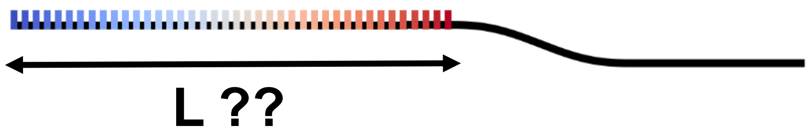
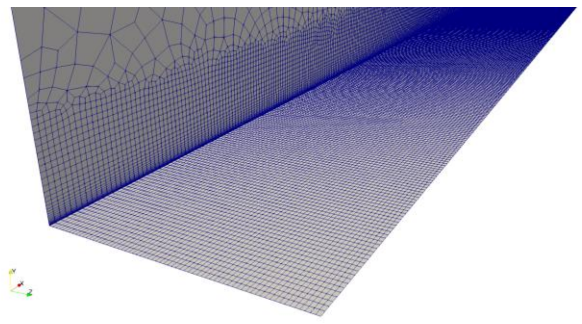
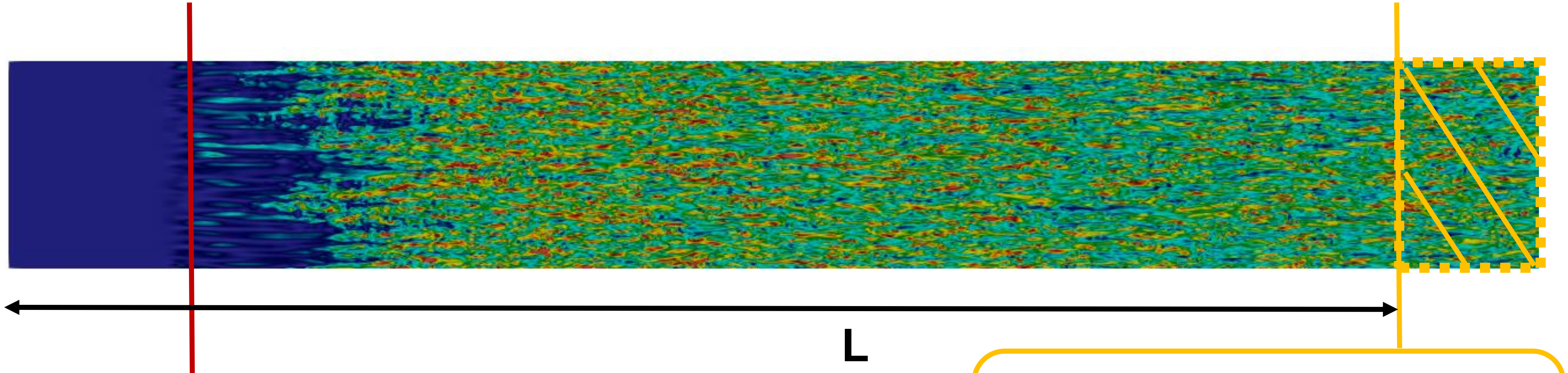
Length of the **flat plate region** upstream of the step ?

Determined using **a precursor flat plate simulation**







Calibrate the **tripping** source term to achieve the **target** $\mathbf{Re_\tau}$ at a reference point upstream of the step

Cut the flat plate domain at the **reference point** and **plug** the rounded **step**

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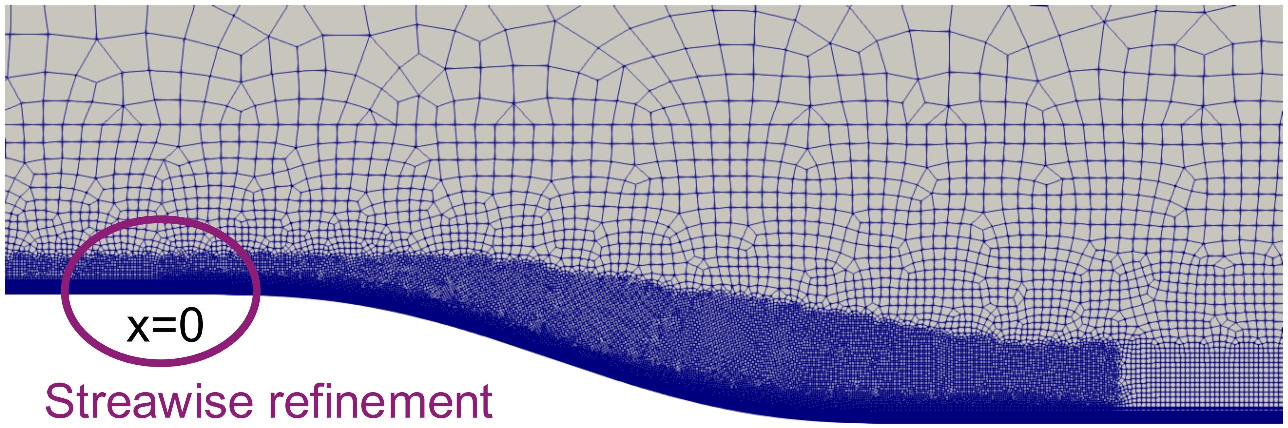
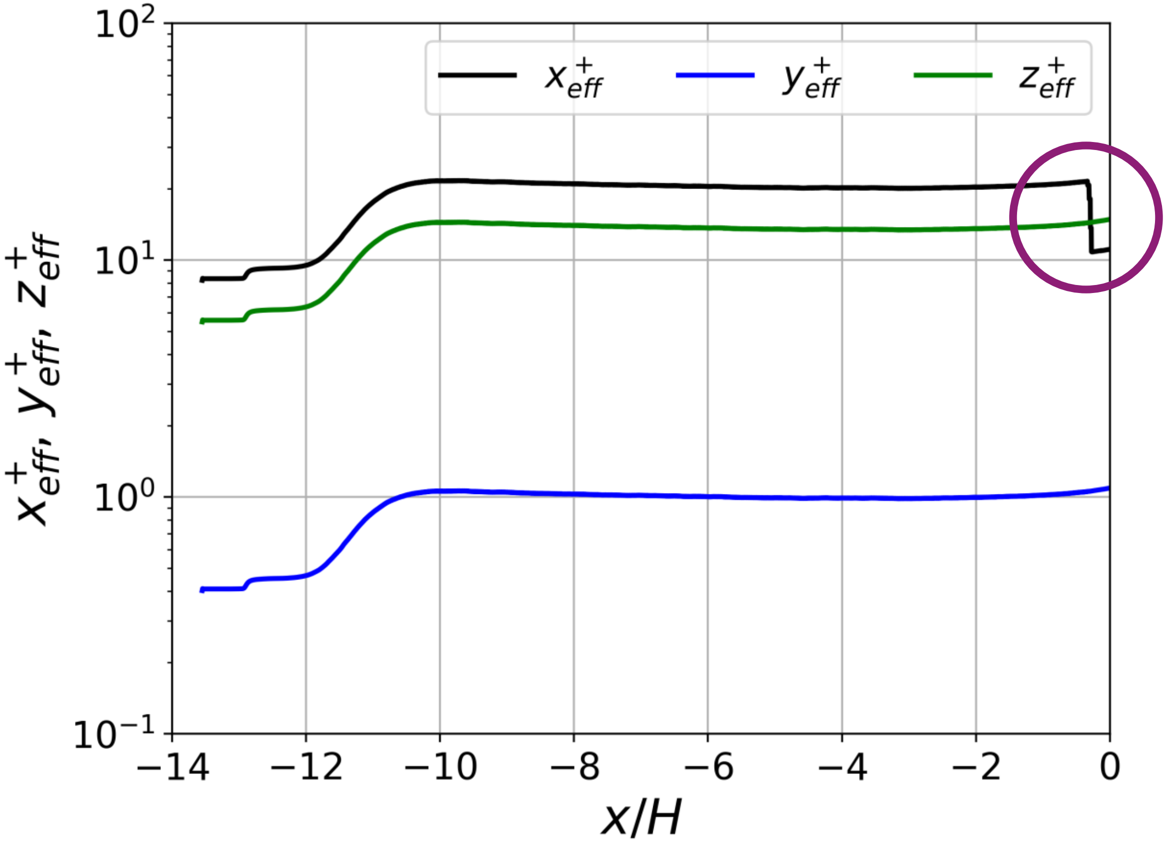
Simulation Methodology
Discretization for LES





- **Argo CFD solver**

- **Spatial discretization**
  - **DGM P4 (5th-order accurate)**
  - **Hybrid hex-dominant mesh: 55k x 188 = 10M hexes**
  - **Total: ~ 1.3B DoF/eq.**
  - **Near-DNS resolution**

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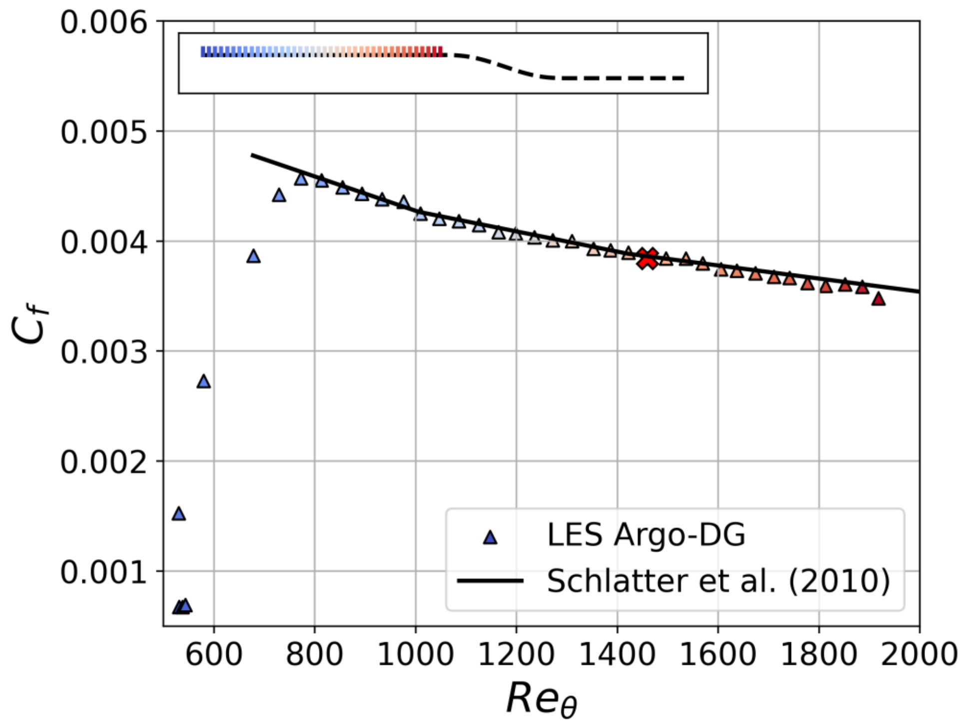
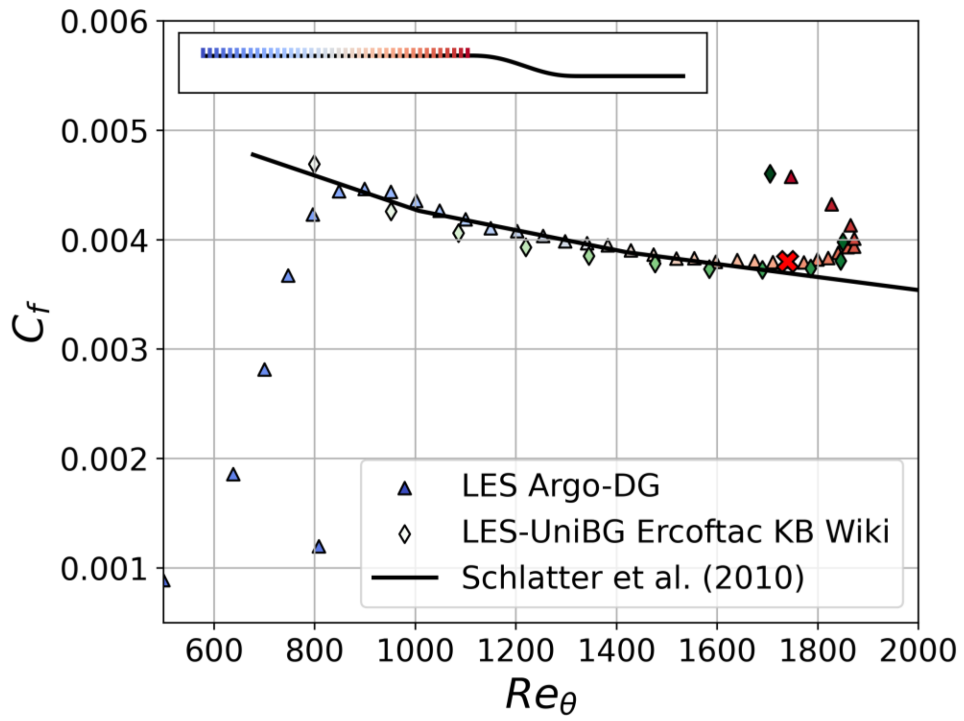
- **Analysis** of the **flat plate with and without** the presence of the **rounded step: C_f vs Re_θ**





Good agreement with the DNS of Schlatter *et al.* (2010), all along the flat plate.

Good agreement up to the **reference point** (red cross), then the C_f increases indicating an **acceleration** of the TBL combined with a **reduction** in the **momentum thickness.**

✖ = Reference point

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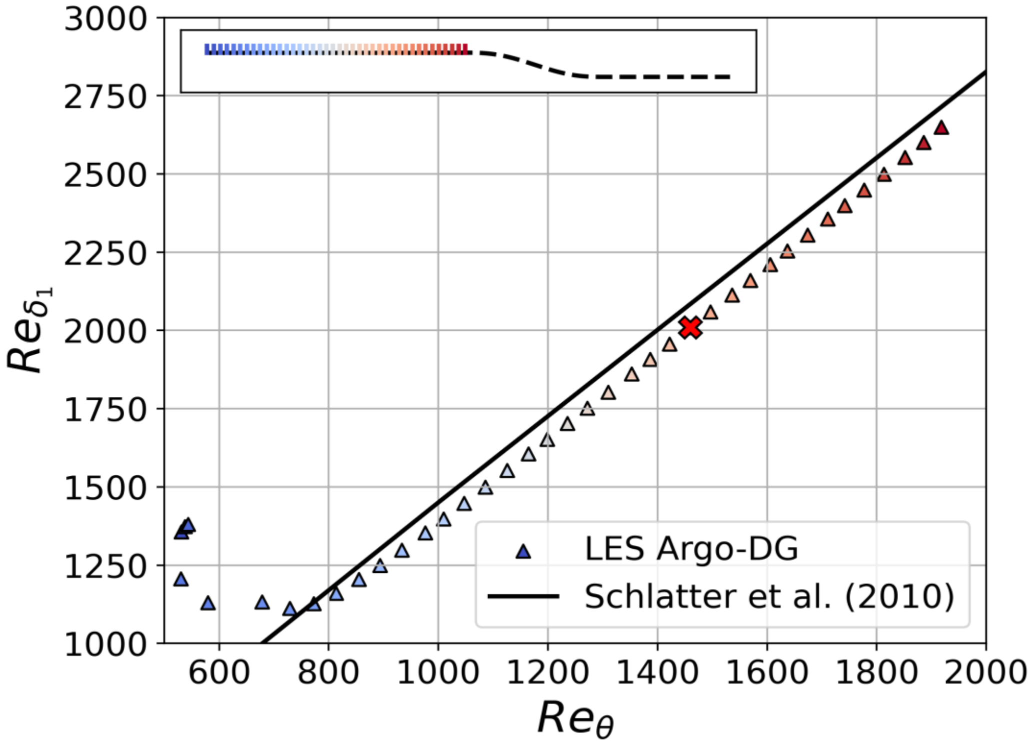
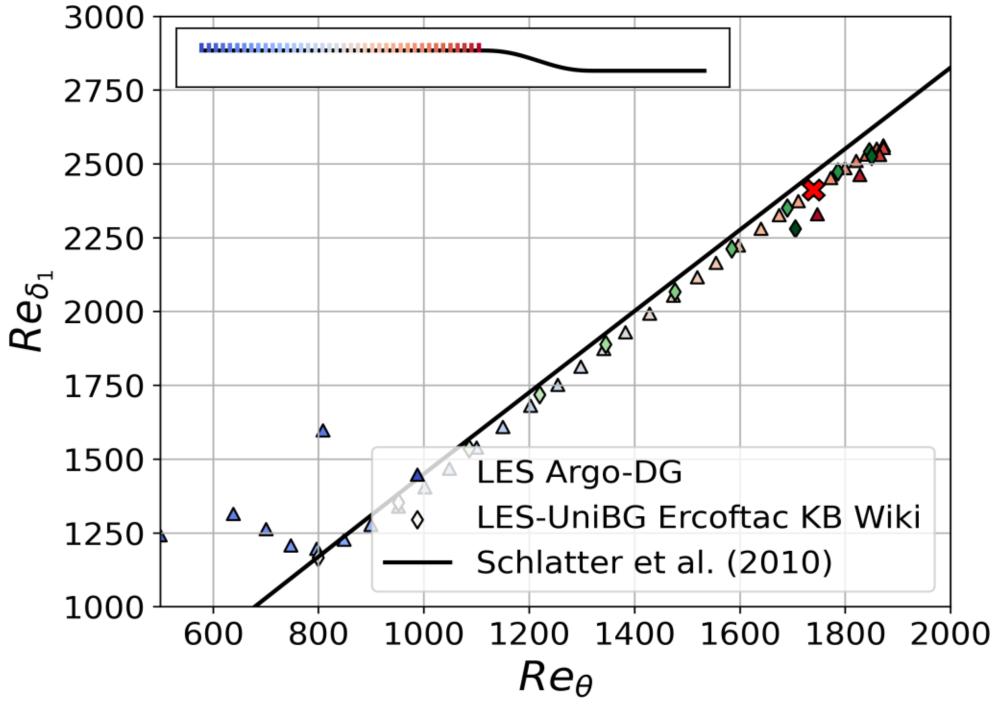
- **Analysis** of the **flat plate with and without** the presence of the **rounded step:** $\mathbf{Re_{\delta 1}}$ **vs** $\mathbf{Re_{\theta}}$





Small offset with the DNS of Schlatter *et al.* (2010) due to BC.

Good agreement up to the **reference point** (red cross), then BL thicknesses are reduced.

✖ = Reference point

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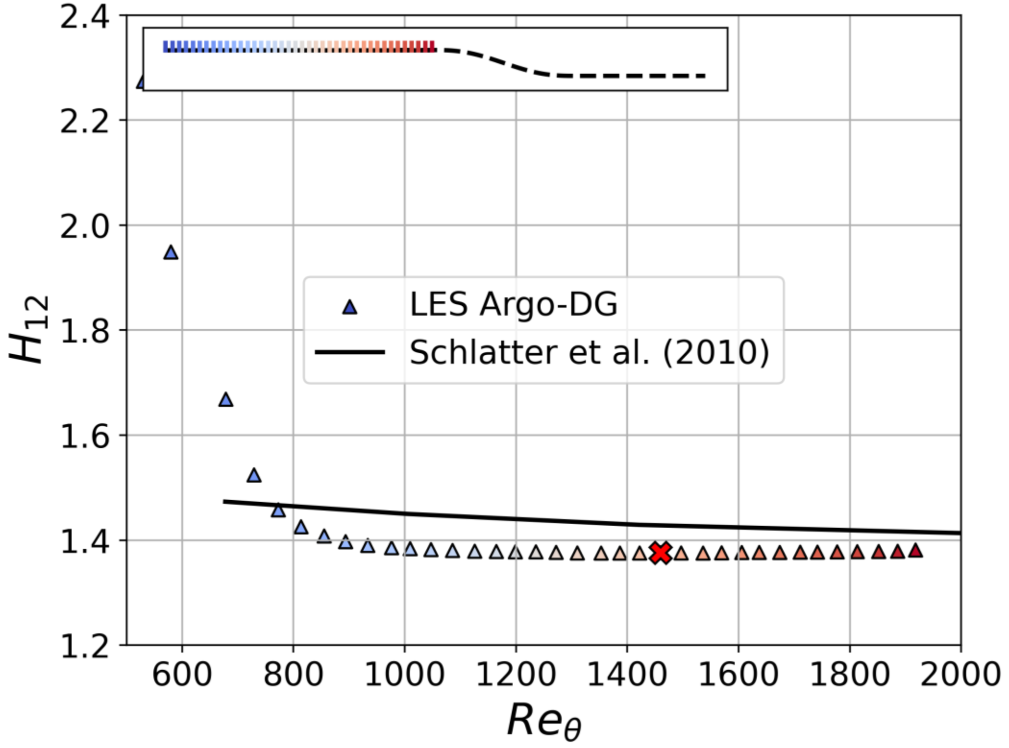
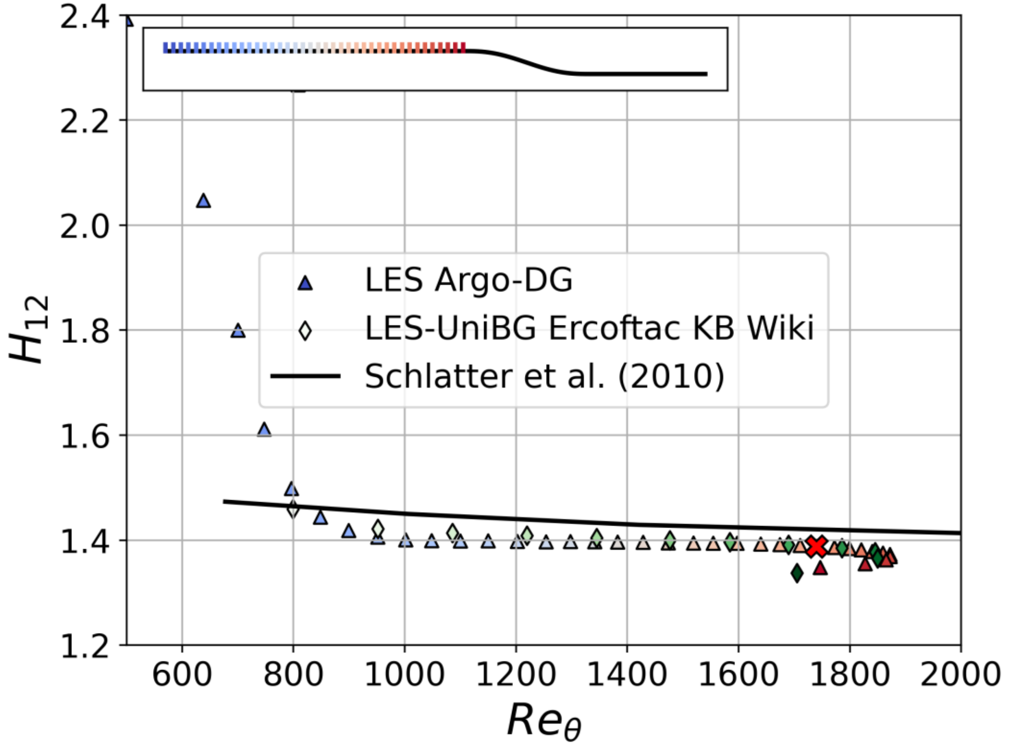
- **Analysis** of the **flat plate with and without** the presence of the **rounded step: H_{12} vs Re_θ**





Underestimation of H_{12} compared with the DNS of Schlatter *et al.* (2010) due to BC.

Smaller H_{12} also observed in the LES from UniBG upstream the step, likely due to the pressure gradient

✖ = Reference point

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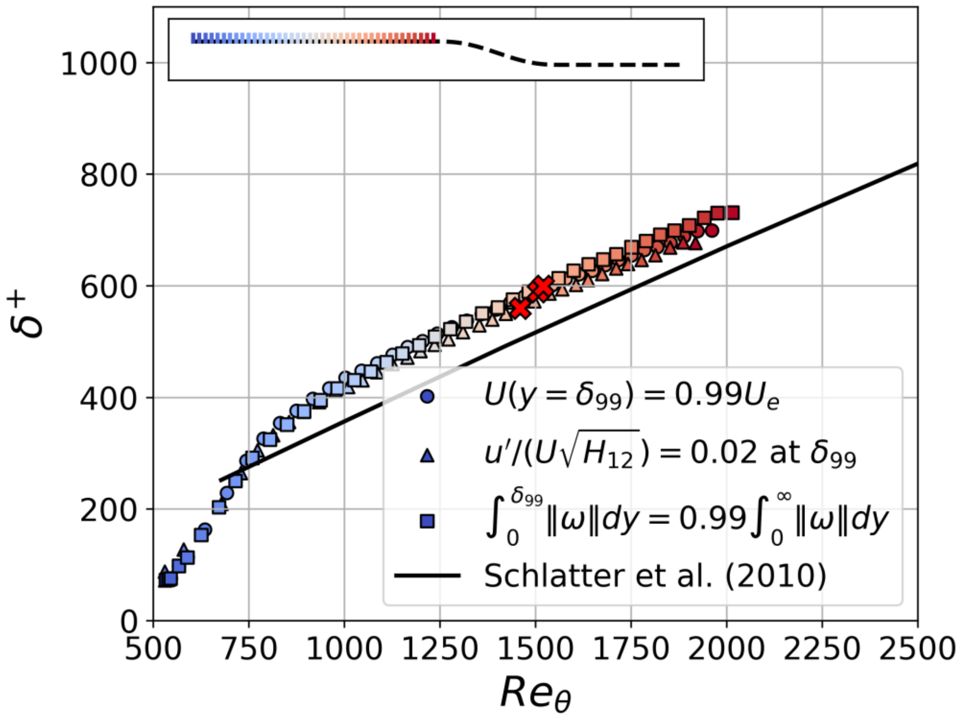
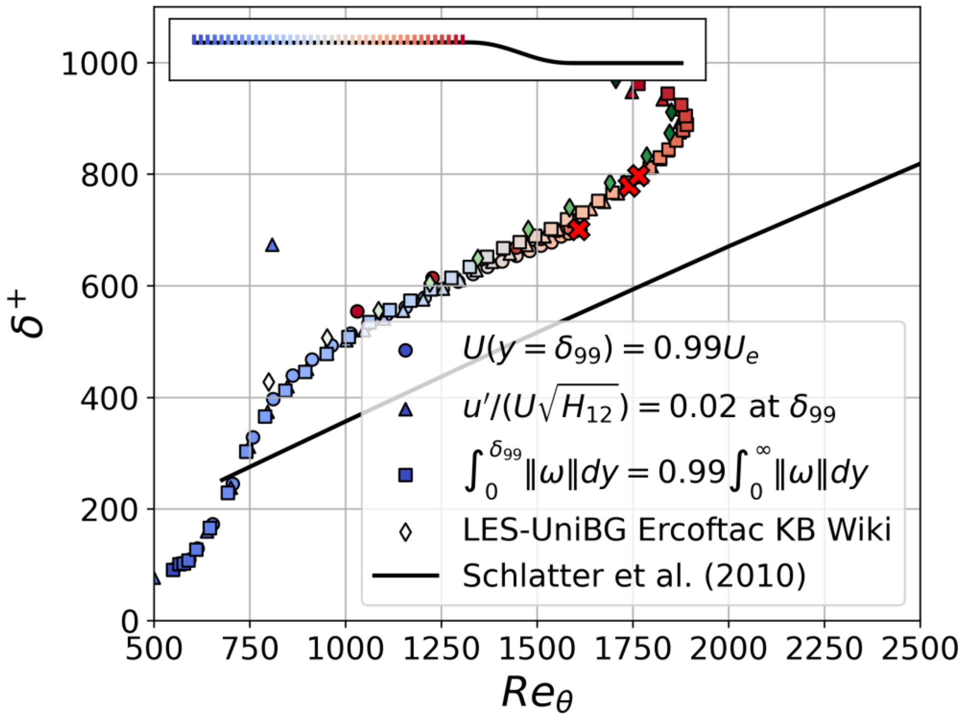
- **Analysis** of the **flat plate with and without** the presence of the **rounded step: Re_τ vs Re_θ**





The **diagnostic plot** (Vinuesa *et al.*,2016) gives the **closest** results compared to the DNS of Schlatter *et al.* (2010), but a **small offset** is still visible (BC) .

The **diagnostic plot** and **vorticity** method produces the **correct far-field velocity** once the **rounded step effect** becomes effective.

✖ = Reference point

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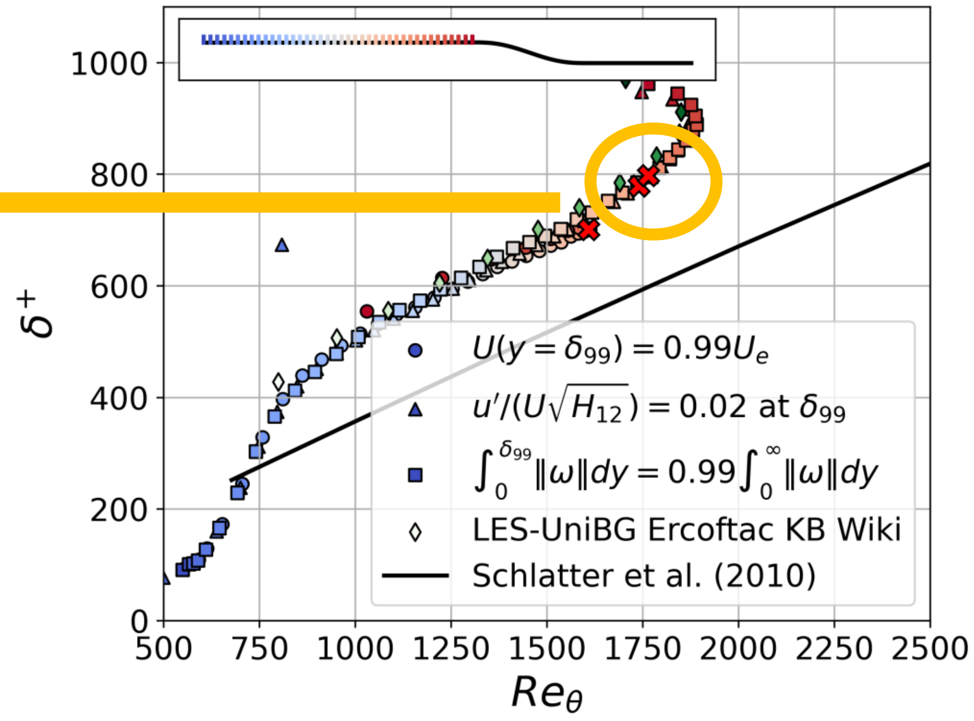
- **Analysis** of the **flat plate with and without** the presence of the **rounded step: Re_τ vs Re_θ**

	x=-3.5H ✖	x=0
Re_τ	766	947
Re_θ	1711	1747
δ_{99} / H	0.185	0.208

✖ = Reference point



The **diagnostic plot** and **vorticity** method produces the **correct far-field velocity** once the **rounded step effect** becomes effective.

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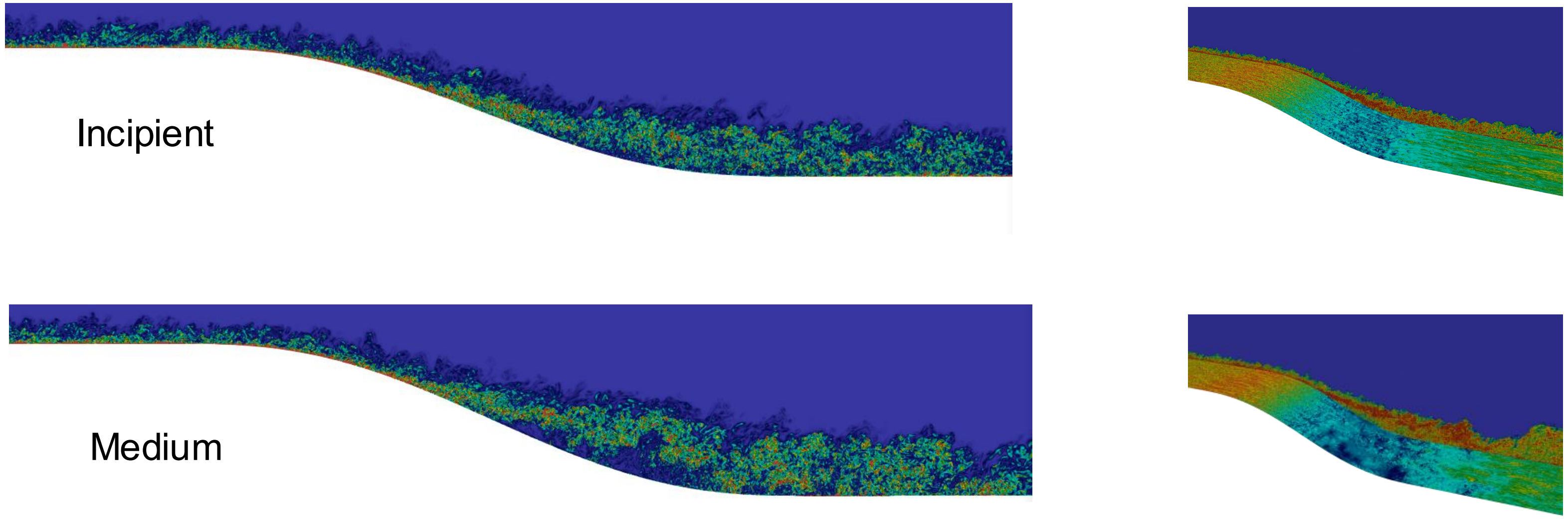
Conclusions and Perspectives

- Assessment of the mesh requirements for budget closure on a channel
- Ongoing generation of a high-fidelity database for the HiFi-Turb DLR rounded step with adverse pressure gradient ongoing
- Analysis of the upstream boundary layer to assess inflow conditions
- Current focus on the incipient separation case; extension to medium separation planned
- Databases can serve as a reference for turbulence model improvement



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HiFi-TURB

ROSAS

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Wallonie

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Wallonie

- For computational resources, we acknowledge
  - **PRACE** for awarding the access to JUWELS hosted by GSC at FZJ, Germany.
  - The **EuroHPC Joint Undertaking** for awarding this project access to the EuroHPC supercomputer LUMI, hosted by CSC (Finland) and the LUMI consortium, and the EuroHPC supercomputer VEGA hosted by IZUM (Slovenia) through EuroHPC Regular Access calls.
  - **EuroCC Belgium** for awarding this project access to the LUMI supercomputer, owned by the EuroHPC Joint Undertaking, hosted by CSC (Finland) and the LUMI consortium

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