DTU

Challenges in wind tunnel measurements and CFD simulations of LER effects at high Reynolds numbers

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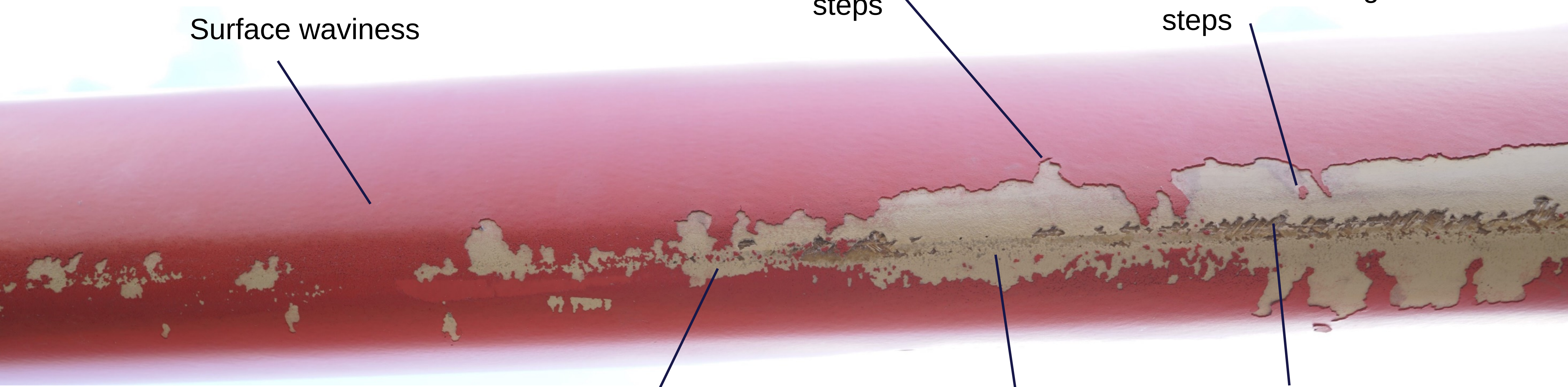
DTU Wind & Energy Systems

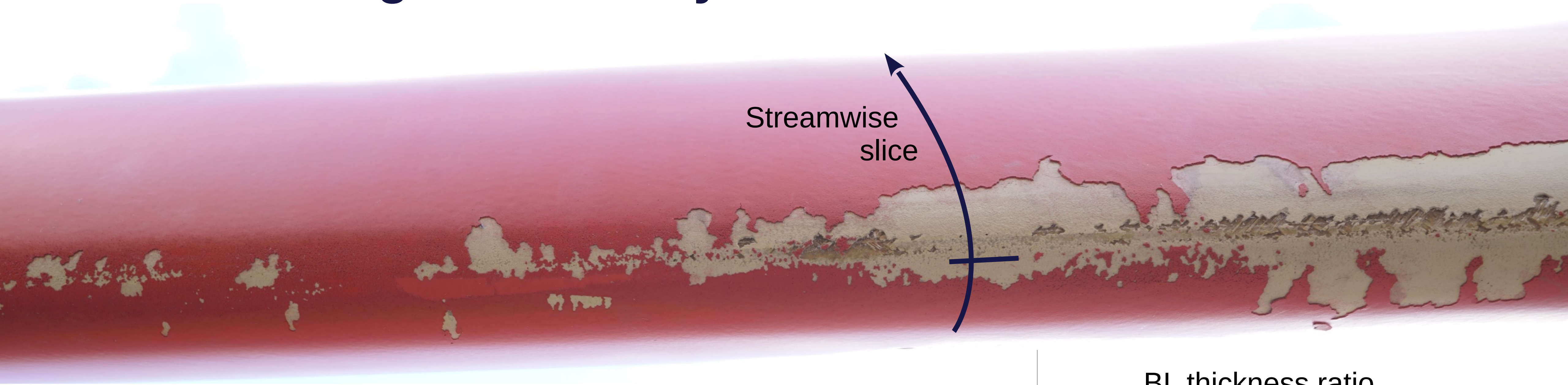
Blade roughness

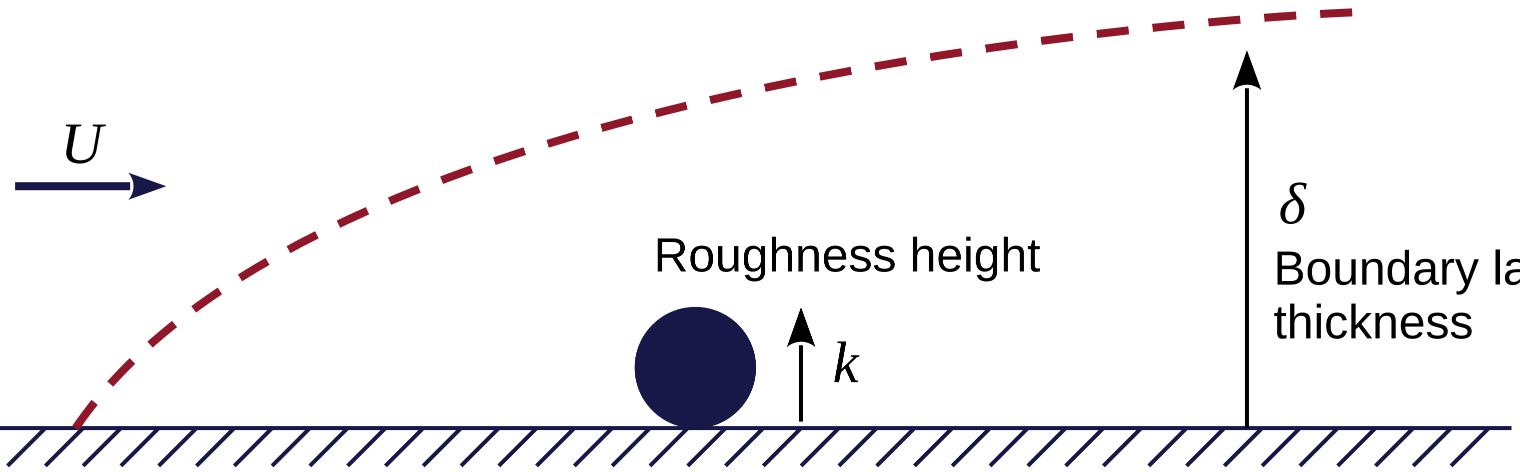
Blade roughness



+ contamination (insects, pollen ..)

Blade roughness & Reynolds number





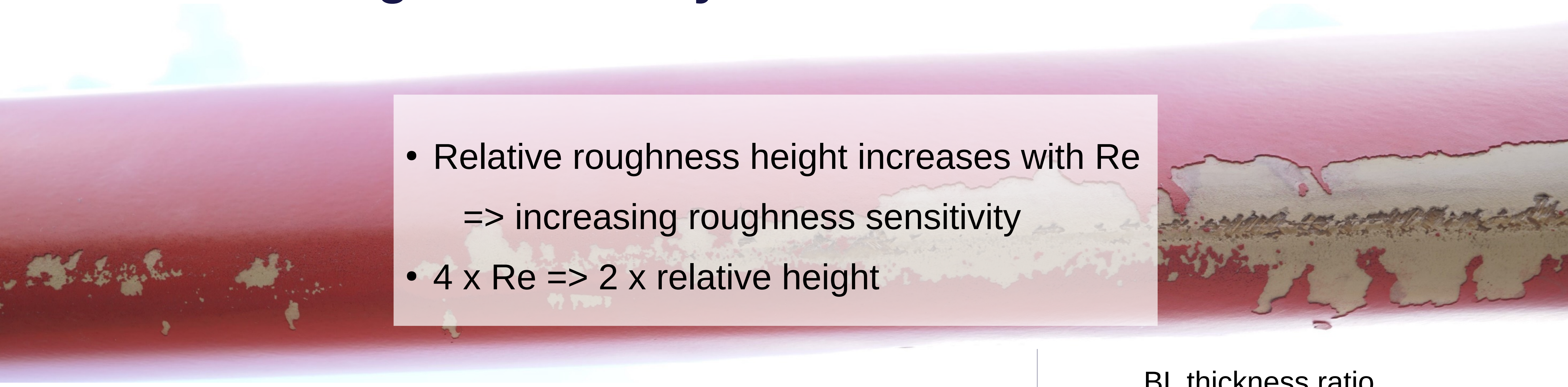
BL thickness ratio

$$\frac{\delta_1}{\delta_2} = \sqrt{\frac{\mathrm{Re}_2}{\mathrm{Re}_1}}$$

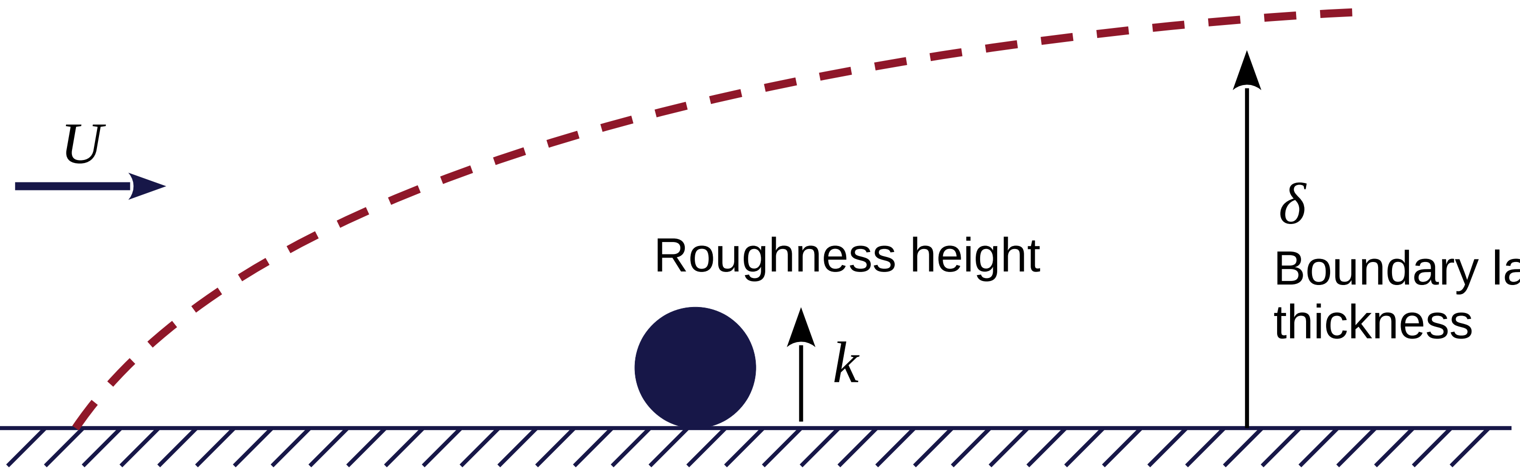
Relative roughness height

$$\frac{k}{\delta_2} = \frac{k}{\delta_1}\sqrt{\frac{\mathrm{Re}_2}{\mathrm{Re}_1}}$$

Blade roughness & Reynolds number



- Relative roughness height increases with Re
  => increasing roughness sensitivity
- 4 x Re => 2 x relative height



BL thickness ratio

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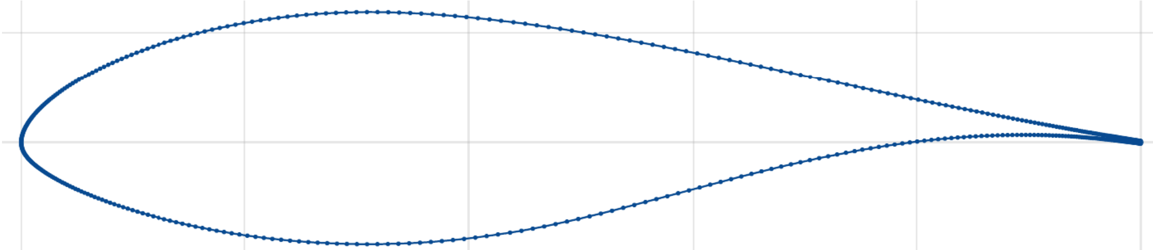
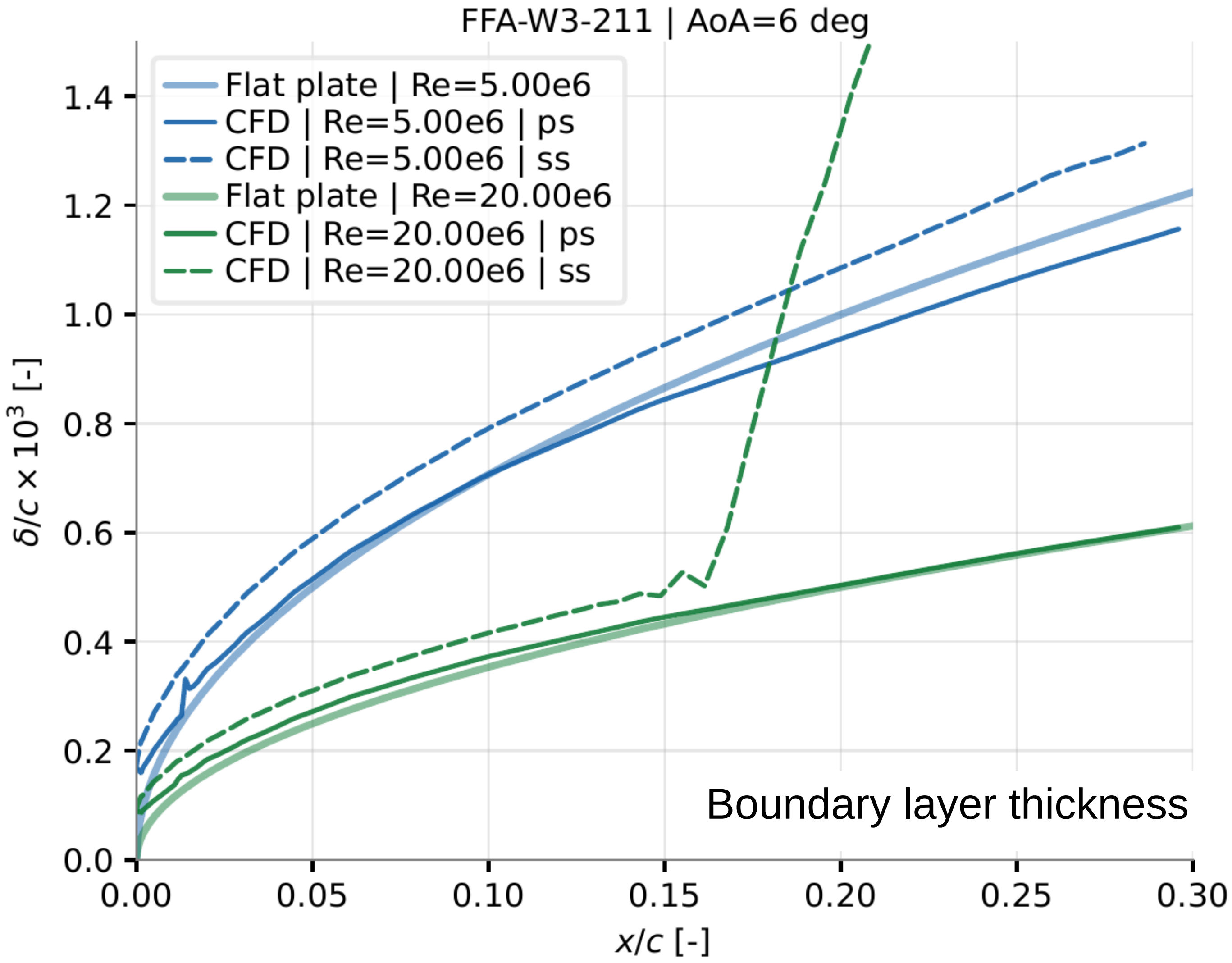
Relative roughness height

$$\frac{k}{\delta_2} = \frac{k}{\delta_1}\sqrt{\frac{\mathrm{Re}_2}{\mathrm{Re}_1}}$$

Example: FFA-W3-211

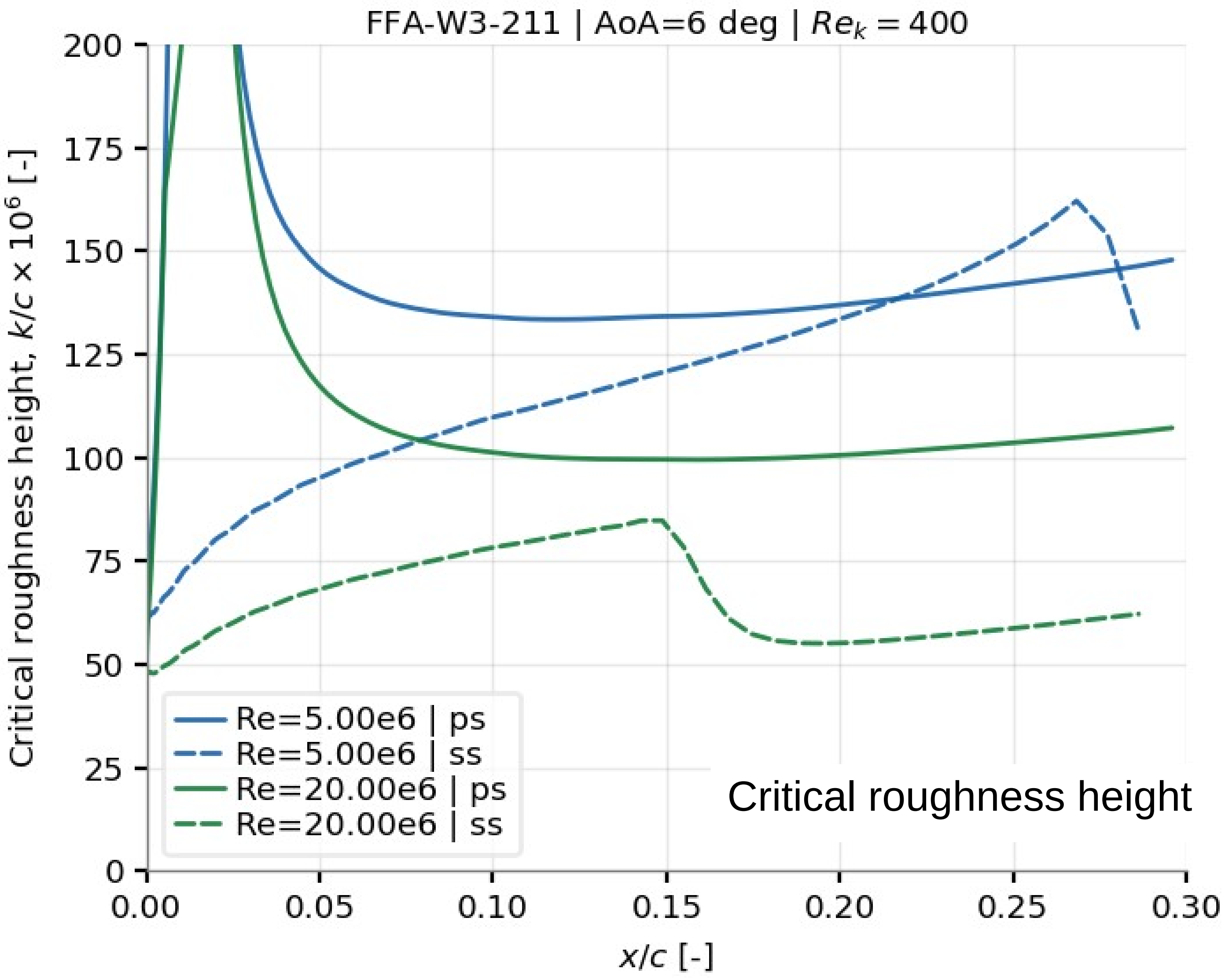




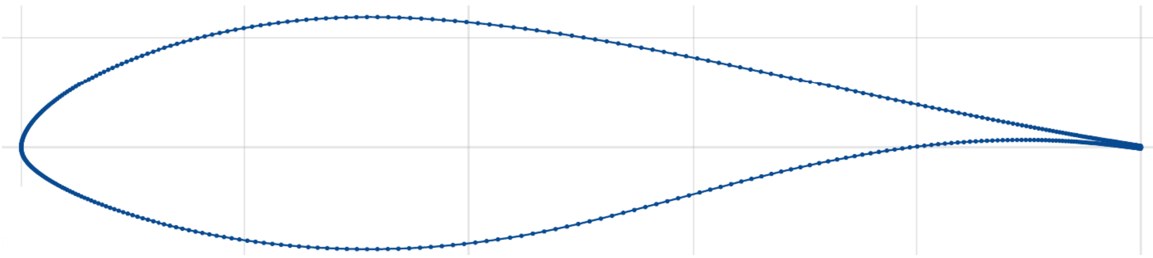
EllipSys2D RANS-CFD

- Incompressible
- k-ω SST
- Structured O-mesh
- 512 chordwise x 256 normal
- Fully automatized workflow: PyE2Dpolar

Critical roughness height



Critical roughness height



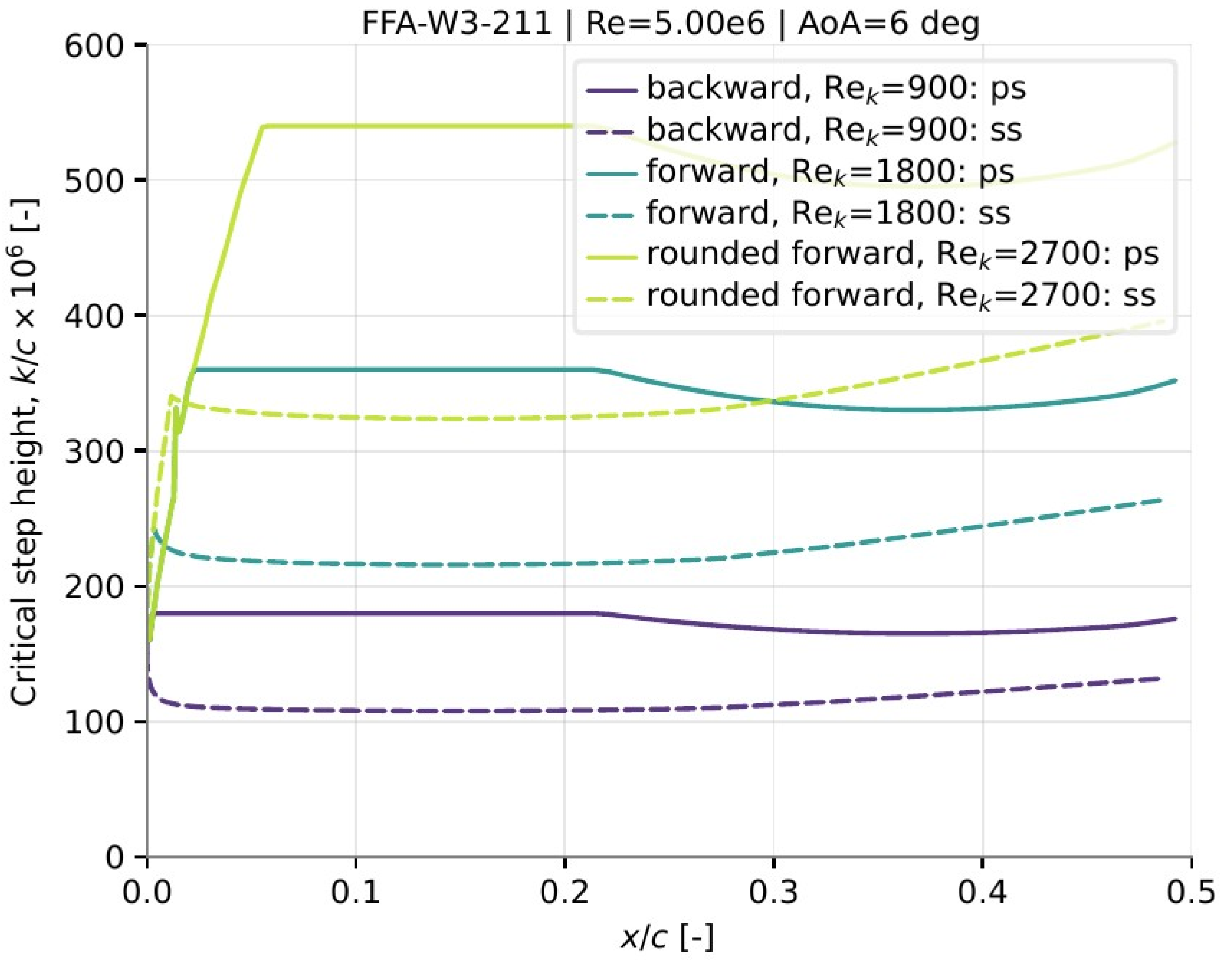
Roughness Reynolds number

$$Re_k = \frac{u(k)k}{\nu}$$

Critical step height

Nenni-Gluyas (1966), Schrauf (2022)

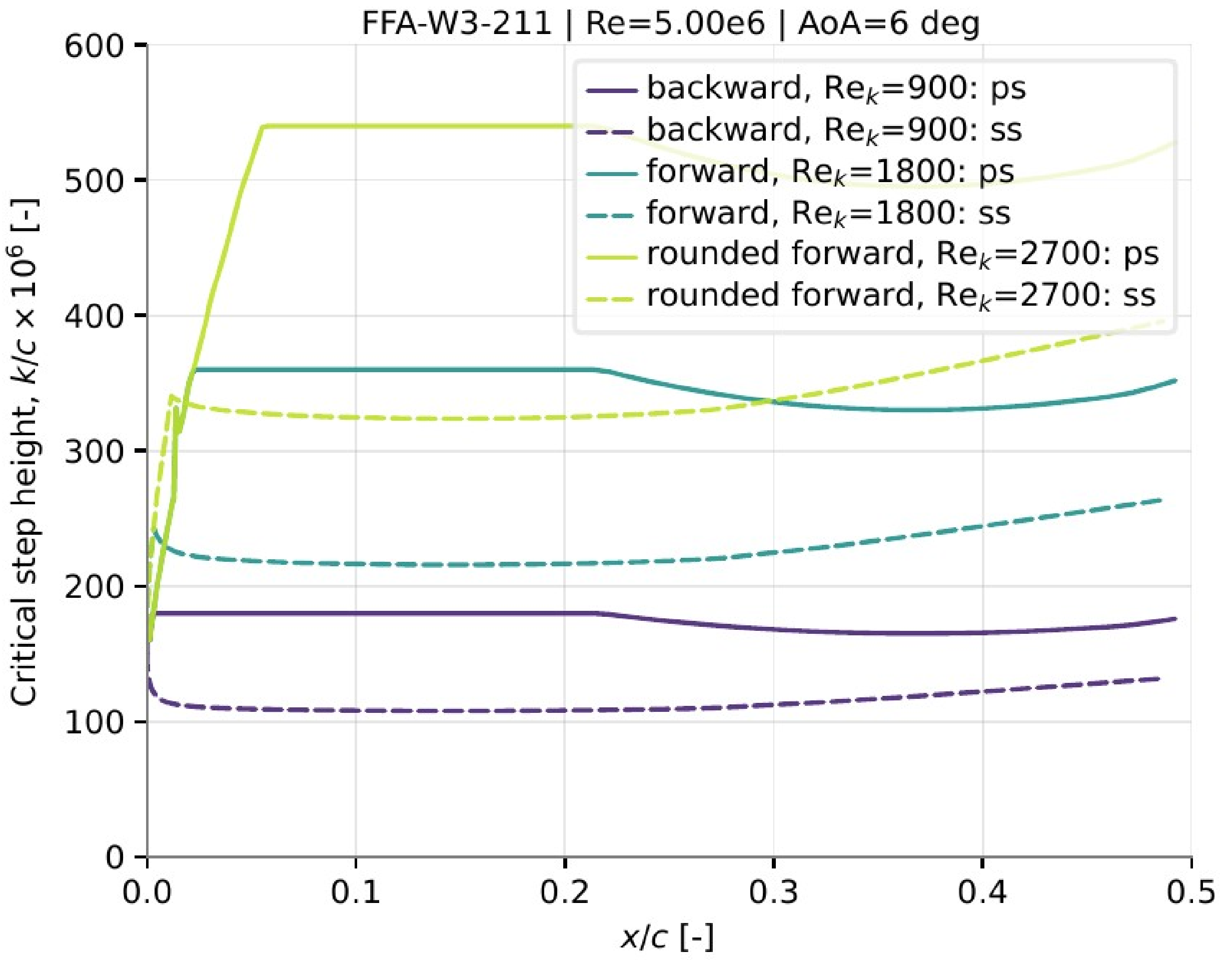
$$\mathrm{Re}_k = \frac{U_e k}{\nu}$$

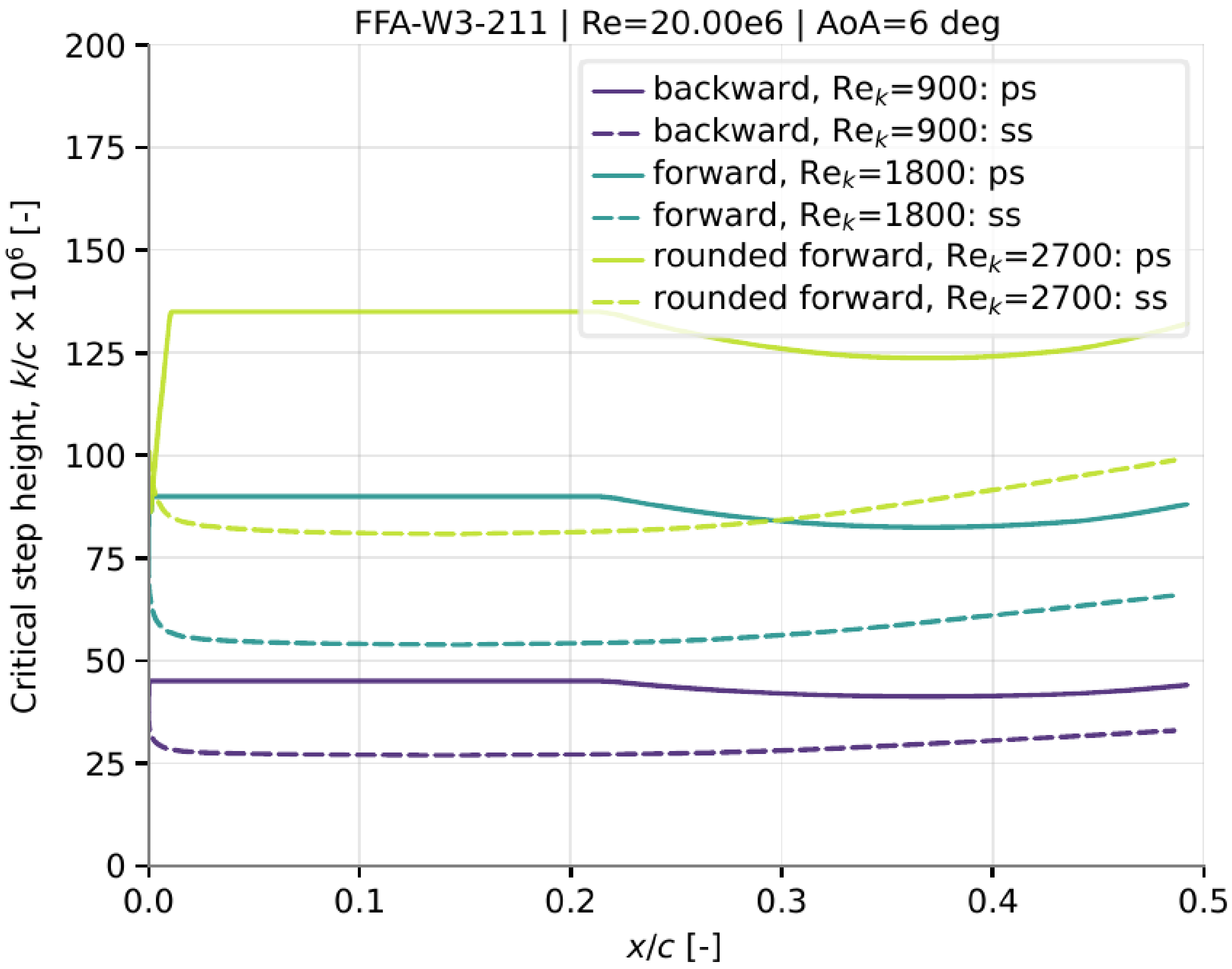


Critical step height

Nenni-Gluyas (1966), Schrauf (2022)

$$\mathrm{Re}_k = \frac{U_e k}{\nu}$$



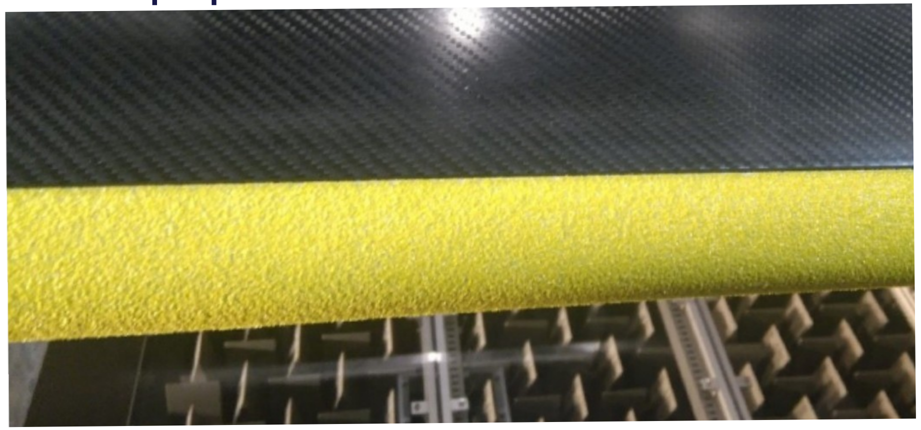


Conventional roughness modelling in ...

Wind tunnels

Zig-zag tape

Sand paper



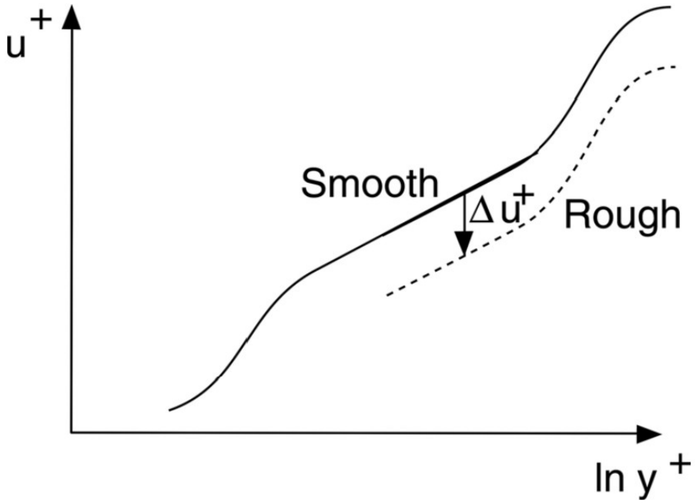
CFD

Trip functions

- Explicit triggering of turbulent production
- Modifications to transition criteria

Rough wall models

- Set non-zero turbulent eddy viscosity at wall
- Relies on equivalent sand grain roughness



Conventional roughness modelling in ...

Wind tunnels

Zig-zag tape

- Needs to shrink with Reynolds number

Sand paper

- (Needs to shrink with Reynolds number)
- Sand paper is not standardized
- Backward facing step

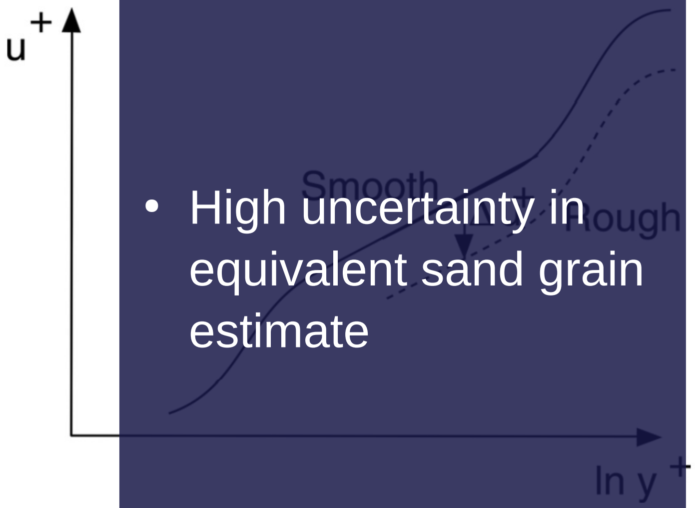
CFD

Trip functions

- Explicit triggering of turbulent production
- Modifications to transition criteria

Rough wall models

- Set non-zero turbulent eddy viscosity at wall
- Relies on equivalent sand grain roughness



… and its challenges

- Transition location known a priori
- High uncertainty in equivalent sand grain estimate

Conventional roughness modelling in ...

Wind tunnels **CFD** **… and its challenges**

But do our approaches apply to real-world LER?

Do we need to resolve LER in more detail?

(especially considering ↑ Re)

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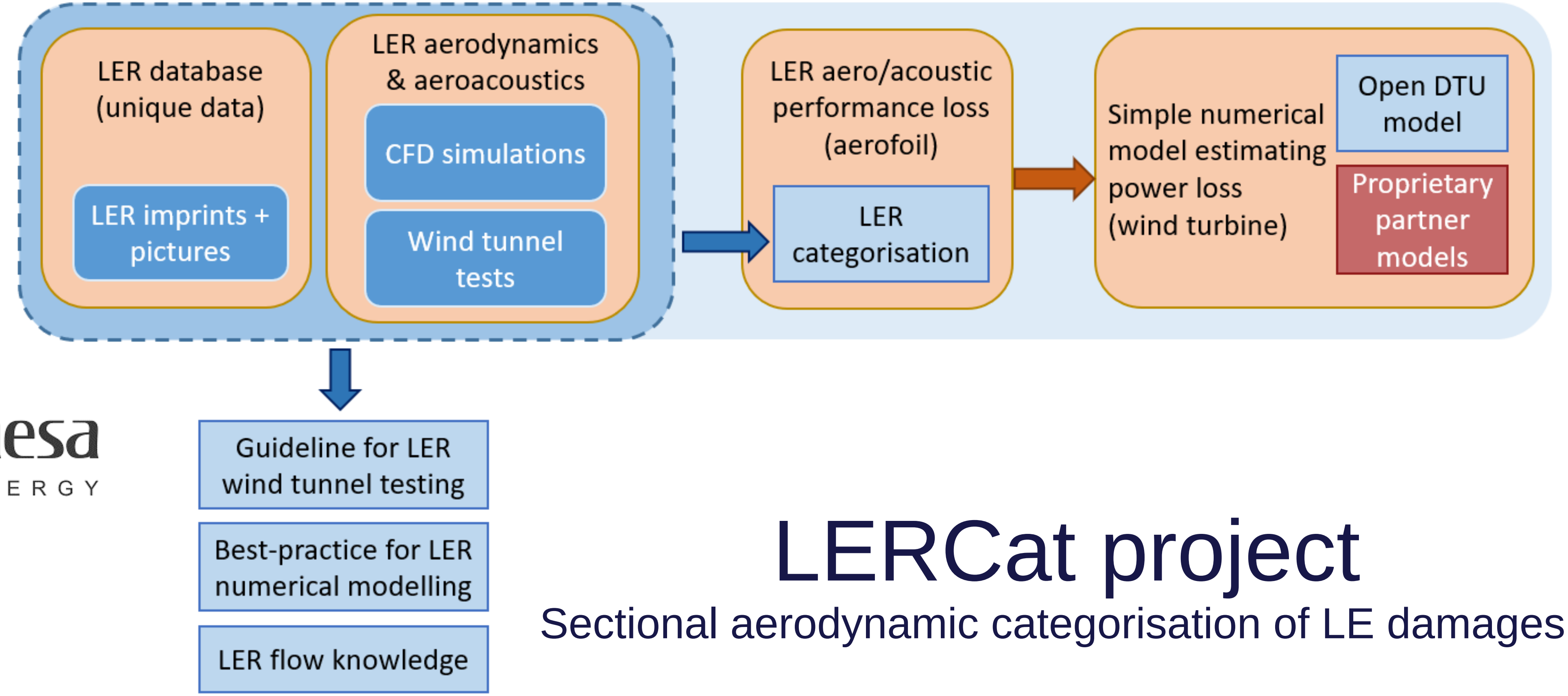
Vestas

SIEMENS Gamesa RENEWABLE ENERGY

LM WIND POWER a GE Renewable Energy business

SUZLON

PowerCurve



LERCat project

Sectional aerodynamic categorisation of LE damages

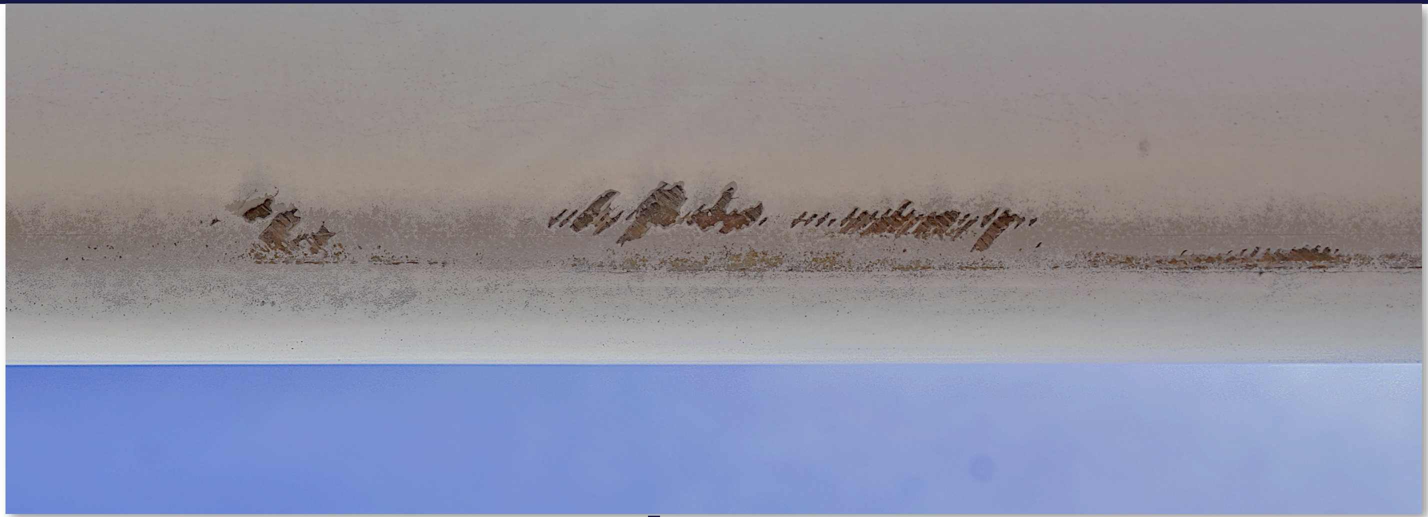
EUDP

Project duration: March 2022 to June 2025

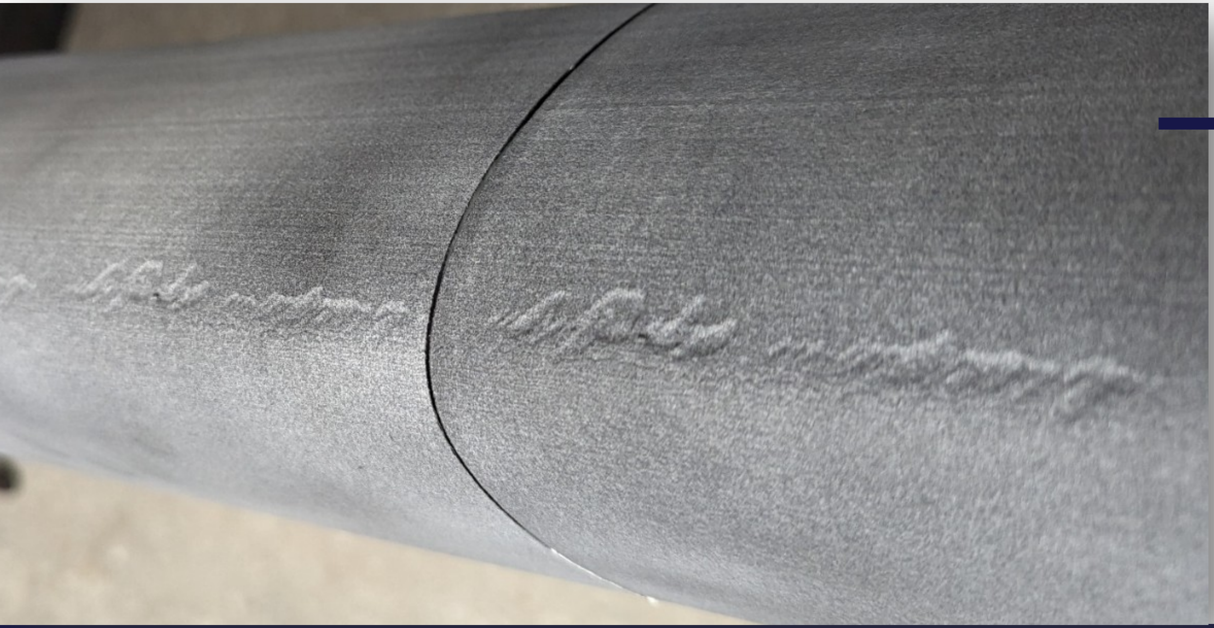
Funding: EUDP (Energy Technology Development & Demonstration)

Danish Ministry of Climate, Energy and Utilities

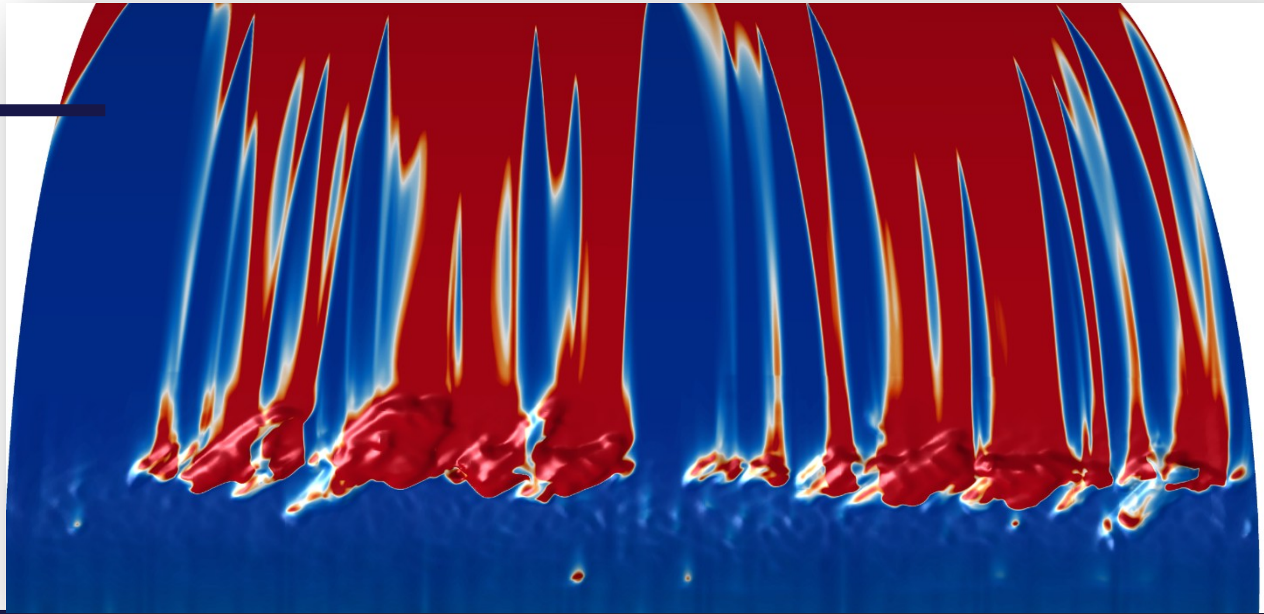
Digital LER



Wind tunnel



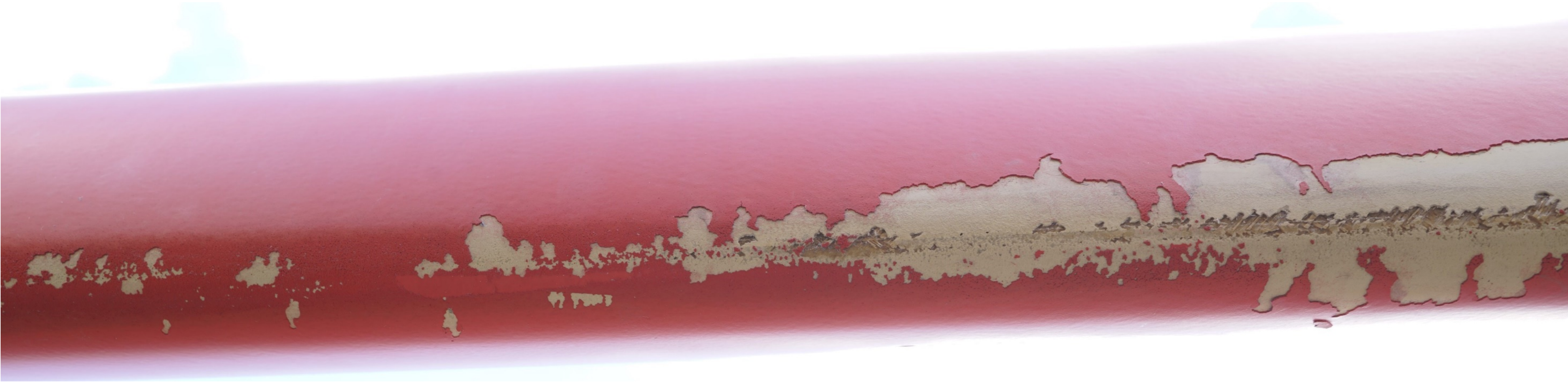
CFD



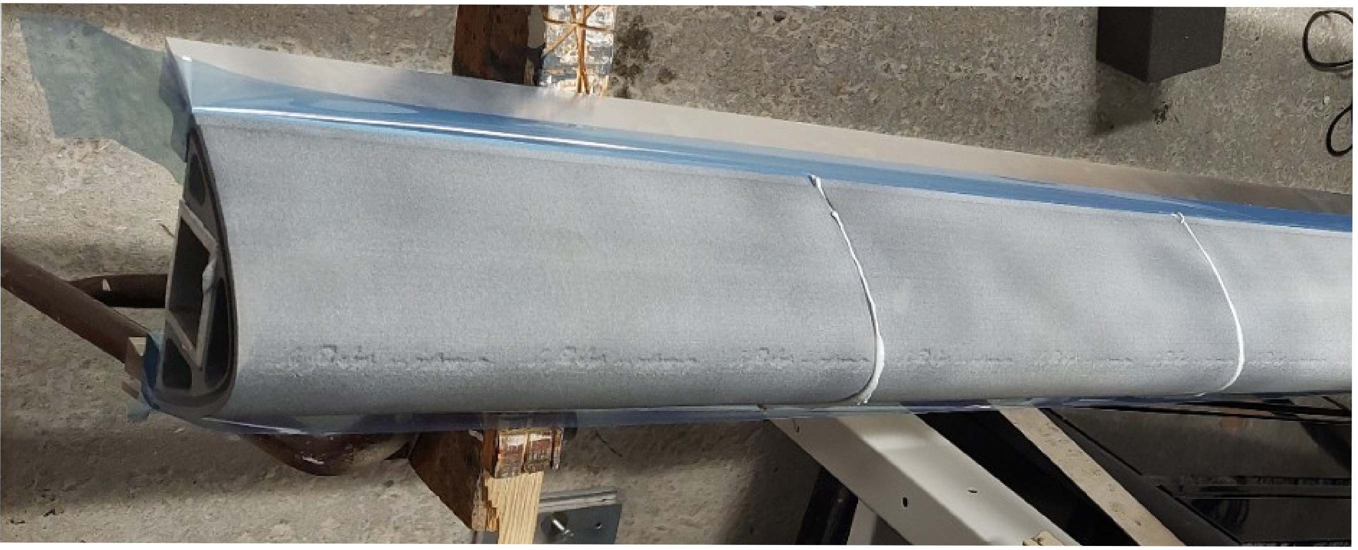
LERCat wind tunnel model

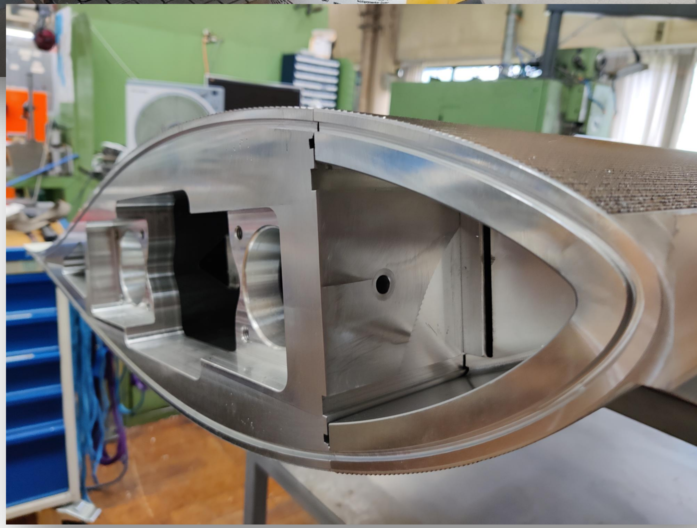
Design criteria

- Reynolds number 3 – 7 million
- Open profile coordinates (shareable)
- Enable testing multiple LER samples
- Enable IR imaging (transition)
- Enable acoustic measurements



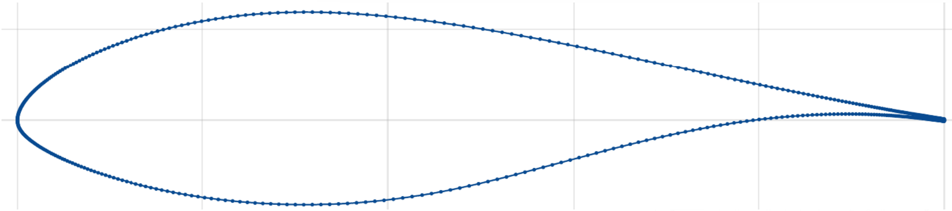
LERCat wind tunnel model





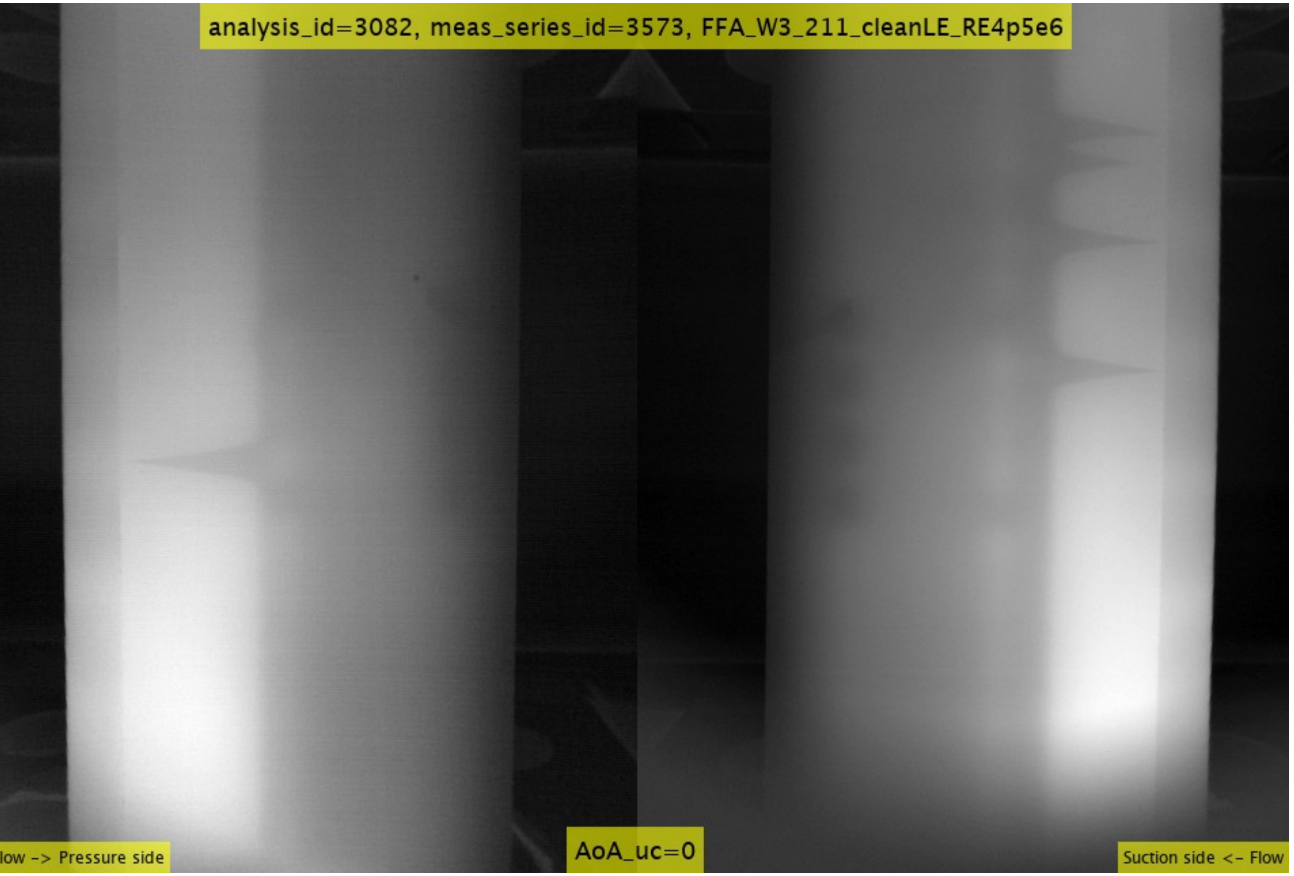
Final design

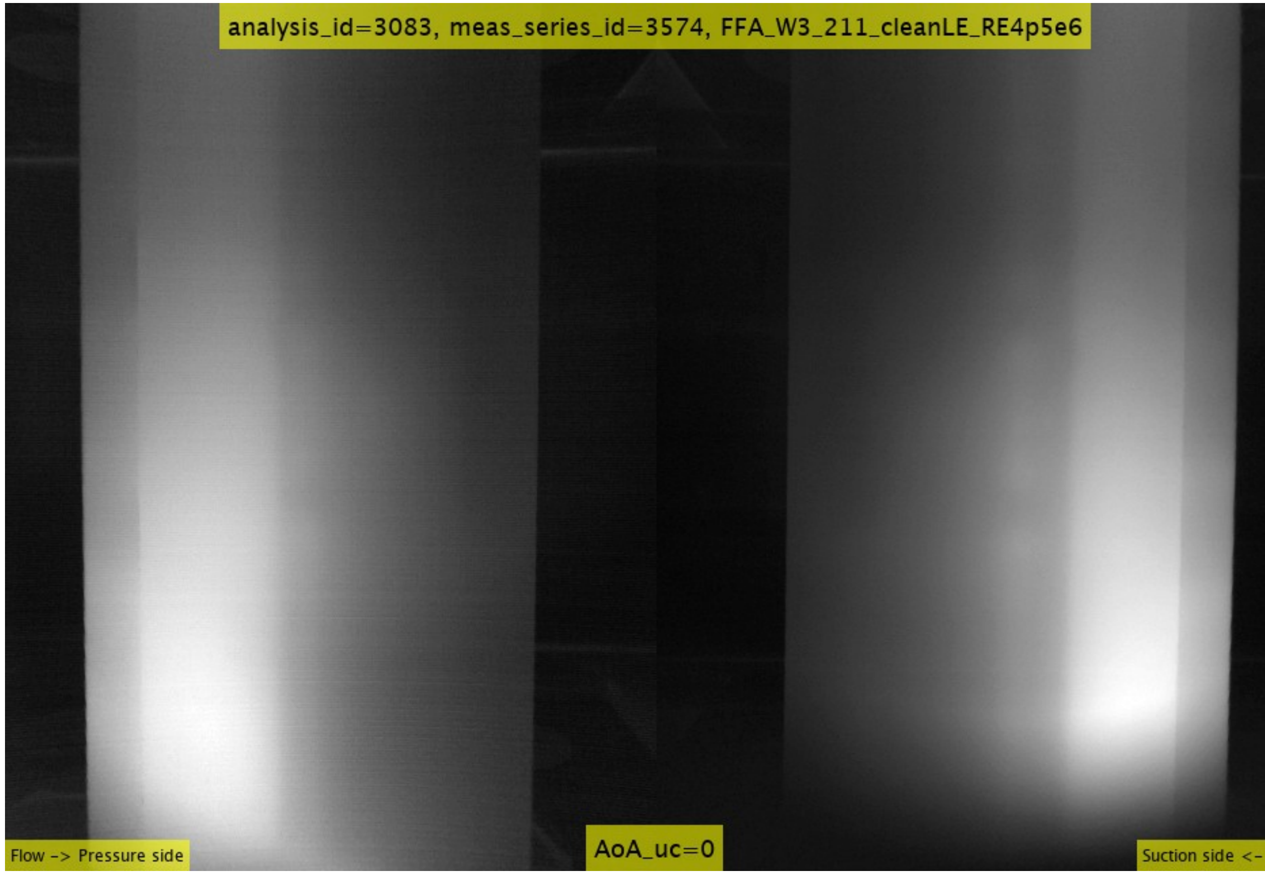
- FFA-W3-211
- Chord: 0.9 m (Re=3 – 6 million)
- Span: 2 m
- Exchangeable LE
  - 3D printed LER (7 x 285mm span, MJF) mounted on AL base
  - Joints at x/c=0.1 (XLE-AL base) + x/c=0.15 (AL base-main body)
- Heated main body



Clean validation - Aluminium LE

Before and after sanding with P1200





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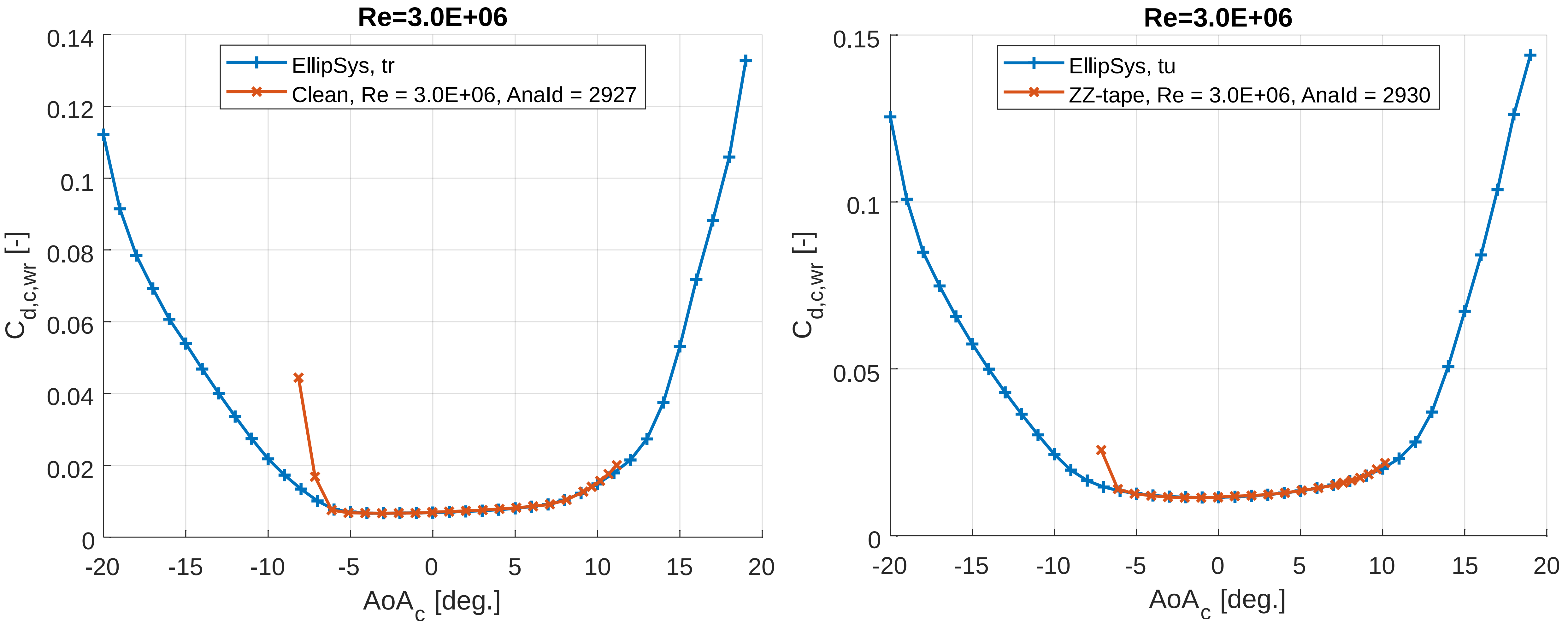
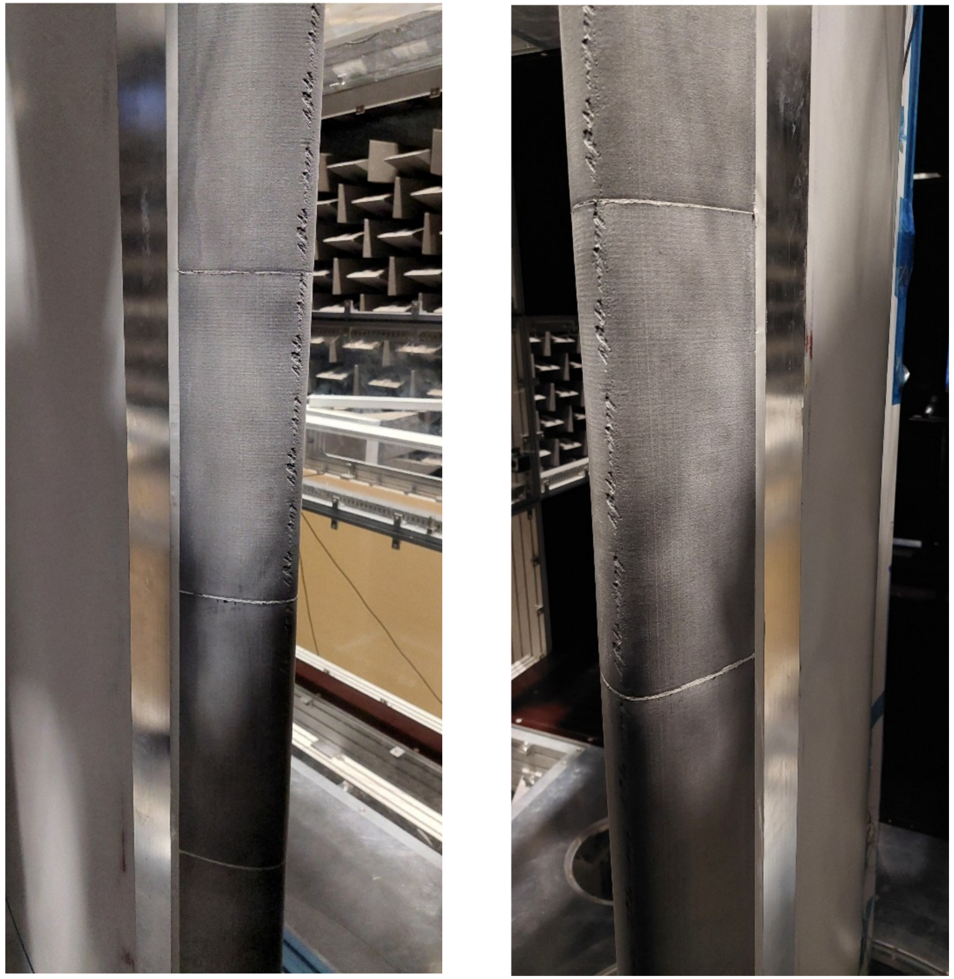
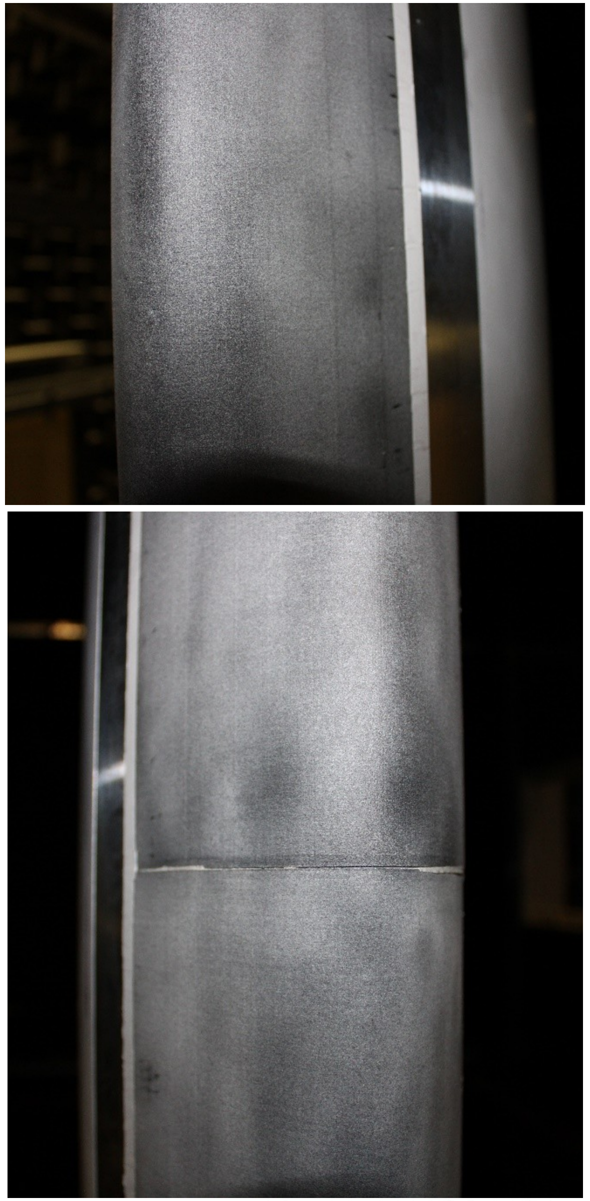


XLE LER samples

XLE LER-2



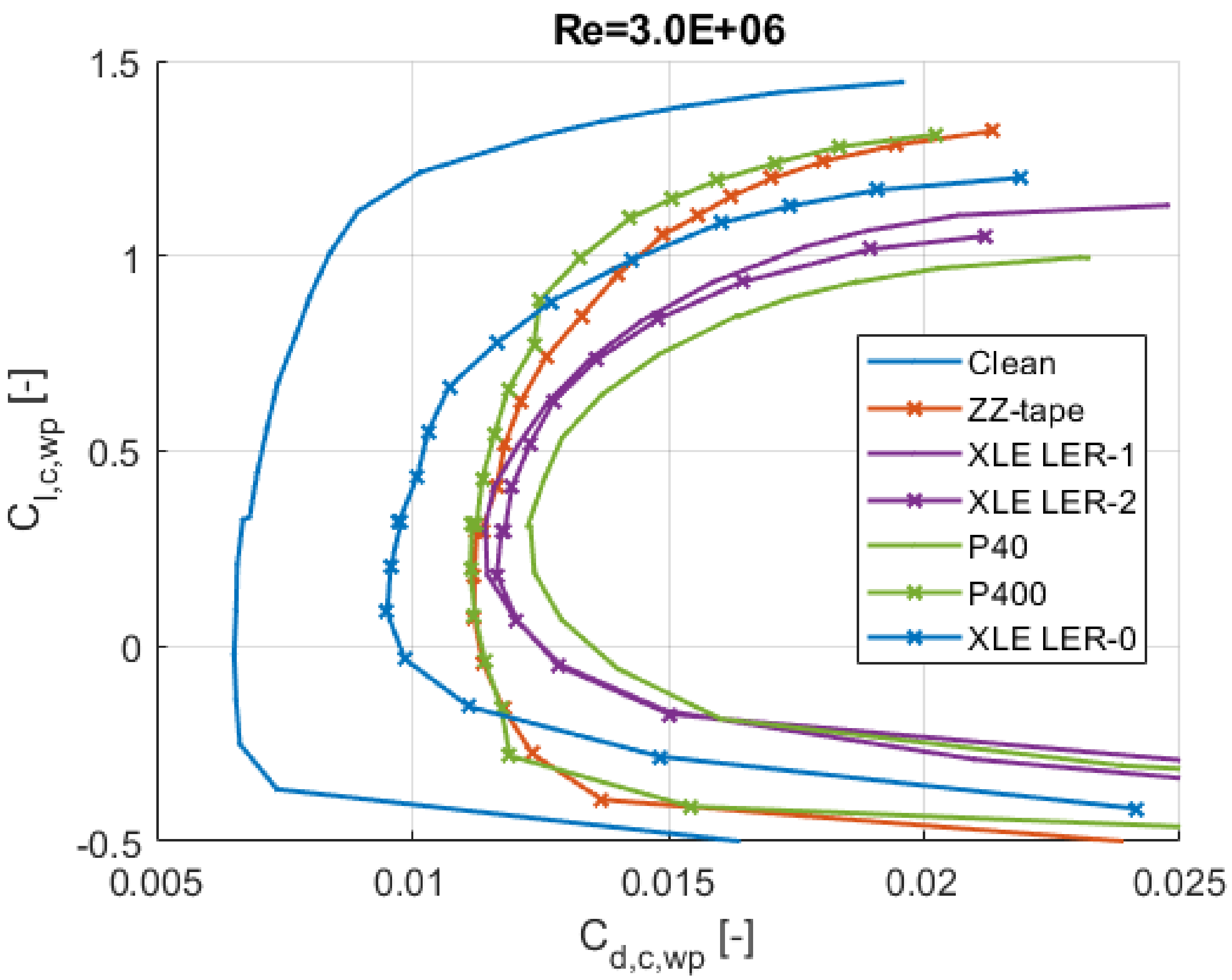
XLE LER-1



XLE LER-0

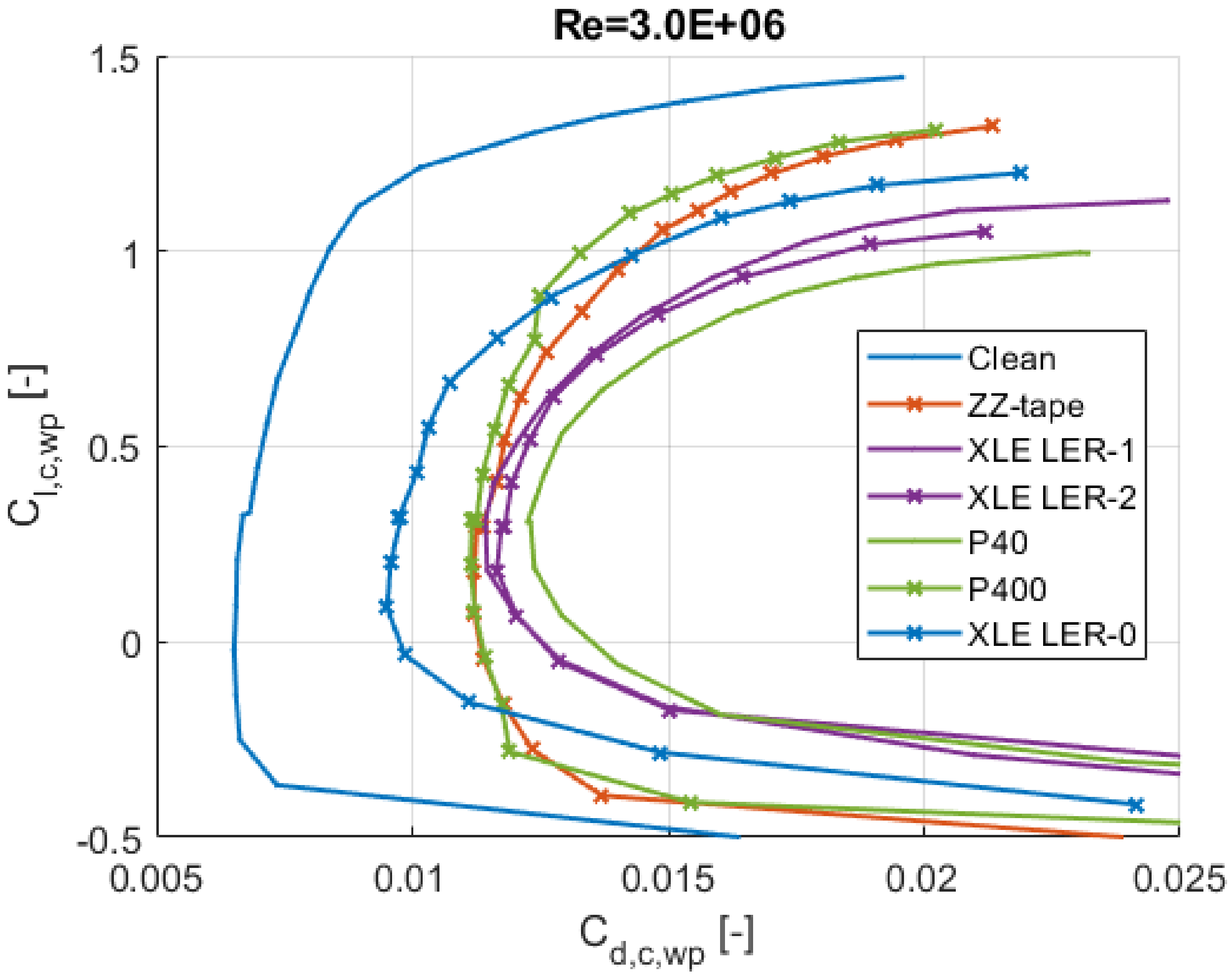
XLE first results

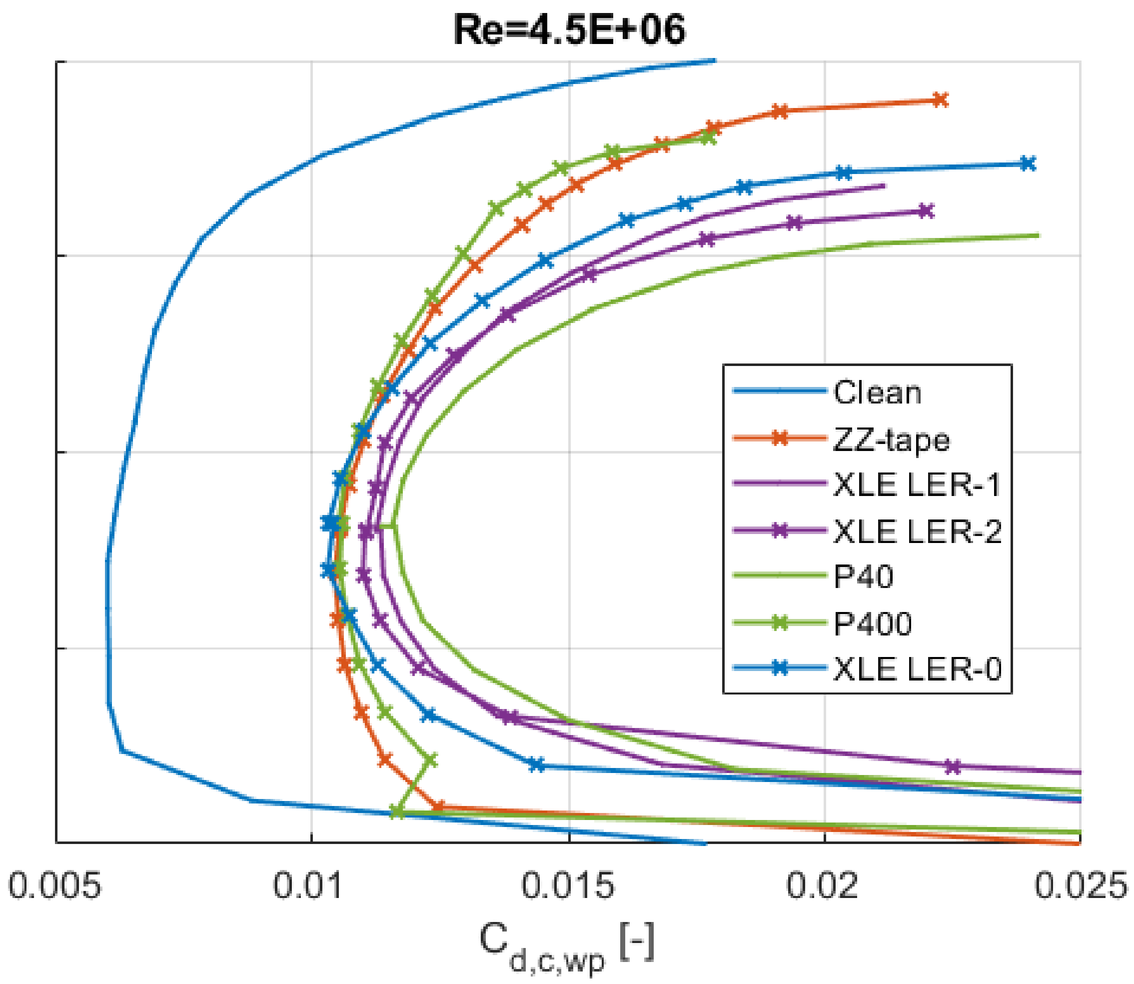
Sand paper x/c=3% SS, 4%PS



XLE first results

Sand paper x/c=3% SS, 4%PS





XLE first results

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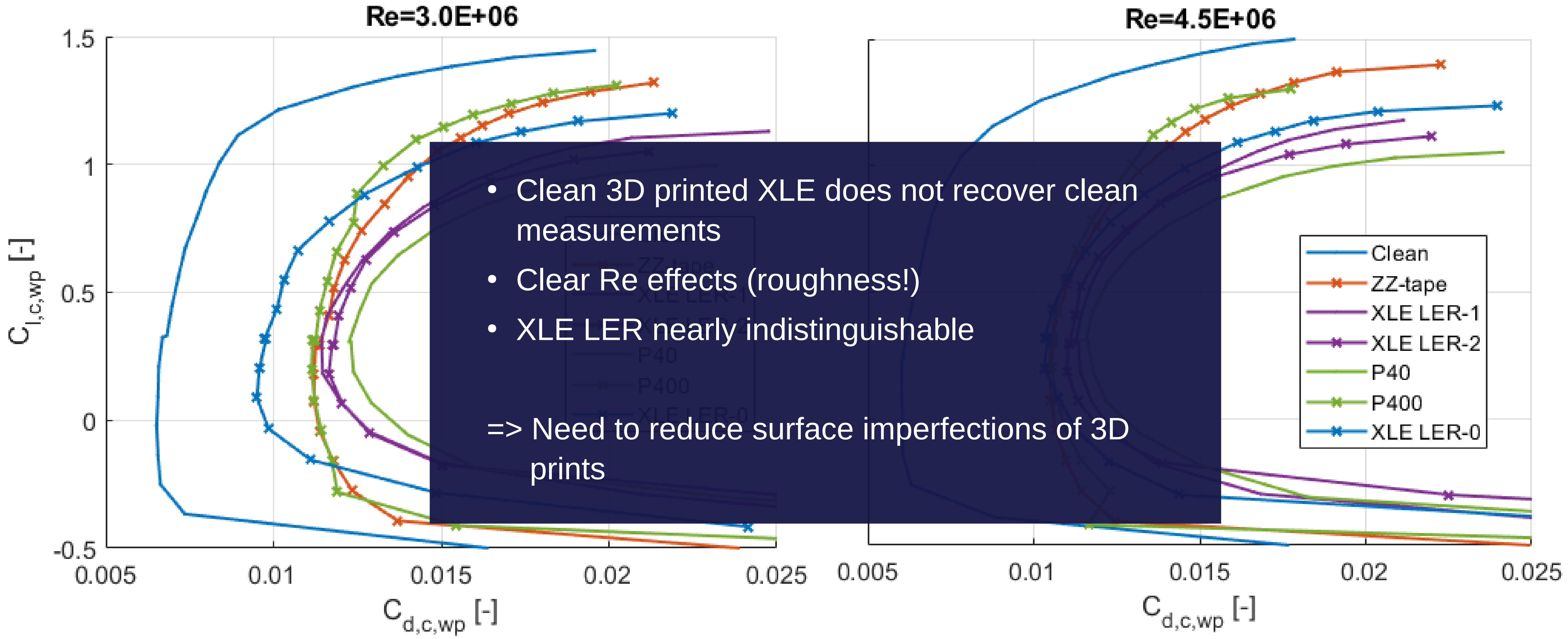
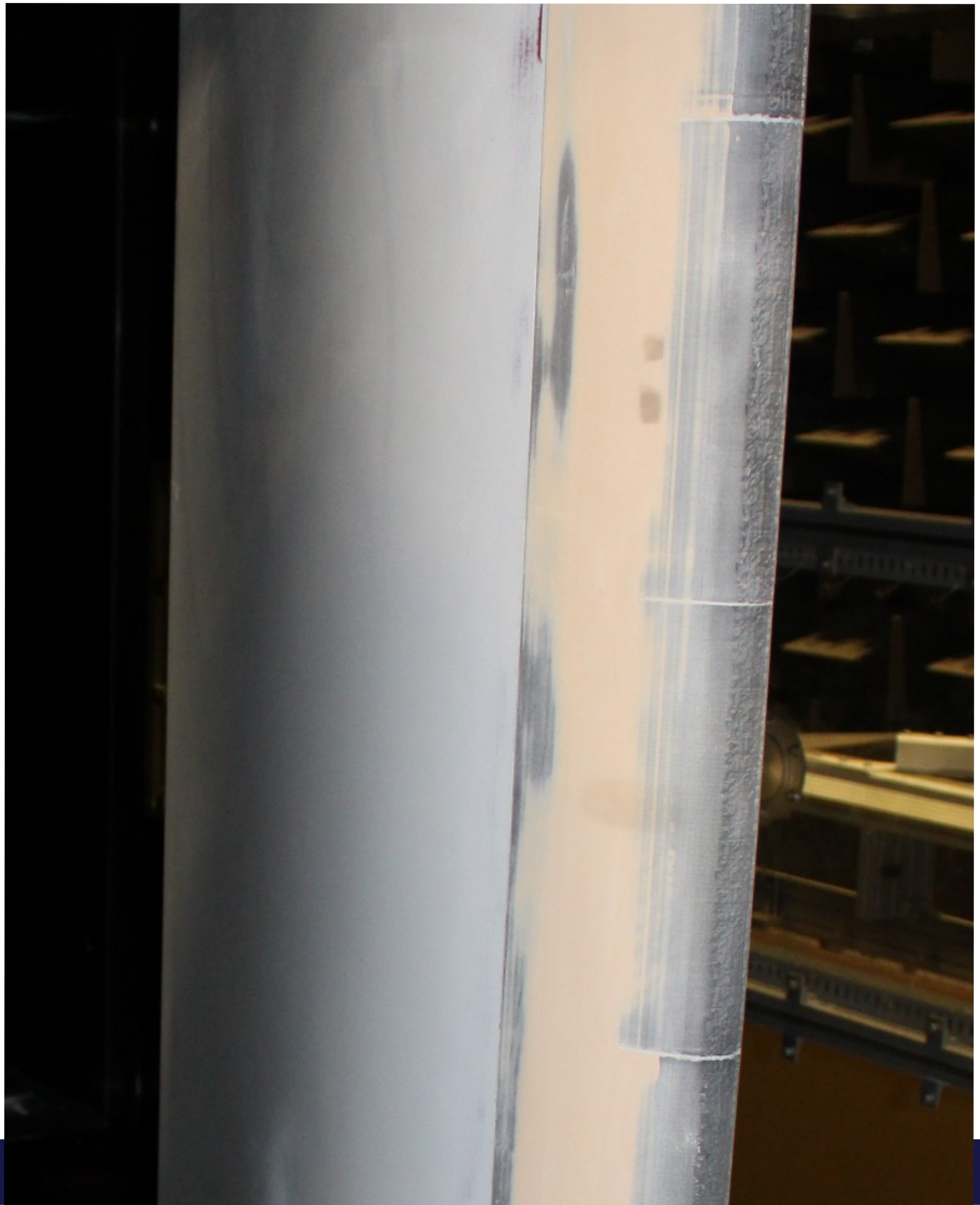


- Clean 3D printed XLE does not recover clean measurements
- Clear Re effects (roughness!)
- XLE LER nearly indistinguishable

=> Need to reduce surface imperfections of 3D prints

Surface treated XLE



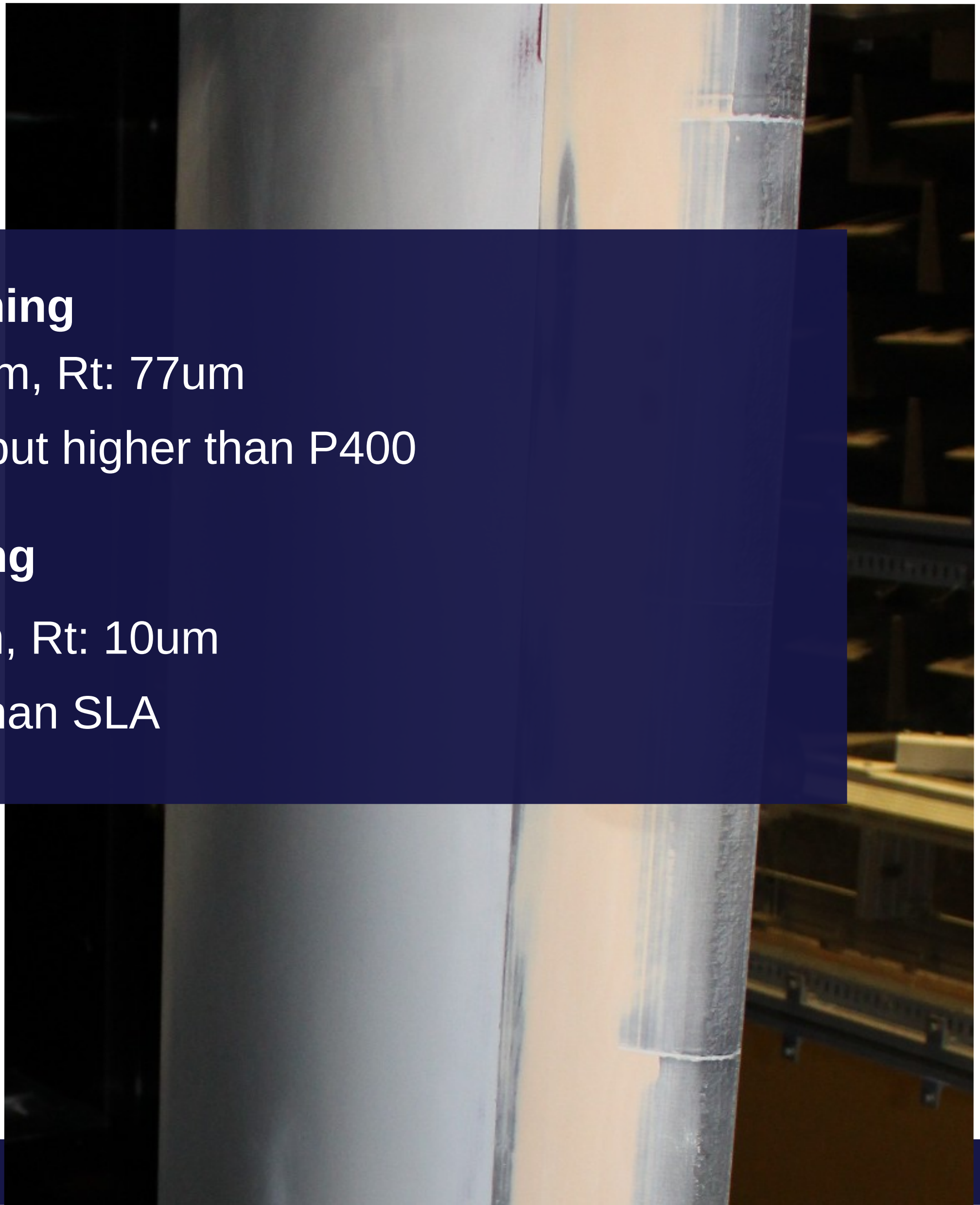
Surface treated XLE

Before polishing

- Ra: 10um, Rt: 77um
- Similar but higher than P400

After polishing

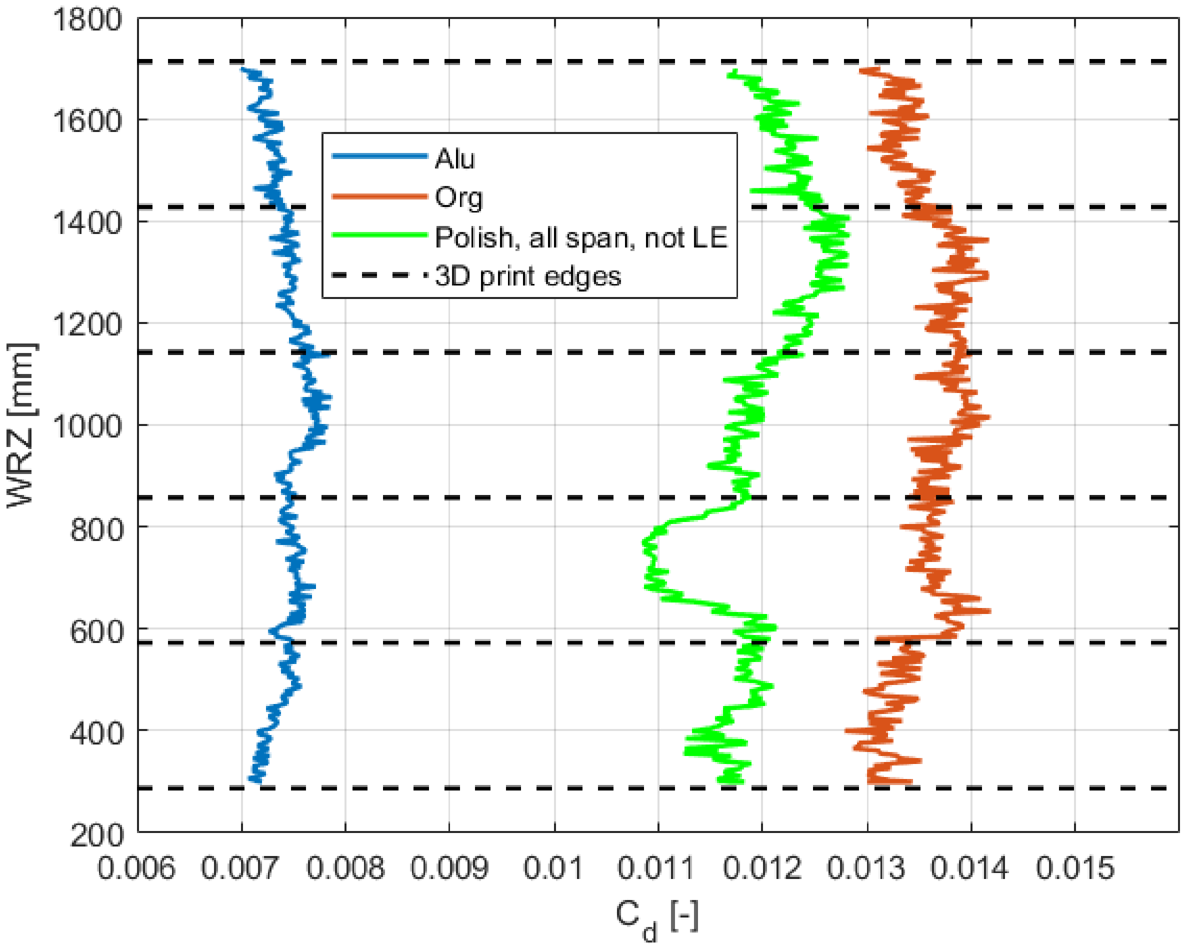
- Ra: 1um, Rt: 10um
- Lower than SLA



Surface treated XLE results

Wake rake measurements

Re=4.5e6 AoA=5 deg



Surface treated XLE results

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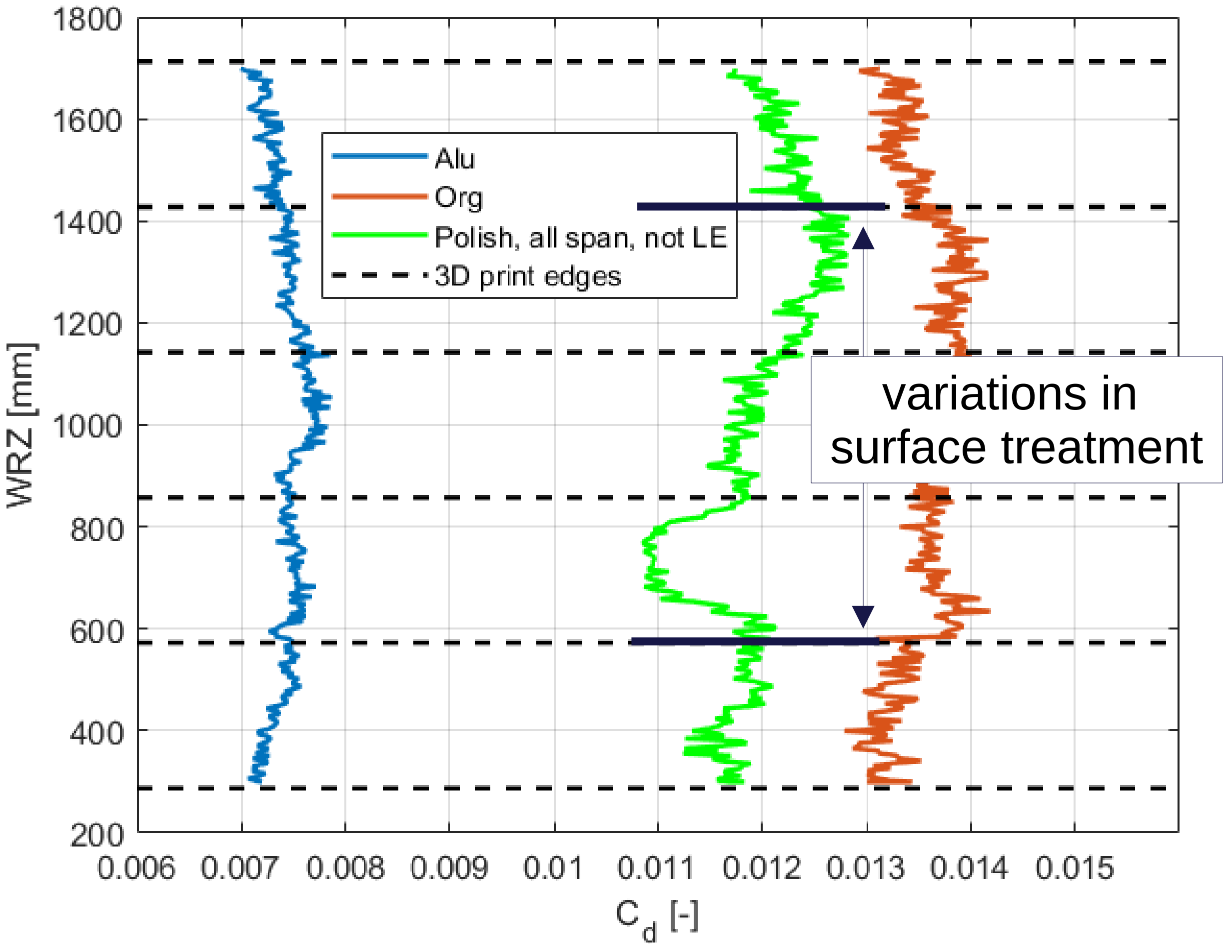

Surface treated XLE results

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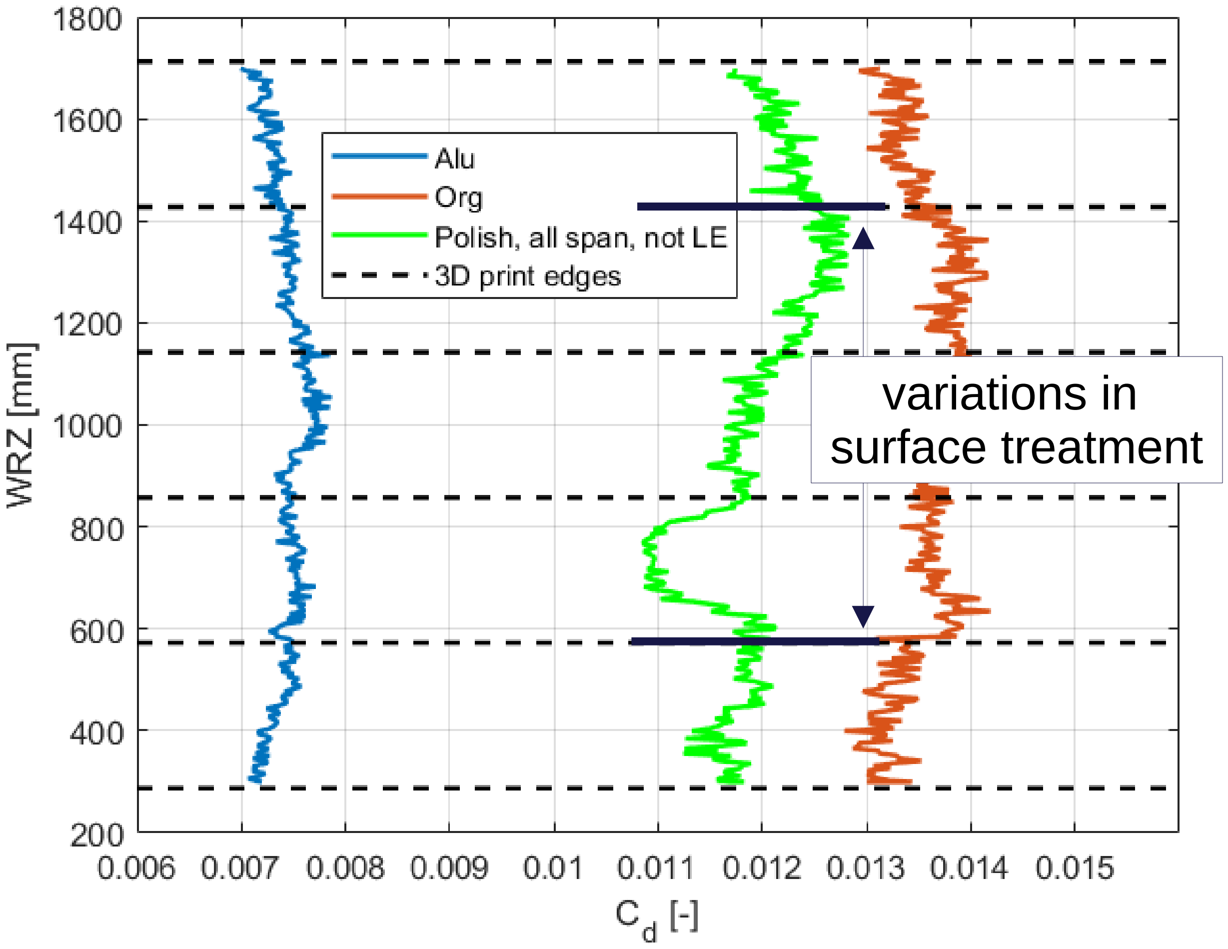

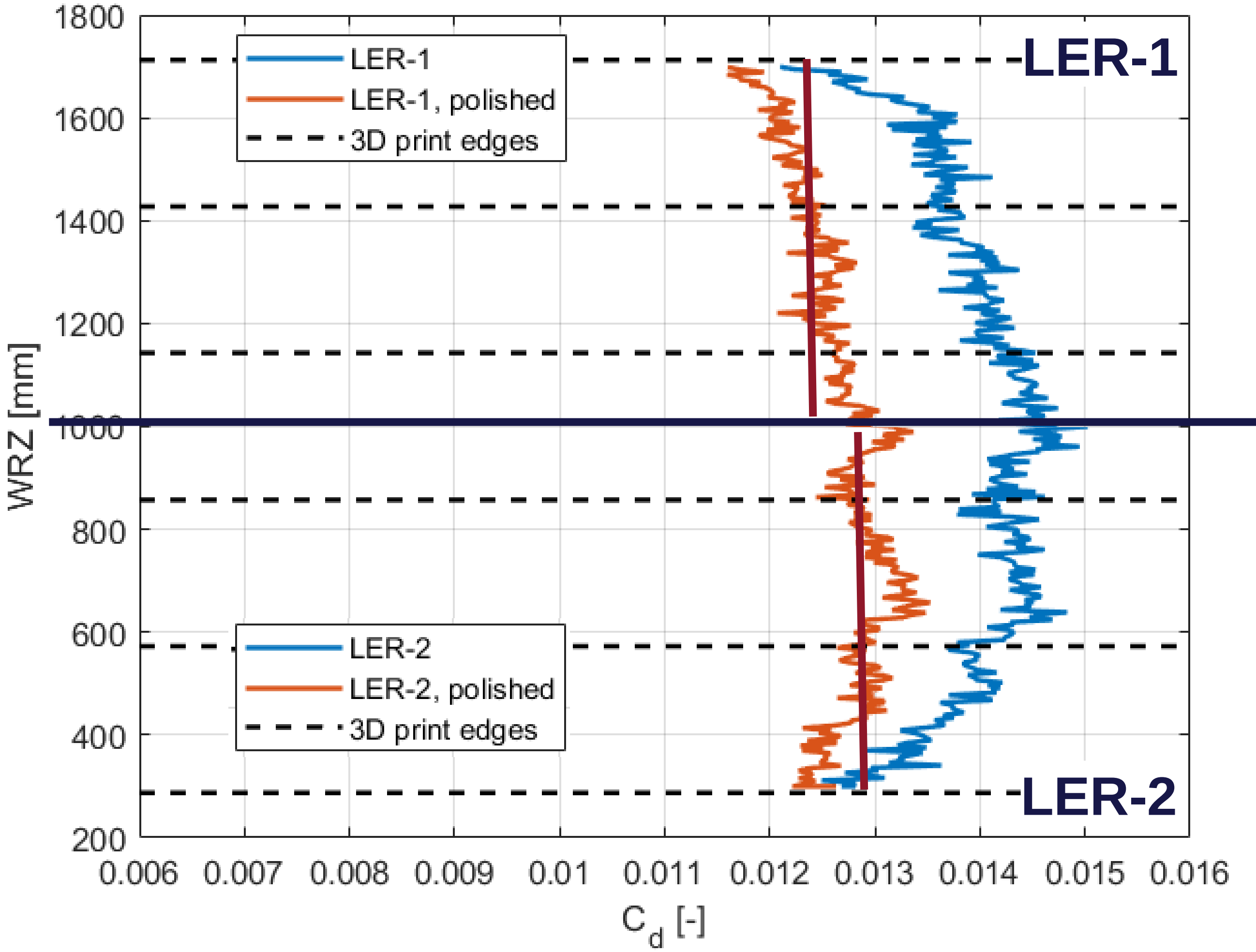

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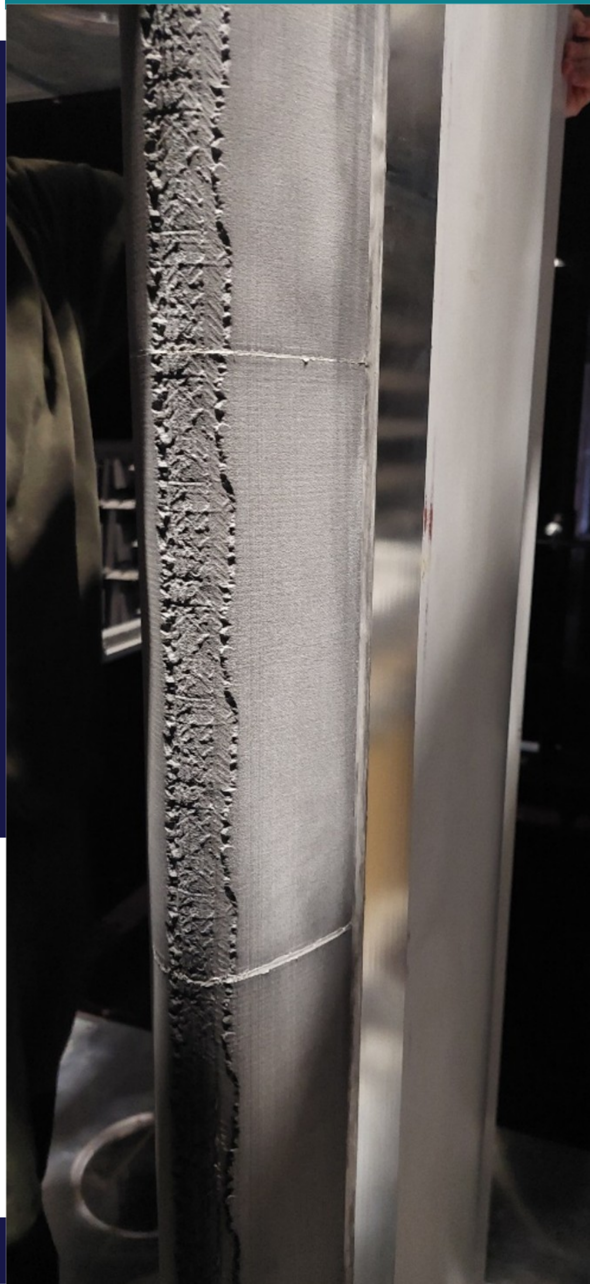
Summary & Outlook



- Roughness effects grow with Reynolds number
- Difficult to model real-world LER in wind tunnels and CFD
- Both wind tunnels experiments and simulations cannot easily be extended to high Res

  CFD: Transition models tuned for Res up to 3 million

  WT: Surface imperfections other than the roughness to be tested become critical
- Sensitivities will be further explored and disseminated, also through IEA task 46

Contacts

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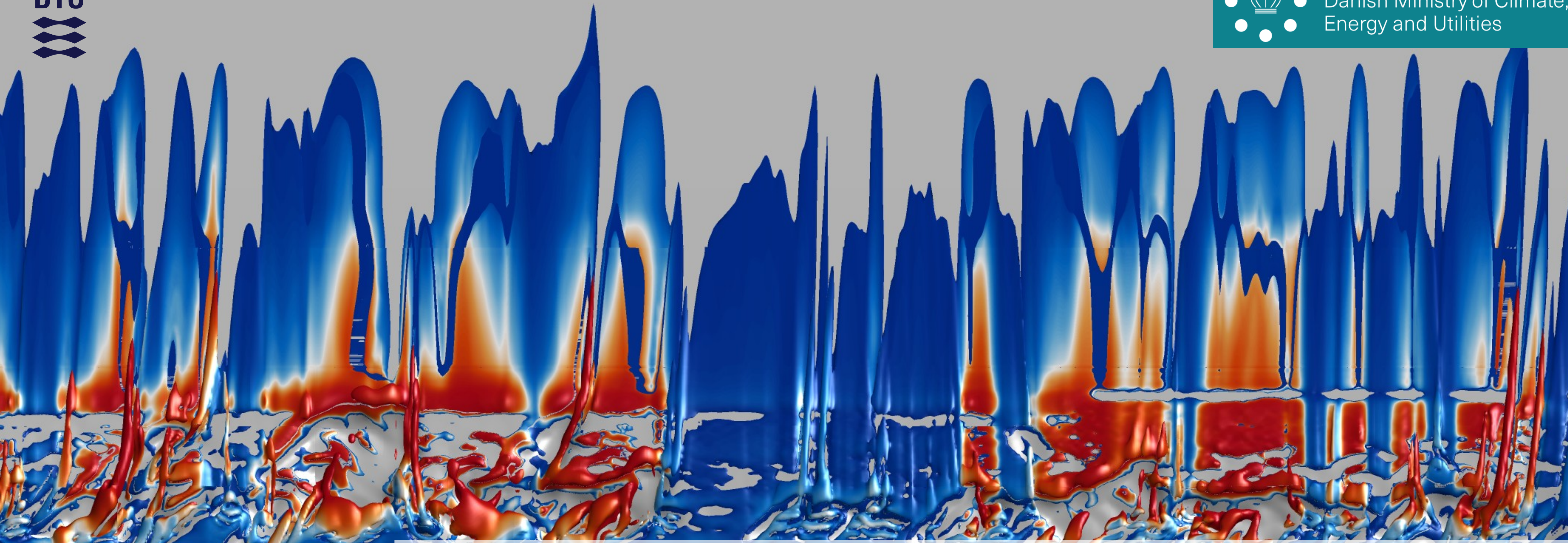

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