CFD-basierte Transitionsvorhersage für den Entwurf von Laminarflugzeugen

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Motivation

- Laminar aircraft design relies on CFD (RANS) simulation including prediction of laminar-turbulent transition
- Linear stability theory (LST) / e^N method is state-of-the-art but automation limited
- Transition transport models (TTM) easier to use and to automize
- DLR γ model is a new TTM for transport aircraft applications, but needs more validation


Source: airbus.com

Airbus laminar wing flight test demonstrator *BLADE*

- Objective: advancement and validation of DLR γ model to meet requirements of the aircraft design process in terms of accuracy and automation

Transition model for laminar airfoil design

SE^{2}A Cluster Collaboration

- Laminar airfoil design with DLR γ model shows good agreement with Linear stability theory / e^N method
- Swept laminar wing design required accurate and reliable prediction of crossflow transition
- Surface roughness is a relevant environmental uncertainty affecting crossflow transition and not yet represented in DLR γ model

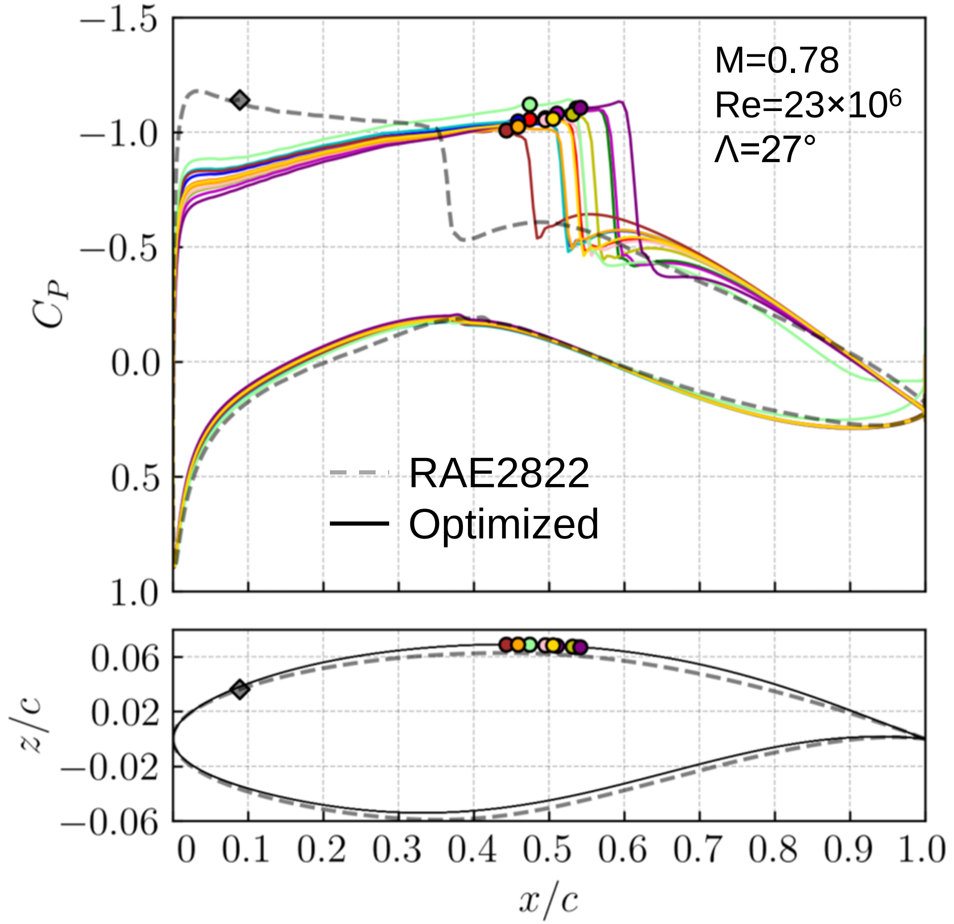


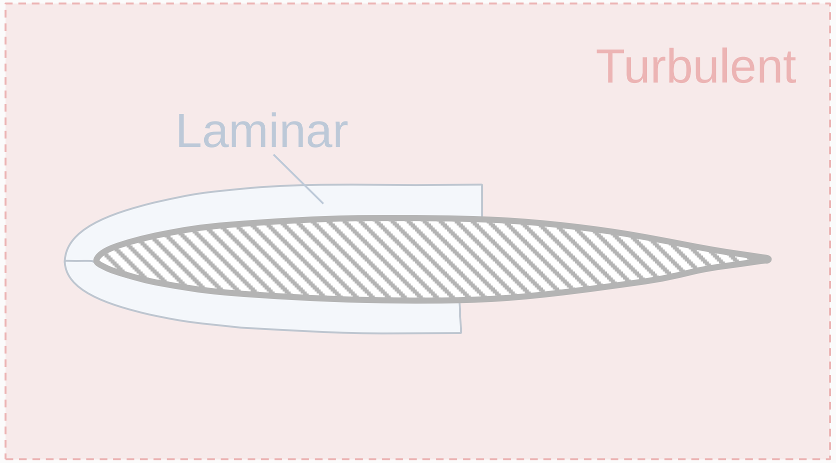
Fig.: Robust optimization of laminar airfoil using the DLR γ model[1]

[1] Parekh et al. DLRK 2023

Transition Models for RANS simulation

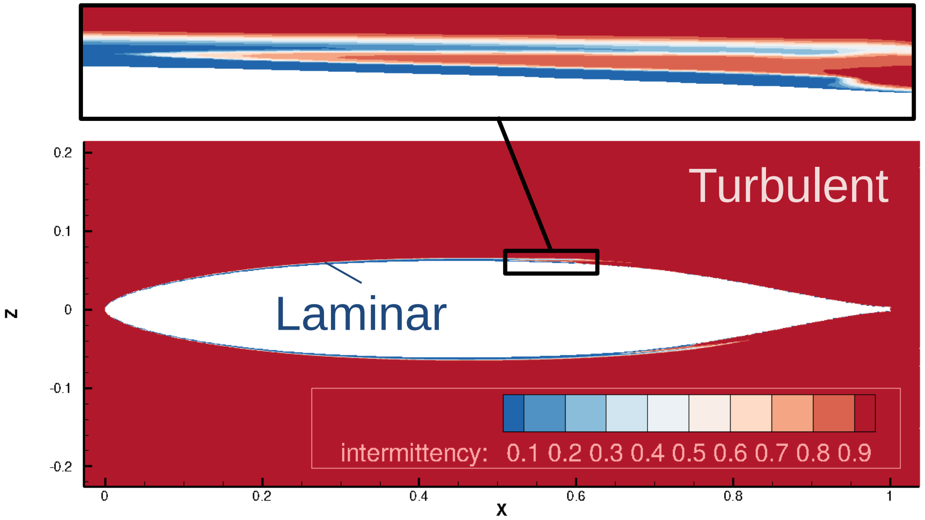
LST / e^N method

- TAU transition module, COCO/LILO
- Physics-based, Semi-empirical
- Complex model setup
- Validated for flight and WT conditions

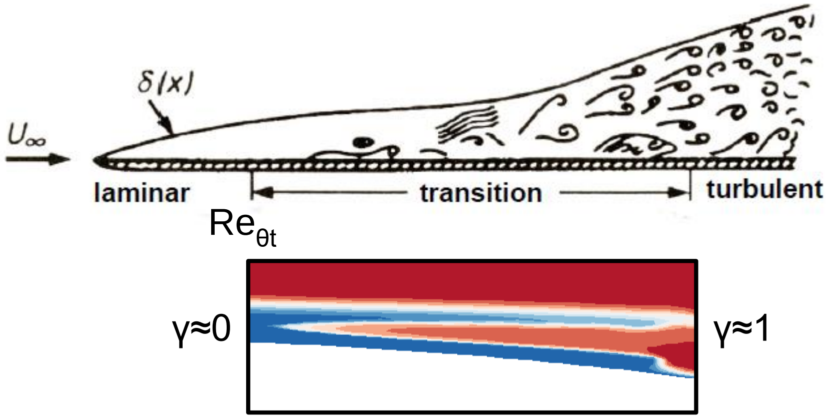


Transition transport models

- γ-Re_θ, γ-Fehrs and DLR γ model
- Empirical (γ-Re_θ, γ-Fehrs) or stability-theory-based criterion (DLR γ model)
- Little expert knowledge required
- Needs more validation



The DLR γ model[1], a transition transport model



- Intermittency transport

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho u_j\gamma)}{\partial x_j}=P_\gamma-E_\gamma+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial\gamma}{\partial x_j}\right]$$

$$P_\gamma=\left(f_{TS}\left(\frac{Re_\theta}{Re_{\theta t}}\right)+f_{CF}\left(\frac{Re_{He}}{Re_{Het}}\right)\right)\rho S(1-\gamma)$$

- Tollmien-Schlichting Transition

$$Re_\theta=\frac{\theta u_e}{\nu_e}$$

$Re_{\theta t}(\lambda_\theta, Tu, M)$ → Simple AHD criterion[2]

- Crossflow Transition

$Re_{He,max}\approx Re_{dv/dy,max}$

$Re_{He,t}(H_{12})$ → Helicity criterion[3]

- Integral parameters are locally modelled

[1] François et al. J. of Aircraft 2023, [2] Perraud et al. IACM and ECCOMAS 2014, [3] Grabe et al. AIAA Journal 2018

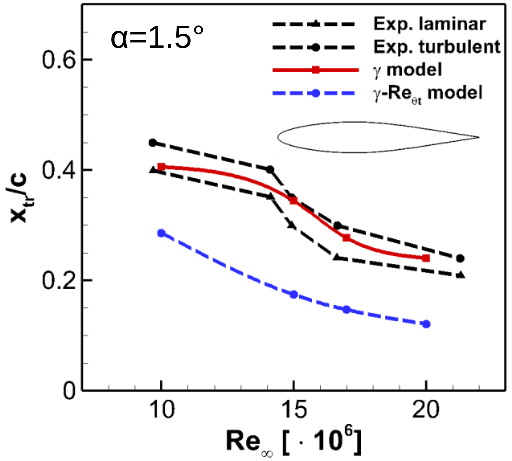
DLR γ model

Baseline

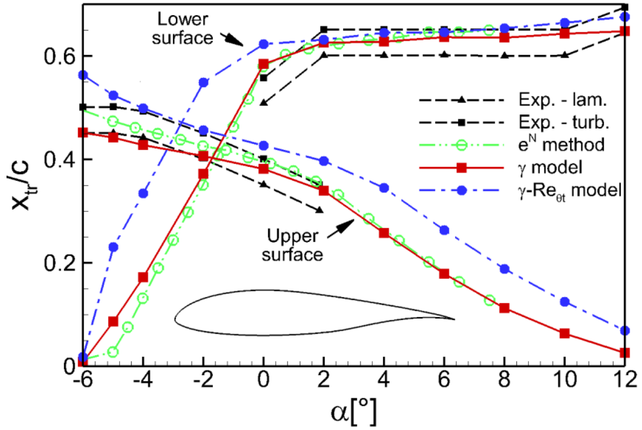
Validation for wide range of cases

- Tollmien-Schlichting transition
- Separation-induced transition

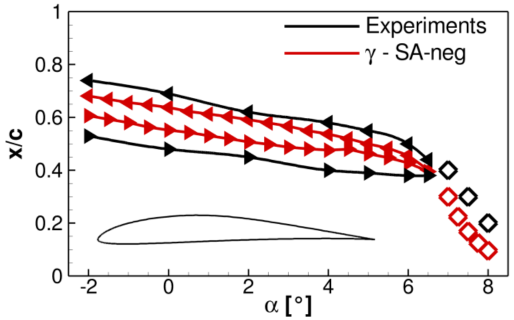
NACA 64_2A015 airfoil[1]



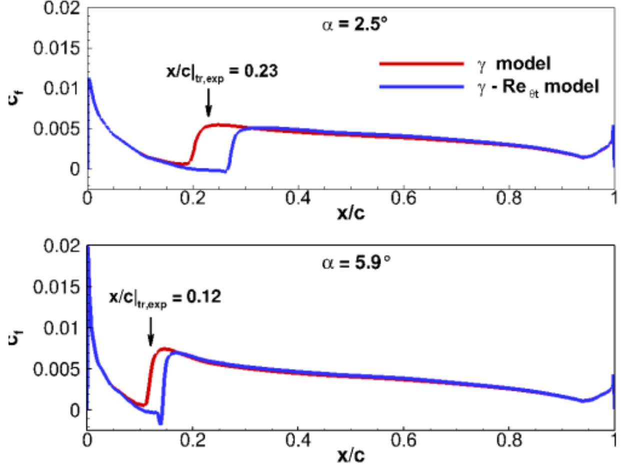
NLF(1)-0416 airfoil[1]



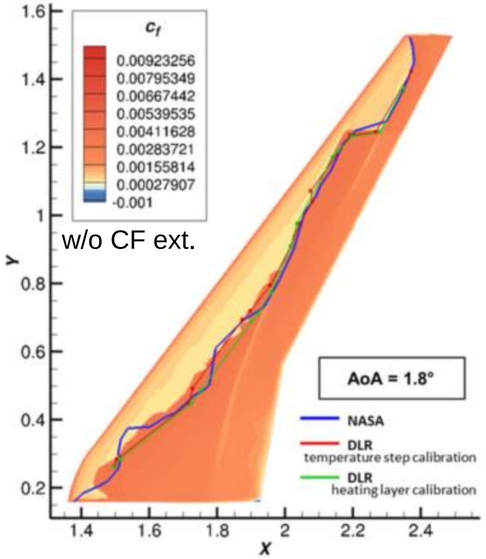
Eppler 387 airfoil[1]



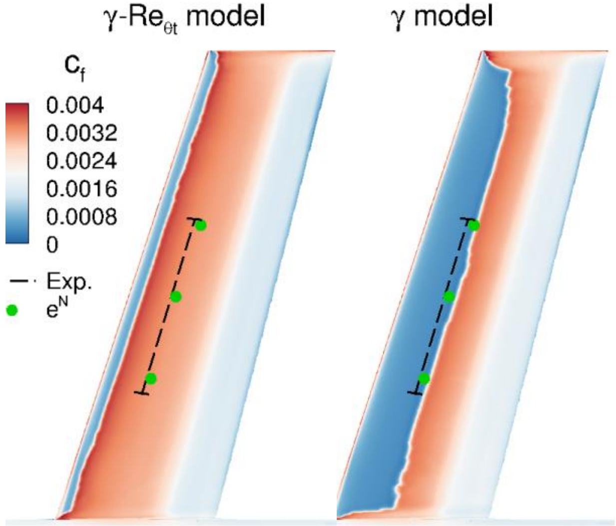
DSA-9A airfoil[1]



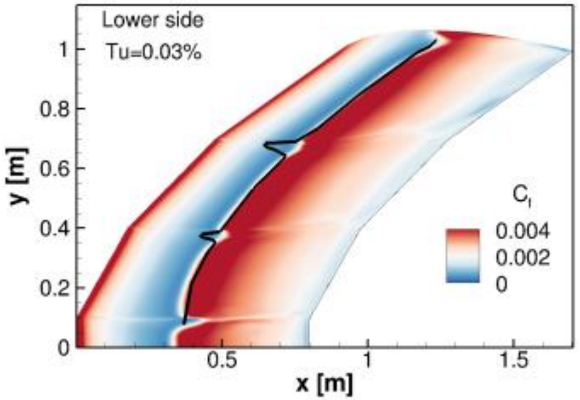
NASA CRM-NLF[2]



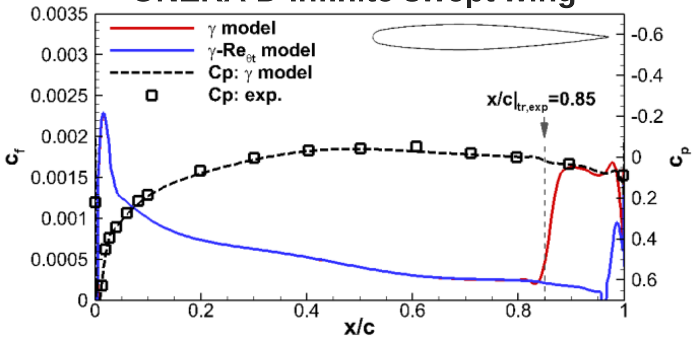
TELFONA Pathfinder[1]



TU BS Sickle Wing[1]



ONERA-D infinite swept wing[1]



[1] Francois et al. AIAA SciTech 2022.

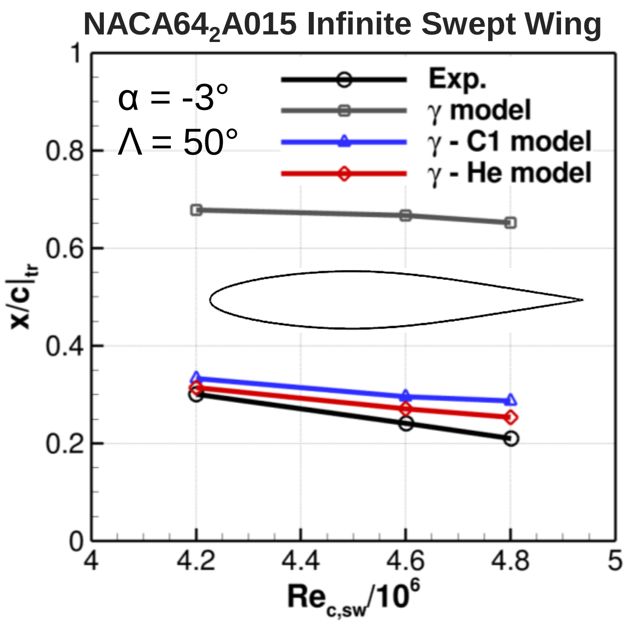
[2] Krumbein et al. Journal of Aircraft 2022.

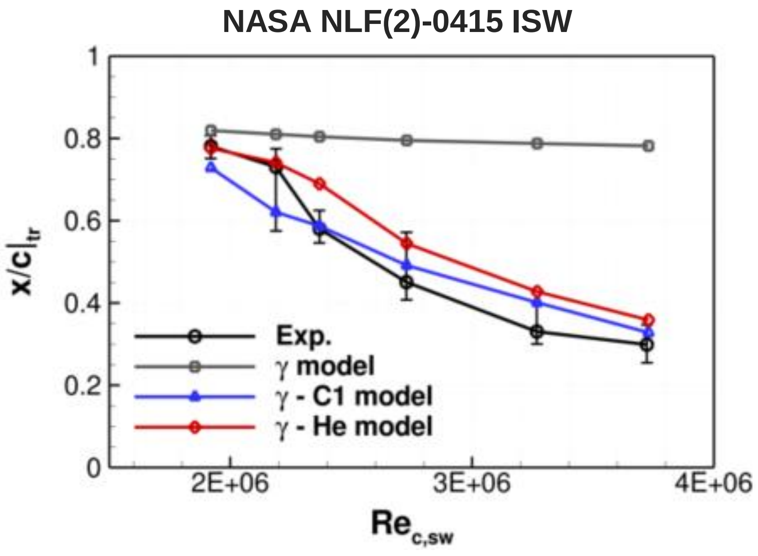
DLR γ model

CF-extensions

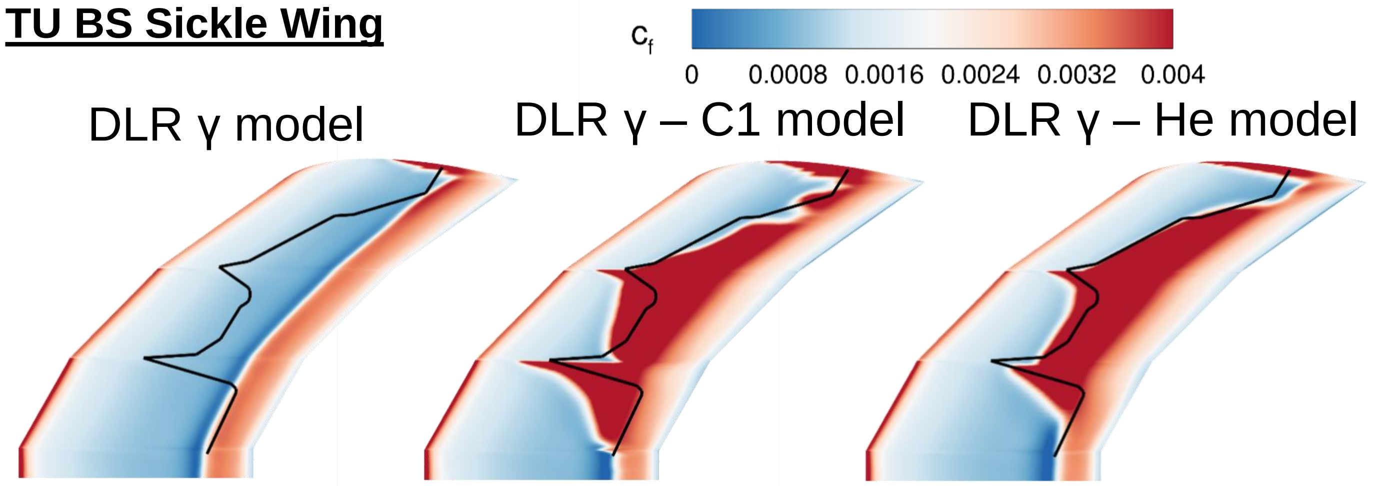
Validation of CF extensions

- C1 criterion for slender wings
- Helicity criterion for general 3D application

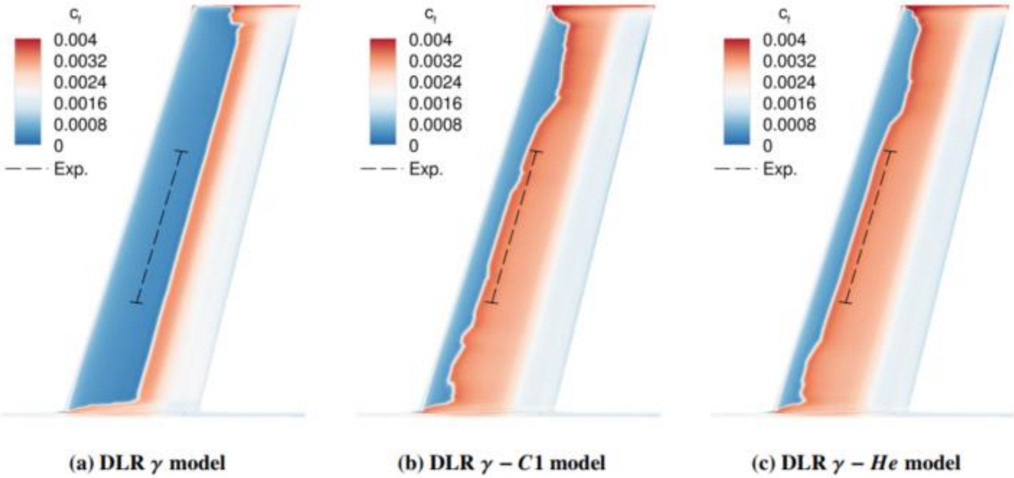




TU BS Sickle Wing



Telfona Pathfinder



(a) DLR γ model (b) DLR γ − C1 model (c) DLR γ − He model

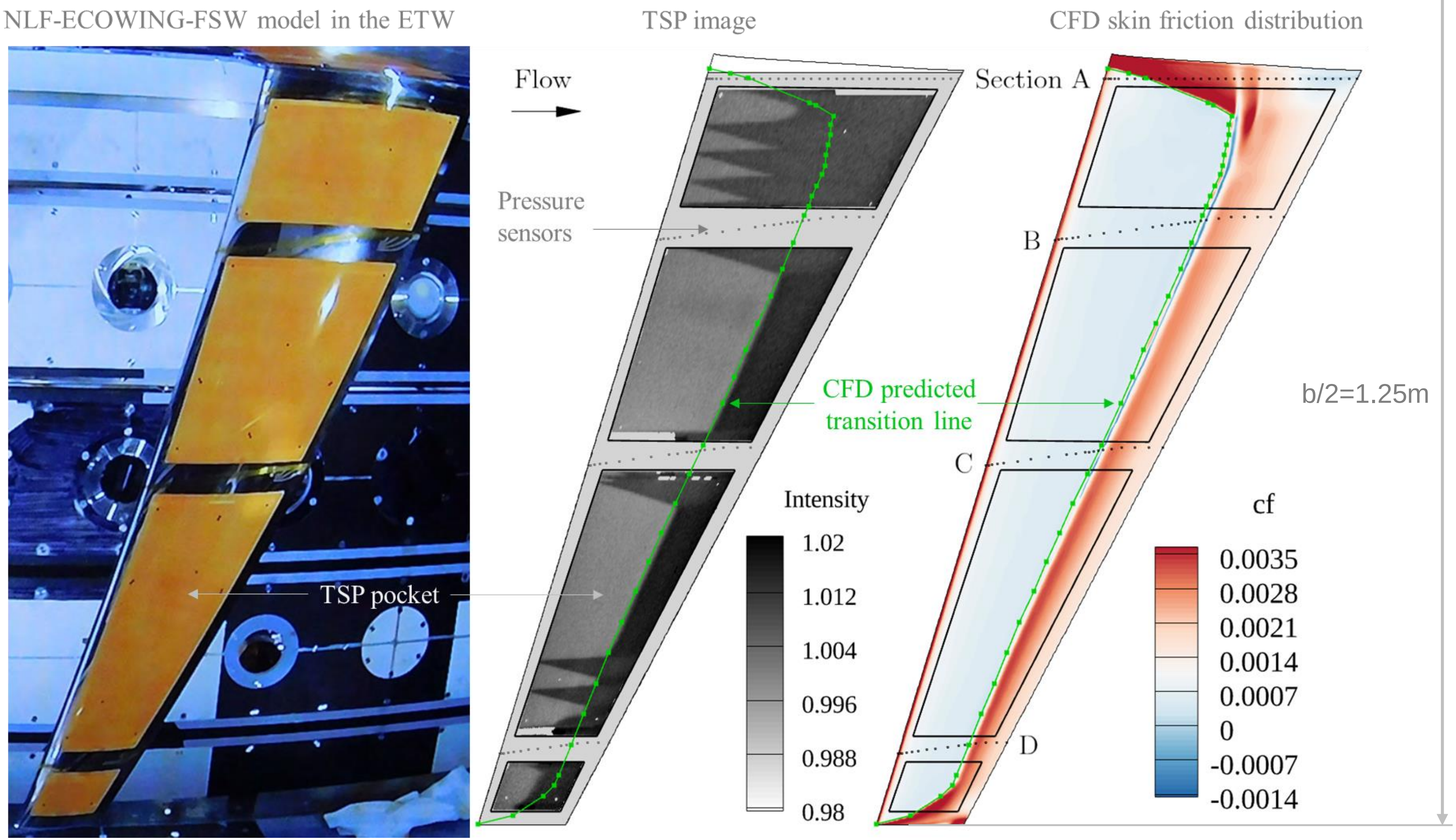
Fig. 10 Skin friction coefficient on the lower surface of the TELFONA Pathfinder Wing

François et al. „Crossflow Extension of a Simplified Transition Transport Model for Three-Dimensional Aerodynamic Configurations”, AIAA AVIATION Forum 2022.

More validation needed!

- 3D Flow conditions
- Flight realistic Mach/Re-numbers
- Unsteady transition

Validation with wind tunnel test



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Bundesministerium für Wirtschaft und Klimaschutz
aufgrund eines Beschlusses des Deutschen Bundestages
LUFO ULTIMATE

Simulation setup

- Steady RANS simulation with DLR TAU-Code
- Negative Spalart-Allmaras turbulence model + QCR + RC
- Transition
  - e^N method (TAU transition module)
    - Boundary-layer data at LoF cuts from COCO (Fig. on the right)
    - Incompressible LST with LILO code
    - $N_{crit,TS} = 9.0$
    - $N_{crit,CF} = 8.0$
  - DLR γ model
    - Tu=0.1%
  - Fully turbulent lower side and fuselage
- Design shape (no aeroelastic deformation)

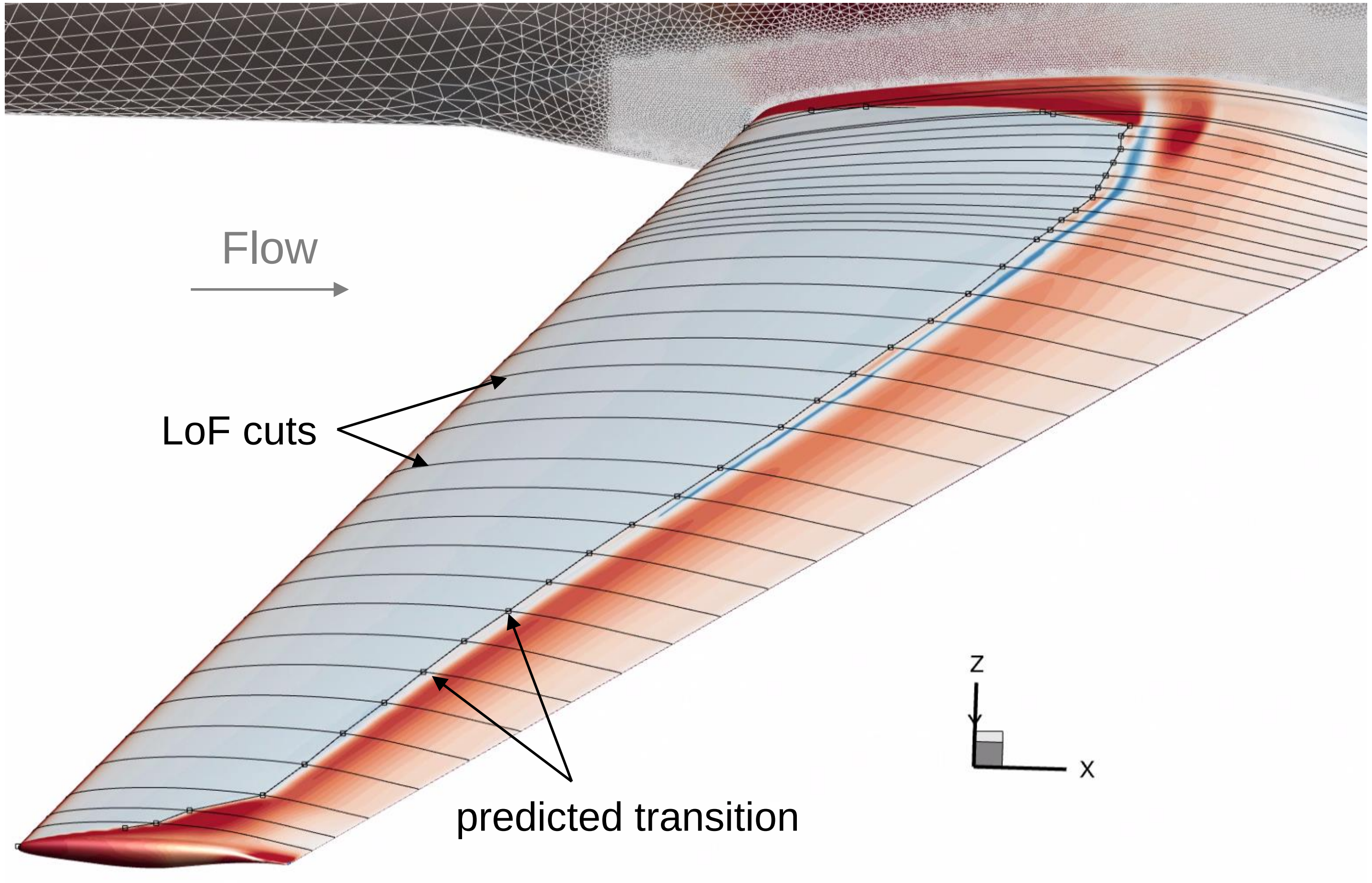
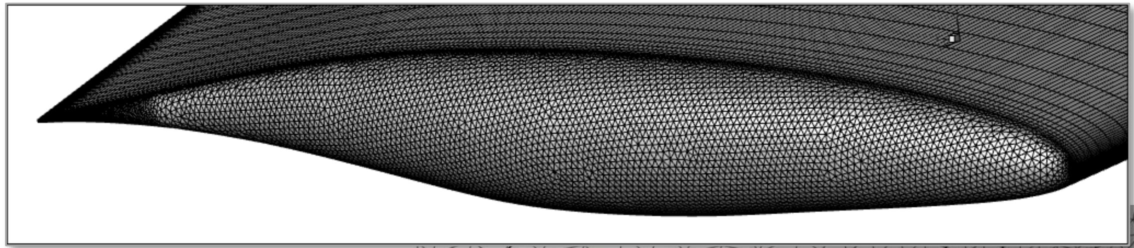
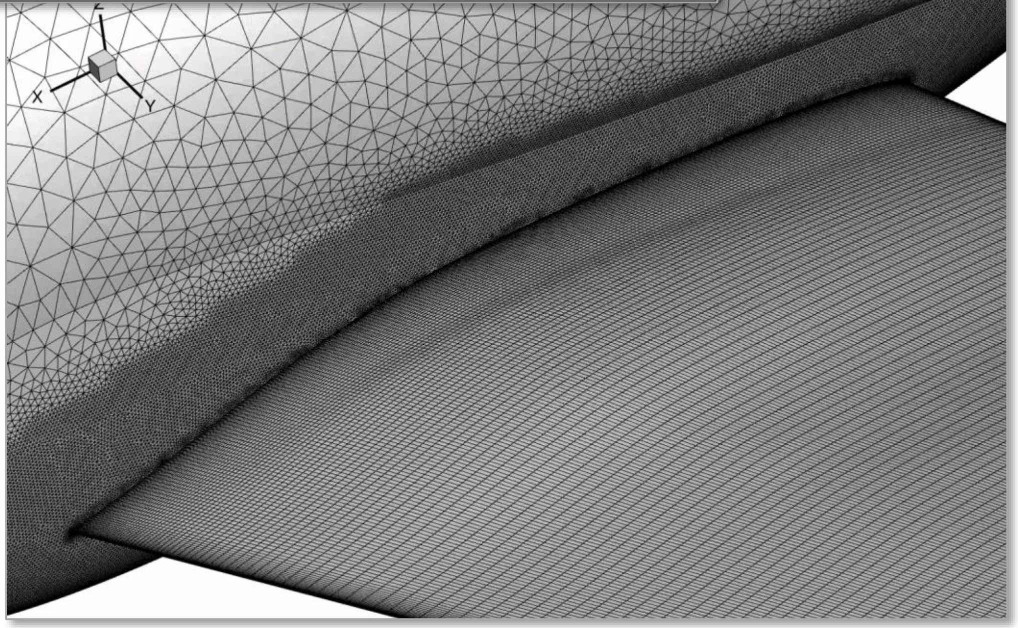


Fig.: Streamline setup and skin friction distribution for e^N method (manual setup of streamlines not necessary for DLR γ model)

Simulation setup

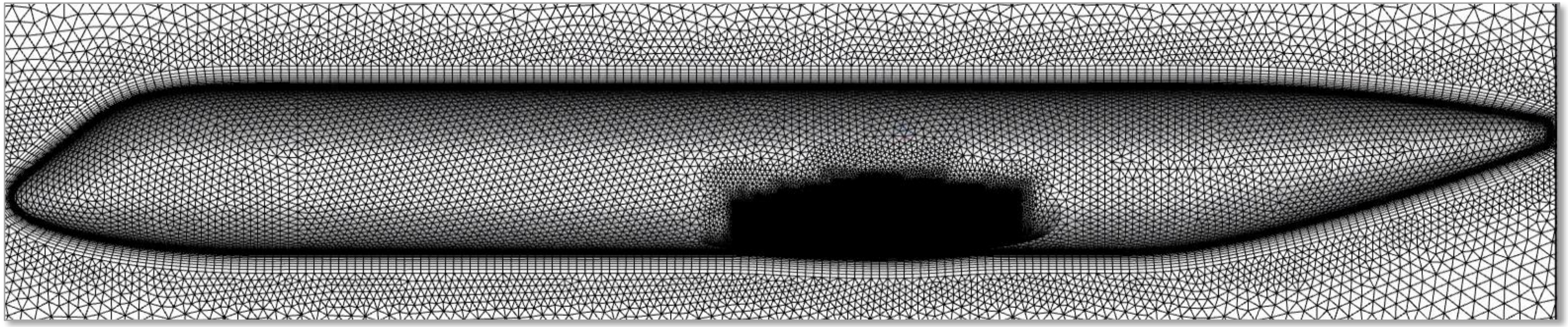
CFD grid





- Wing-fuselage half model
- Free-flight (farfield at 30 b/2)
- Maximum $y^+ \approx 0.8$
- Centaur grid family
- Structured boundary-layer mesh at wing surface

Netz	Points / 10^6	N_{span}	N_{chord}	N_{BL}
Coarse	**12.7**	**250**	**250**	**61**

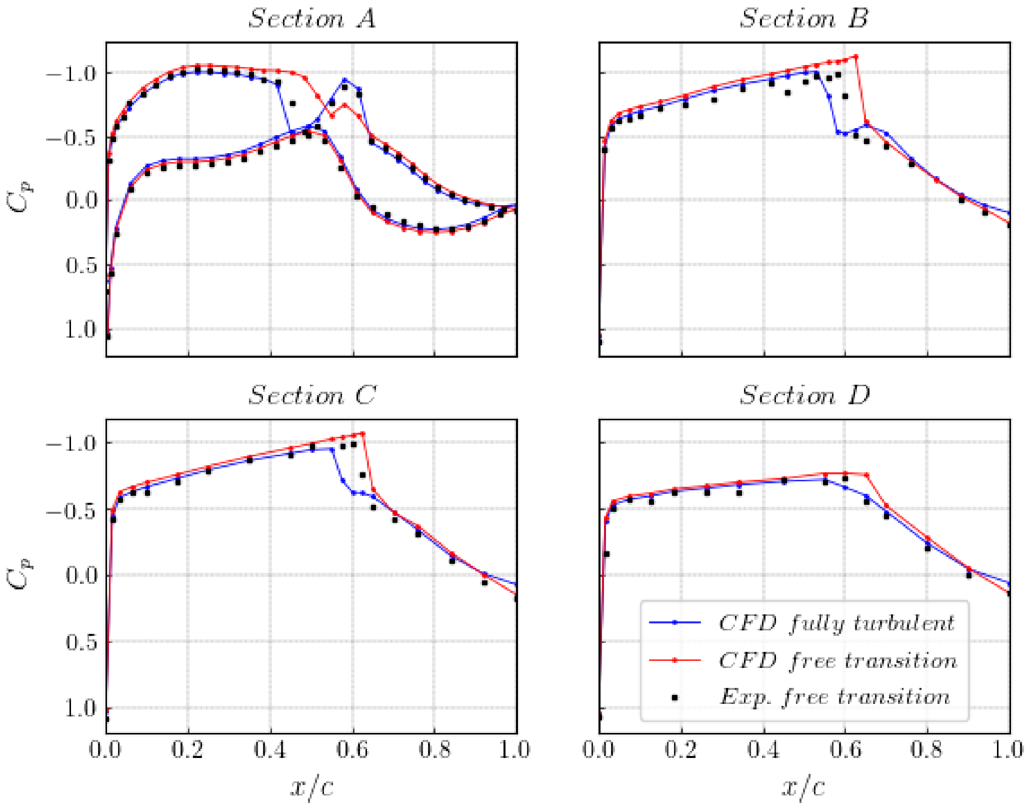


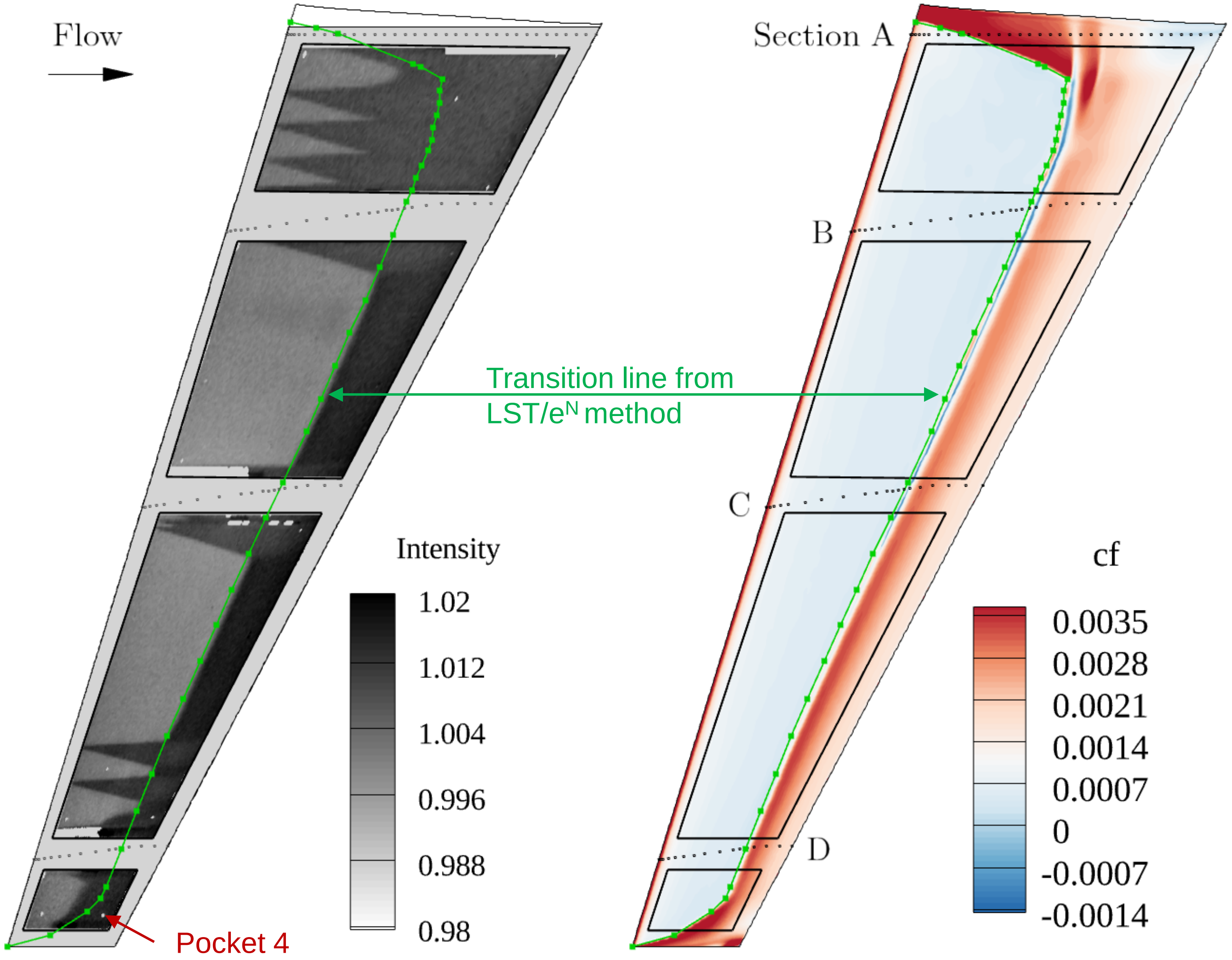
Results LST / e^N method

Overview

M=0.78
Re=16M
α=1.06°

- Favorable pressure gradient up to shock
- Good CFD/WTT agreement
- Transition slightly off at TSP pocket 4





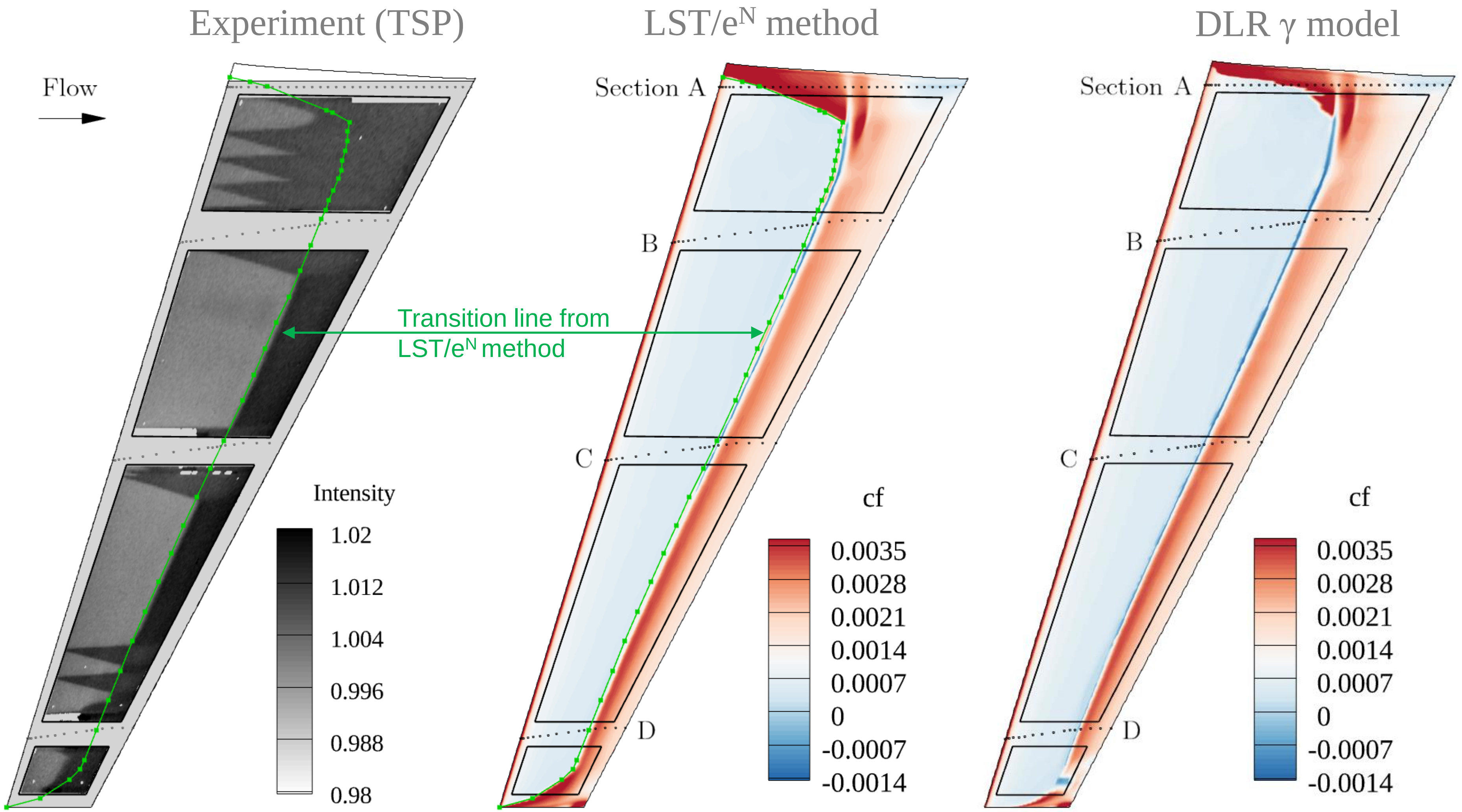
Transition line from LST/e^N method

Pocket 4

Comparison of DLR γ model

M=0.78
Re=16M
α=1.06°

- Good agreement for design conditions



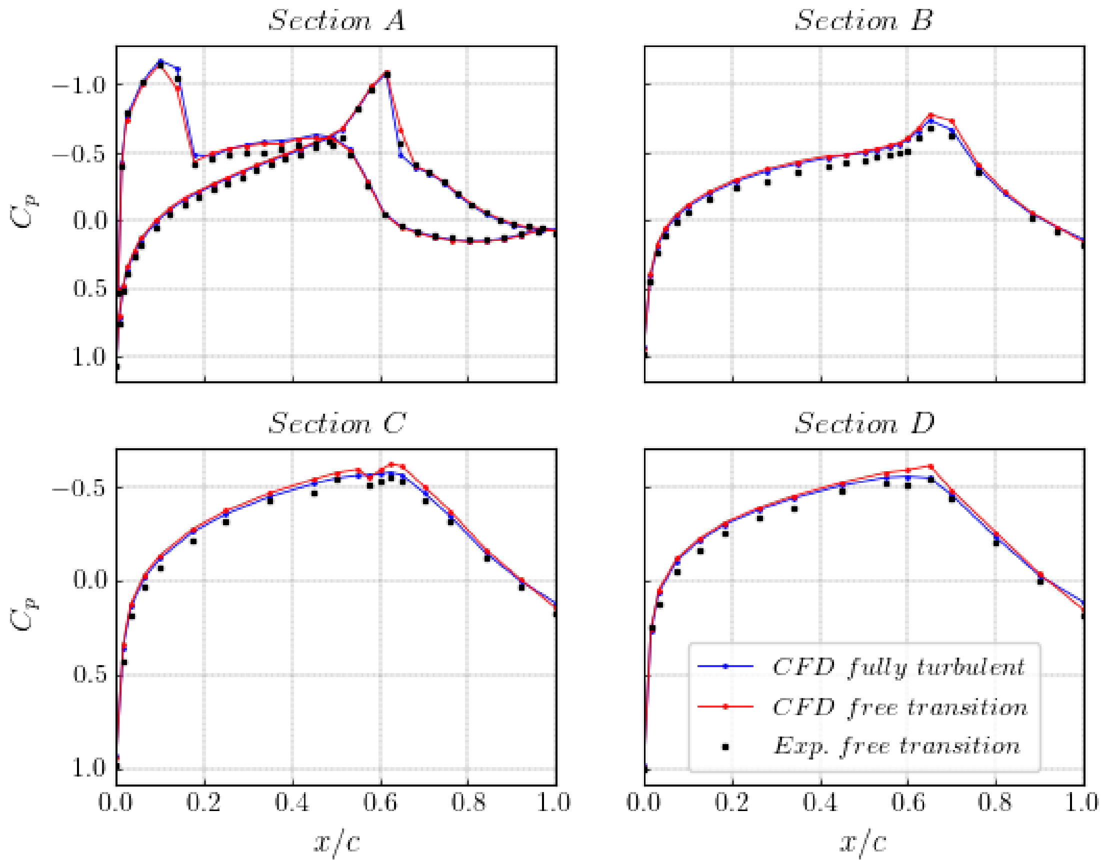
Transition line from LST/e^N method

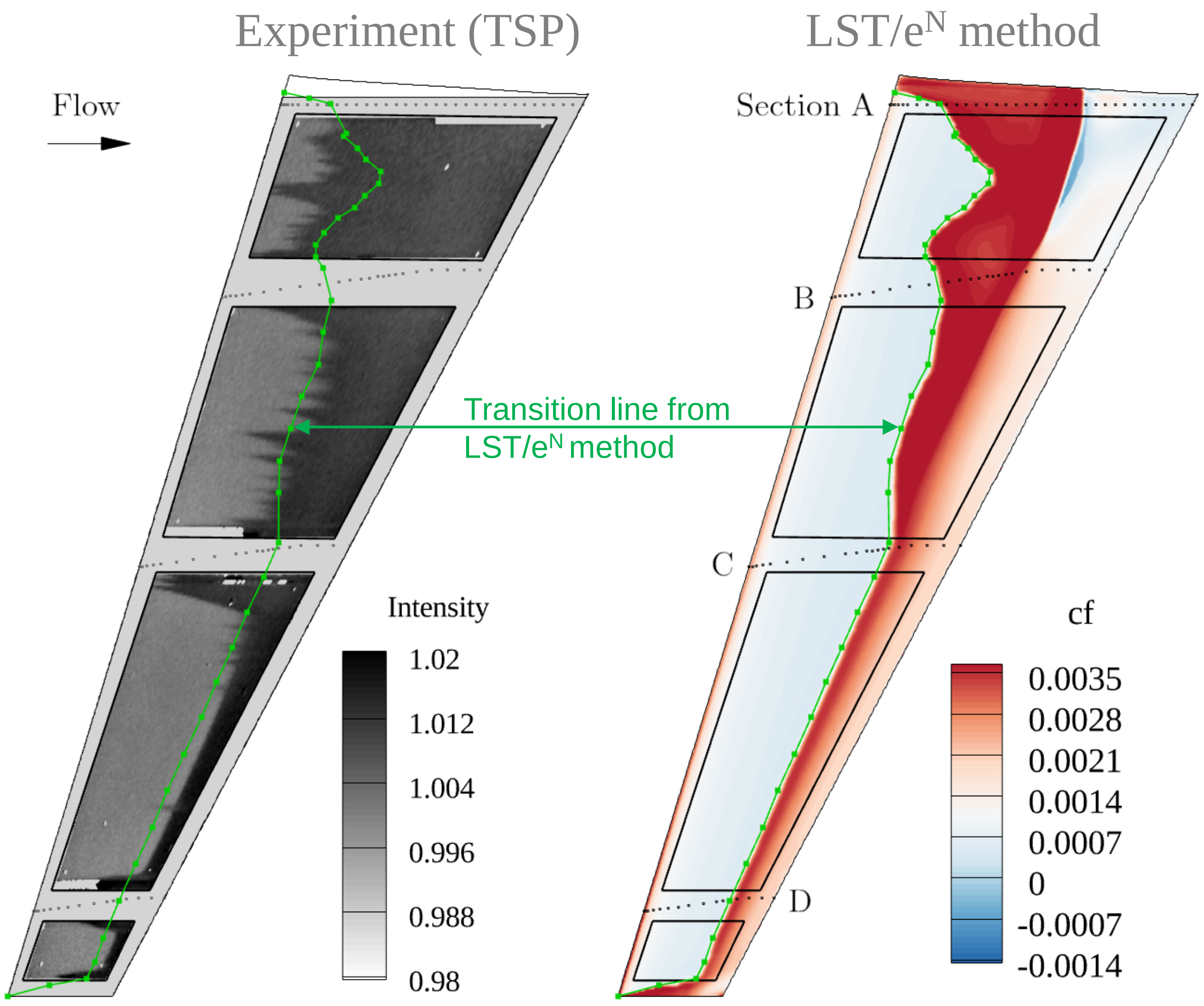
Low Angles-of-Attack

Crossflow-dominated

M=0.78
Re=16M
α=-3.0°

- Extensive laminar flow in off-design
- High quality TSP data
- Transition well captured by LST / e^N method





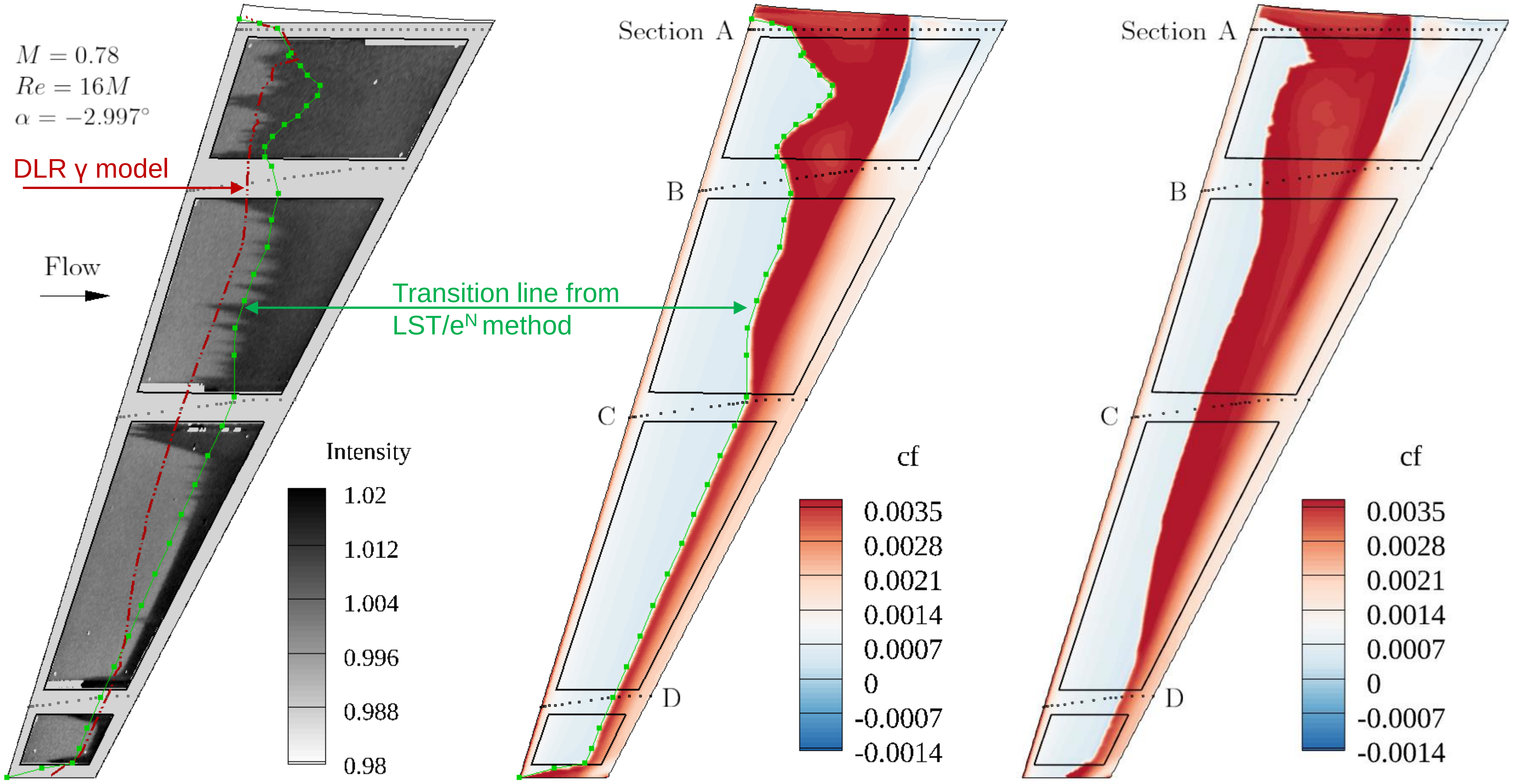
Transition line from LST/e^N method

Low Angles-of-Attack

Crossflow-dominated

- Crossflow transition captured qualitatively by DLR γ model but too upstream
- How to improve?

Experiment (TSP) LST/e^N method DLR γ model



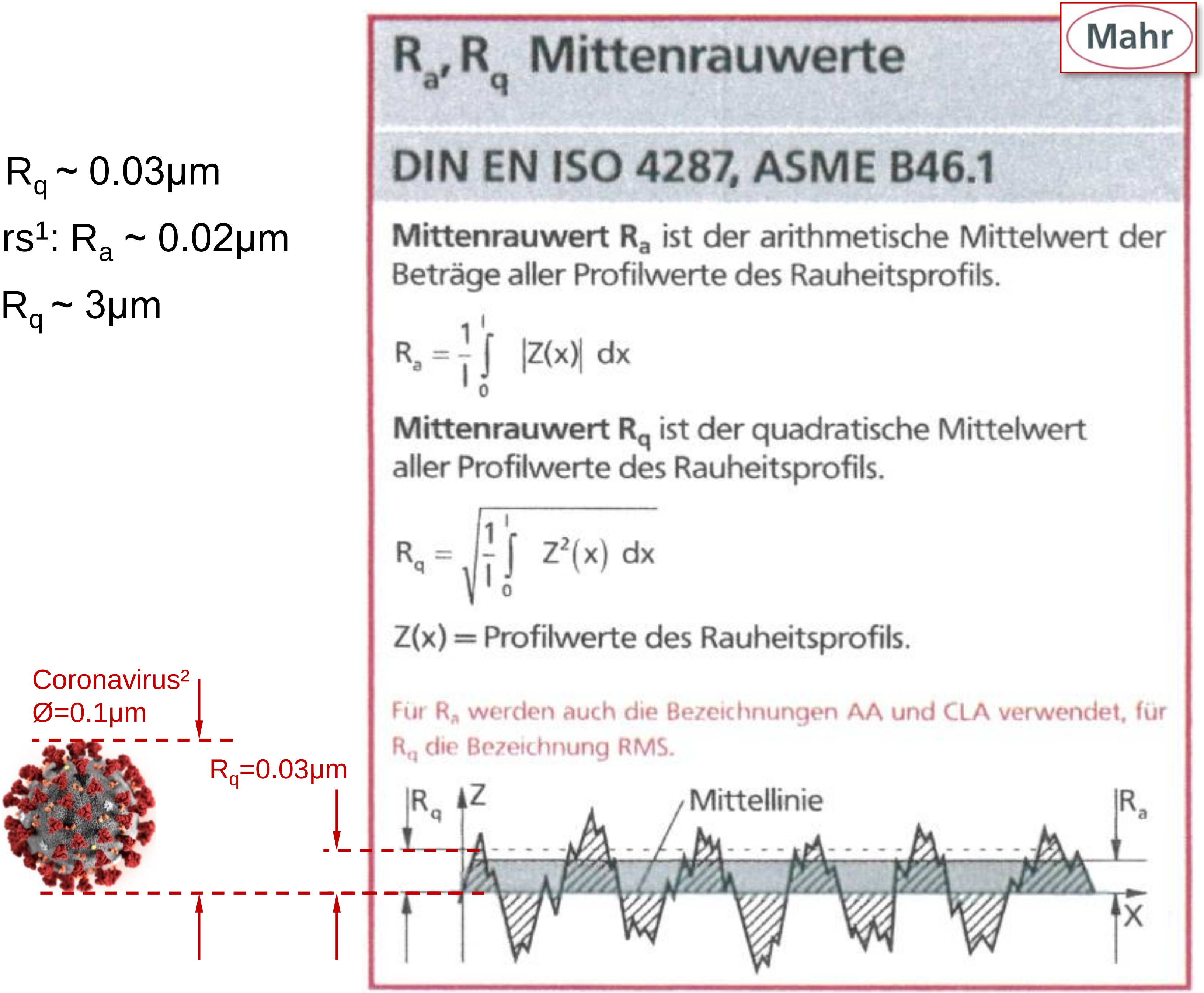
DLR γ model

Transition line from LST/e^N method

„Roughness"

- NLF-ECOWING-FSW model: $R_q \sim 0.03\mu m$
- James Webb Telescope Mirrors[1]: $R_a \sim 0.02\mu m$
- Standard painted roughness: $R_q \sim 3\mu m$

Fig.: one of Webb telescope's mirrors in clean room[1]



Coronavirus[2]
Ø=0.1µm

R_q=0.03µm

R_a, R_q Mittenrauwerte

DIN EN ISO 4287, ASME B46.1

Mittenrauwert R_a ist der arithmetische Mittelwert der Beträge aller Profilwerte des Rauheitsprofils.

$$R_a = \frac{1}{l}\int_0^l |Z(x)|\,dx$$

Mittenrauwert R_q ist der quadratische Mittelwert aller Profilwerte des Rauheitsprofils.

$$R_q = \sqrt{\frac{1}{l}\int_0^l Z^2(x)\,dx}$$

$Z(x)$ = Profilwerte des Rauheitsprofils.

Für R_a werden auch die Bezeichnungen AA und CLA verwendet, für R_q die Bezeichnung RMS.

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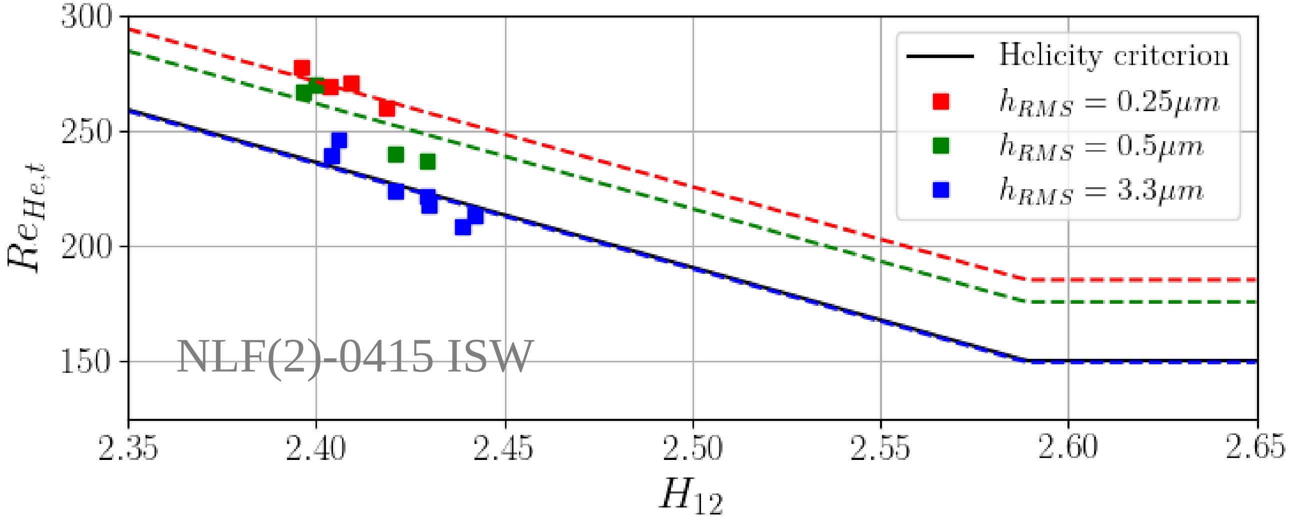
[1] https://www.nasa.gov/content/goddard/the-amazing-anatomy-of-james-webb-space-telescope-mirrors/
[2] Von CDC/ Alissa Eckert, MS; Dan Higgins, Centers for Disease Control and Prevention's Public Health Image Library (PHIL) https://commons.wikimedia.org

Roughness effect

Original helicity criterion

$$Re_{He,t} = \max(-456.83\, H_{12} + 1332.7, 150.0)$$



- Criterion value ($Re_{He,t}$) and momentum loss thickness from simulation with BL enforced to be laminar at least up to experimental transition location[1]

- NLF(2)-0415 is the only case with roughness variation we have
- How to normalize roughness?
  - Crouch et al. used displacement thickness at indifference point (δ*) → non-local
  - Langtry et al. used momentum loss thickness (θ) → local approximation availible
  - We approximate by Blasius boundary layer → prototype

$$\theta = 0.665 \sqrt{\frac{\nu x}{U_e}}$$

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[1] Data from M. Höchel master thesis

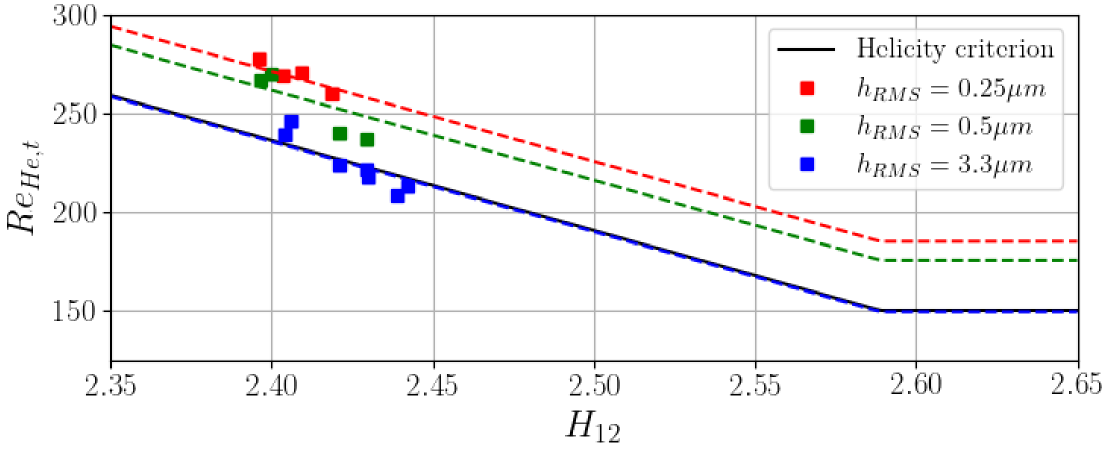
Roughness extension

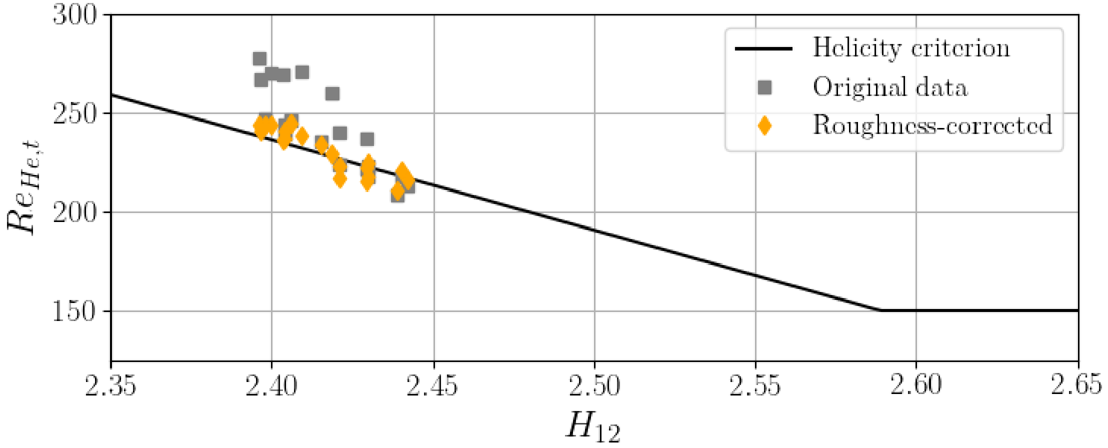
Helicity criterion

- Adjustment of the criterion by roughness-dependent logarithmic curve fit

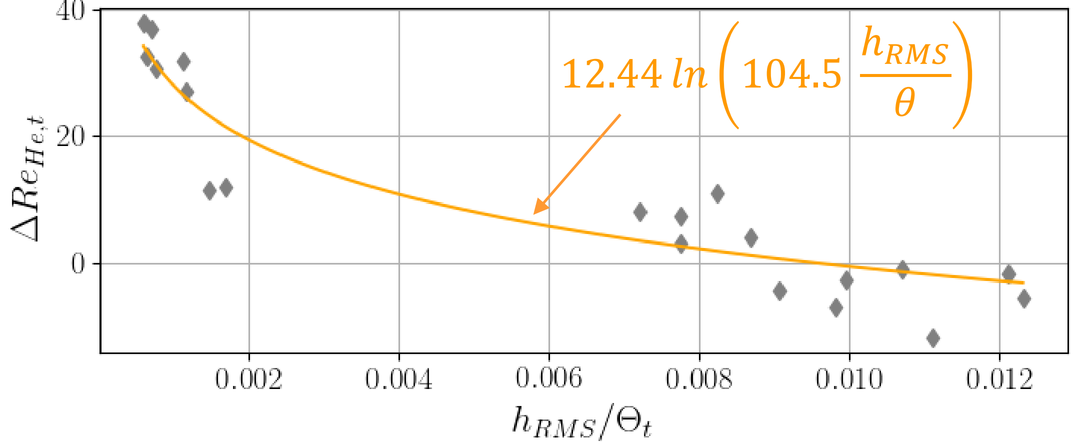
Original helicity criterion

$$Re_{He,t} = \max(-456.83\, H_{12} + 1332.7, 150.0)$$





Roughness-dependent error of criterion



Proposed criterion including roughness effect

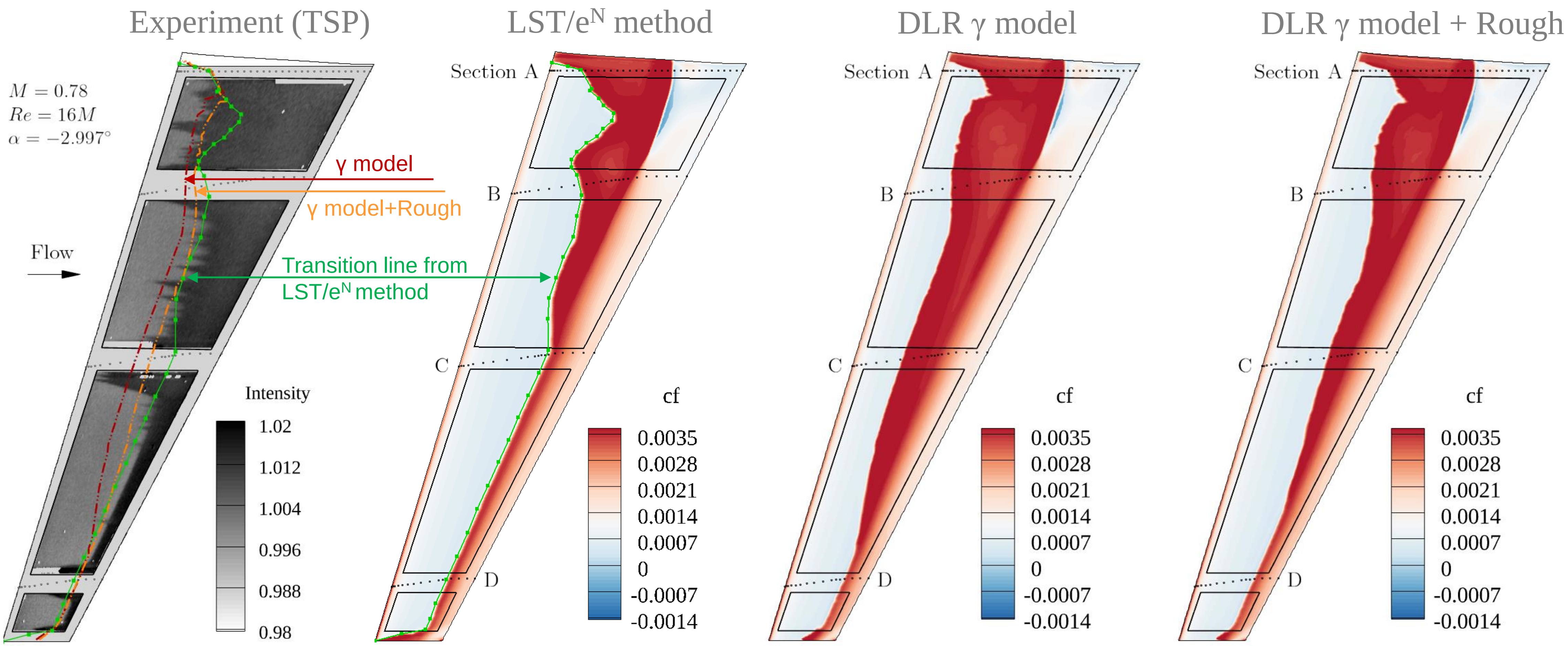
$$Re_{He,t} = \max\left(-456.83\, H_{12} - 12.44 \ln\left(104.5\, \frac{h_{RMS}}{\theta}\right) + 1332.7, 100.0\right)$$

Results

3D Testcases

NLF-ECOWING-FSW

- Roughness extension shows improved (more downstream) CF transition



γ model

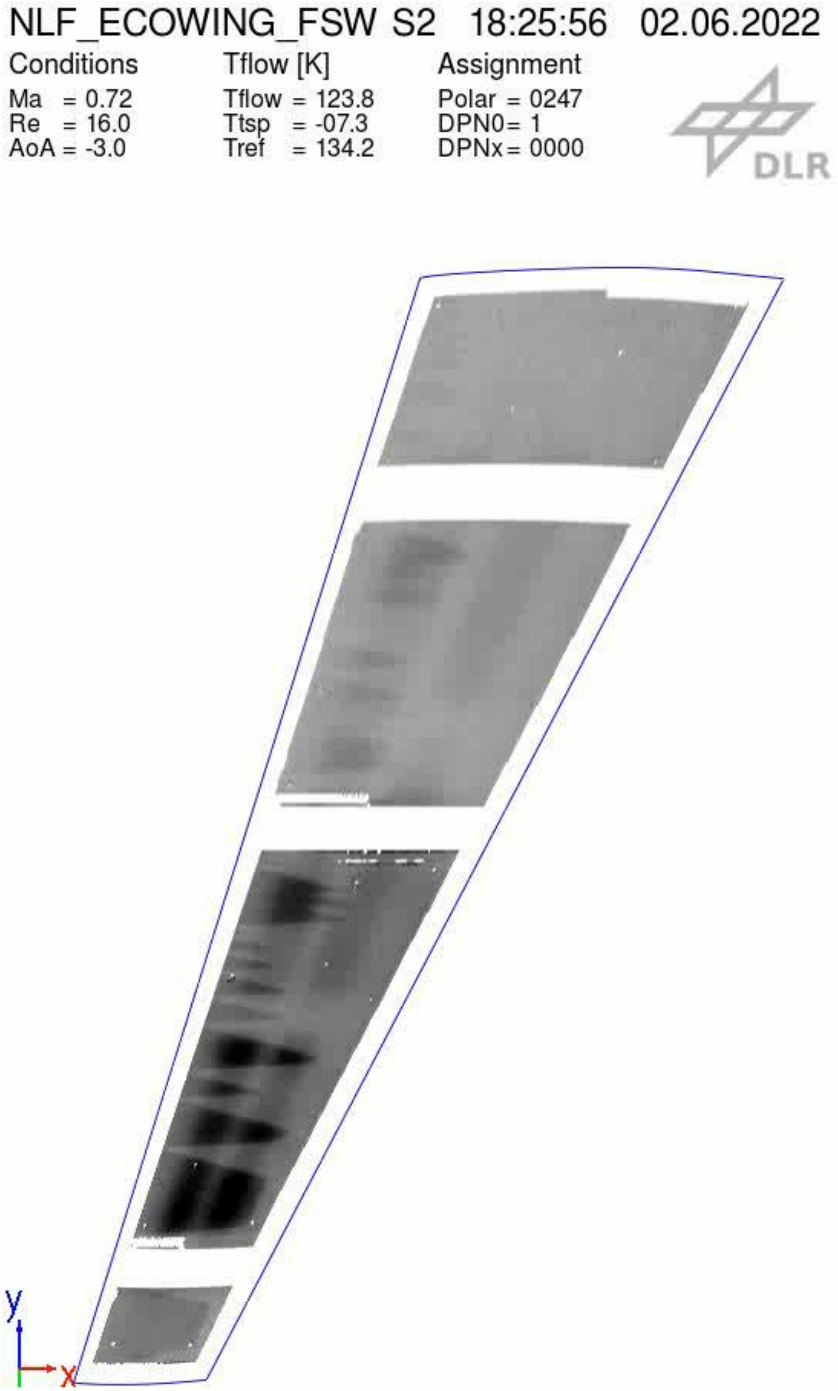
γ model+Rough

Transition line from LST/e^N method

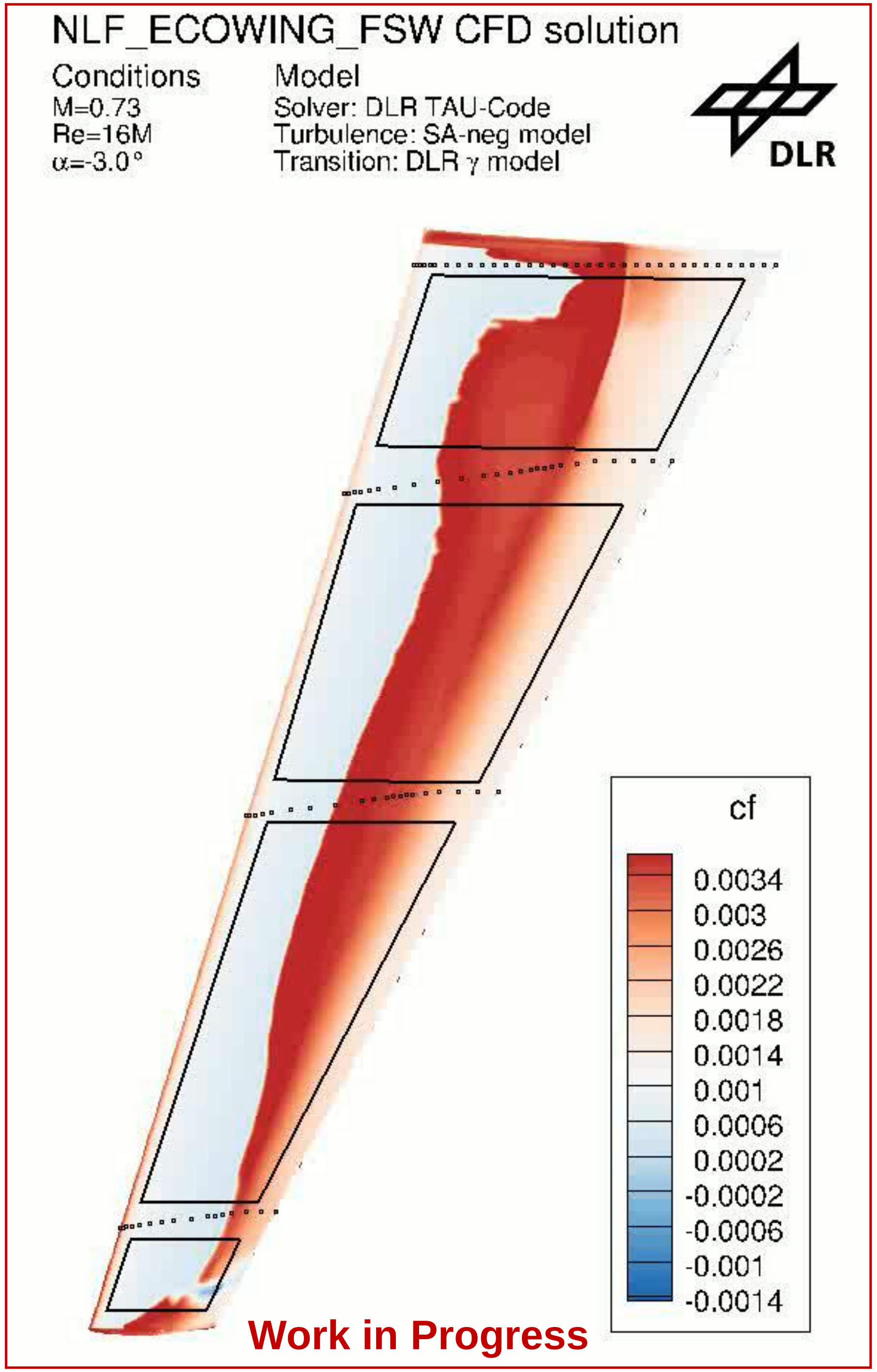
Next-level Validation

α-Sweep

- WT: 0.12 °/sec
- Steady CFD simulation



WT data from LUFO project ULTIMATE



Work in Progress

Conclusions

Validation of DLR γ model based on ULTIMATE-FSW Performance Test

- CF transition captured qualitatively with original helicity criterion, but too upstream
- Inclusion of surface roughness effect
  - improves CF prediction
  - can be used as environmental uncertainty in robust design
- Unprecedented validation possible thanks to experimental data
- Global trends of transition reflected in challenging α-Sweep

Outlook

- Further validation
  - CF-extension based on upcoming tests
  - Roughness extension is promising first shot (based on 1 test case only, non-local approximation) but needs further validation (more data)
  - 3D configurations
- Improvements of the robustness of the model → Student work ongoing

Thank you for your attention!

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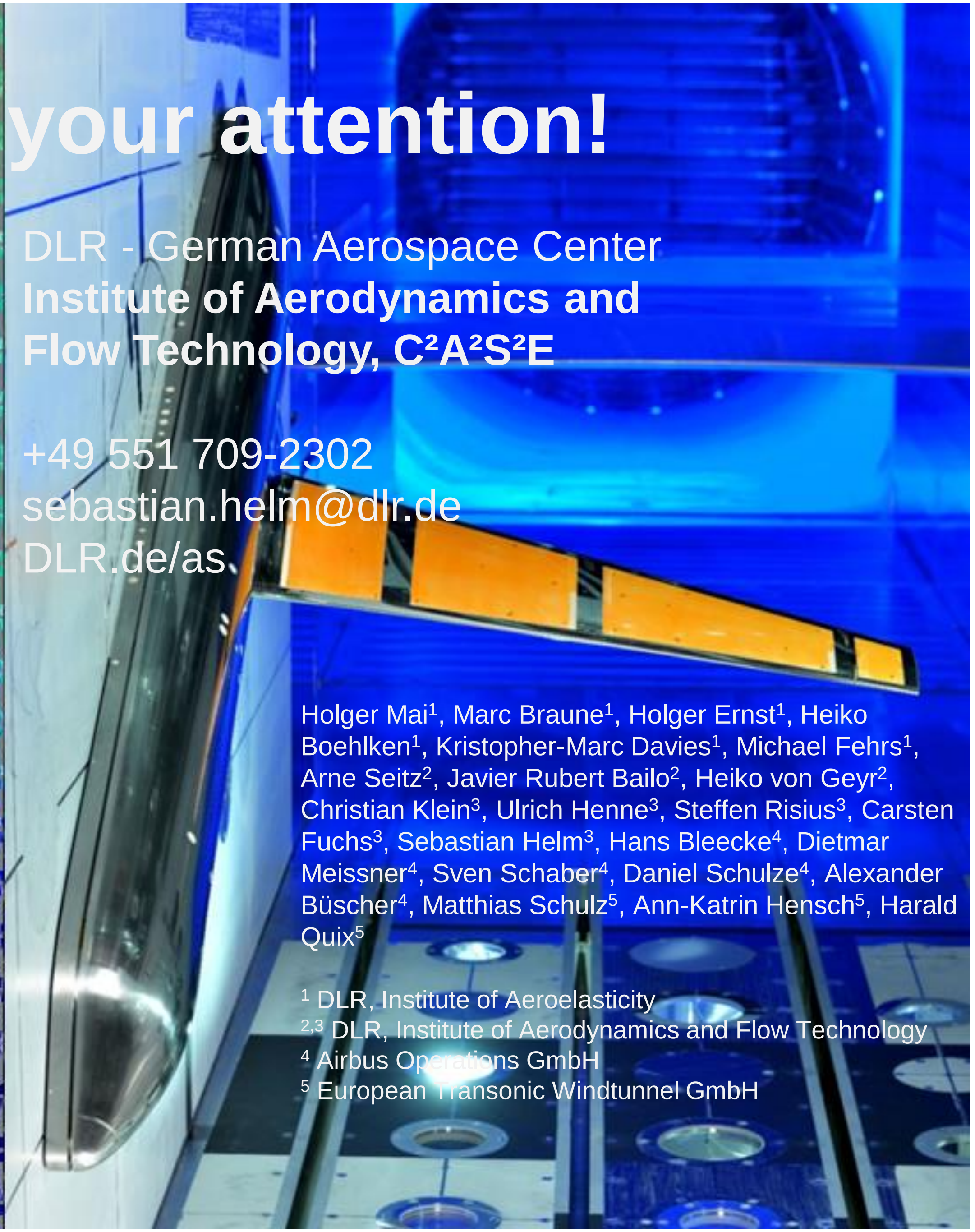

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[1] DLR, Institute of Aeroelasticity
[2,3] DLR, Institute of Aerodynamics and Flow Technology
[4] Airbus Operations GmbH
[5] European Transonic Windtunnel GmbH

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aufgrund eines Beschlusses des Deutschen Bundestages
LUFO ULTIMATE

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