# Blade Surface Pressure Measurements in the Field

## and their usage for aerodynamic model validation

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# Importance of aerodynamic field measurements

## Background and motivation

- Since 80s there have been joint efforts to validate and improve rotor aerodynamic models (IEA TCP Wind)
- With the advent of larger rotors, the topic of efficient but accurate models remains work in progress
- It is acknowledged that detailed sectional aerodynamic measurements (such as blade surface pressures) are needed to advance, a.o. to prevent compensating errors from integral measurements
- The wind energy community lacks publications featuring field databases of representative scale and measurement duration for this purpose
- Can we tackle this shortcoming??

iea wind

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# Outline

## Overview

- Background and motivation
- Methodology
  - Test set-up
  - Simulations
- Results
  - Pressure measurements
  - Comparison to simulations
- Conclusions and recommendations

# Project overview

## TIADE (Turbine Improvements for Additional Energy)

2020 - 2024

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LM WIND POWER a GE Renewable Energy business

GE Renewable Energy


Scope of TIADE project:

- Blade improvement (innovative tip shapes, VGs, turbulator tips)
- Validation (erosion, yawed inflow, stall and/or vortex induced vibrations)
- Measurement innovations (aerodynamic pressure, torsion deformation, fibre optics)

K. Boorsma et al, *TIADE final report*, TNO-2024-R12112, December 2024, https://publications.tno.nl/publication/34643564/vPzmF6yO/TNO-2024-R12112.pdf

TIADE has partly been financed with Topsector Energiesubsidie from the Dutch Ministry of Economic Affairs under grant no. TEHE119018

# Test set-up

## Overview

- GB LiDAR system is used to measure the wind field

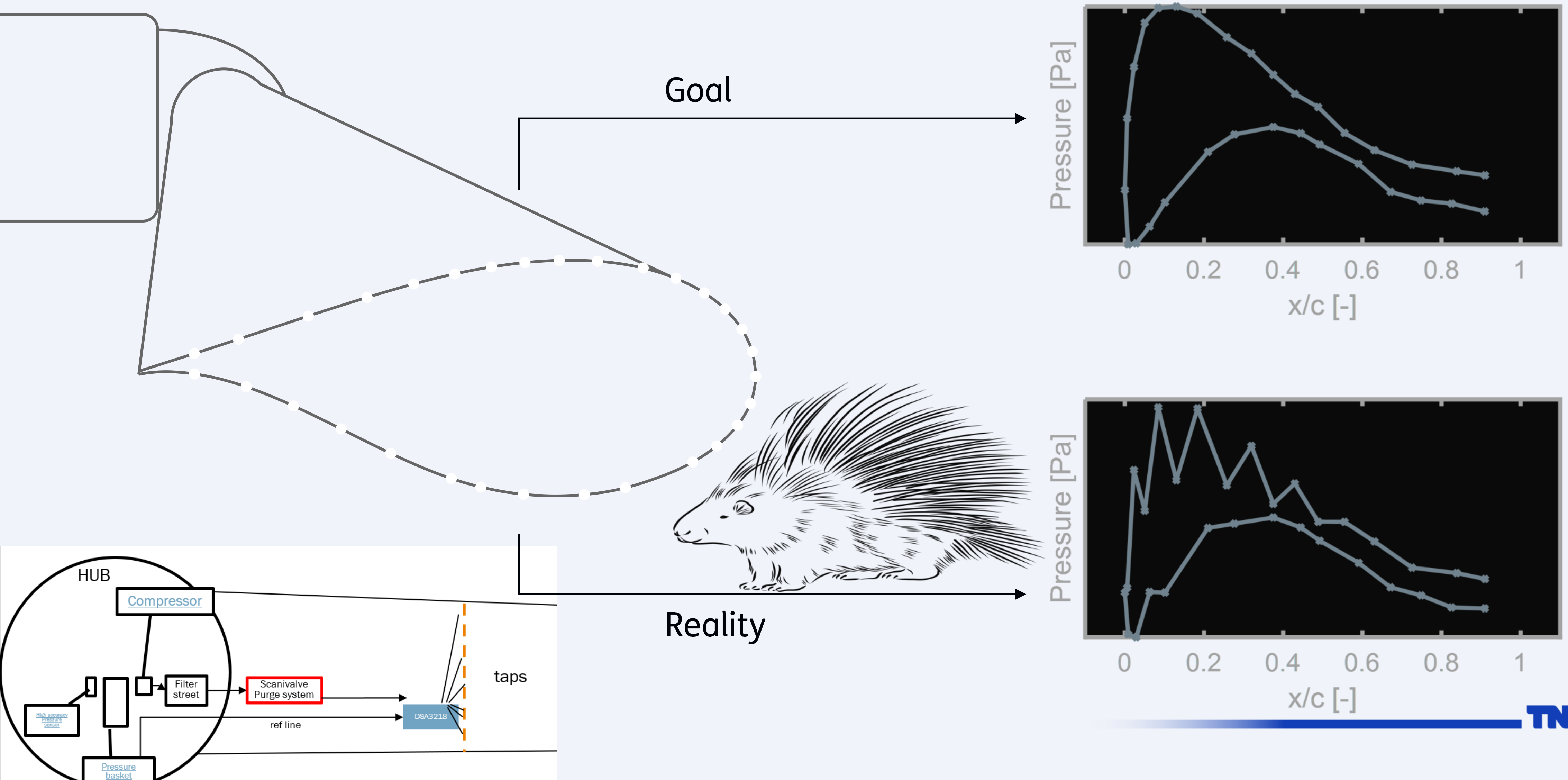
- The blade is equipped with pressure sensors at about 25% of the blade radius

3.8MW / 110 m hub / ⌀ 130 m

- Performance, loads and operational conditions are monitored

# Test set-up

## Challenges

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# Numerical simulations

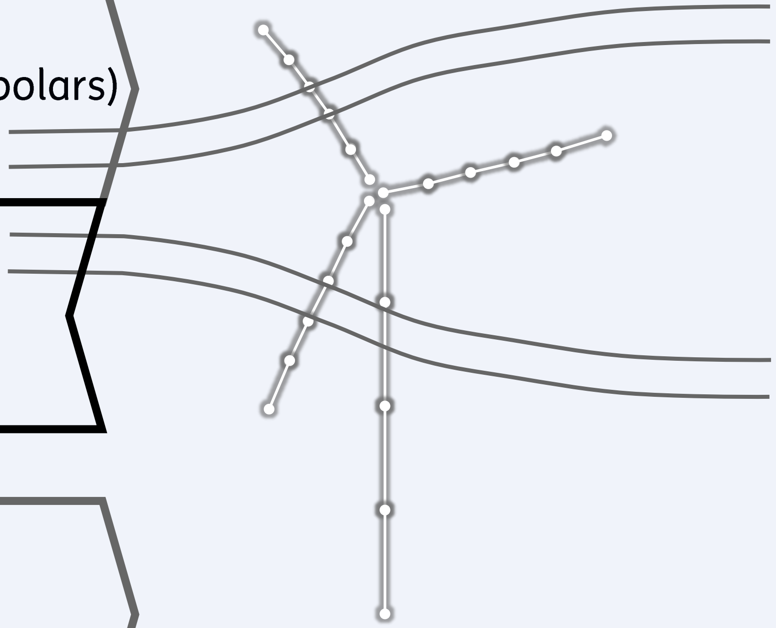
## Simulation tools

Input:

- Aerodynamic and structural turbine model (wind tunnel polars)
- Operating conditions

Output:

- Power, thrust
- Blade aerodynamics, moments and deformations



**Phatas**

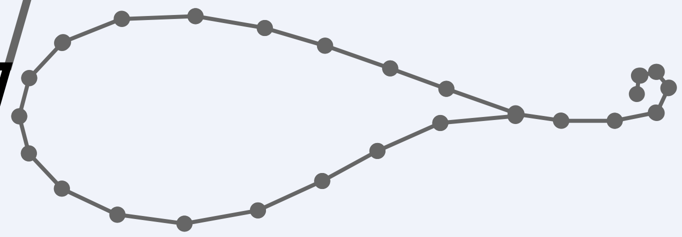
- BEM
- Structural solver

Input:

- Airfoil geometry
- Reynolds number, Angle of attack, c/r value

Output:

- Airfoil polars: $c_l,\ c_d,\ c_m$
- Pressure coefficient distribution



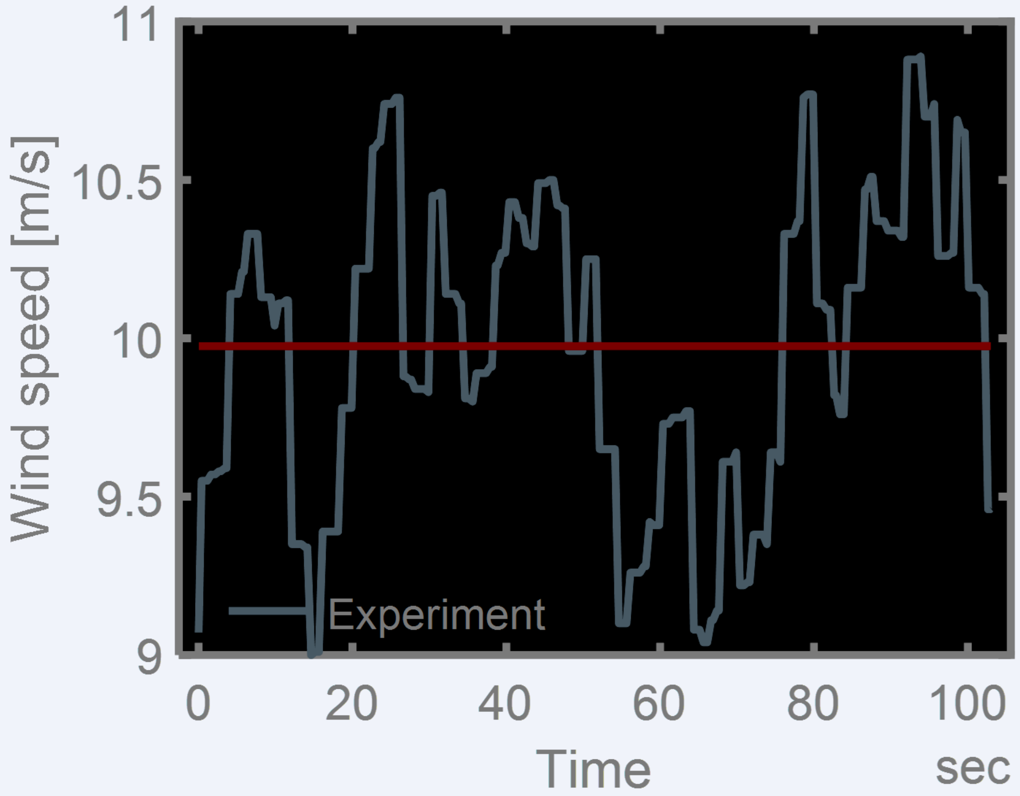
**RFOIL**

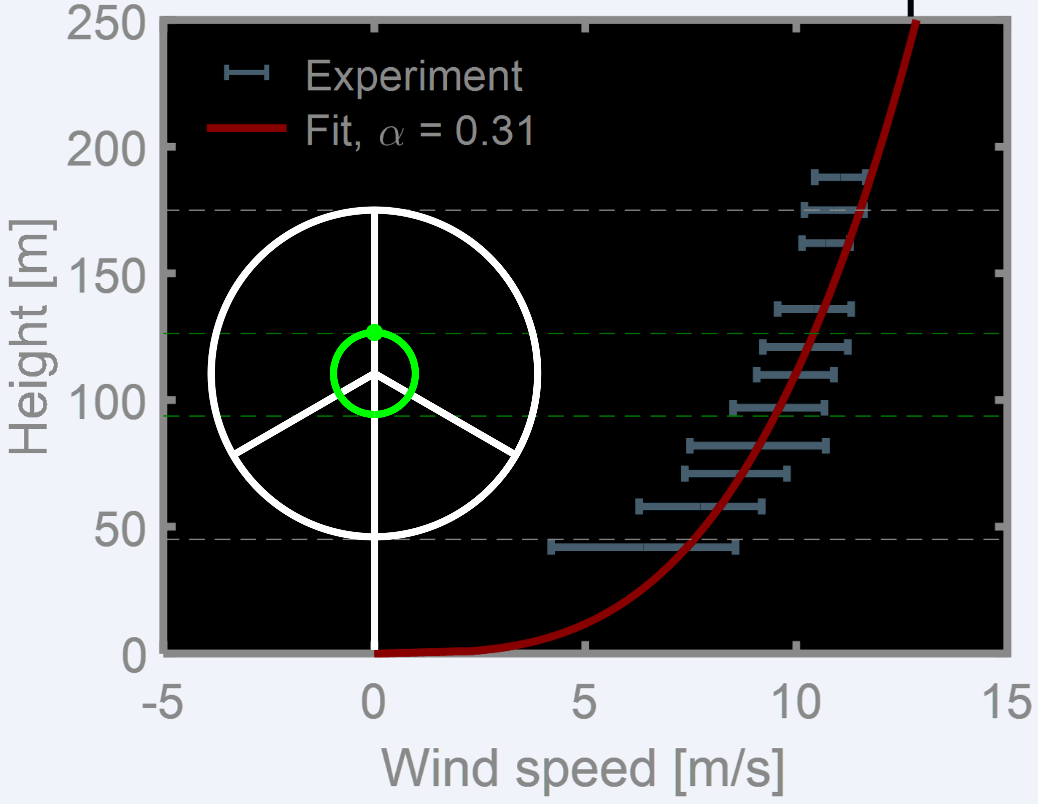
- 2D panel method
- Based on XFOIL
- Modified for rotating airfoils

# Results

## Operational conditions

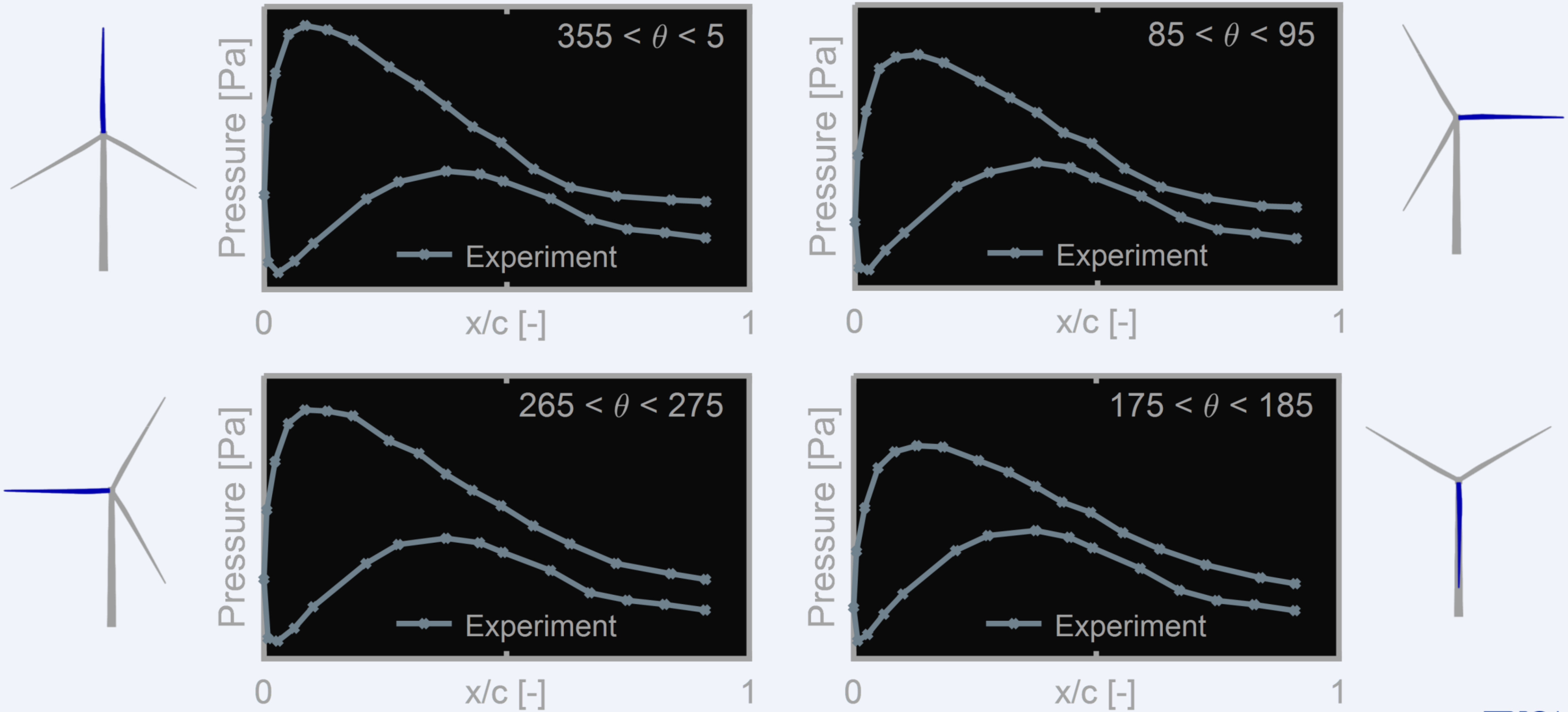
$$V(z) = V_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha}$$



# Results

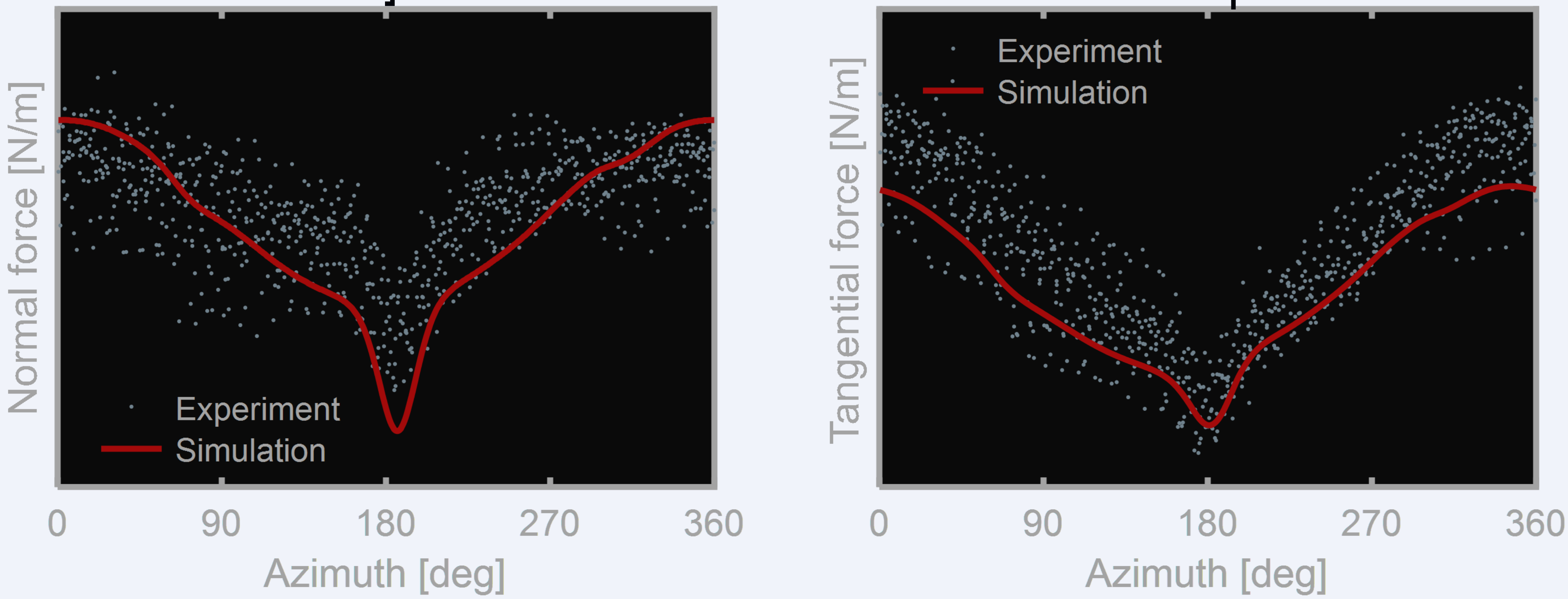
## Pressure distribution variation over a rotation



# Results

## Sectional forces

Effect of wind shear and tower passage visible



# Results

## Obtaining trends

Filter samples of 10-minute statistics for

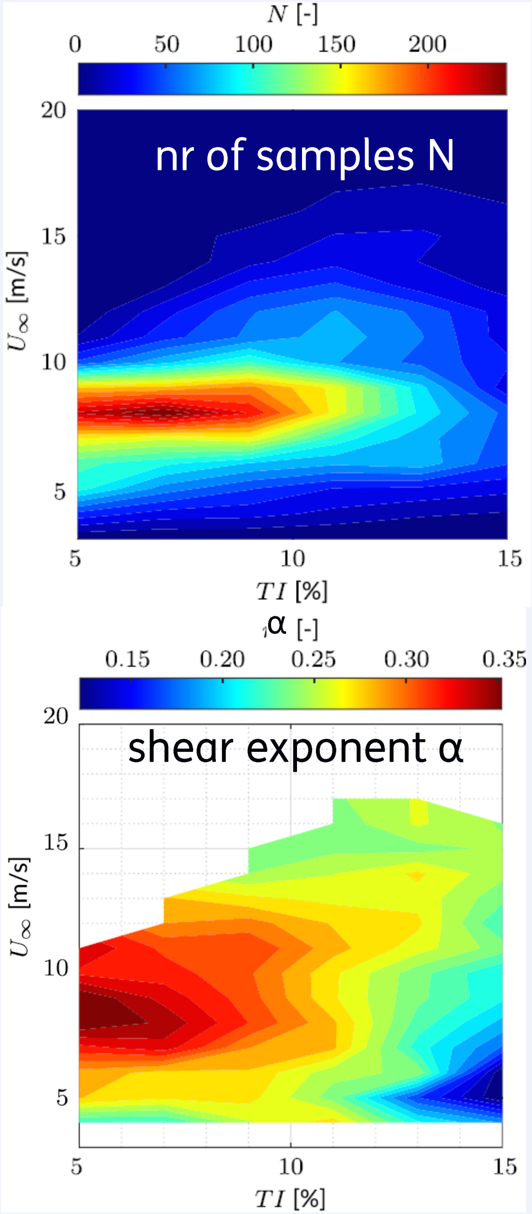
- Normal operating conditions (no standstill)
- Undisturbed wind sector (no waked inflow)
- No extreme events (exclude large yaw misalignment, TI and shear)
- Malfunctioning sensors

***~10% of data remains***

Bin average the resulting samples

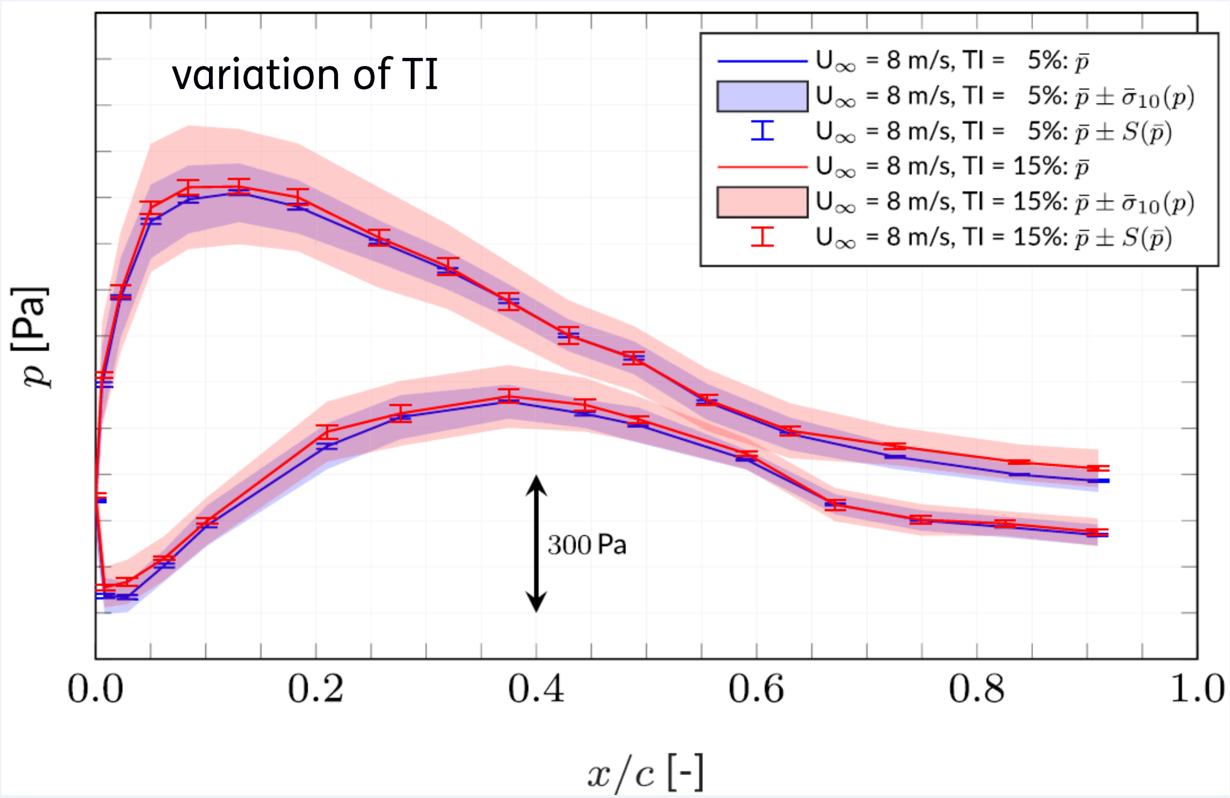
- Wind speed 3 to 20 m/s in steps of 1 m/s
- TI between 5% to 15% in steps of 2%
- Exclude bins < 6 samples
- Standard error to observe repeatability

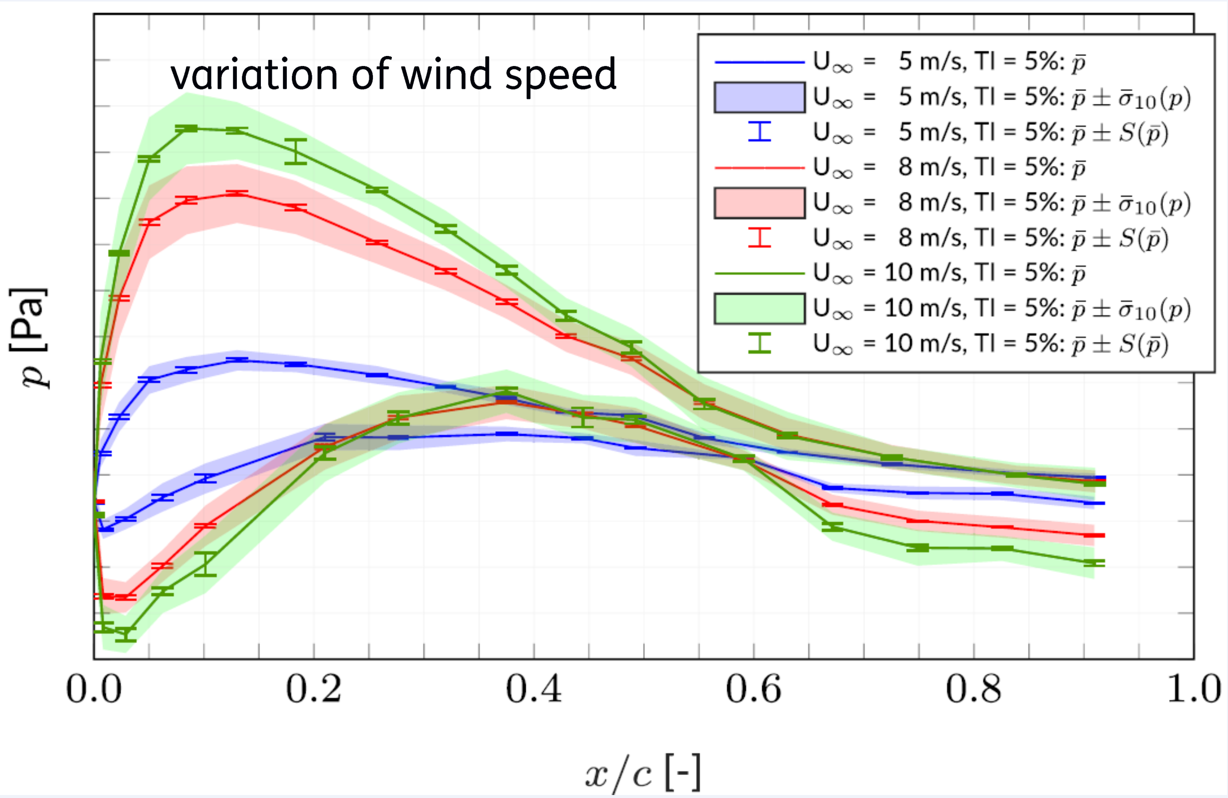
$$S(\bar{\xi}) = \frac{\sigma_{bin}(\bar{\xi})}{\sqrt{N}}$$



# Results

## Trends: Variation with wind speed and TI

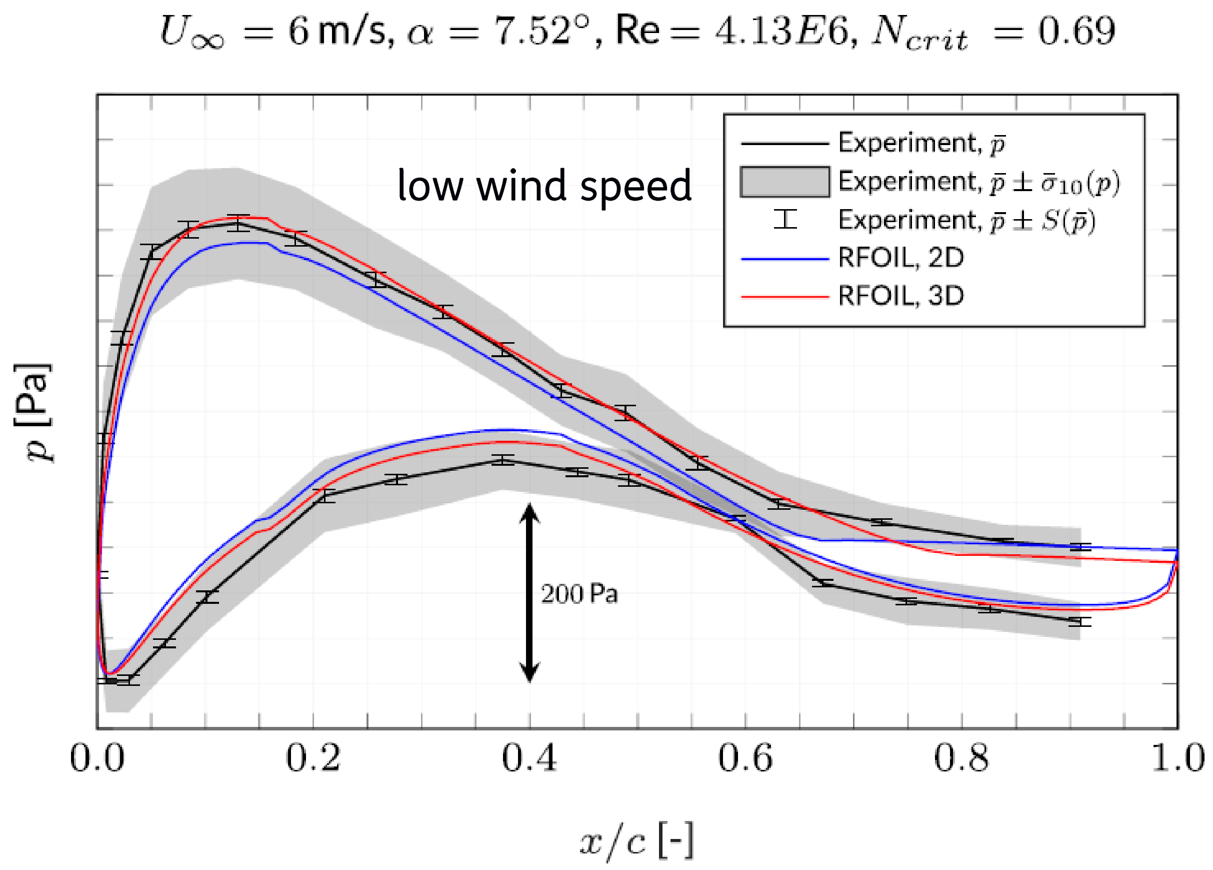


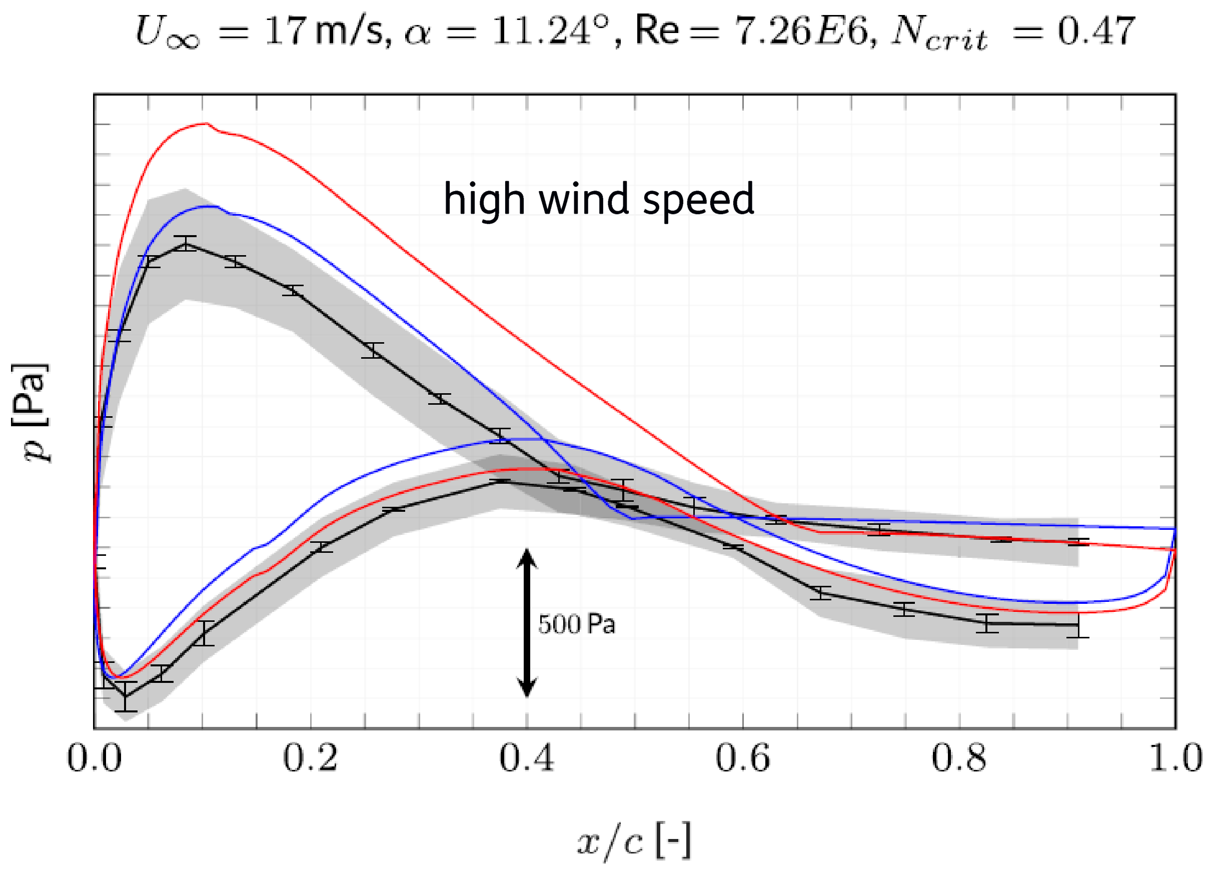



# Results

## Comparison to RFOIL – pressure distribution

- Input bin avg operational conditions to Phatas to obtain sectional conditions
- Input AOA and Re to RFOIL

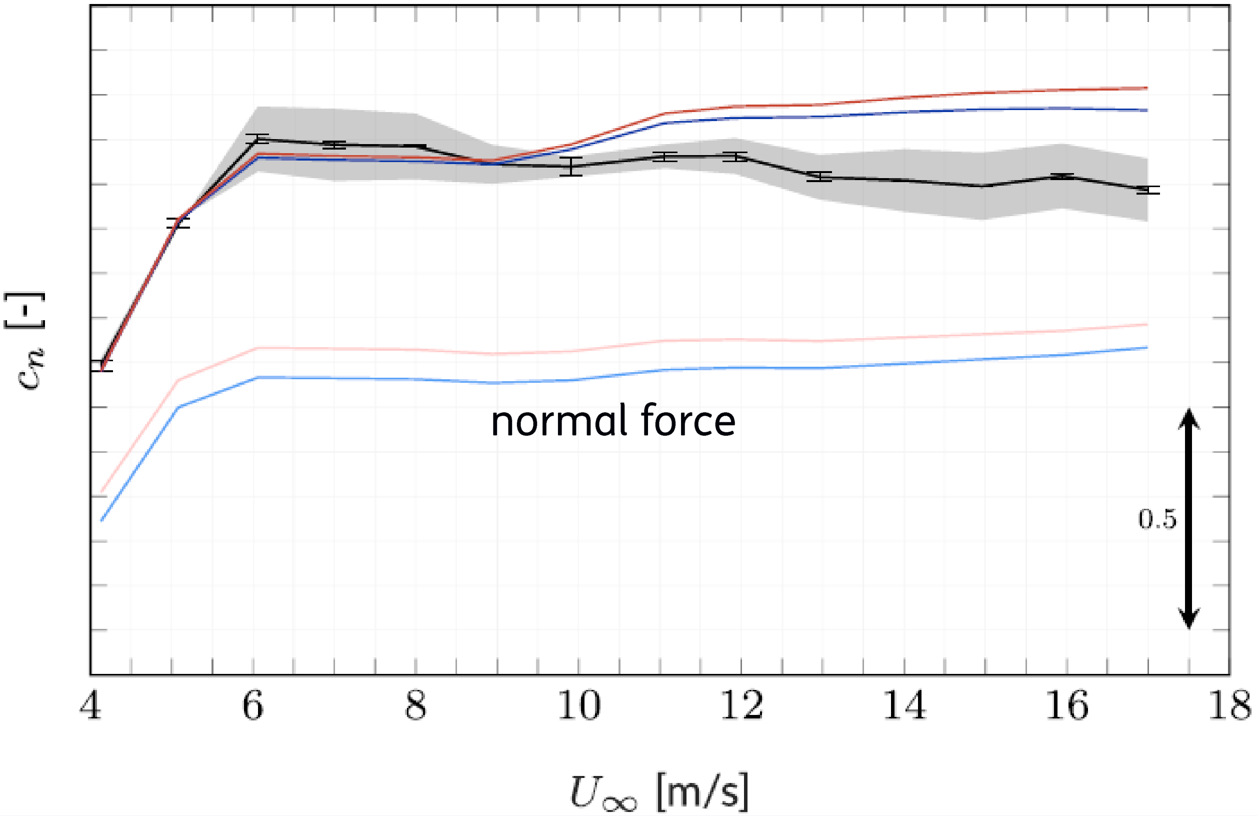


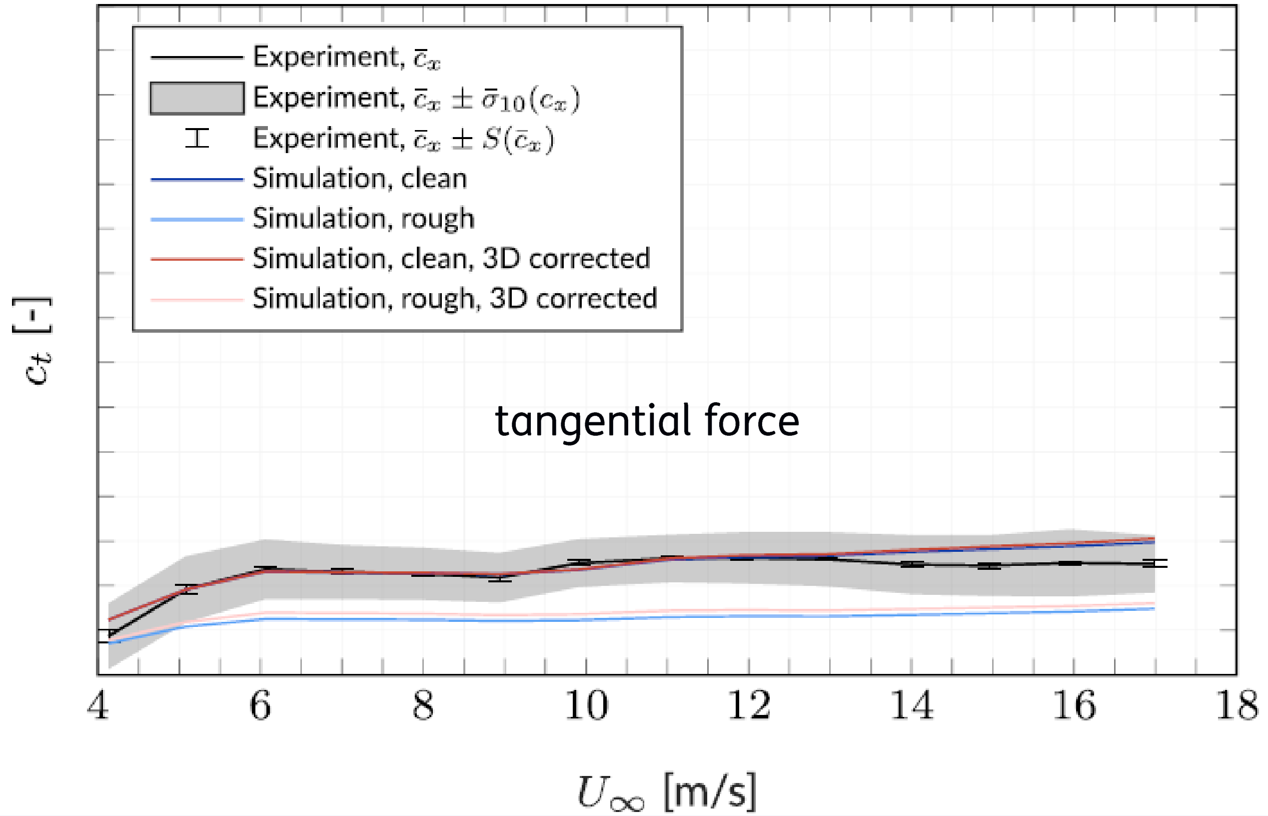



# Results

## Comparison to Phatas – normal and tangential force (steady)

- Measured and simulated coefficients non-dimenionalized without induced velocities



# Conclusions and recommendations

- Blade surface pressures were successfully measured on a state of the art R&D 3.8 MW wind turbine over a 2 year period, providing invaluable means for validating design tools
- The resulting measurement database gives a good insight in the aerodynamic performance at the measured section
- Overall a reasonable agreement has been obtained between numerical simulations and field experiments
  - Numerical tools based on blade element momentum theory and panel methods with viscous-inviscid interaction remain relevant for simulating modern multi-megawatt wind turbines
  - Larger discrepancies can be observed for higher wind speeds, when stalled flow occurs
- More details and results, e.g. about correlation with unsteady simulations, in the dedicated publication: E. Fritz et al, *Blade Surface Pressure Measurements in the Field and Their Usage for Aerodynamic Model Validation*. Wind Energy 27(12), December 2024, https://doi.org/10.1002/we.2952

# Thank you for your attention

Take a look:

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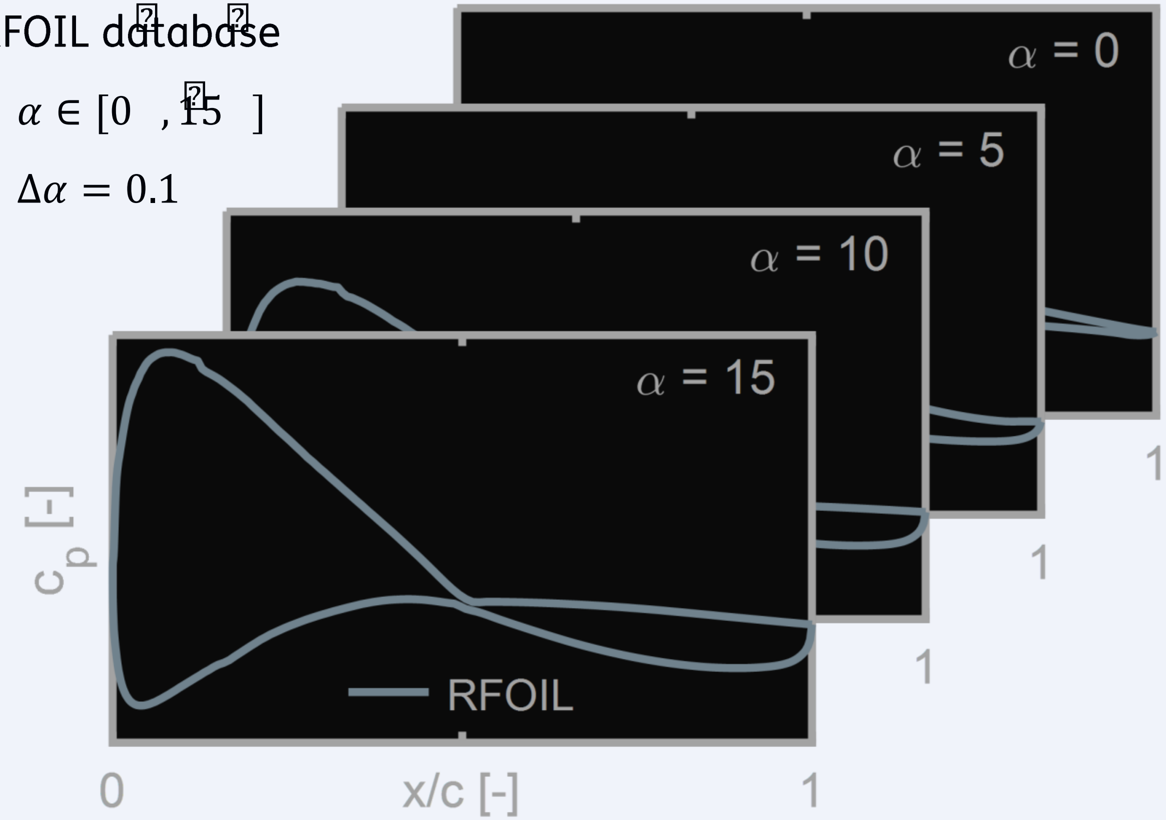
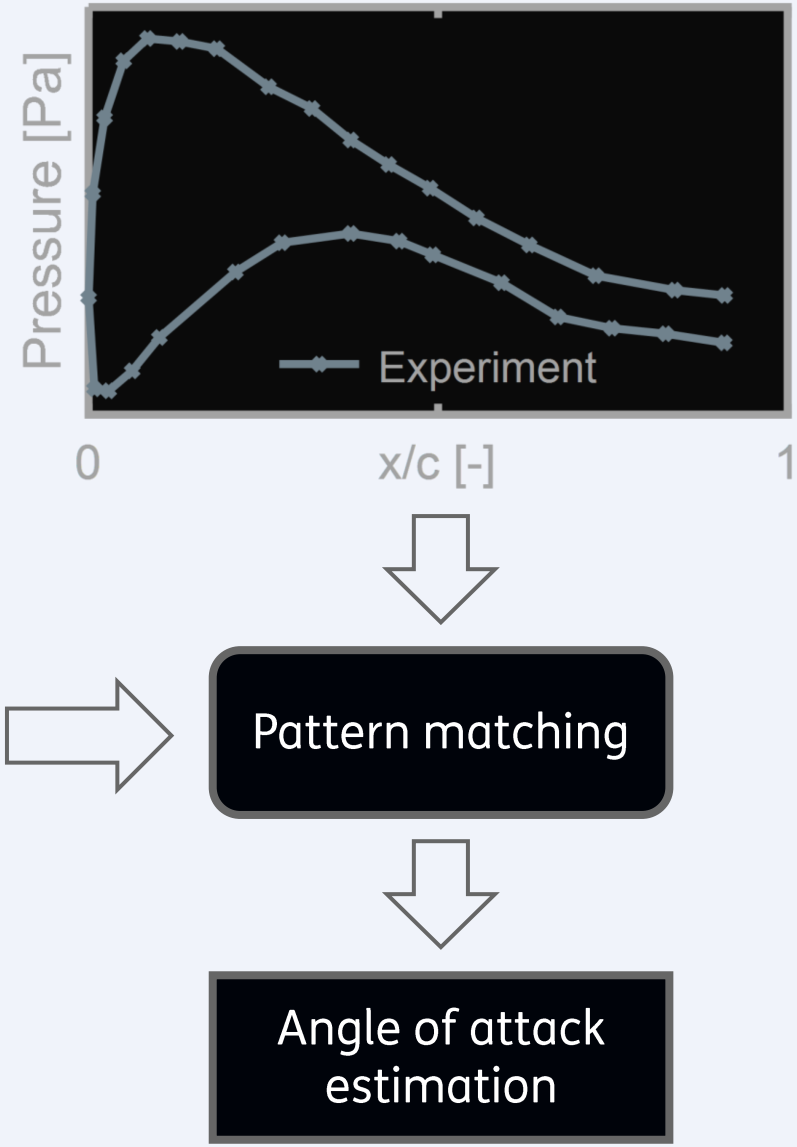
# Results

## Angle of attack estimation

- RFOIL database
  - $\alpha \in [0 \; , 15 \; ]$
  - $\Delta\alpha = 0.1$

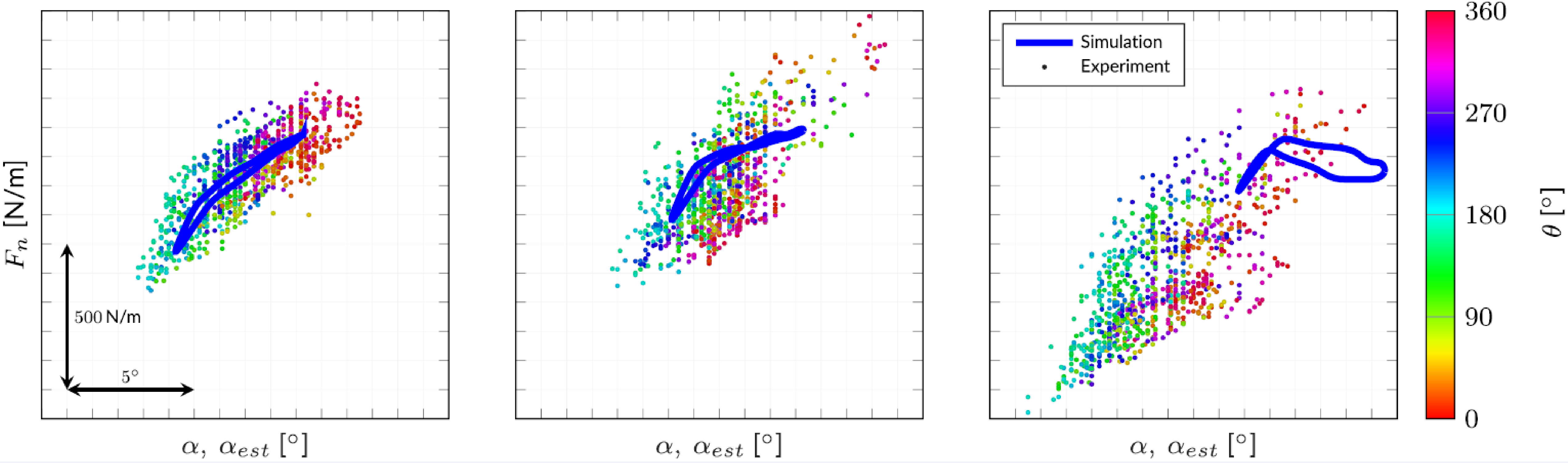


# Results

## Comparison to Phatas – normal force (unsteady loops)

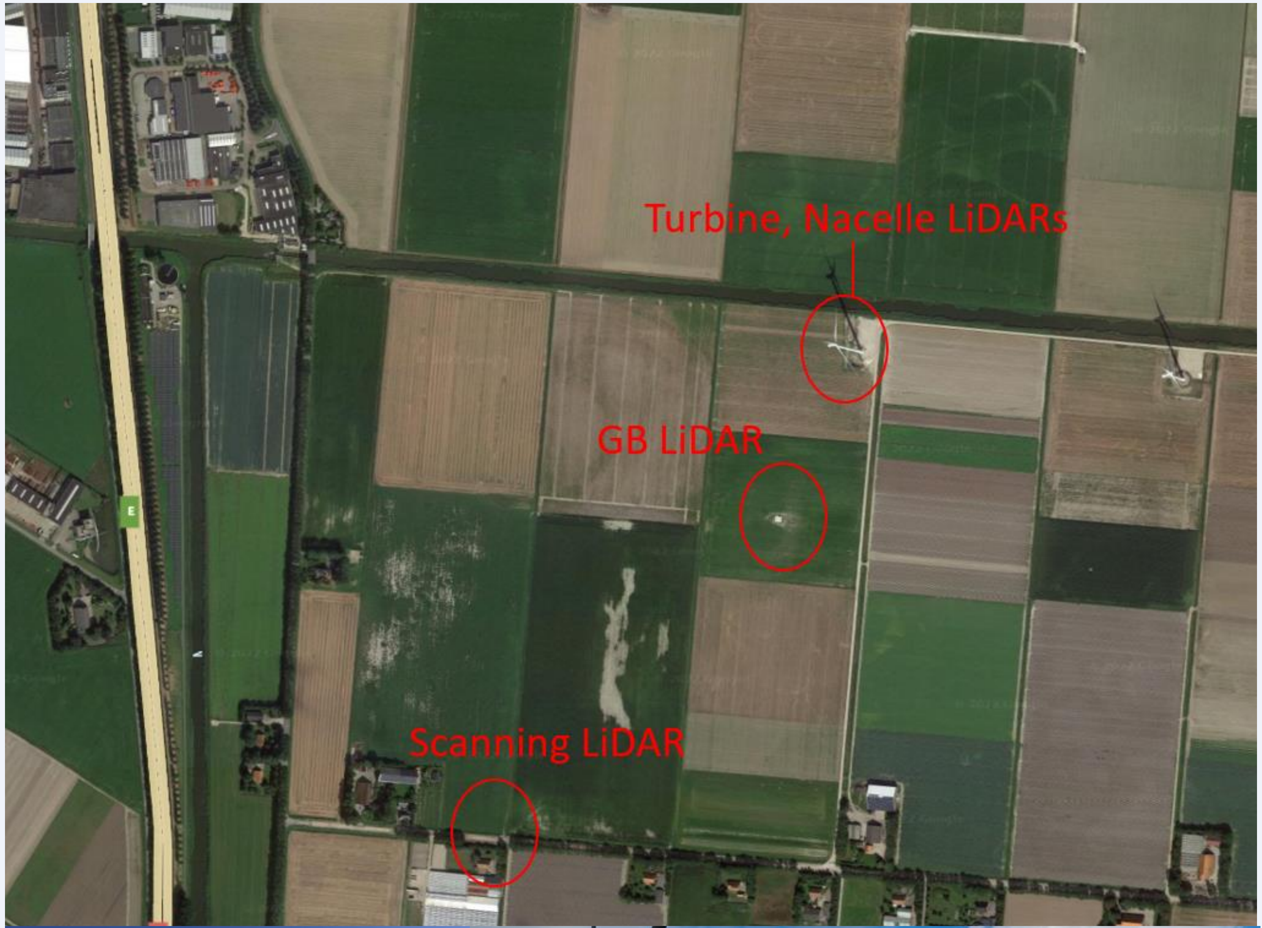
- Measurements: Estimated angle of attack $\alpha_{est}$ using pattern matching
- Simulations: Snel 1st order dynamic stall
- Agreement between measurements and simulation varies between samples



# Test set-up

## Test site overview

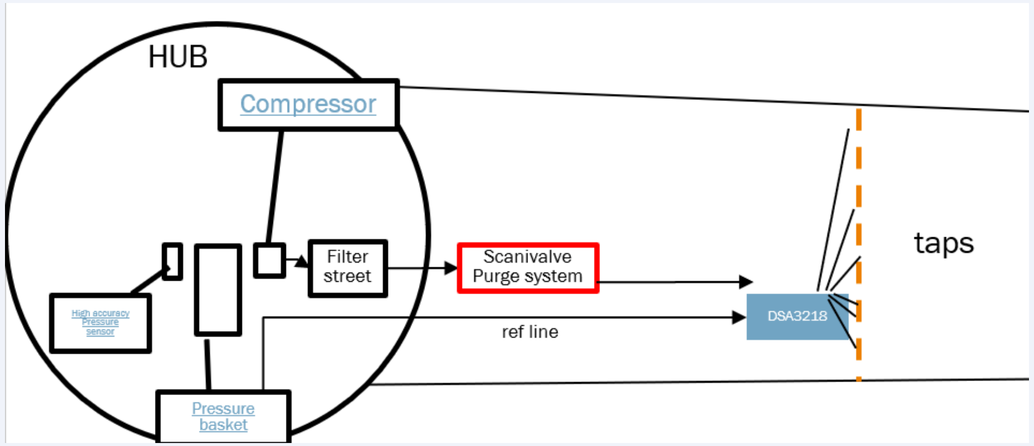
- Turbine type: 3.8MW, 110 m hub height, 130 m rotor diameter
- Ground based Windcube LiDAR @ 11 heights (42 - 188 m)
- 2 Nacelle based fwd looking LiDARs (~0.25D - 5D)
- Meteo mast at 2 km from turbine (wind, press, temp, disdro)
- Scanning LiDAR to measure wake at hub height (1D – 5D)

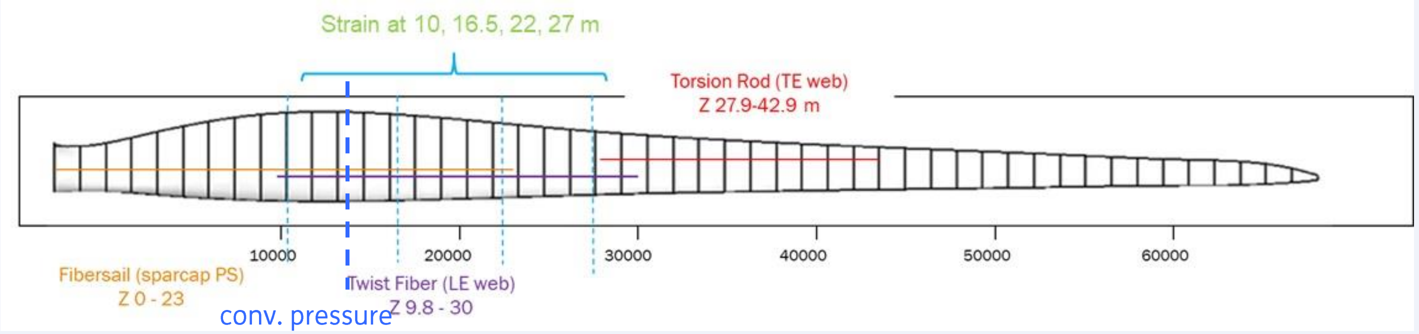



# Test set-up

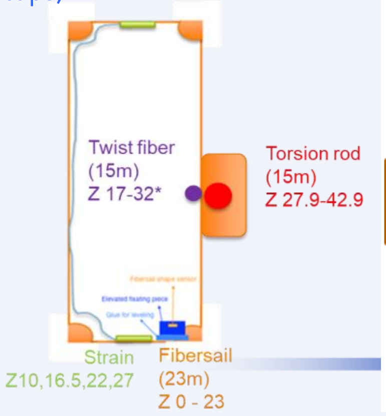
## Turbine instrumentation

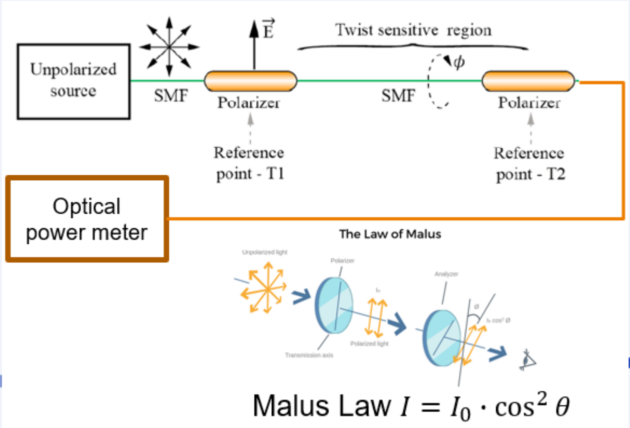
- IEC compliant power performance and loads (tower/shaft/blade)
- SCADA and tower top acceleration/inclination
- Deformation (torsion / flap / edge)  and tufts @ blade roots
- Conventional pressure (+ fibre optic trial) @ 25% r/R (~2 years!)



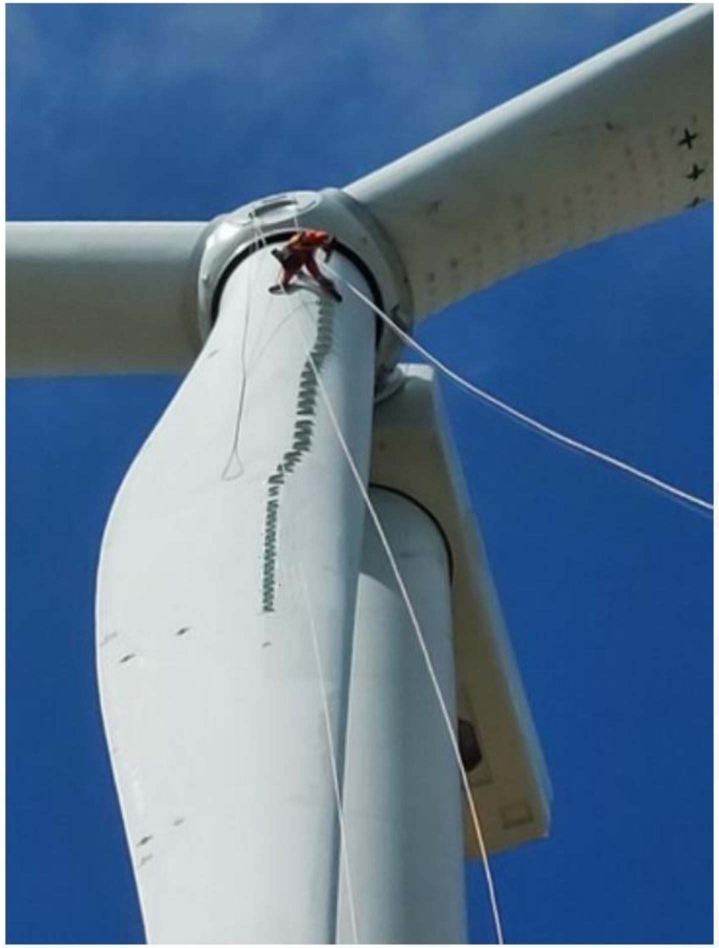

conv. pressure
(30 taps)



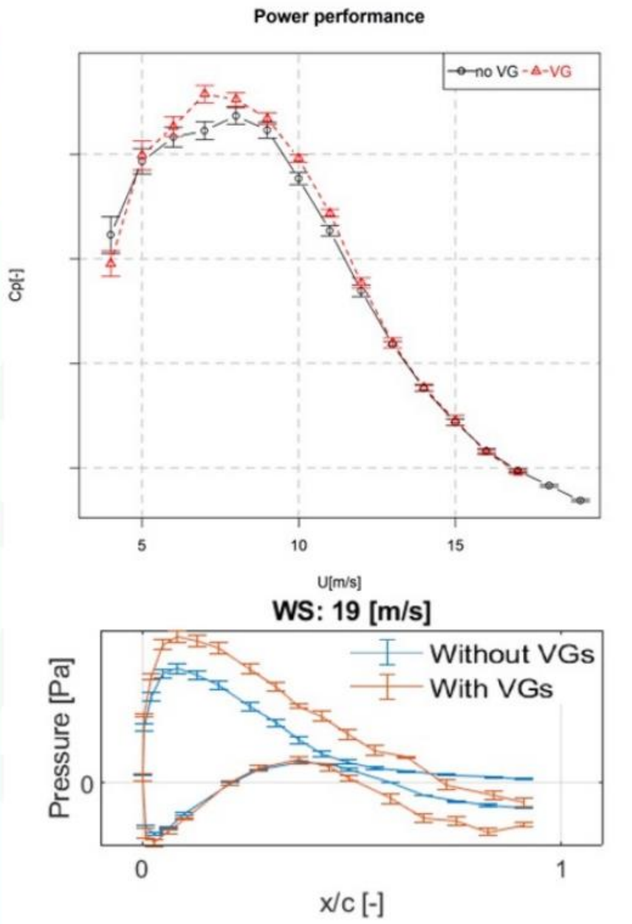



# Effect of Vortex Generators

## Vortex generators



(a) Installation of VGs using rope access



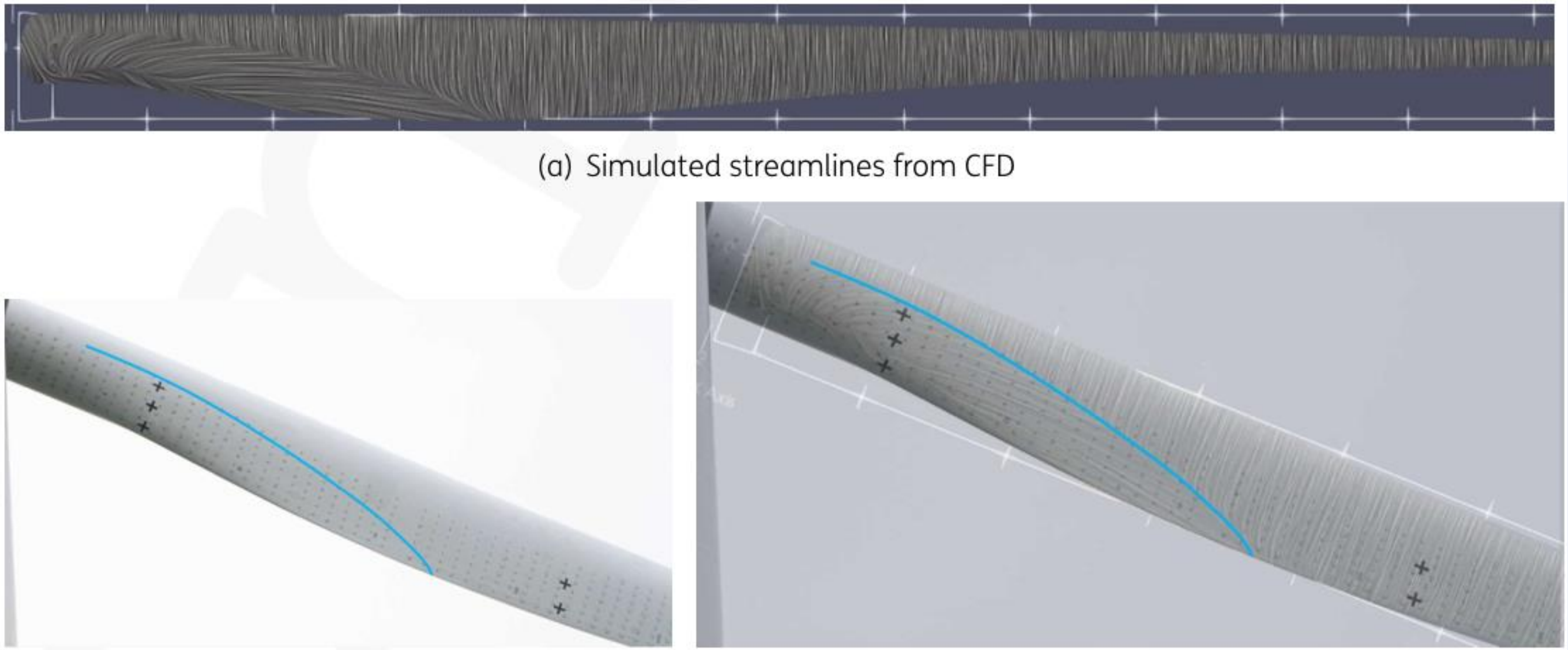

(b) Measured power coefficients (above) and pressure distibutions (below) with and without VGs [19]


[18] K. Vimalakanthan. *Vortex generator layout design for TIADE blade section at 15m blade span*. Tech. rep. TNO 2024 R12151. TNO, 2024.

[19] G. Vanino. *Vortex Generators applied to large-scale Wind Turbines*. Tech. rep. TNO 2023 M12095. TNO, 2023.

# Validation of models

## Tuft measurements



(a) Simulated streamlines from CFD

(b) Tuft visualization with separation line in blue

(c) Overlay of tuft and CFD results

Figure 3.11: Comparison between measured and predicted streamlines using tufts visualization and CFD simulations at 8 m/s [13]

[13] M. Caboni et al. *3D RANS-based CFD simulations on the LM637P blade*. Tech. rep. TNO 2024 M11257. TNO, Nov. 2024.