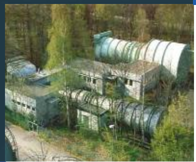
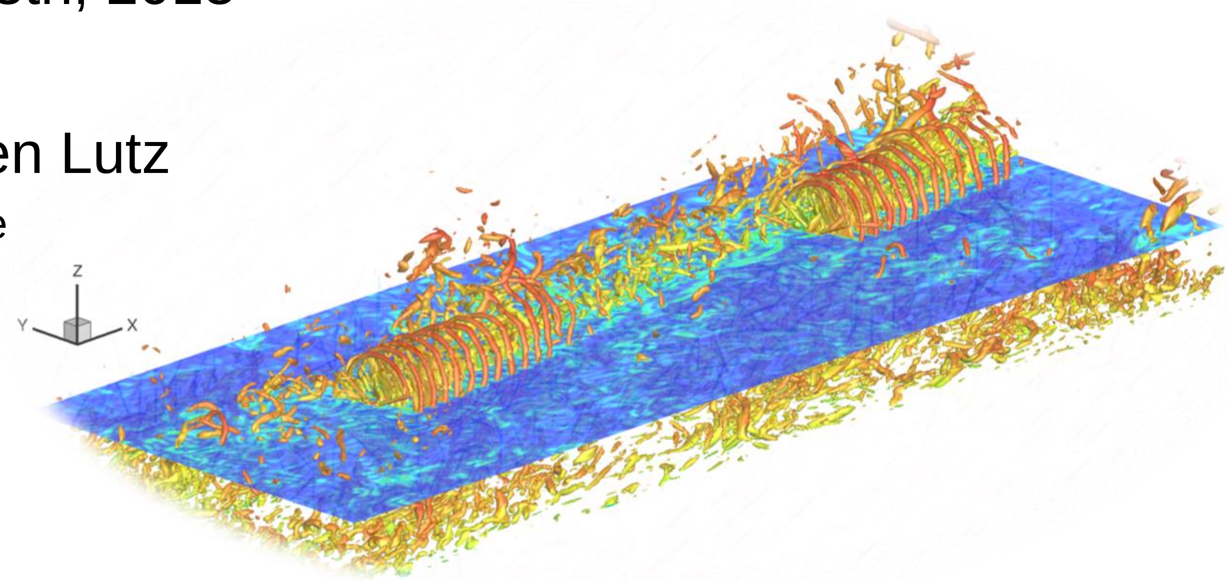


Numerical Simulations of Wake Turbine Interactions in Alpha Ventus

Bremerhaven, October 13th, 2015

Pascal Weihing, Thorsten Lutz
{weihing, lutz}@iag.uni-stuttgart.de



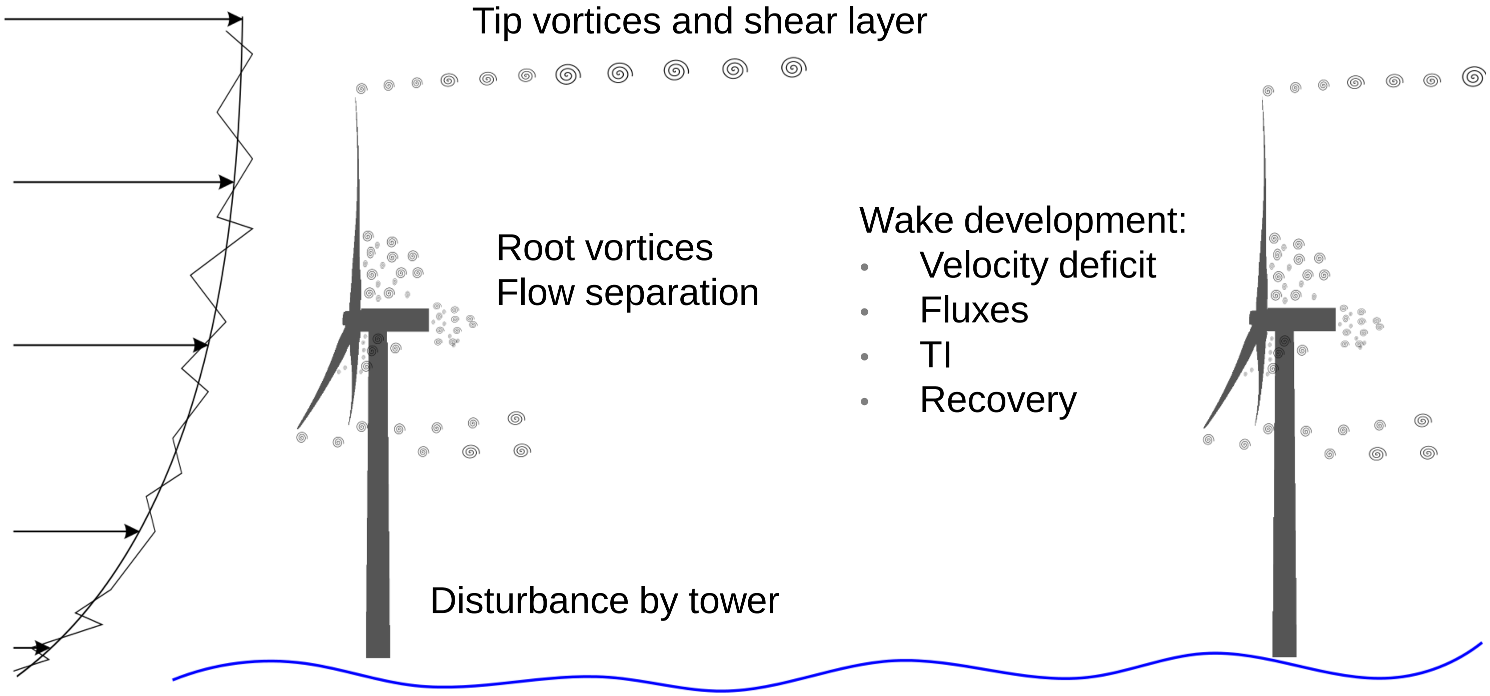
Contents

- Motivation
- Numerical wind turbine/farm model
- Test case and setup
- Results
- Conclusions

Motivation

Complex flow situation within a wind farm

Turbulent atmospheric inflow



Research Questions:

- Wake development of the upstream turbine
- Flow conditions at the downstream turbine which highly influence
  - Power output
  - Loads
  - Wake development

➔ What is the appropriate numerical model to shed light into these problems?

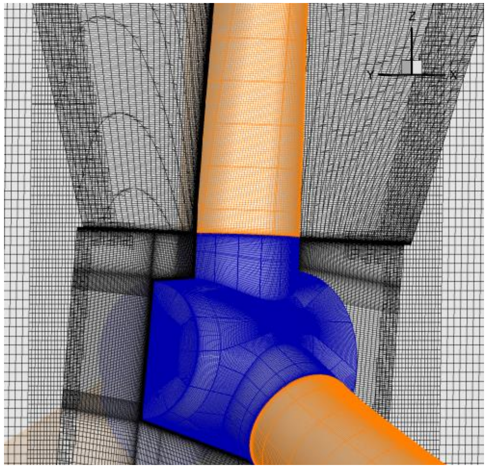
Numerical Modeling of Wind Turbines at IAG

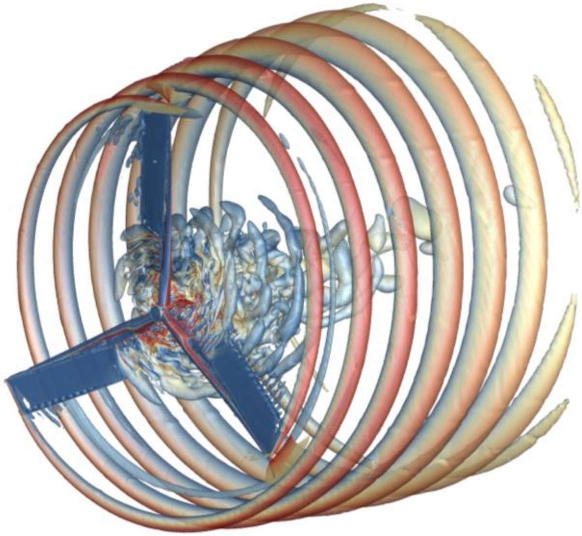
Fully resolved rotor (FR)

- Boundary layer of the airfoil is resolved $y^+ \approx 1$
- Turbine components are separately meshed and integrated using the overset grid technique [1]

→ Detailed view into flow phenomena around the rotor

→ Accurate prediction of loads and power including unsteady aerodynamic effects without need for further modeling



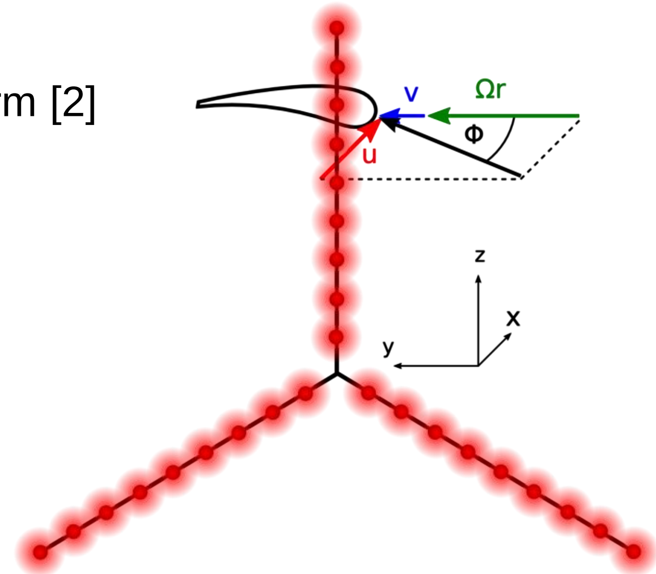


Disadvantages:

- Time consuming meshing
- High computational effort

→ Only suitable for simulation of wind farms to a limited extent

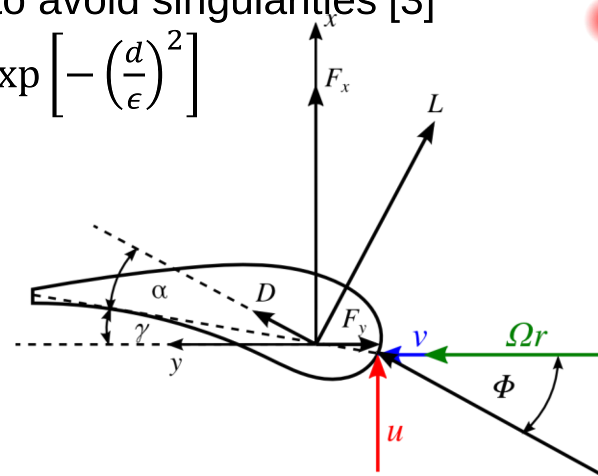
Numerical Modeling of Wind Farms at IAG

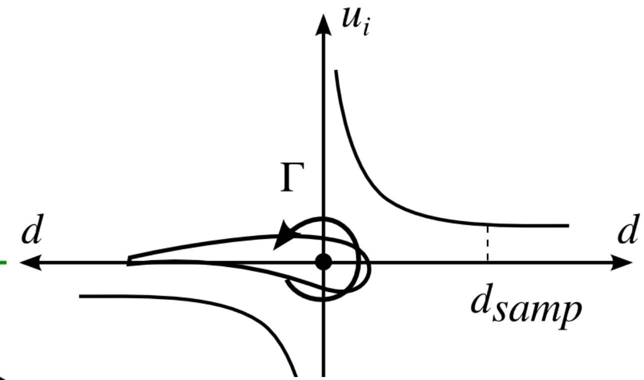


Actuator Line Model (AL)

- Effect of blades on the flow modeled by a momentum source term [2]
- Tower Modeled similarly as AL drag line
- Aerodynamic forces: $f_{2D} = \frac{1}{2}\rho v_{rel}^2 c(c_l(\alpha)e_L,\ c_d(\alpha)e_d)$
- Sampling points for velocity upstream of the bound vortex, inflow angle corrected with Biot-Savart Law
- Gaussian smearing of the forces to avoid singularities [3]

$$f = f_{2D} \otimes \eta_{\epsilon,3D}, \qquad \eta_{\epsilon,3D} = \frac{1}{\epsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{d}{\epsilon}\right)^2\right]$$





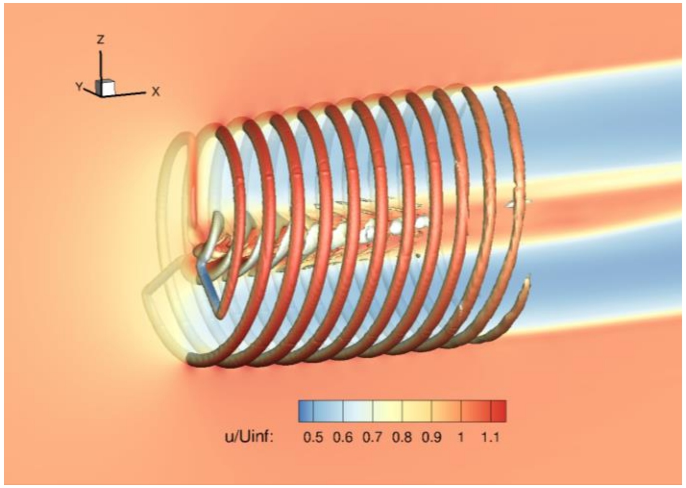
Numerical Modeling of Wind Farms at IAG

Strengths of the AL

- ➔ Saves grid points
- ➔ Easy to integrate in a simple mesh

- ➔ Effect of the circulation of each blade on the flow field can be simulated
  - ➔ Velocity deficit
  - ➔ root and tip vortices

- ➔ Well suited to simulate the flow field within wind farms



Disadvantages:

- ➔ Uncertainties in prediction of power and loads:
  - ➔ Smearing function ϵ [4,5]
  - ➔ Determination of α
  - ➔ Based on 2D airfoil polars
- ➔ Can only simulate equilibrium state of flow field and loads
- ➔ Further modeling of nacelle needed

The Flow Solver at IAG

FLOWer (DLR)

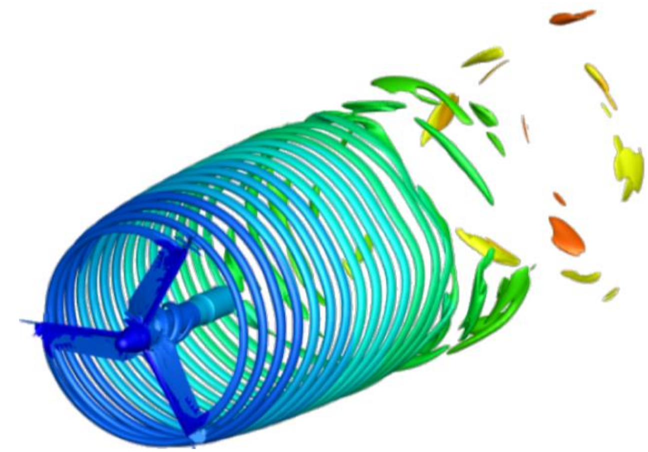
- Block- structured solver
- Compressible Navier-Stokes equations
- Multigrid

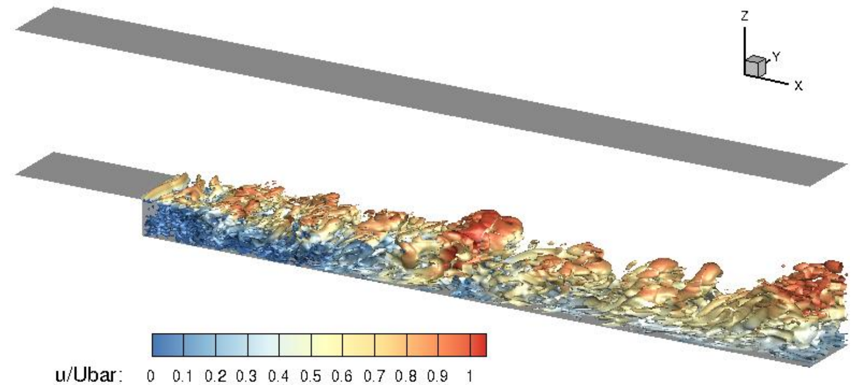
Discretization

- Second order dual timestepping
- Second order JST (CDS + artificial damping)
- 5th order weighted essentially non-oscillatory (WENO) schemes

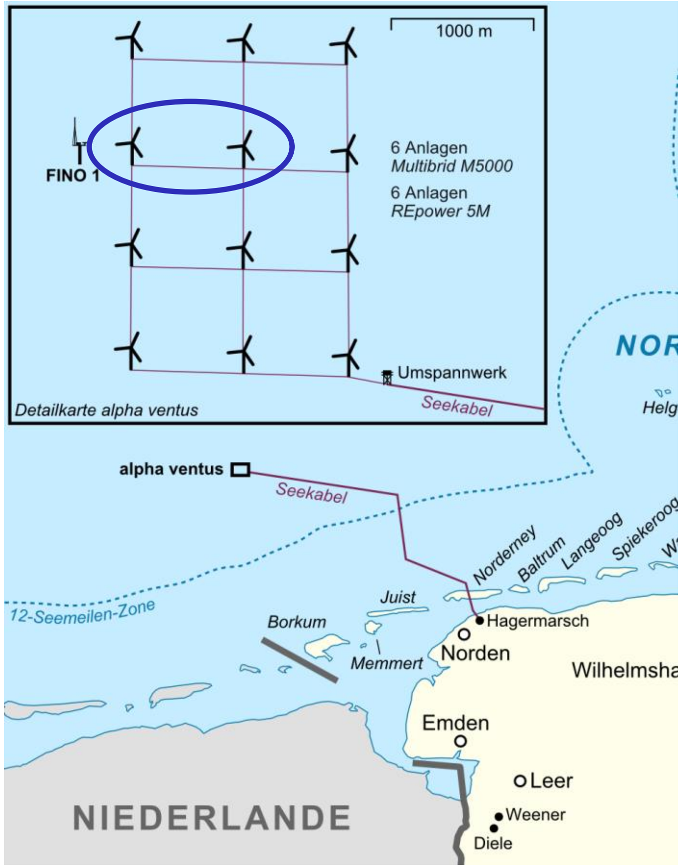
Turbulence Modeling

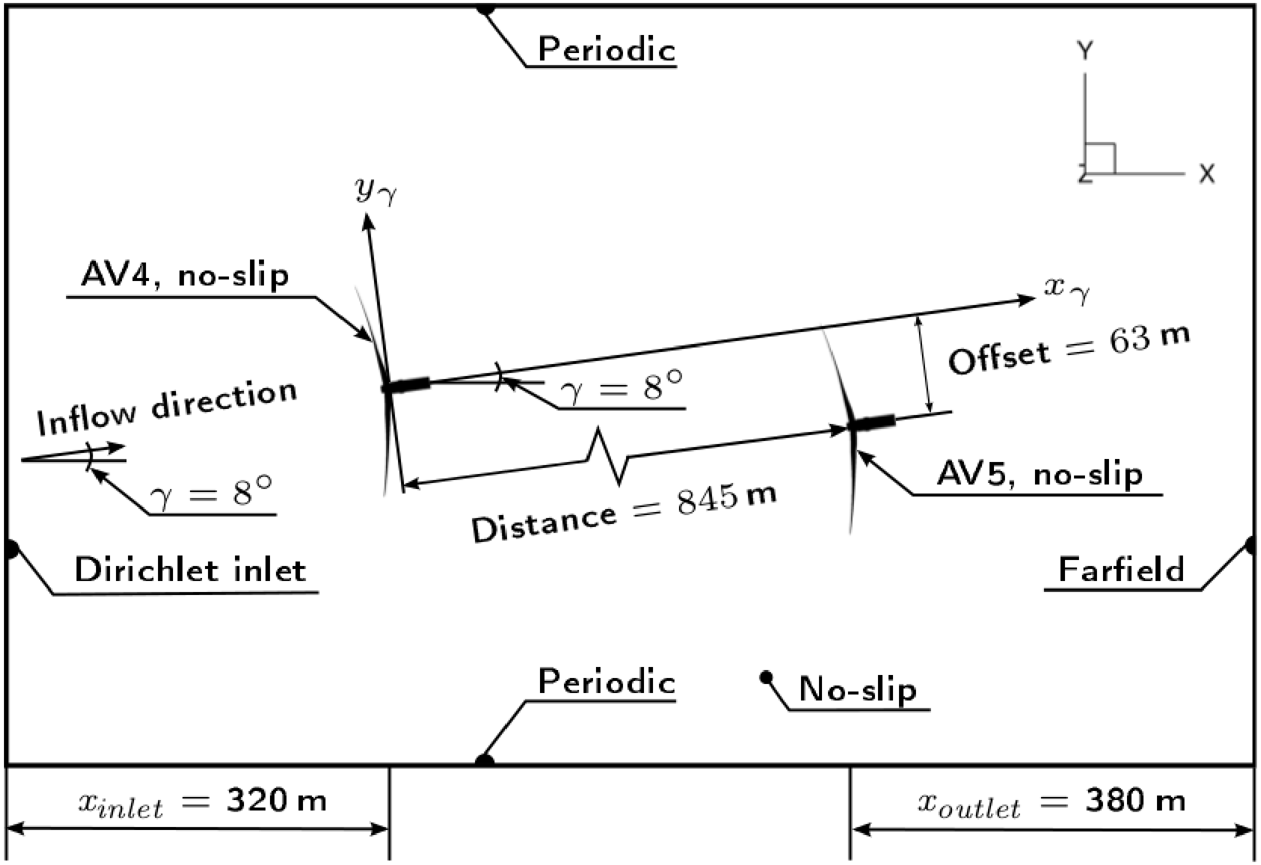
- Classical RANS (Eddy viscosity models, RSM)
- Hybrid RANS/LES (DES97, DDES, IDDES)





Test Case and Setup





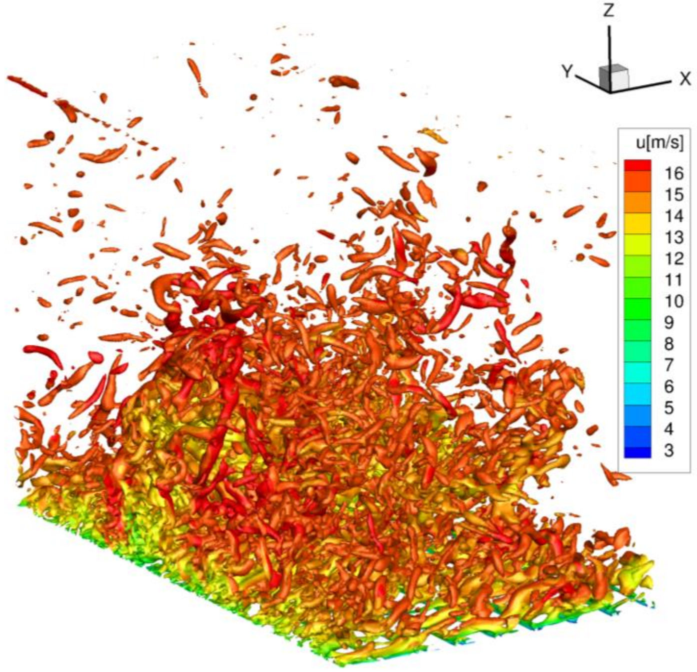
➔ **"Half-wake": ➔ higher fatigue loads expected for the downstream turbine**

Operating conditions

Turbulent inflow

Precursor LES by ForWind Oldenburg with PALM

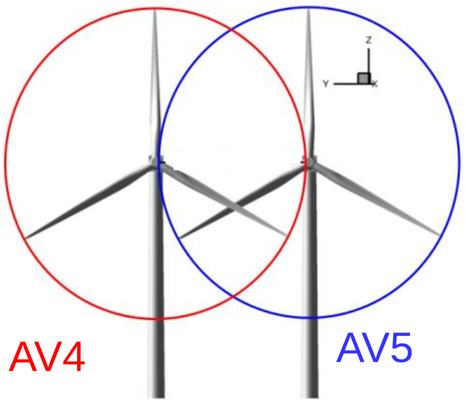
- Wind direction 262°
- Velocity at hub height: $15.2\ m/s$
- Turbulence intensity at hub height $\mathrm{Ti} \approx 2 \dots 4\ \%$
- Neutral stratification
- Signal is made periodic over 60s [6]



Turbine settings of AV4 and AV5

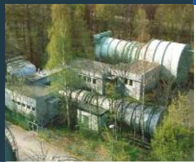
Senvion 5M

- RPM: 12
- TSR: 5.2
- Pitch angle $11.2°$ (all blades)
- Rigid turbine model



Simulations

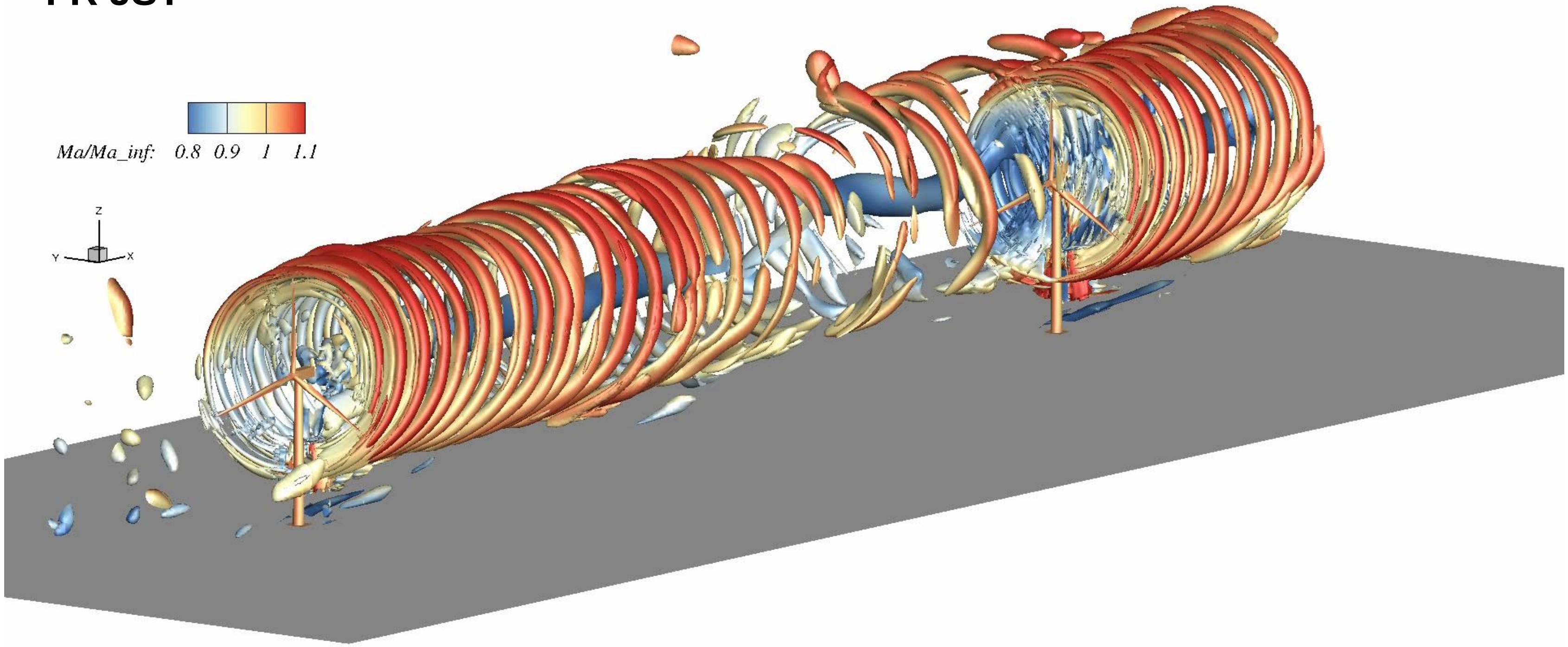
Turbine Model	FR – JST	AL – JST	AL – WENO
Cells	100 Mio.	67 Mio.	67 Mio.
Time step	3° azimuth	1.5° azimuth	1.5° azimuth
No. of inner iterations	30	20	20
Pre-calculation	36 revs.	36 revs.	36 revs.
Evaluation signal	60s = 12 revs.	60s = 12 revs.	60s = 12 revs.
Spatial discretization scheme	Central differences (Jameson)	Central differences (Jameson)	5^{th} order WENO



Results
Flow field and Wake Development

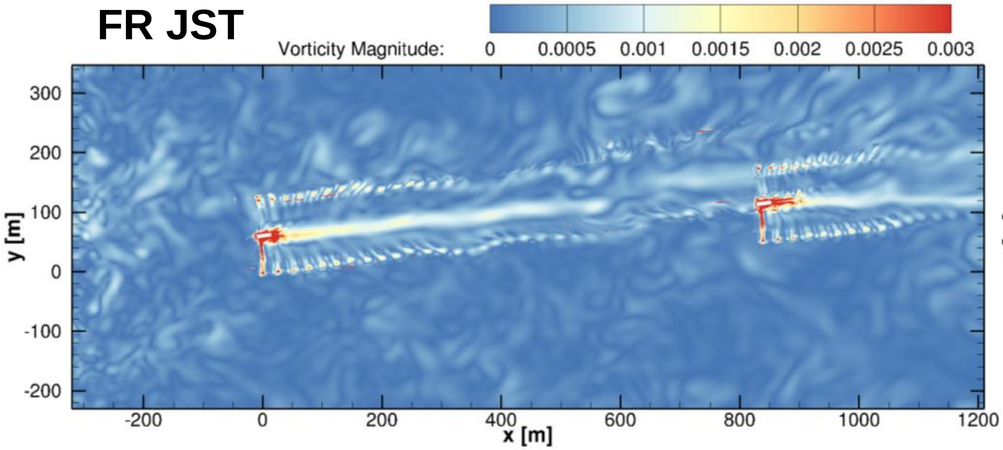
Λ_2-Vortex visualization

FR JST

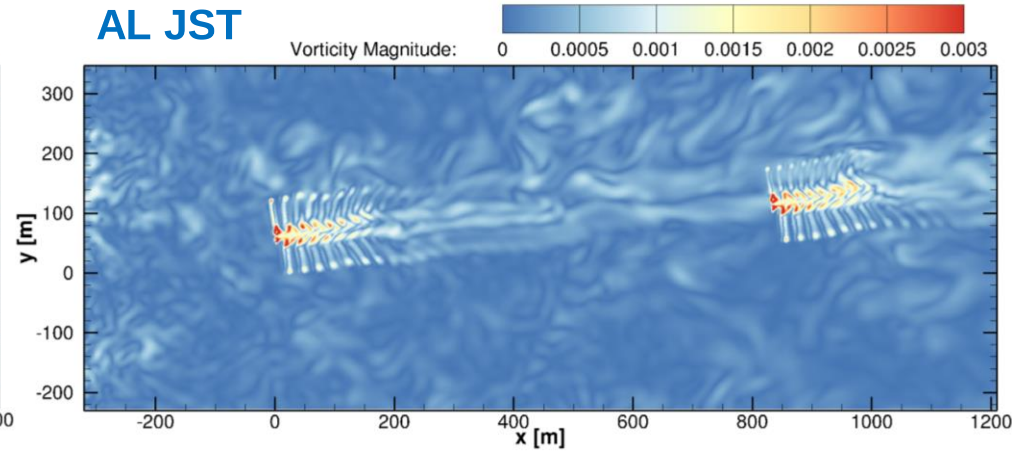


Vortex convection

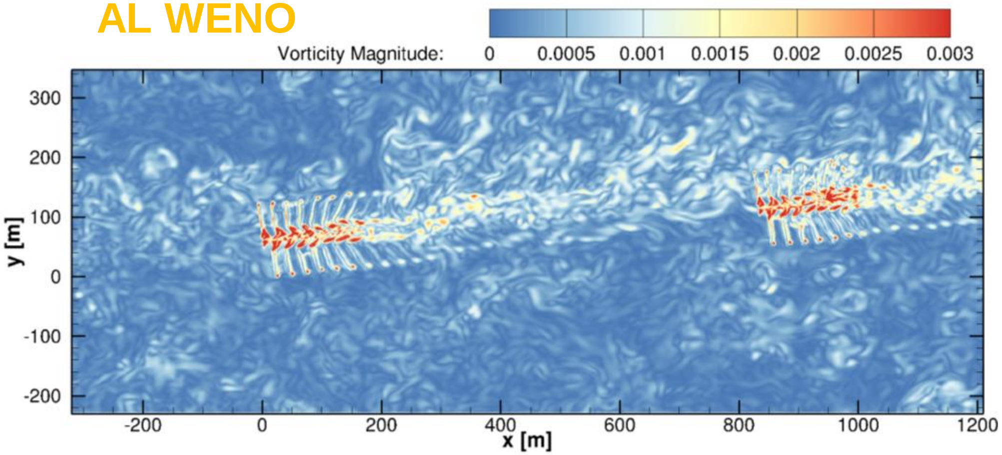
FR JST



AL JST



AL WENO



FR:

- Hub vortices less pronounced
- Longer preservation of the wake due to tip refinement

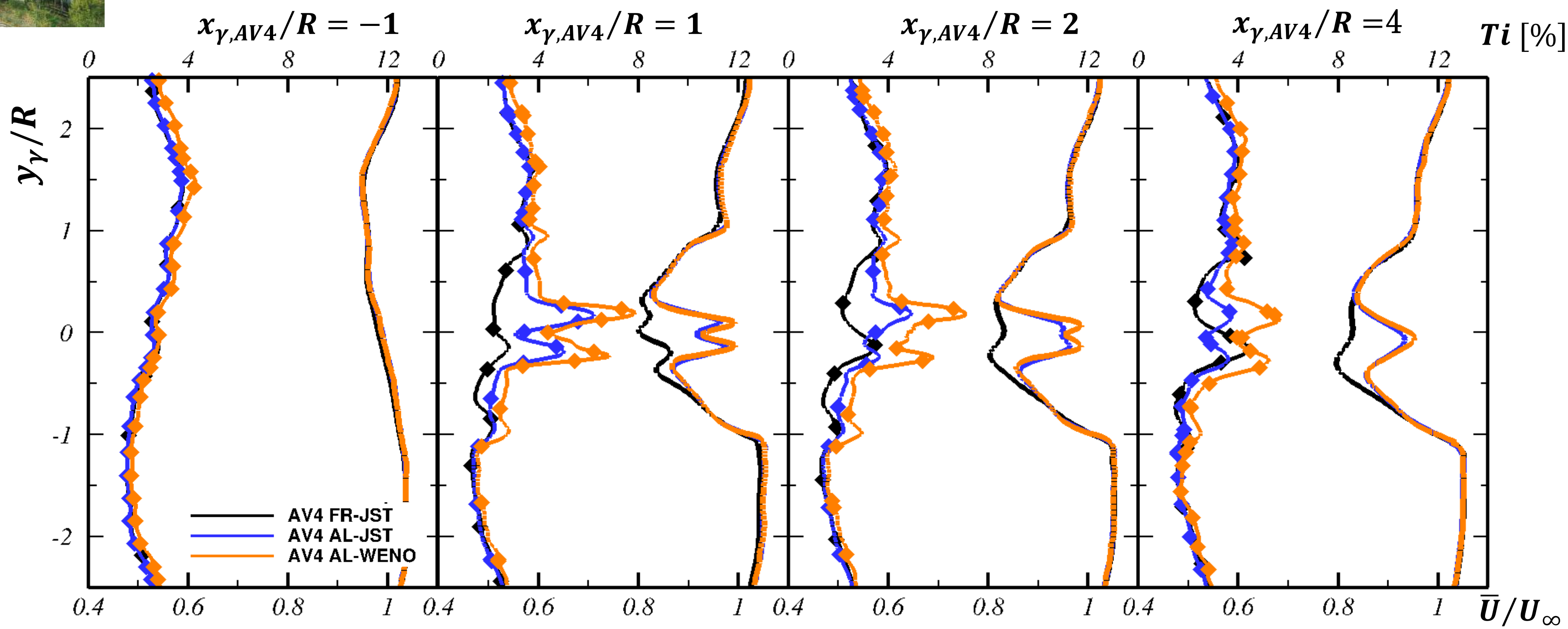
AL:

- Strong hub vortices
- Earlier break up of the wake

5th order WENO:

- Preservation of small scale ABL vortices for WENO
- Higher vorticity values for tip/root vortices
- Highly turbulent ABL – Wake – Turbine interaction

Horizontal wake deficit and turbulence intensity



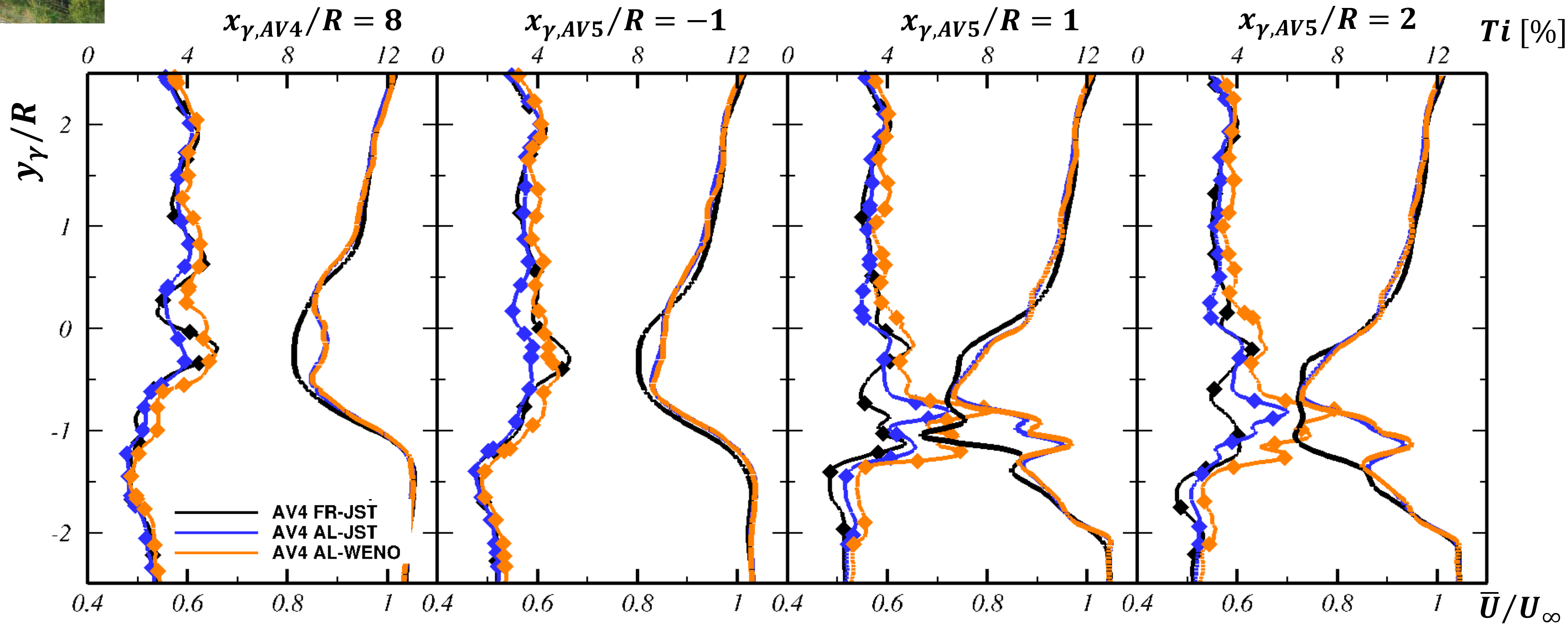
Upstream of AV4:

- Quite good agreement of the upstream flow conditions for all models
- WENO predicts slightly higher Ti

Downstream of the AV4:

- Good agreement of AL with FR, except for the hub region, due to missing nacelle model
- Higher Ti in the hub region for AL, since hub vortices are stronger
- In general, higher Ti predicted by WENO

Horizontal wake deficit and turbulence intensity



Upstream of AV5:

- Largest deficit predicted by FR
- Negligible influence of higher order WENO scheme on mean velocity deficit
- However, WENO can preserve turbulence better!

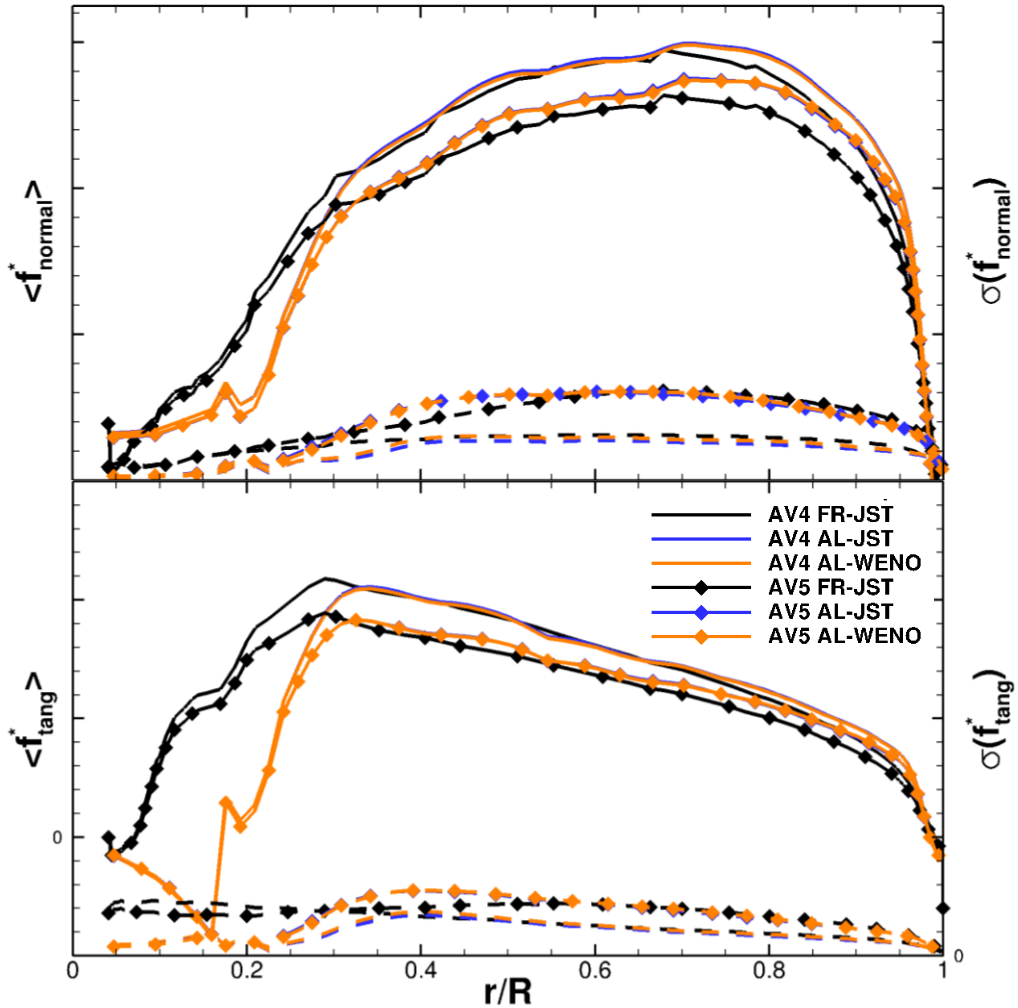
Downstream of AV5:

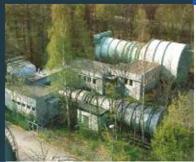
- Overall, good agreement for AL, however stronger wake deflection predicted by FR

Results
Blade Loads

Normal and tangential blade force

- AV5: Power loss 15% compared to AV4
- AL predicts 4% less power for AV4 and 0.4% less power for AV5 compared to FR
- Overall, good agreement of AL with FR for loads and their fluctuations
- Disagreement at the inner portion of the blade:
  - 3D flow separation
  - Inaccuracies of the airfoil polars for AL





Conclusions

- Numerical simulations were performed of a „half-wake“ situation in Alpha Ventus
- Different numerical models were compared
  - Fully resolved turbine
  - Actuator line model
  - Higher order scheme
- Overall, good agreement of AL model and FR for wake development and loads
- Higher order WENO scheme significantly improves resolution of the interaction of the wake and the atmospheric turbulence
- Numerical dissipation remains the main problem for the convection of the wake!

References

[1] Buningt, P. G. (1985). A 3-D chimera grid embedding technique.

[2] Sørensen, J. N., & Shen, W. Z. (2002). Numerical modeling of wind turbine wakes. Journal of fluids engineering, 124(2), 393-399.

[3] Mikkelsen, R. (2003). Actuator disc methods applied to wind turbines (Doctoral dissertation, Technical University of Denmark).

[4] Martınez, L. A., Leonardi, S., Churchfield, M. J., & Moriarty, P. J. (2012). A comparison of actuator disk and actuator line wind turbine models and best practices for their use. AIAA Paper, (2012-0900).

[5] Jha, P. K., Churchfield, M. J., Moriarty, P. J., & Schmitz, S. (2013). Accuracy of State-of-the-Art Actuator-Line Modeling for Wind Turbine Wakes. AIAA Paper, (2013-0608).

[6] Meister, K., Lutz, T., & Krämer, E. (2014, December). Simulation of a 5MW wind turbine in an atmospheric boundary layer. In Journal of Physics: Conference Series (Vol. 555, No. 1, p. 012071). IOP Publishing.

Thank you for your attention!

University of Stuttgart
Germany

WINDFORS
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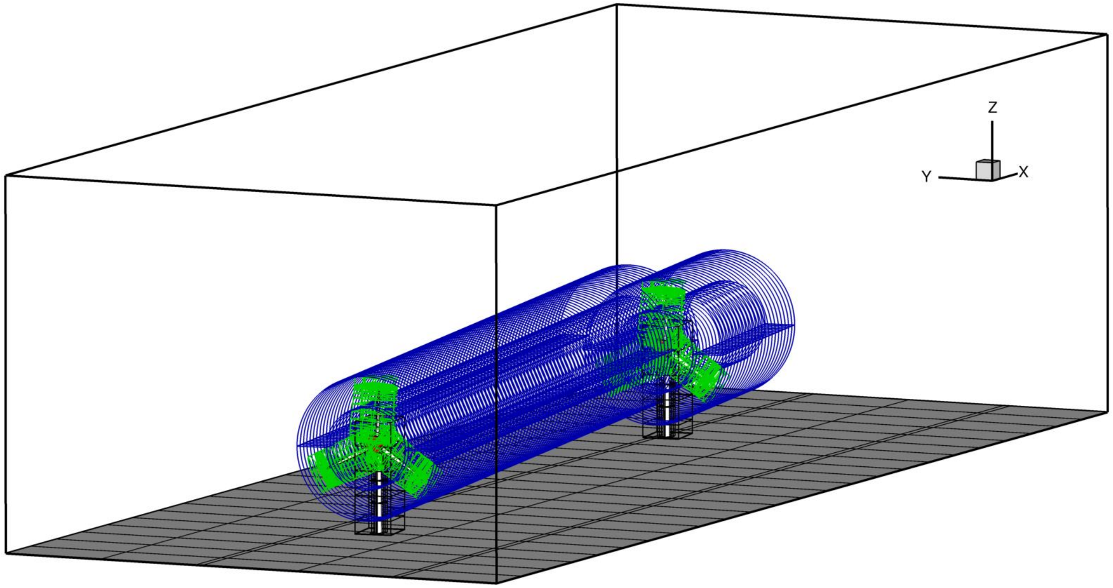
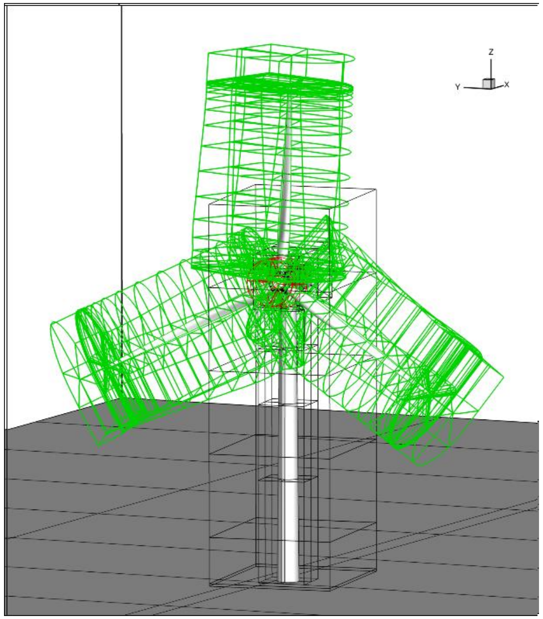
Overset grids for FR simulation

▪ Tower + background mesh for tower:	$2 \times 3.8\ Mio.$
▪ Spinner:	$2 \times 1.6\ Mio.$
▪ Blades + blade connectors:	$6 \times 4.9\ Mio.$
▪ Vortex transport meshes:	$12.7\ Mio.$
▪ Background mesh:	$47\ Mio.$
→ **Total No. of cells:**	$\mathbf{100}\ Mio.$



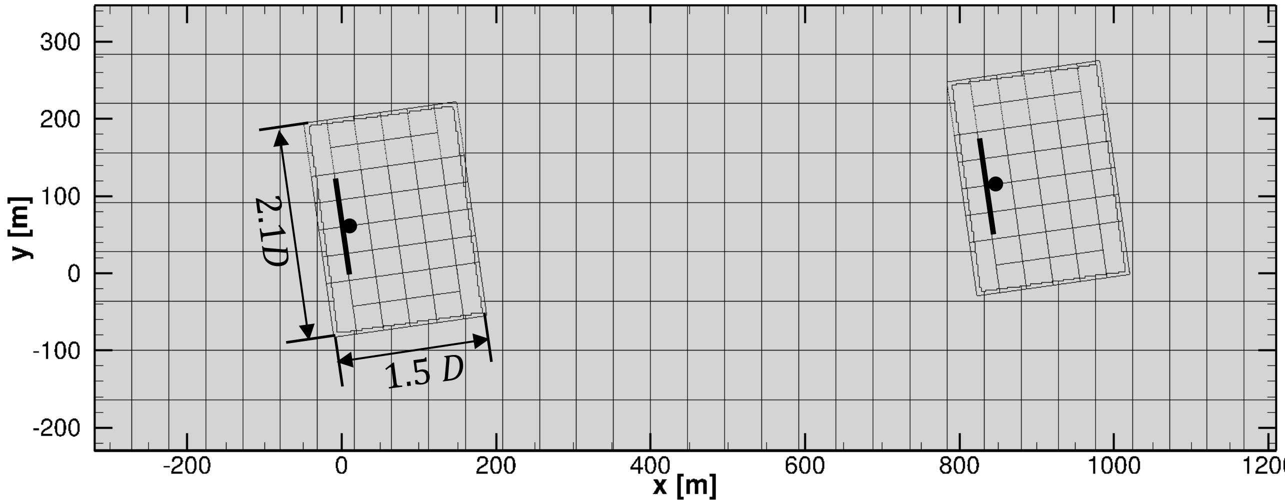


Grid for AL simulation

Simple mesh configuration

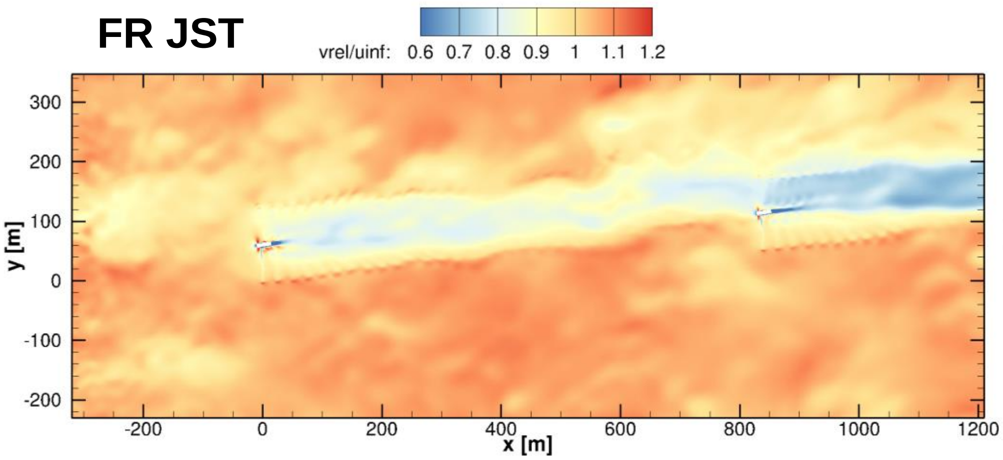
▪ Refinement around the turbine	$2 \times 10.0 Mio.$
▪ Background mesh:	$47\ Mio.$
➔ **Total No. of cells:**	$67\ Mio.$

▪ Aerodynamic forces calculated at 97 actuator points

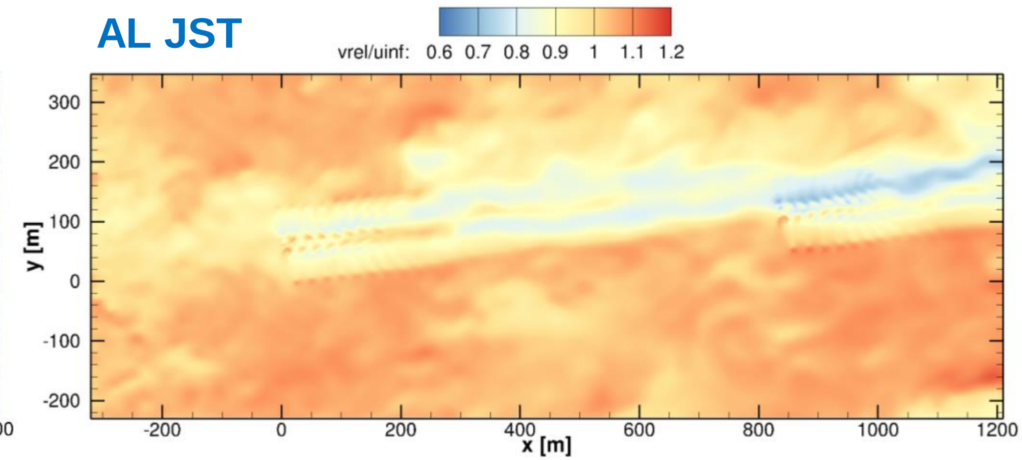


Wake development – velocity

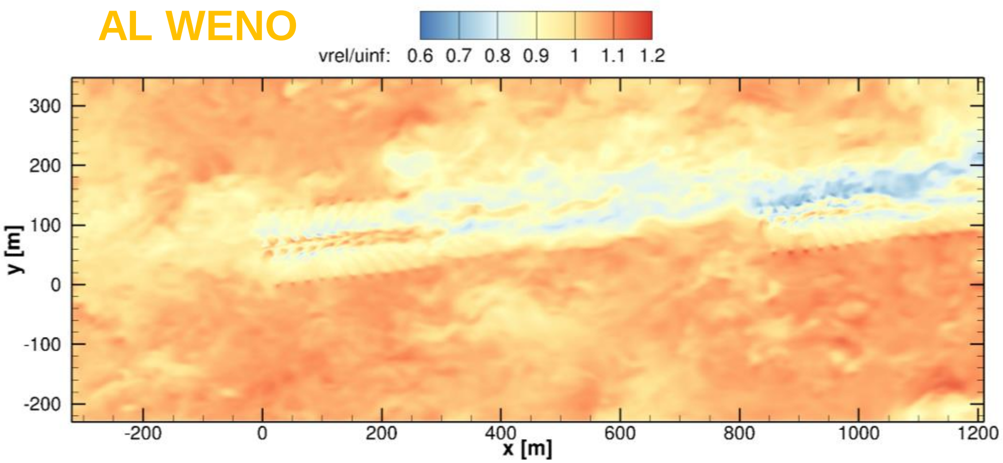
FR JST



AL JST



AL WENO



FR:

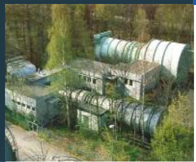
- Hub vortices less pronounced
- Deceleration in the hub region
- Significant wake deflection downstream of AV5

AL:

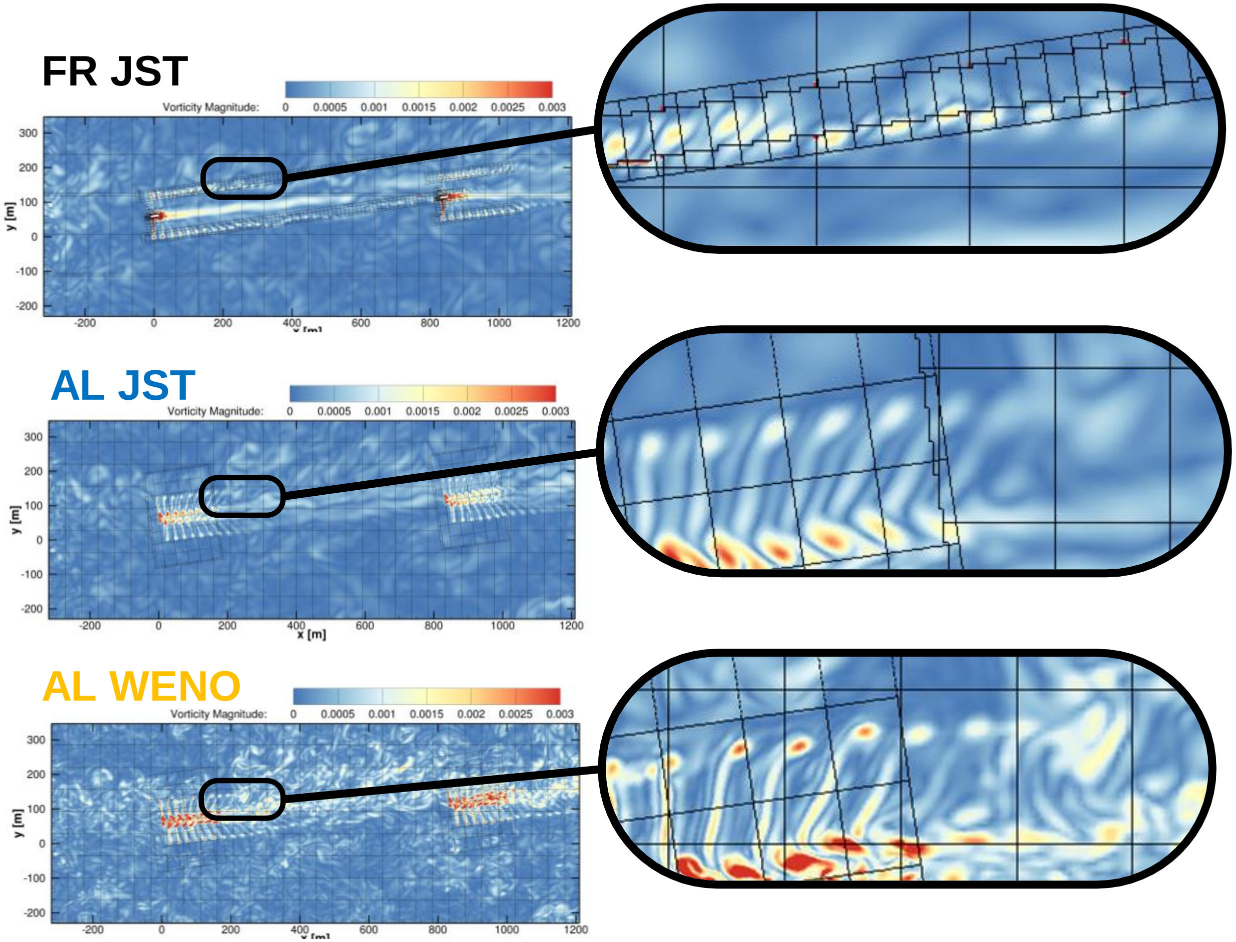
- „jet“ in the hub reagion due to missing nacelle model
- Smaller wake deflection downstream of AV5

5th order WENO:

- Improved resoultion of wake and ABL turbulence, particularly for the wake interaction with the AV5



Vortex convection



Problem vortex dissipation:

- As soon as tip/root vortices run out refined meshes

➔ Vorticity decreases to the order of the ambient turbulence

➔ Tip/root vortices interact with the ambient turbulence

➔ Premature break up of the wake

➔ Always look critically at your numerical model!