# Large-eddy simulations of wind turbine wakes

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# Outline

- Scope
- Numerical method
- Results
  - Tjaereborg wind turbine
  - NTNU Blind Test experiment
  - Interaction with a squared building
- Conclusions

# Introduction on wake modelling

- Challenge
  - Complex geometry
  - Large range of spatial and temporal scales
- Computational modelling
  - DNS not affordable
  - Low dispersion and diffusion errors needed
- State-of-the-art:
  - Large-eddy simulations (LES)
  - Actuator line model
  - Structured mesh: missing hub, nacelle, tower + flat terrain
  - Second-order schemes: poor resolution of the far wake

# Research questions

- How accurate can unstructured meshes be for this problem?
- What is the importance of high-order schemes?
- What is the influence of geometrical details?
- What is the effect of terrain topography

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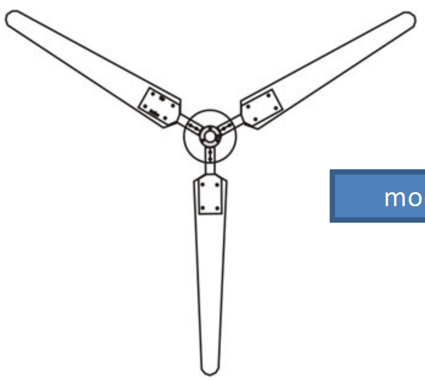
# Numerical method

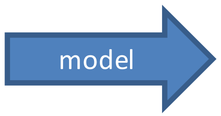
- YALES2 LES Solver
  - Developed at CORIA
  - Incompressible Navier-Stokes equations (variable density) solved with a projection method
  - 4$^{th}$-order finite-volume and 4$^{th}$ order RK time integration
  - Unstructured meshes with adaptive grid refinement
  - Massively parallelised (>32,000 procs)
  - Additional applications to two-phase flows, combustion, etc.

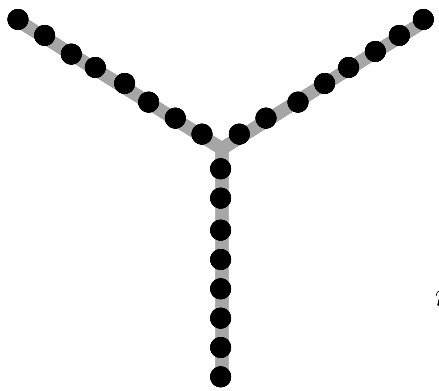
http://www.coria-cfd.fr

# Numerical method

- Actuator-line model
  - Blades are replaced by lines with a prescribed motion
  - Forces are computed on each point of the line
  - Forces are interpolated on the Eulerian grid
  - Used in the momentum conservation equation





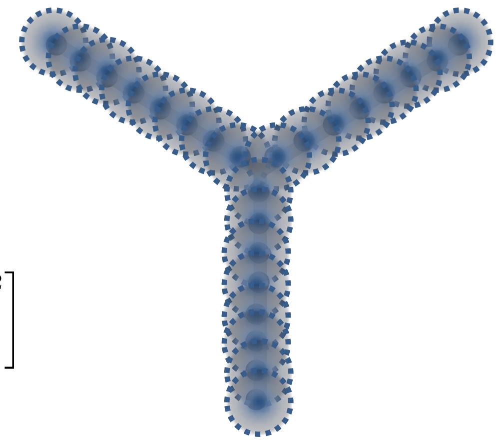



$$\mathbf{f} = L\,\mathbf{e_L} + D\,\mathbf{e_D}$$

$$L = \frac{1}{2} C_l\left(\alpha\right)\rho V_{rel}^2 cw$$

$$D = \frac{1}{2} C_d\left(\alpha\right)\rho V_{rel}^2 cw$$


$$\eta_\epsilon(d) = \frac{1}{\epsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{d}{\epsilon}\right)^2\right]$$



$$\vec{\mathbf{F}}(x,y,z,t) = -\sum_{i=1}^{N} \vec{\mathbf{f}}(x_i,y_i,z_i,t)\eta_\epsilon(|\vec{r} - \vec{r_i}|)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot \mathbf{uu} = -\frac{1}{\rho}\nabla P + \frac{1}{\rho}\nabla \cdot \underline{\underline{\tau}} + \frac{1}{\rho}\mathbf{F}$$

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Sorensen et. al., J Fluids Eng, 2012

# Results
## Tjaereborg turbine

- Geometry
  - NACA4418 profiles 3-blade rotor
  - D = 61 m
  - Hub height = 60 m

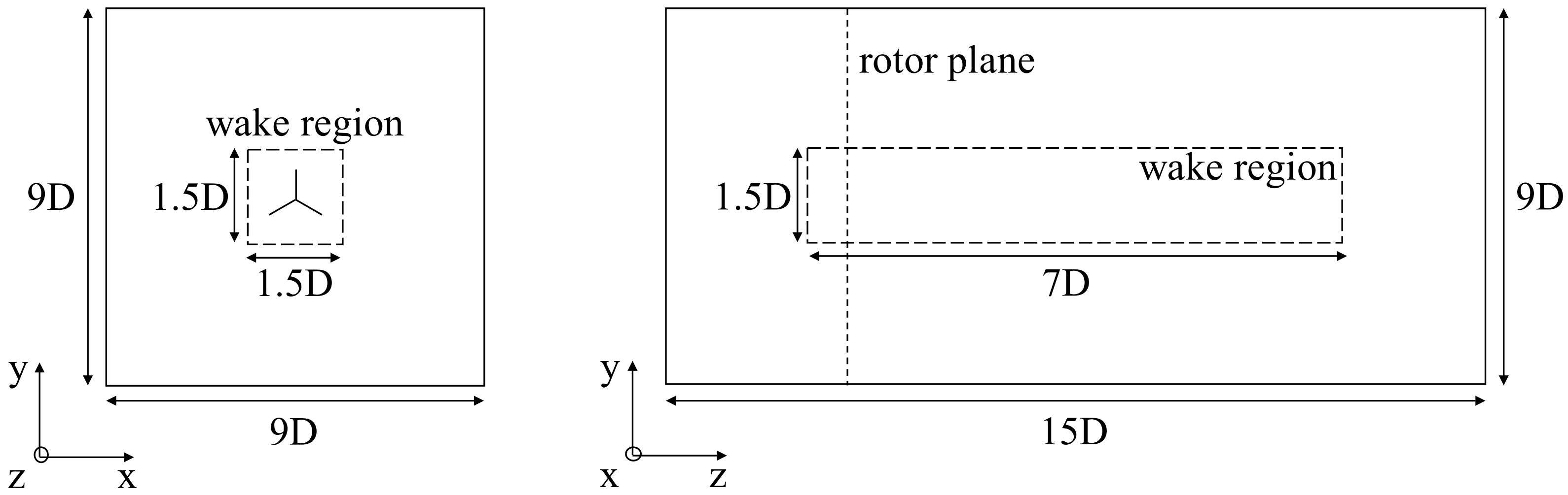
- Operating conditions
  - TSR = 7.07

- LES SIGMA model

  Nicoud et al. *Physics of Fluids (2011)*

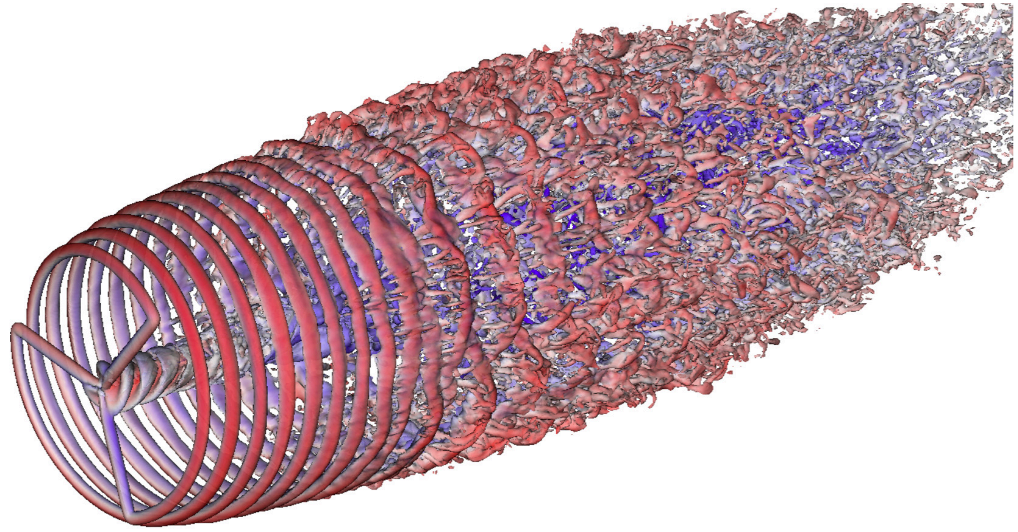
The Tjaereborg wind turbine, Final report, Power Station Engineering, NEI-DK-1018 (1992)

# Results
## Tjaereborg turbine

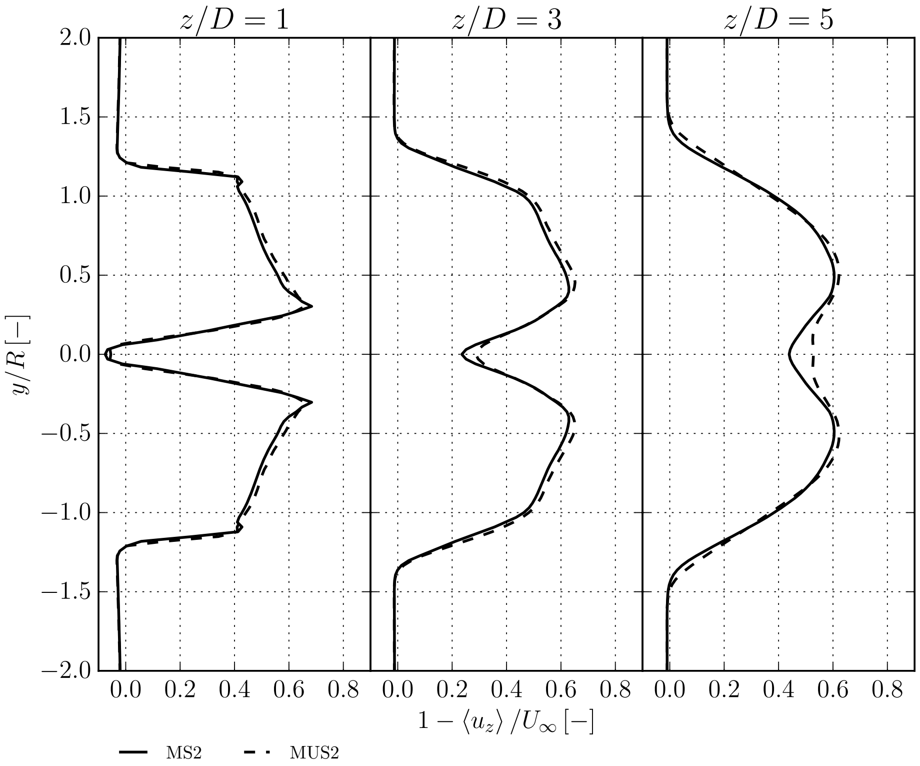



| | M1 | M2 | M3 |
|---|---|---|---|
| # nodes | 0.77M | 6M | 49.3M |
| $\Delta x/D$ in rotor zone [-] | 0.031 | 0.015 | 0.008 |
| # particles/blade | 14 | 28 | 57 |
| CPU hours / rotation | 0.24 | 5.8 | 129.3 |

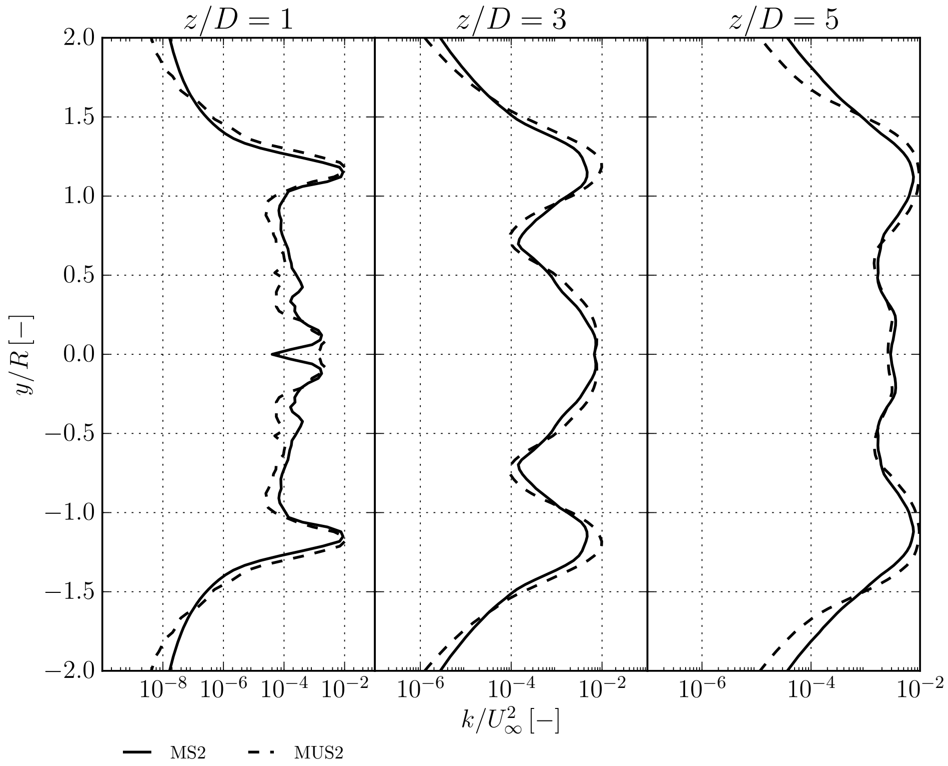
# Results
## Tjaereborg turbine



**Velocity deficit**




**Turbulent kinetic energy**

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# Results
## NTNU blind test experiment

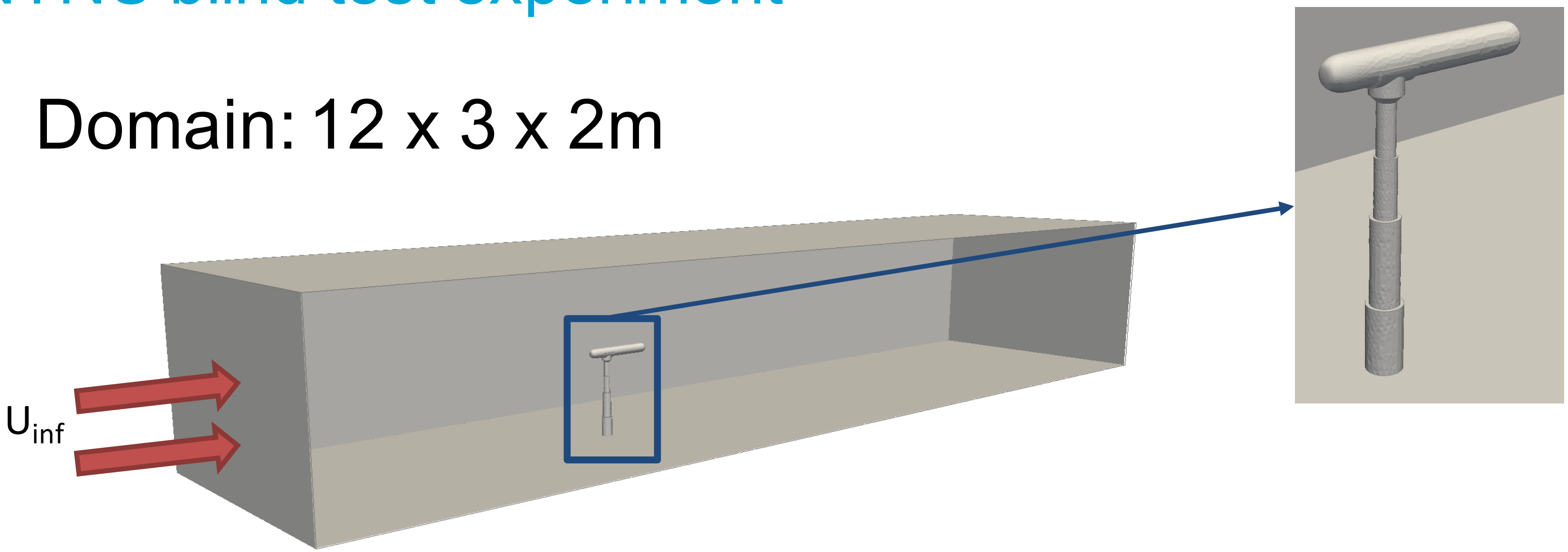
- Geometry
  - S826 profile 3-blade rotor with D = 0.894 m
  - Circular nacelle and semi-spherical hub at z = 0.817 m
  - 4-cylinder tower
  - Wind tunnel L x l x h = 12 x 3 x 2 m

- Operating conditions
  - TSR = 6
  - $U_{inf}$ = 10 m/s


[1] Eriksen et. al., Energy Procedia, 2012
[2] Krogstad et. al., Renawable Energy, 2013
[3] Sorensen et. al., Philosophical Transactions A, 2017

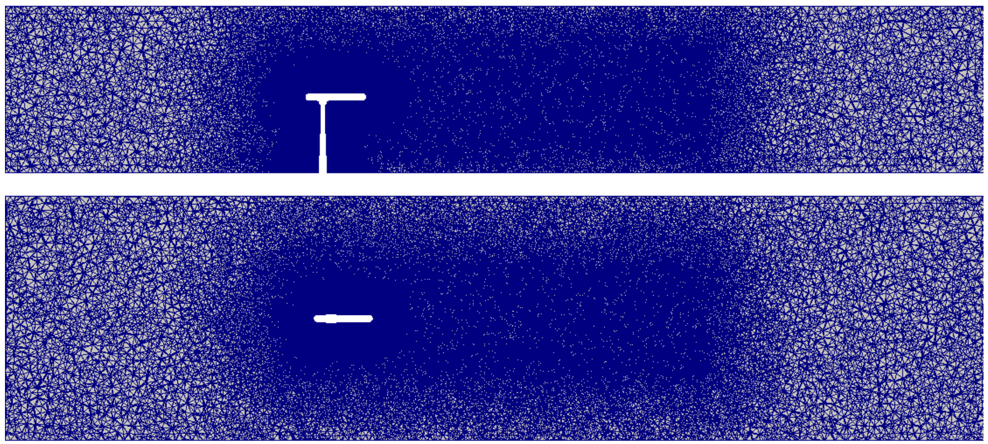
# Results
## NTNU blind test experiment

- Domain: 12 x 3 x 2m



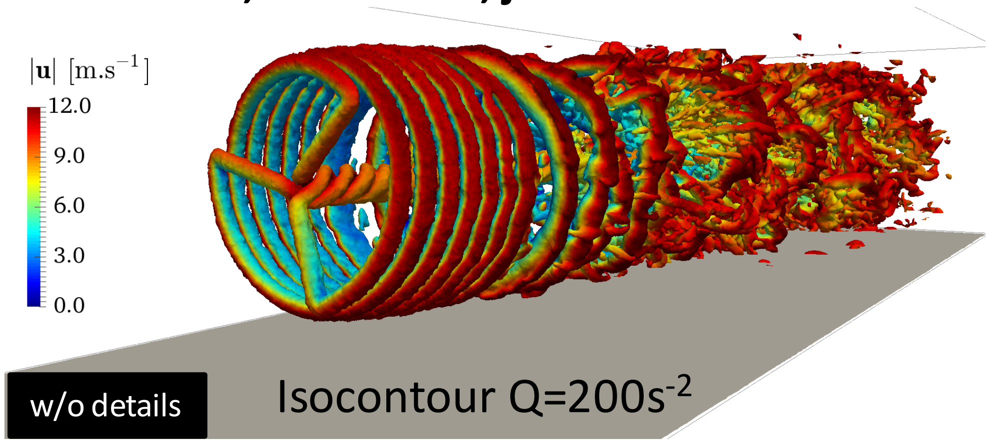

- Mesh

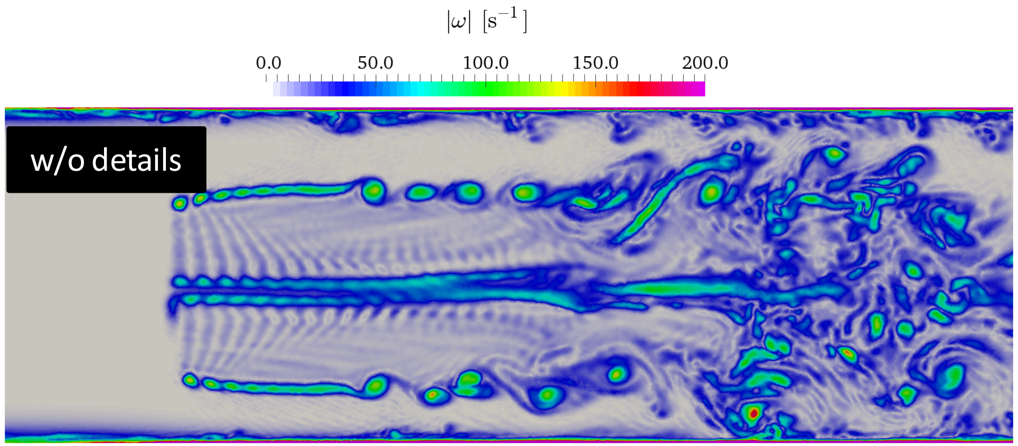
| Mesh characteristics | |
|---|---|
| # elements | 130M |
| $\Delta$x/D in rotor zone [-] | 0.015 |
| # particles/blade | 32 |



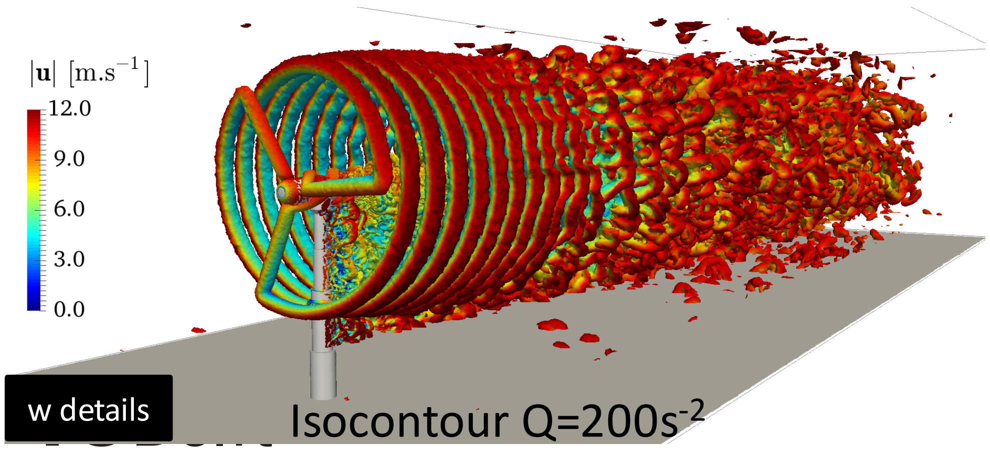
# Results
## NTNU blind test experiment

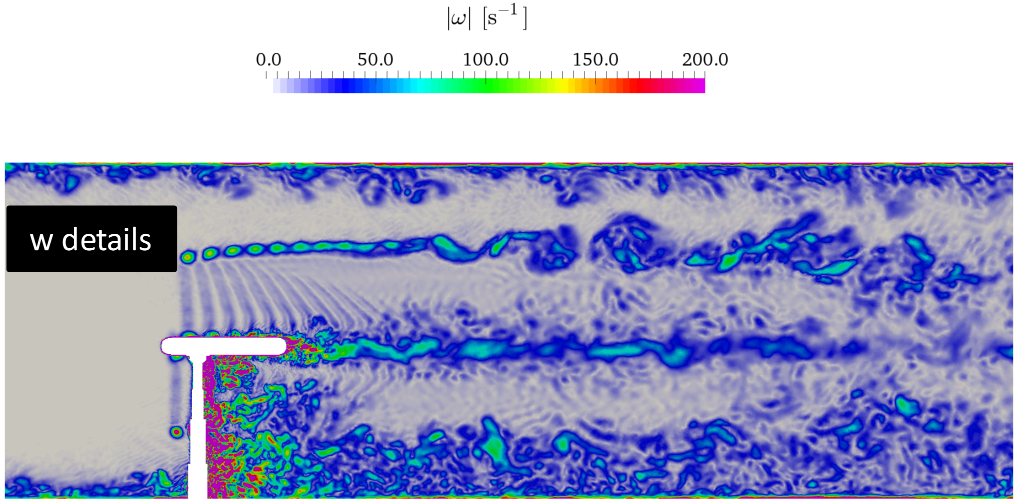
**No tower, no nacelle, just wind tunnel**




**With tower, nacelle and wind tunnel**

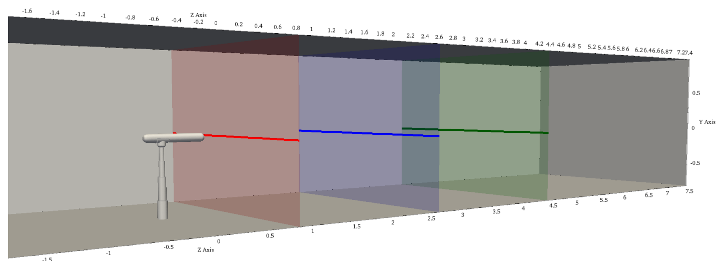


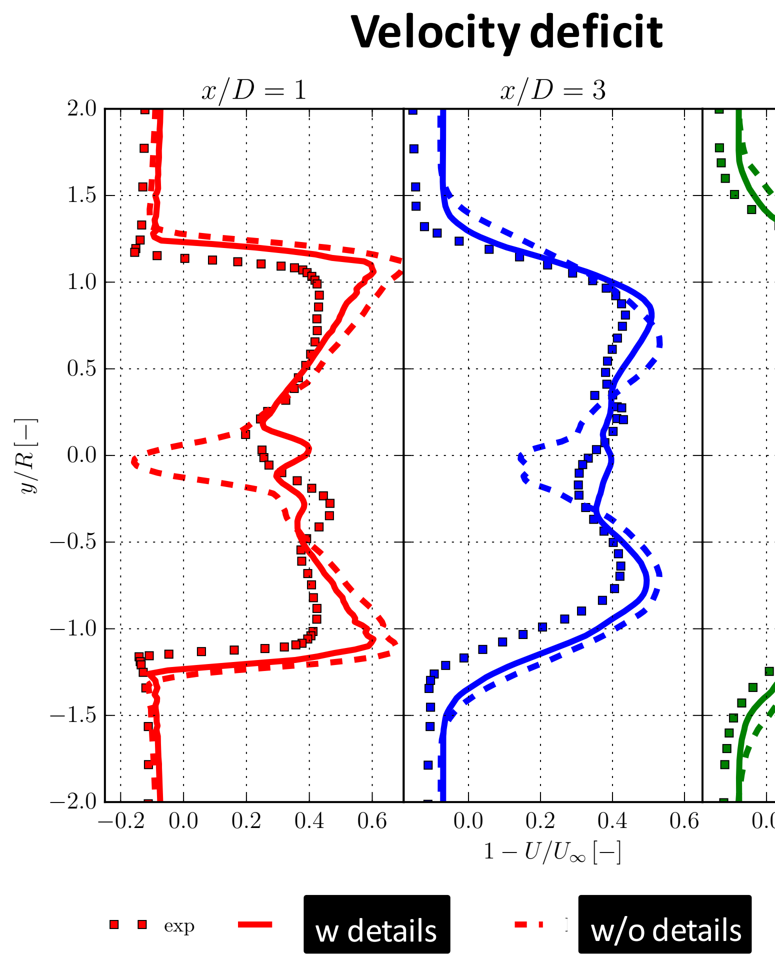



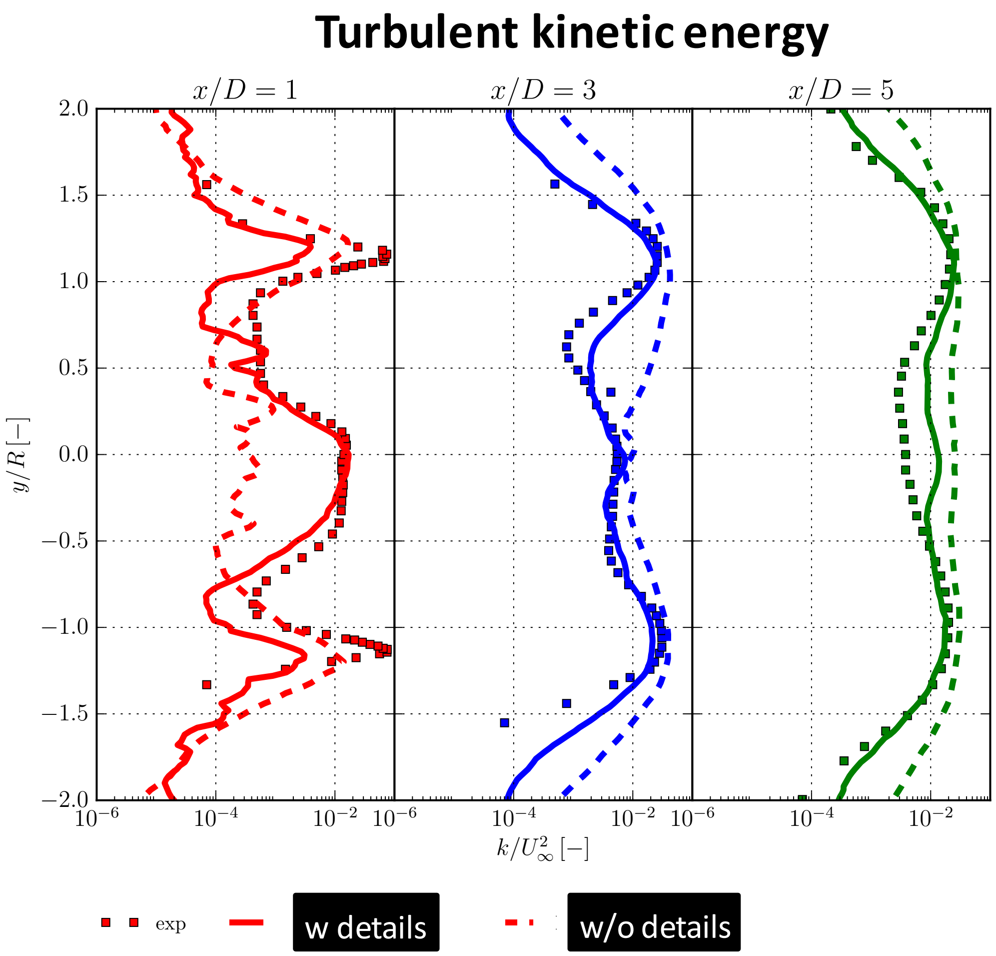

The nacelle destabilises the hub vortex

# Results
## NTNU blind test experiment

- The profiles loose symmetry
- Better agreement with experiments





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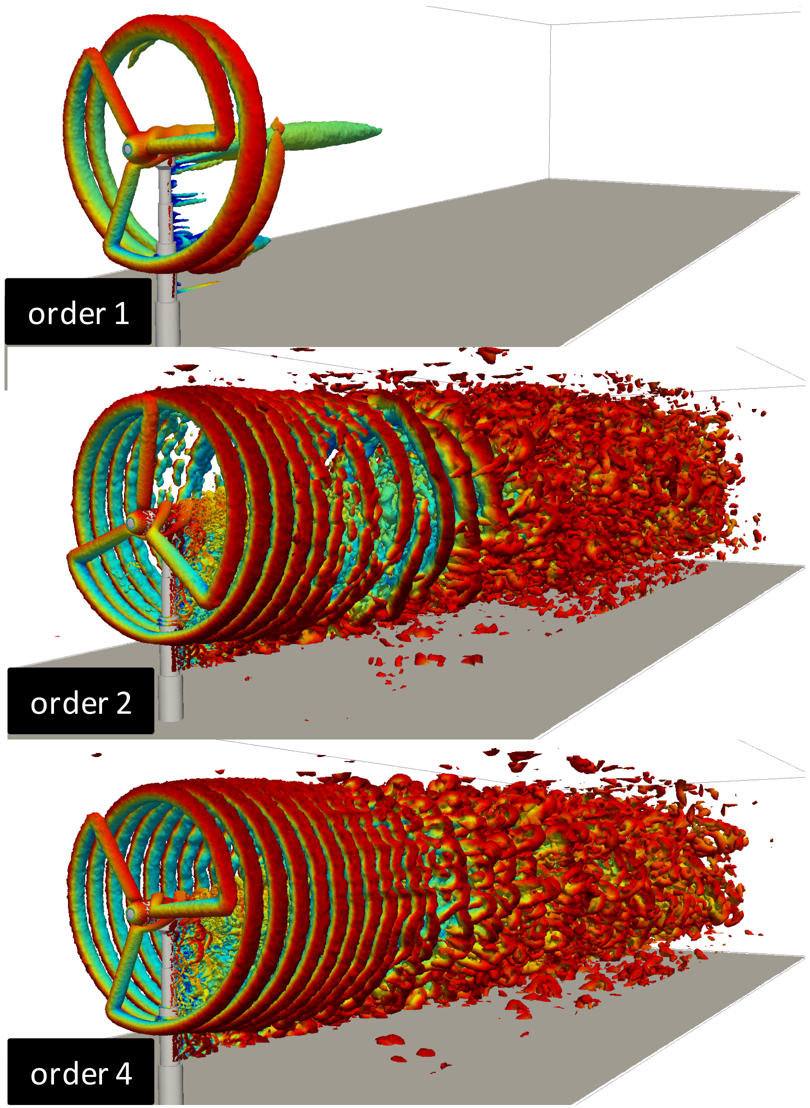


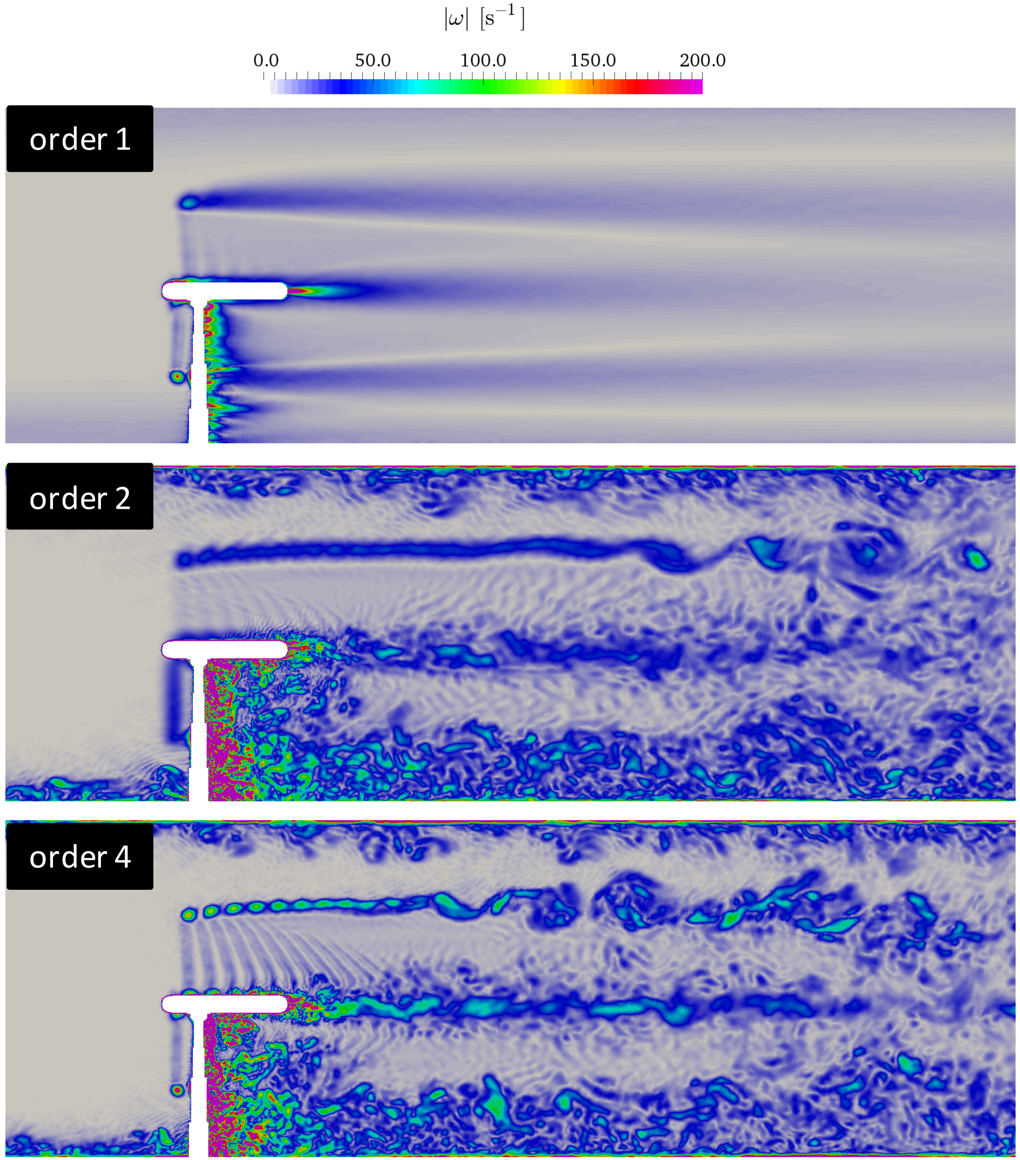


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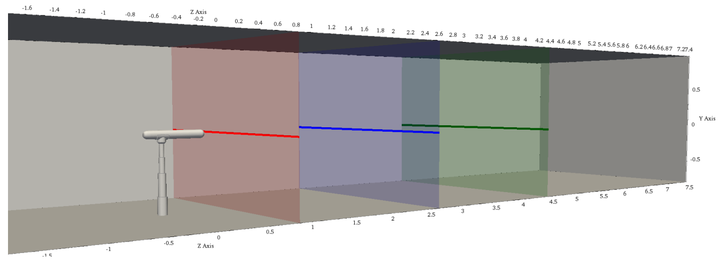
# Results

## NTNU blind test experiment



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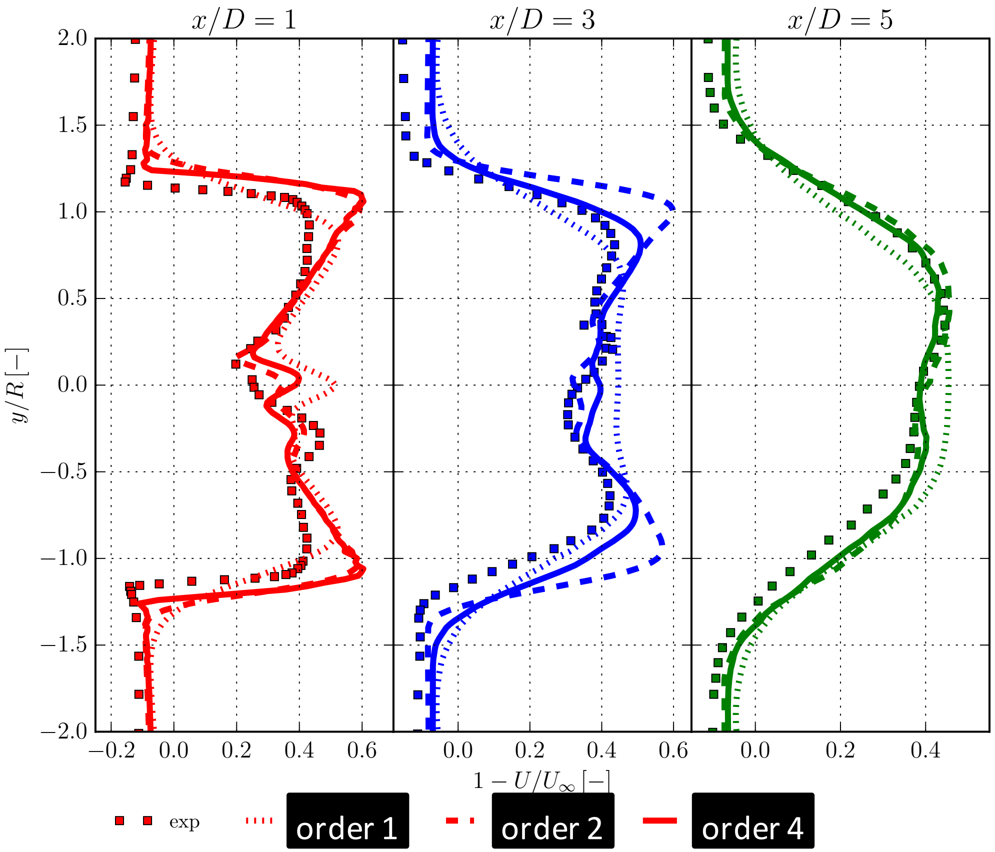


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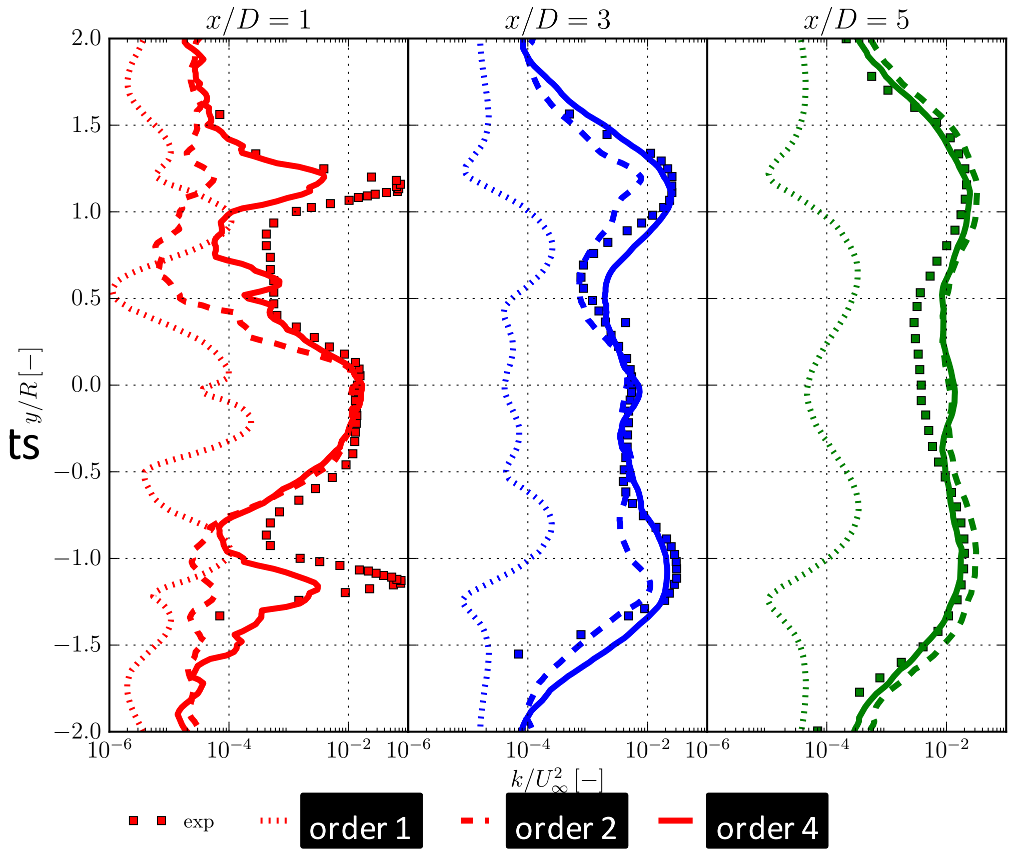
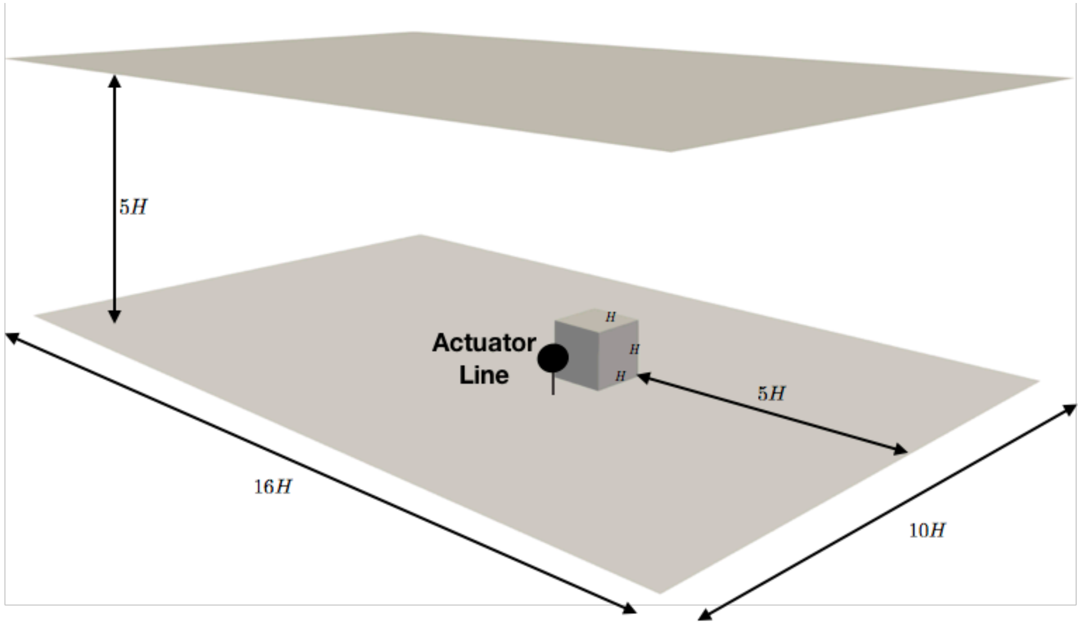


# Results
## Effect of topography

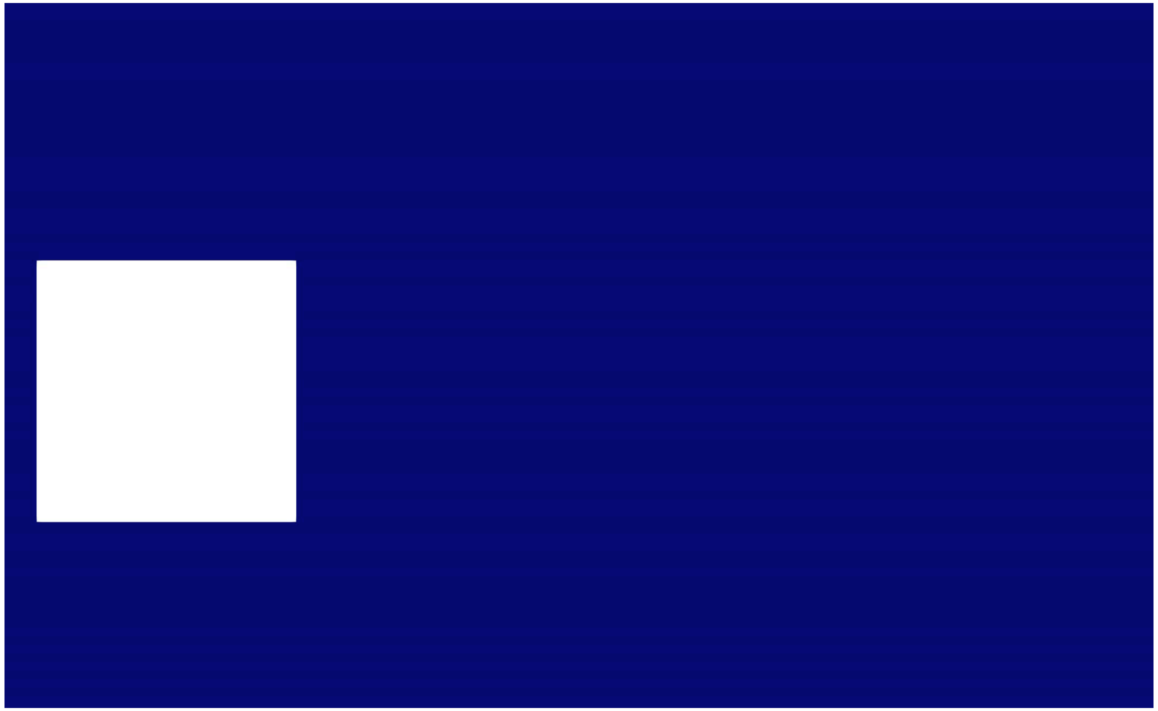
- Rotor Diameter D=H/2
- 65M grid points (refined), 32 points per blades, 12.3K cpu hours
- Re=6.6x10^5
- Dynamic Smagorinsky model with smooth wall functions



# Results
## Effect of topography

- Detached boundary layer interacts with wind turbine wake
- Structures emanate from the ground

Mid-plane (y=H/2)



# Conclusions

- Validated LES-AL framework in YALES2
  Benard et al., Computers & Fluids 173:133-139 (2018)

- Preliminary results on the interaction with urban environment and application to realistic turbines

- Future work
  - Further work on effect of topography
  - Realistic wind conditions
  - Extension to wind turbine farms
  - Role of adaptive grid refinement
  - Other wind energy concepts

## Acknowledgments