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Global blockage effects in wind farms

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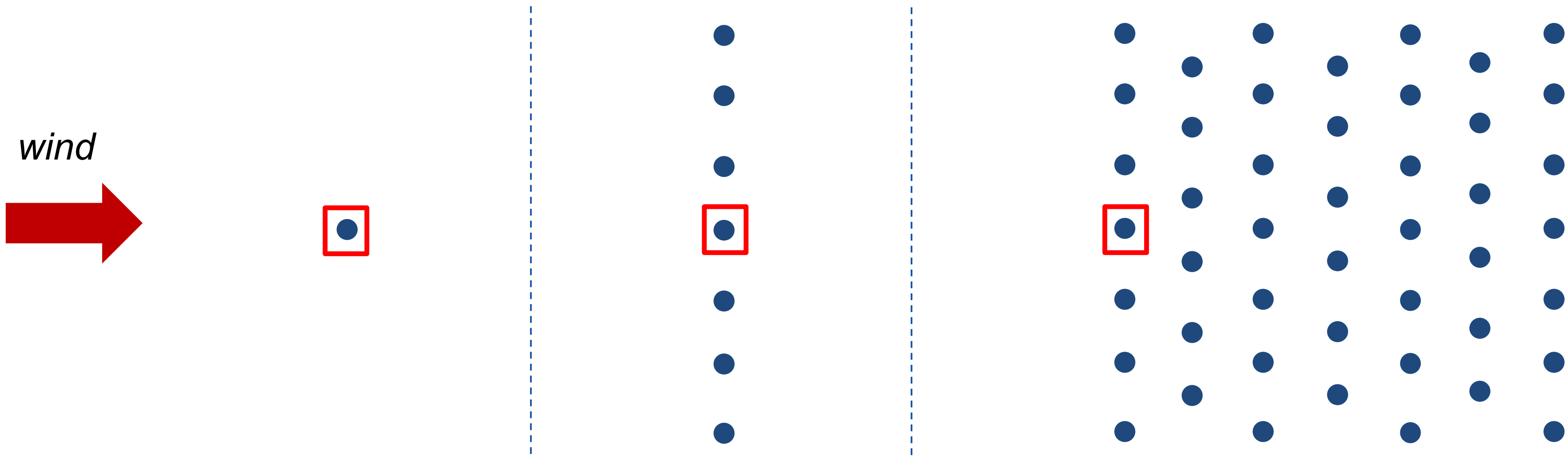
Introduction

- The current understanding of wind farms is based on a "wake-only" approach, where the upstream turbines generate wakes that affect the downstream ones, without any upstream influence
- This means that the first row of the three layouts below will experience the same free-stream velocity

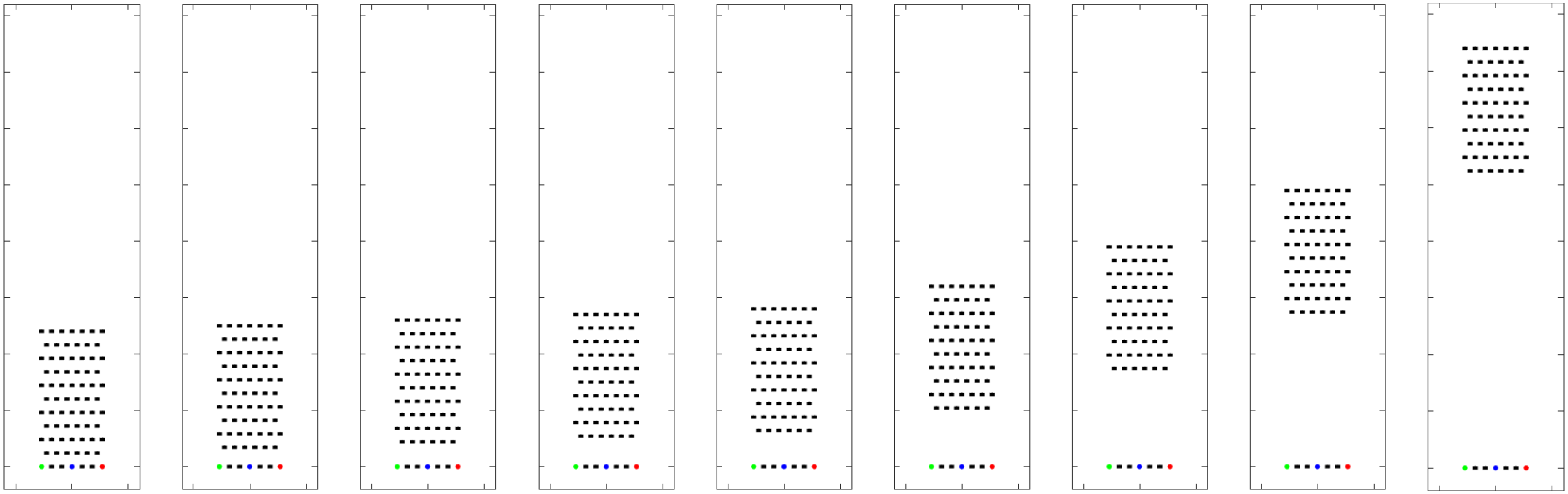


Motivations

- The upstream effects are expected to be small, but a quantification of them is important since they will reduce the energy yield compared to the case where they are absent (accounted as a loss)
- Wake models (and all software based on them) cannot estimate how much the rows will affect the upstream ones
- High-accuracy RANS/LES simulations (without wake models) and experiments are needed to characterise the global blockage effects
- It is expected that blockage effects should be influenced by the farm layout (distance between turbines), number of turbines, thrust coefficient, terrain layout …

Experimental procedure

- In order to assess the existence of blockage, an experiment was planned where the turbines in the first row were fixed and the turbines downstream moved increasingly back
- Three turbines sitting in the first row were monitored (one in the middle, two on the sides)



Experimental setup

- 3 monitored turbines in the first row
- 4 monitored propeller anemometers at the test-section inlet
- Homogeneous incoming flow

Only the RPM were measured by means of a laser and photodiode

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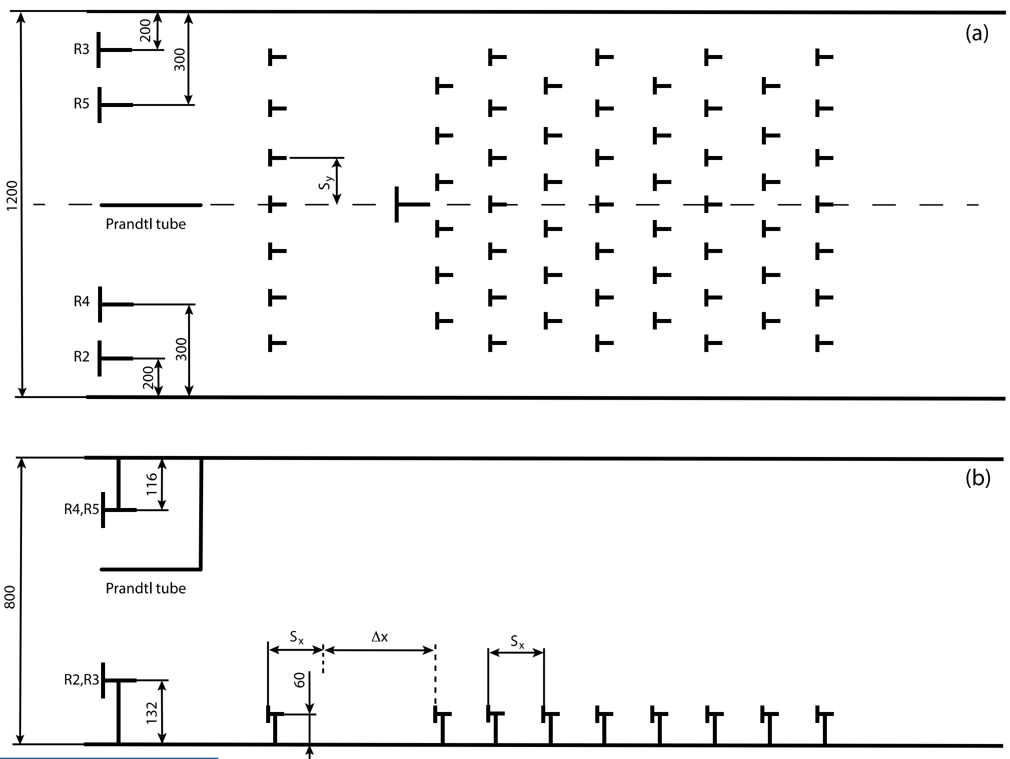
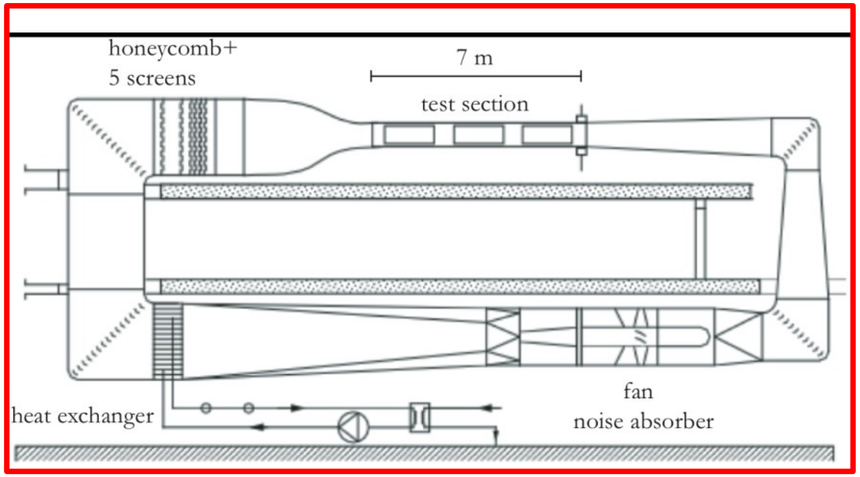
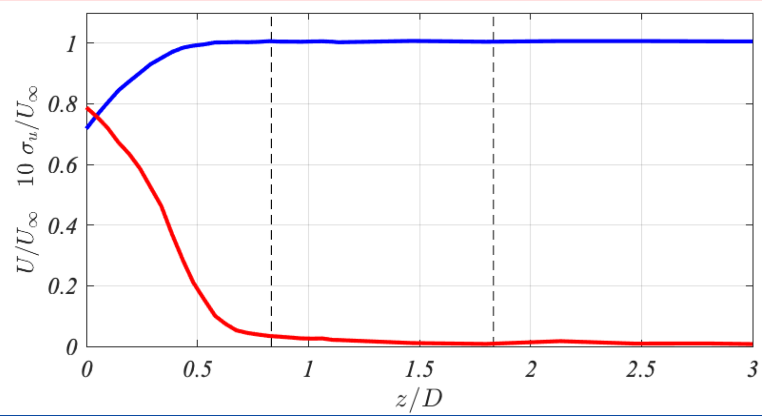
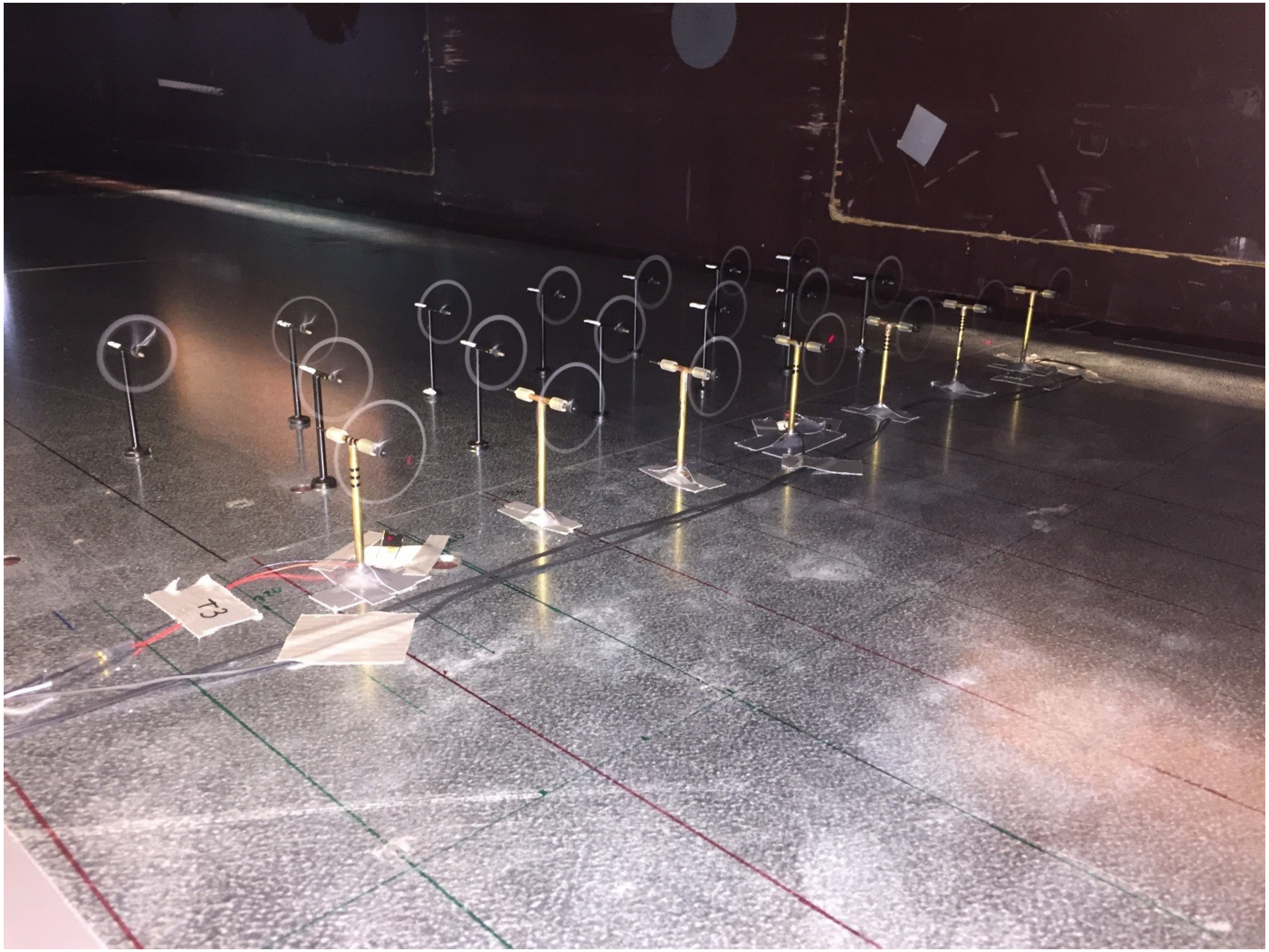






Picture of the setup



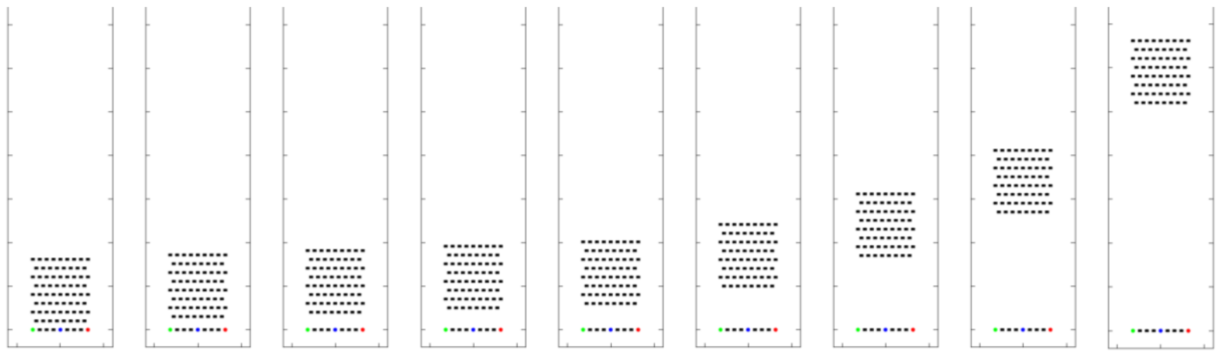
Experimental setup (turbines)

- Diameter 45 mm
- Hub height 60 mm
- C_T=0.6 (measured with strain-gauge balance)
- C_P=0 (freely rotating)

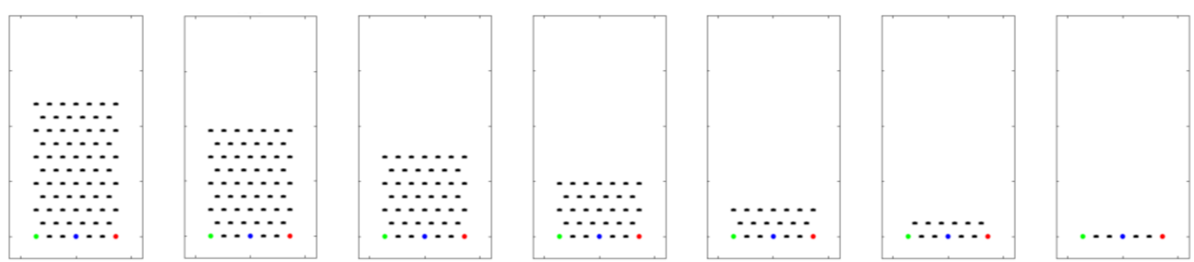
Investigated layouts/experiments

N_{tot}	N_{rows}	S_x/D	$N_{turb,1st}$	S_y/D
59	9	2.24	7	2.33
46	7	3.00	7	2.33
33	5	4.51	7	2.33
77	9	2.24	9	1.76
60	7	3.00	9	1.76
43	5	4.51	9	1.76
41	9	2.24	5	3.51
32	7	3.00	5	3.51
23	5	4.51	5	3.51
72	11	3.33	7	2.33
72	11	4.00	7	2.33
72	11	2.67	7	2.33
72	11	2.67	7	2.00
72	11	3.33	7	2.00
72	11	4.00	7	2.00
72	11	2.67	7	2.67
72	11	3.33	7	2.67
72	11	4.00	7	2.67
72(*)	11	3.33	7	2.33
72(*)	11	4.00	7	2.33
98(*)	15	2.67	7	2.33
98(*)	15	2.67	7	2.00
72(*)	11	3.33	7	2.00
72(*)	11	4.00	7	2.00
72(*)	11	2.67	7	2.67
72(*)	11	3.33	7	2.67
72(*)	11	4.00	7	2.67

The farm downstream was moved (Δx changed)

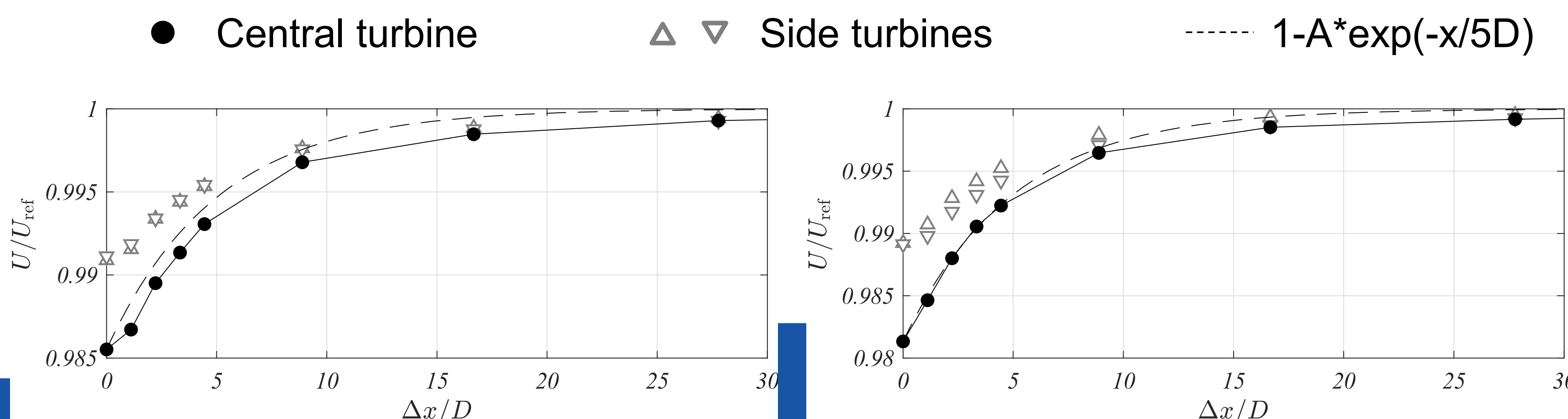


N_{rows} was changed from the maximum to 1 only



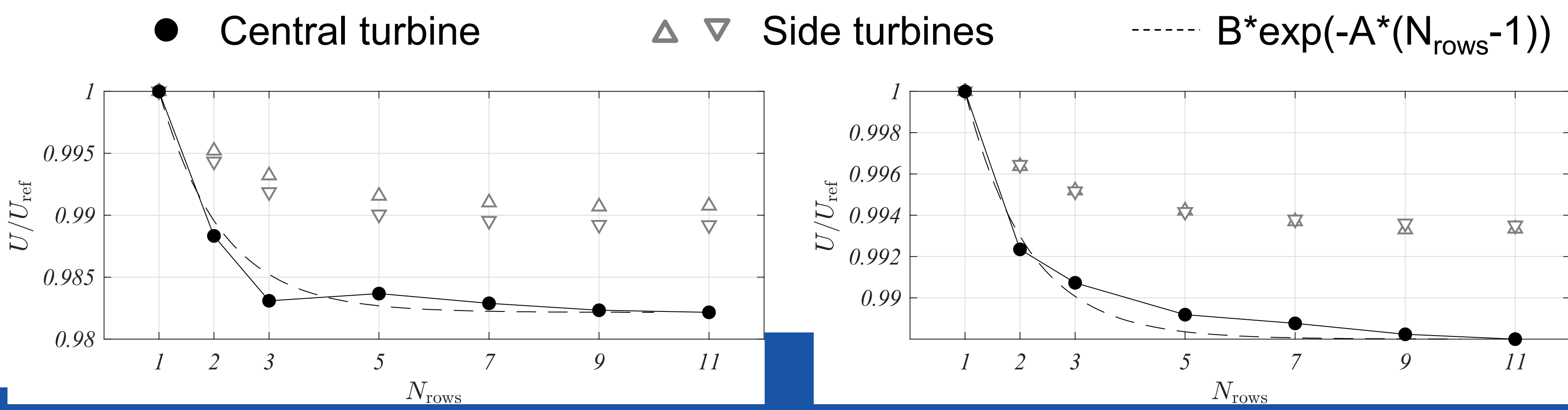
Results (varying Δx)

- All the experiments indicated a decrease of the velocity of the all the turbines placed in the first row as the farm downstream got closer
- Decrease up to 2.5% of U_∞ was observed for the central turbine
- The edge turbines experienced a reduced velocity decrease (no speed-up was observed)

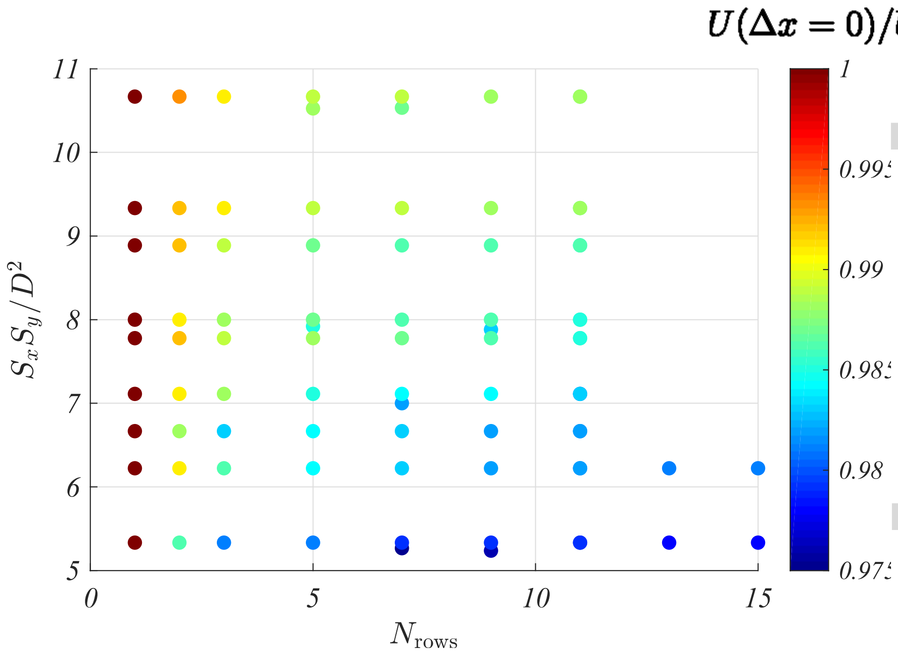


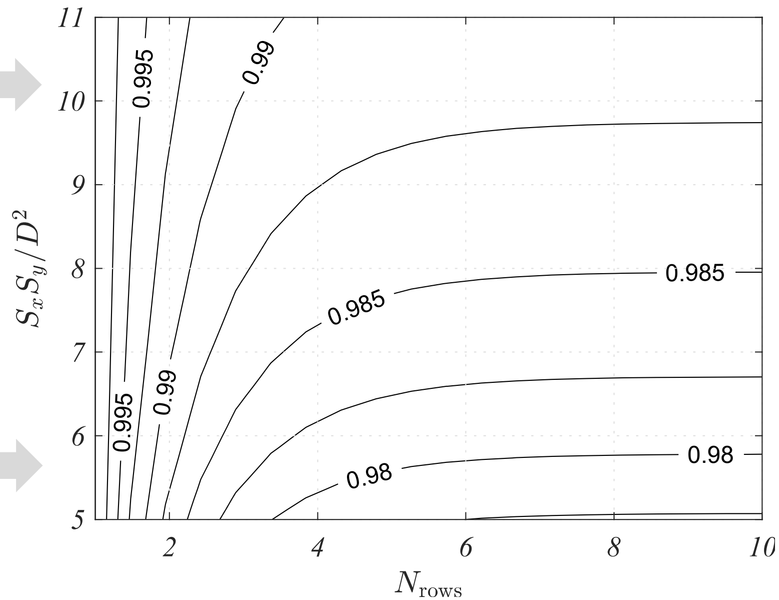
Results (varying N_{rows})

- The effect of the number of rows has clearly a negative effect and saturates for $N_{rows}>3$
- The central turbine experiences the highest velocity decrease
- The edge turbines experience the smallest velocity decrease



Collection of results (85 farm configurations)





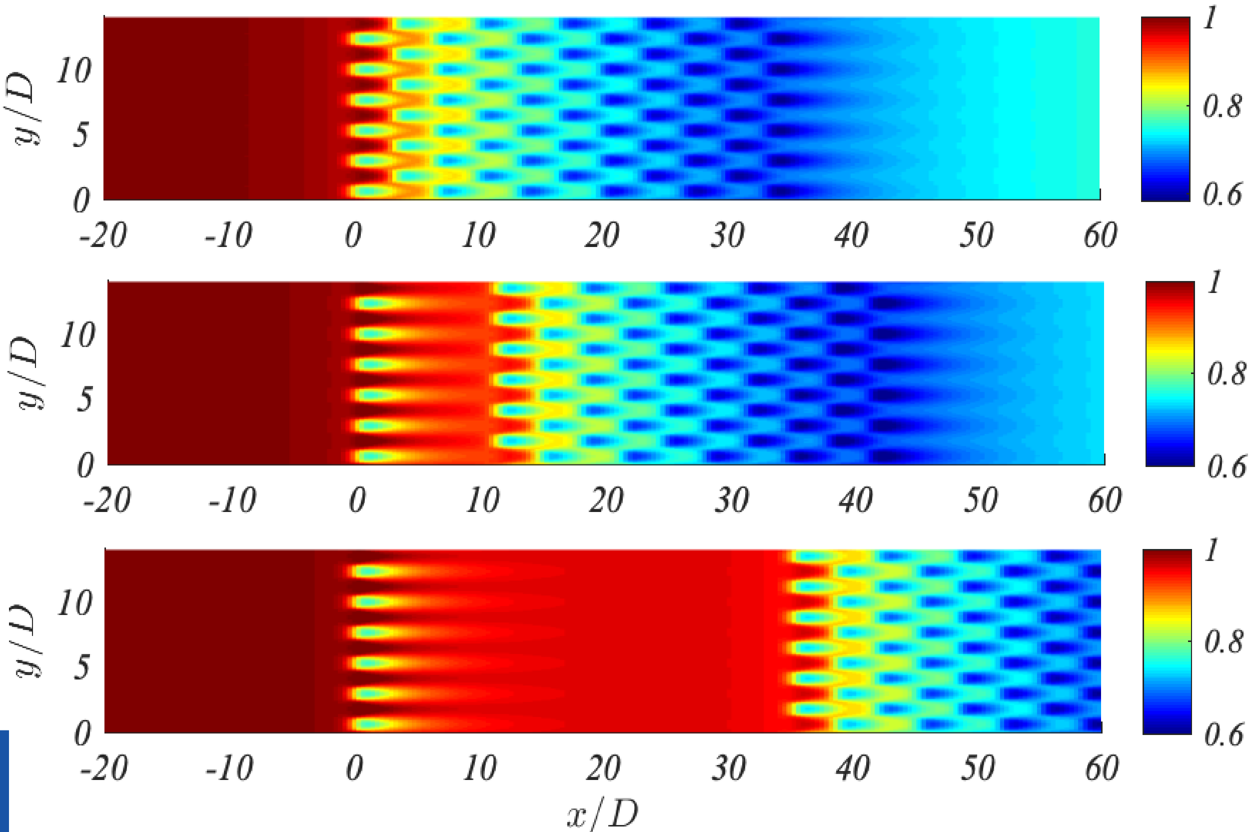
- From each experiment it was possible to determine the speed reduction of the first row for the given farm density and number of rows
- An empirical formula that fits the data is given by

$$U\left(\Delta x = 0\right) = U_{\text{ref}} \left\{ 1 - 0.097 \left(\frac{S_x S_y}{D^2} \right)^{-0.9} \left[1 - \exp\left(0.88 - 0.88 N_{\text{rows}} \right) \right] \right\}$$

Segalini & Dahlberg (Wind Energy, 2019)

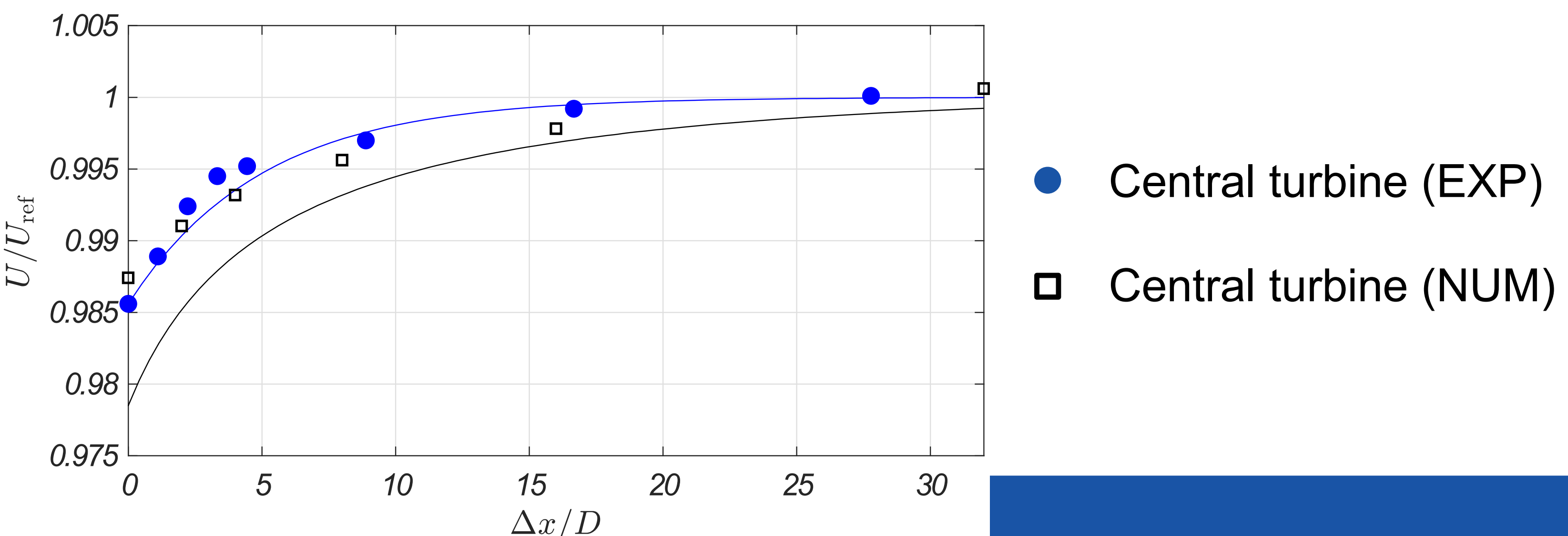
Numerical simulations

- Simulations with the linearised spectral code ORFEUS developed at KTH were performed to compare the code against simulation results (T_{comp}=5 min)



Numerical simulations

- The simulation performed with ORFEUS indicated a good quantitative agreement between experiments and simulations
- The analogy between the velocity decrease of the turbines and the upstream decrease seems to be qualitatively correct



Conclusions

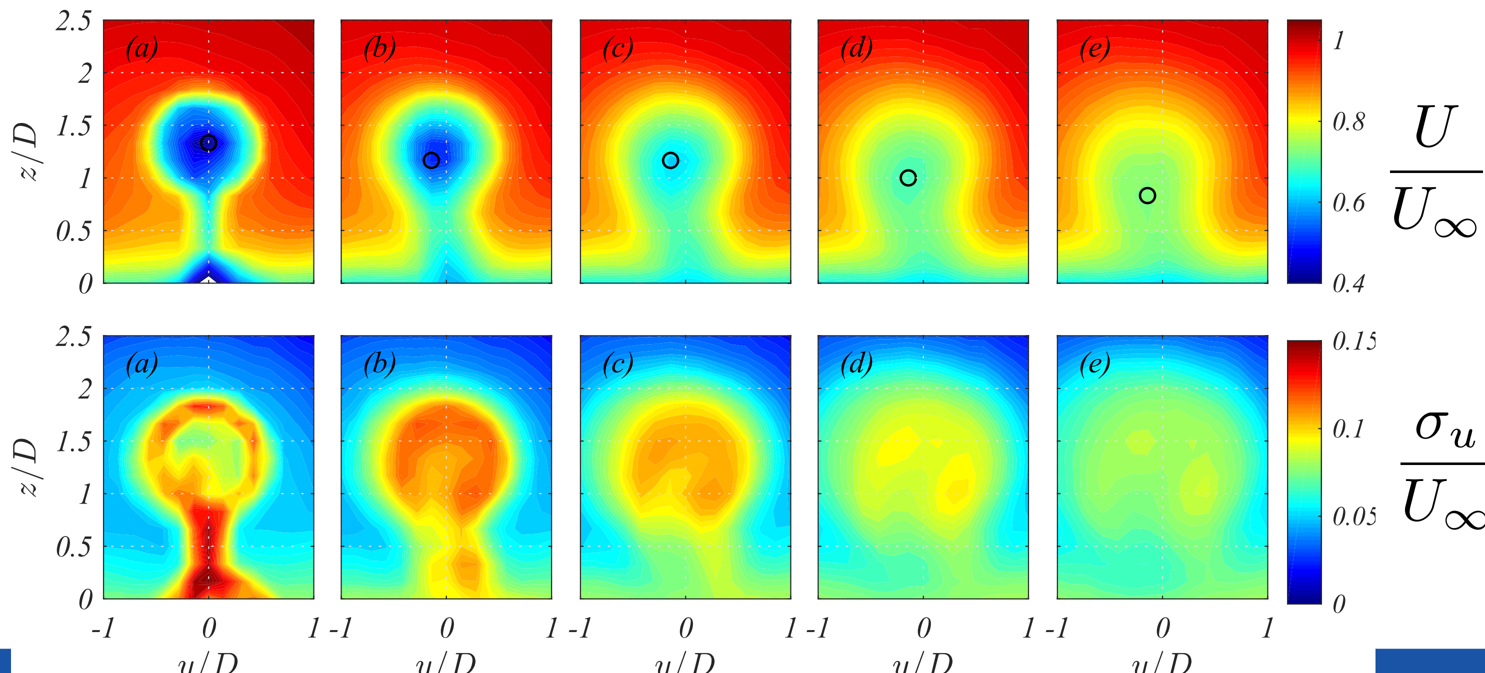
- Experiments and simulations demonstrate **the existence of a global-blockage phenomenon**
- The blockage effect of the first row generated by a downstream wind farm has been studied here and velocity decreases up to 2.5% were observed
- The velocity upstream of a wind farm is affected more than expected from the single-turbine theory suggests
- An estimate of the blockage correction for a wind farm has been proposed as function of the farm density and number of rows
- Good comparison between numerical simulations and experiments

Thank you for your attention

Questions?

Experimental setup (turbines)

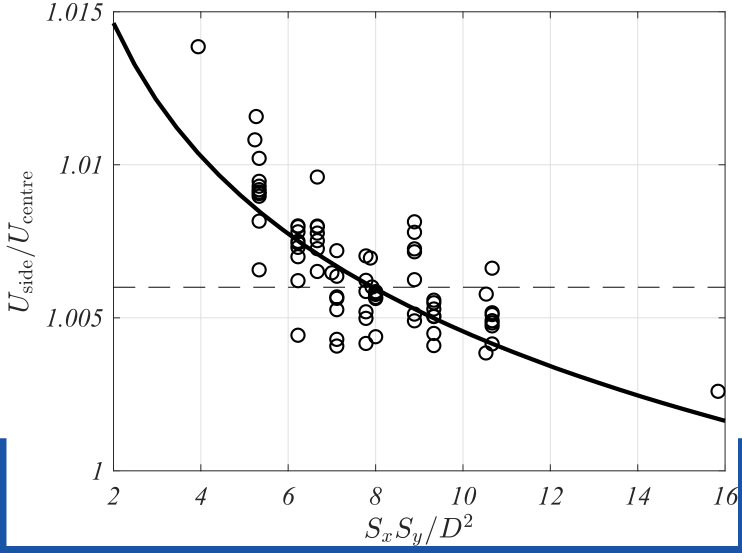
- Diameter 45 mm
- Hub height 60mm
- C_T=0.6 (measured with strain-gauge balance)
- C_P=0 (freely rotating)



Ebenhoch et al., Wind Energy (2016)

Side turbines

- Opposite to what expected, the side turbines did not show any speed-up, although their velocity decrease (with respect to the incoming wind) is lower than what experienced by the centre turbine
- An estimate of the velocity ratio is reported below (purely empirical)
- Additional experiments demonstrated that turbines not located at the edge behave as the central turbine



Thrust coefficient sensitivity

- Some simulations were performed to assess how the low thrust coefficient of the turbines (C_T=0.6) could affect the blockage
- The simulation results indicate that the thrust coefficient plays a major role for low CT, but saturates approximately at 0.6, supporting the results for realistic wind turbines as well (with C_T=0.8)