Design of Wind Energy Systems
SS 2016

CARL VON OSSIETZKY universität OLDENBURG

Lecture 11 & 12: Wake and wind farm effects on turbine performance

Prof. Dr. Martin Kühn
Wind energy systems

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I. Single wake
II. Wake measurements
III. Wind flow in windfarms
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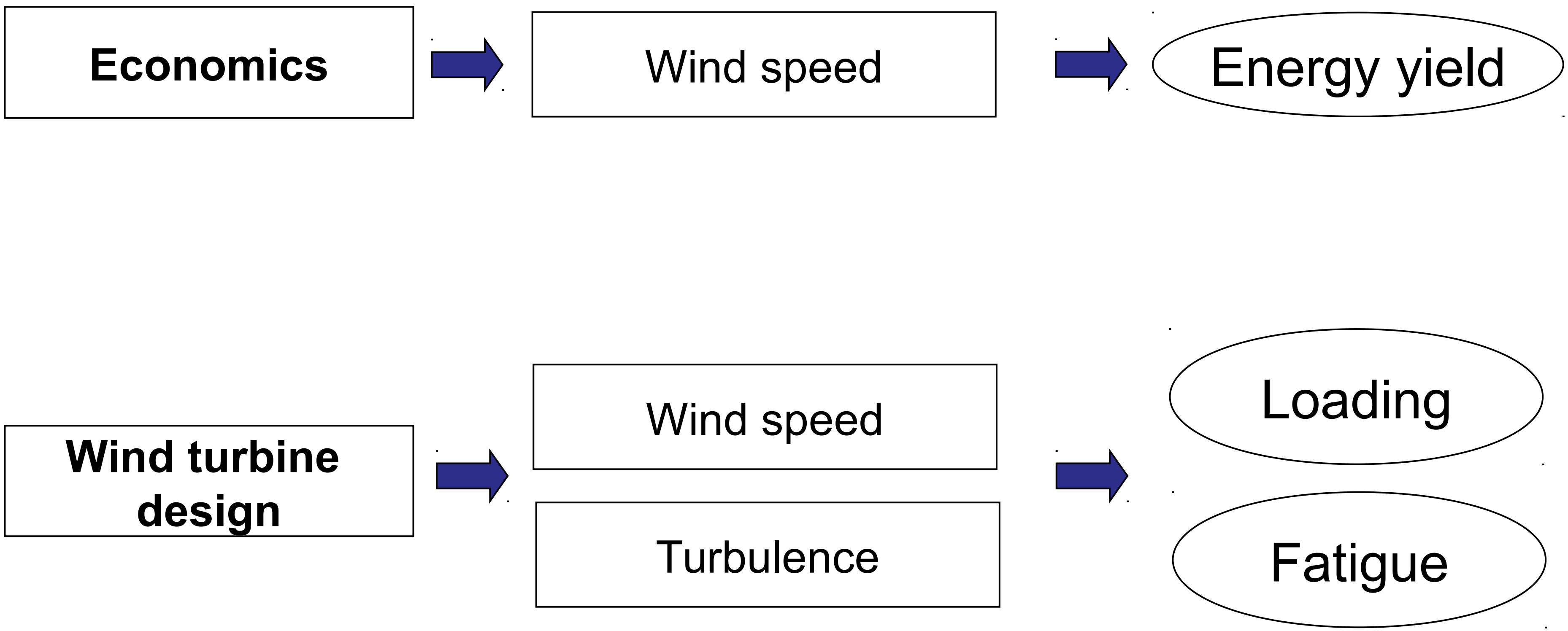
The use of lecture material developed by the author at SWE - University of Stuttgart is acknowledged.

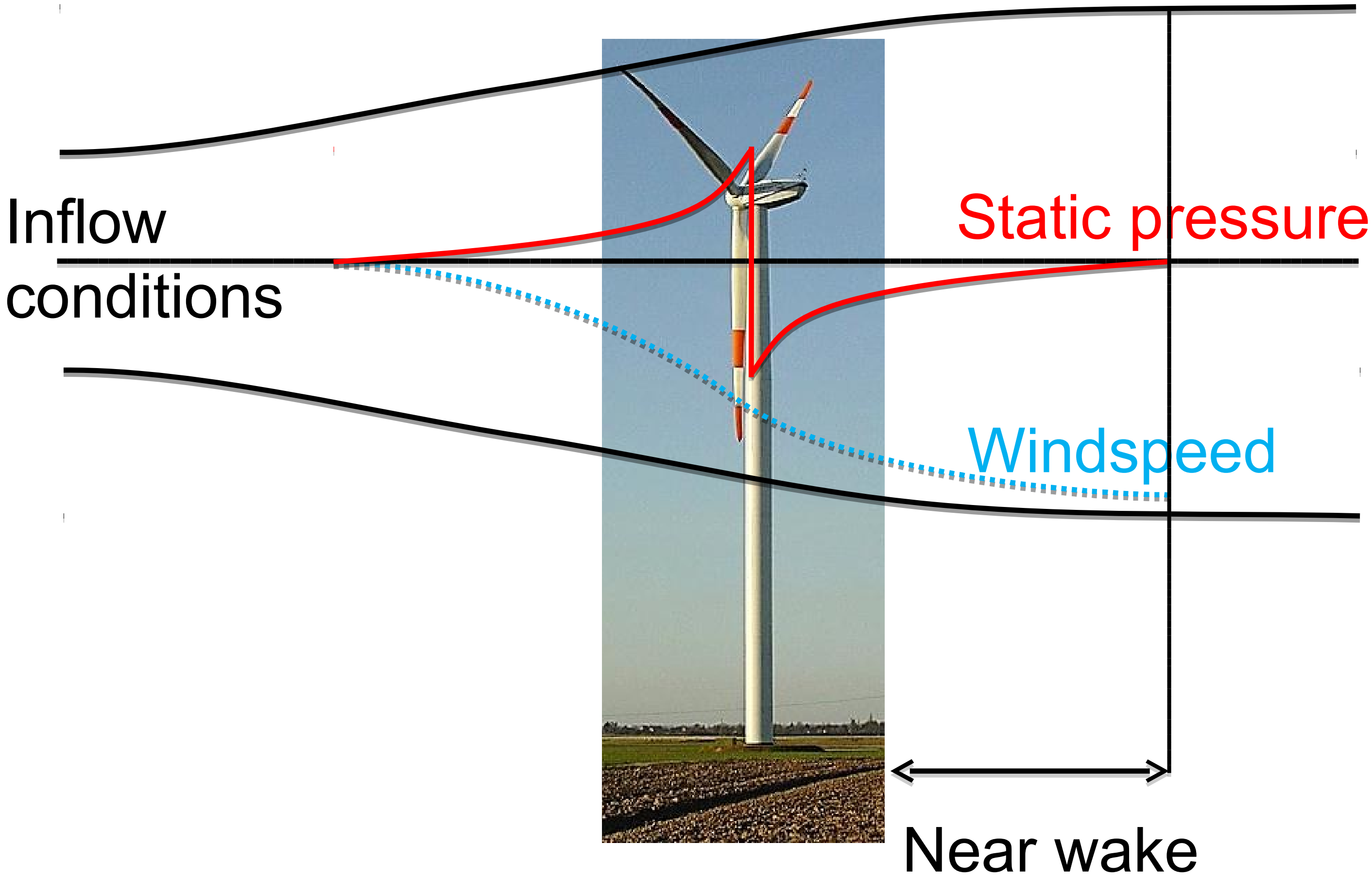
Oldenburg, June 2016 Martin Kühn

Relevance of wake assessment



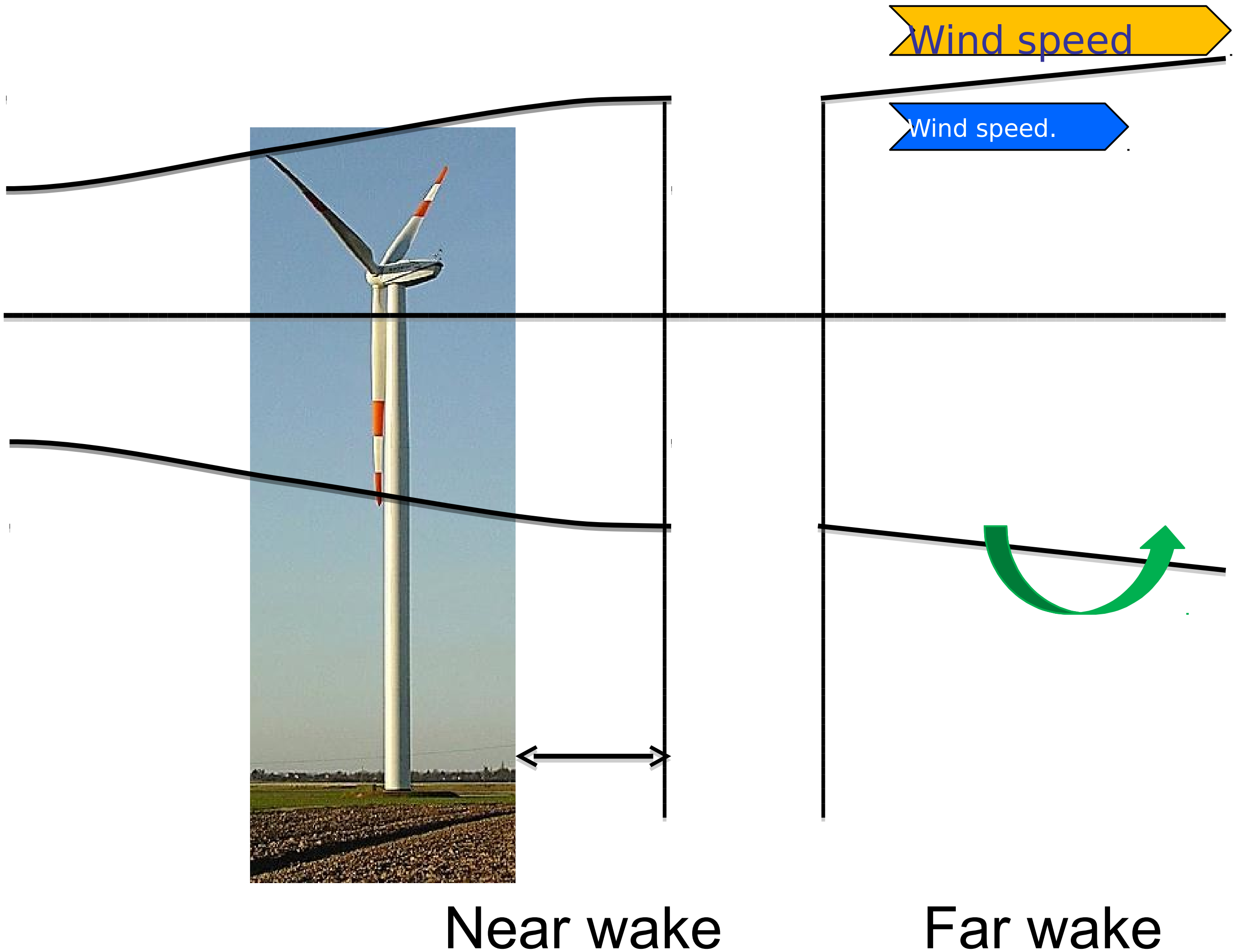
Single wakes

Wake development : Near wake



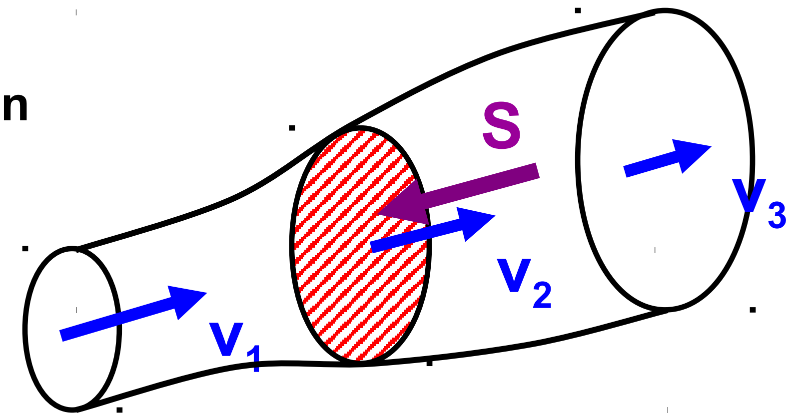
- Pressure gradients diminish at the end of the near wake
- Reduced wind speed due to induction at the rotor

Wake development: far wake



- **Shear forces**
- **Turbulent exchange**

Inflow and wake wind speed



Thrust S from momentum conservation

$$S = \dot{m} \cdot \left(v_1 - v_3\right)$$

$$S = \frac{1}{2} \cdot \rho \cdot F \cdot \left(v_1^2 - v_3^2\right)$$

Thrust coefficient

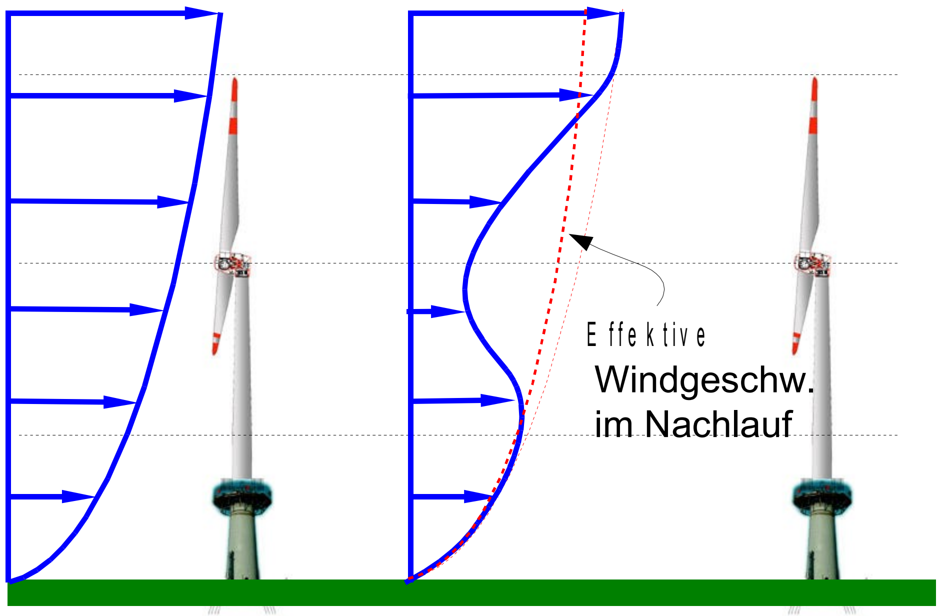
$$c_S = \frac{Schub}{Staudruck} = \frac{\frac{1}{2} \cdot \rho \cdot F \cdot \left(v_1^2 - v_3^2\right)}{\frac{1}{2} \cdot \rho \cdot F \cdot v_1^2} = 1 - \left(\frac{v_3}{v_1}\right)^2$$

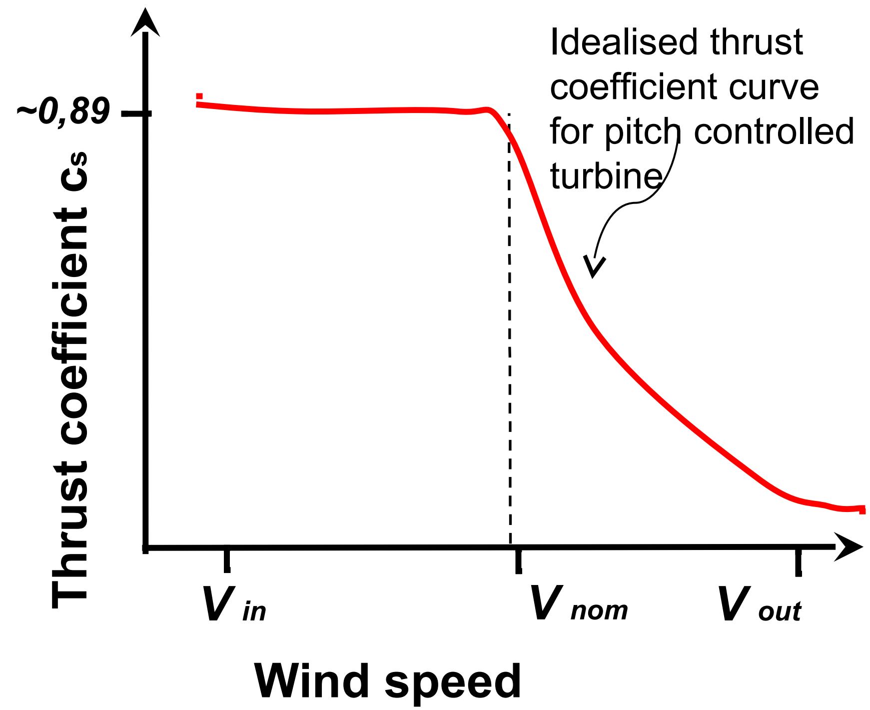
$$\boxed{\frac{v_3}{v_1} = \sqrt{1 - c_S}}$$

Wind speed in wake is dependent on the thrust curve coefficient of the turbine

Wind speed in wake

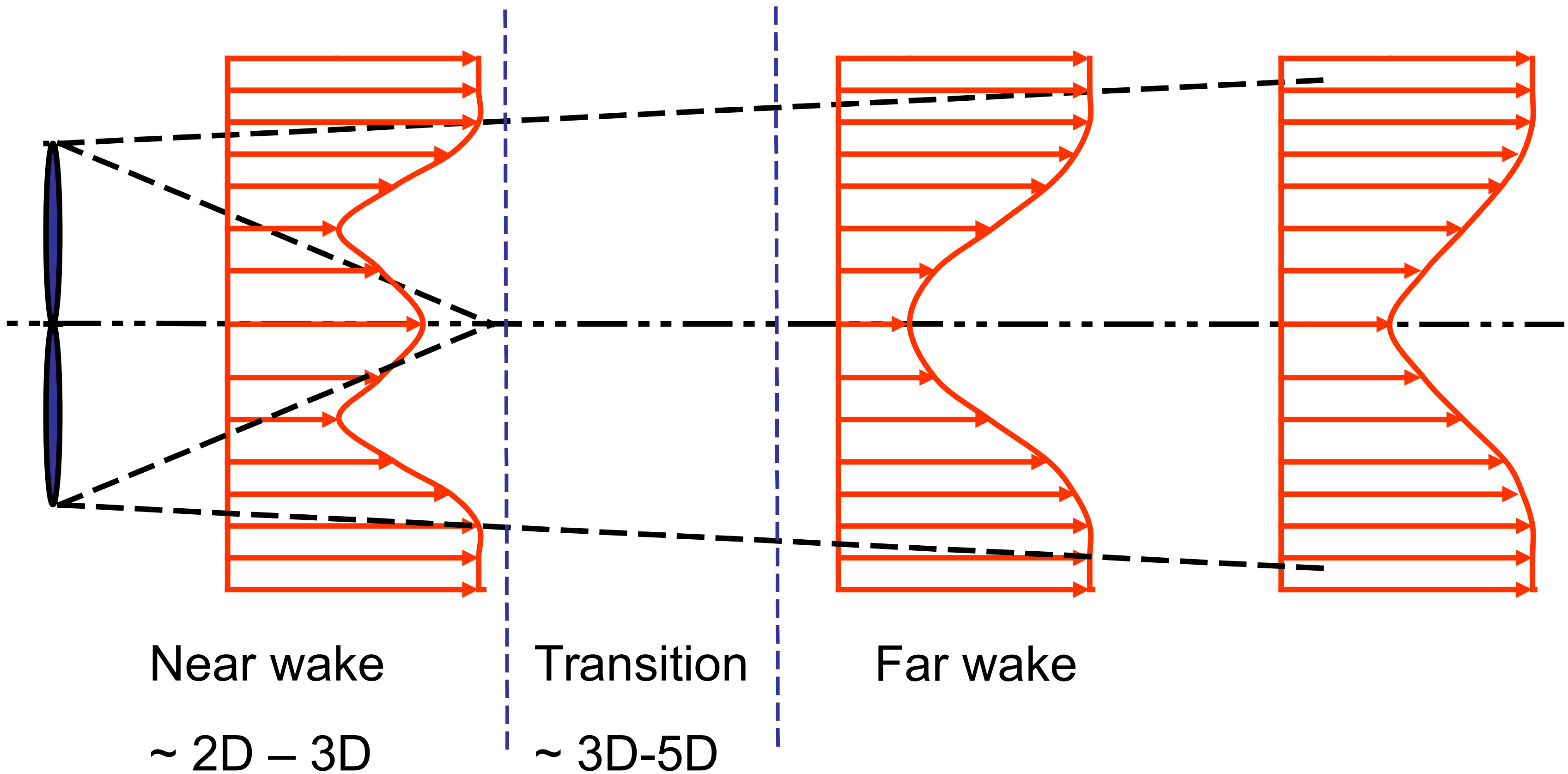
$$\frac{v_3}{v_1} = \sqrt{1 - c_S}$$





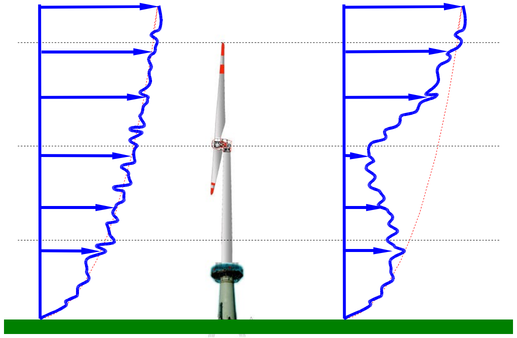
Mean wind speed in wake

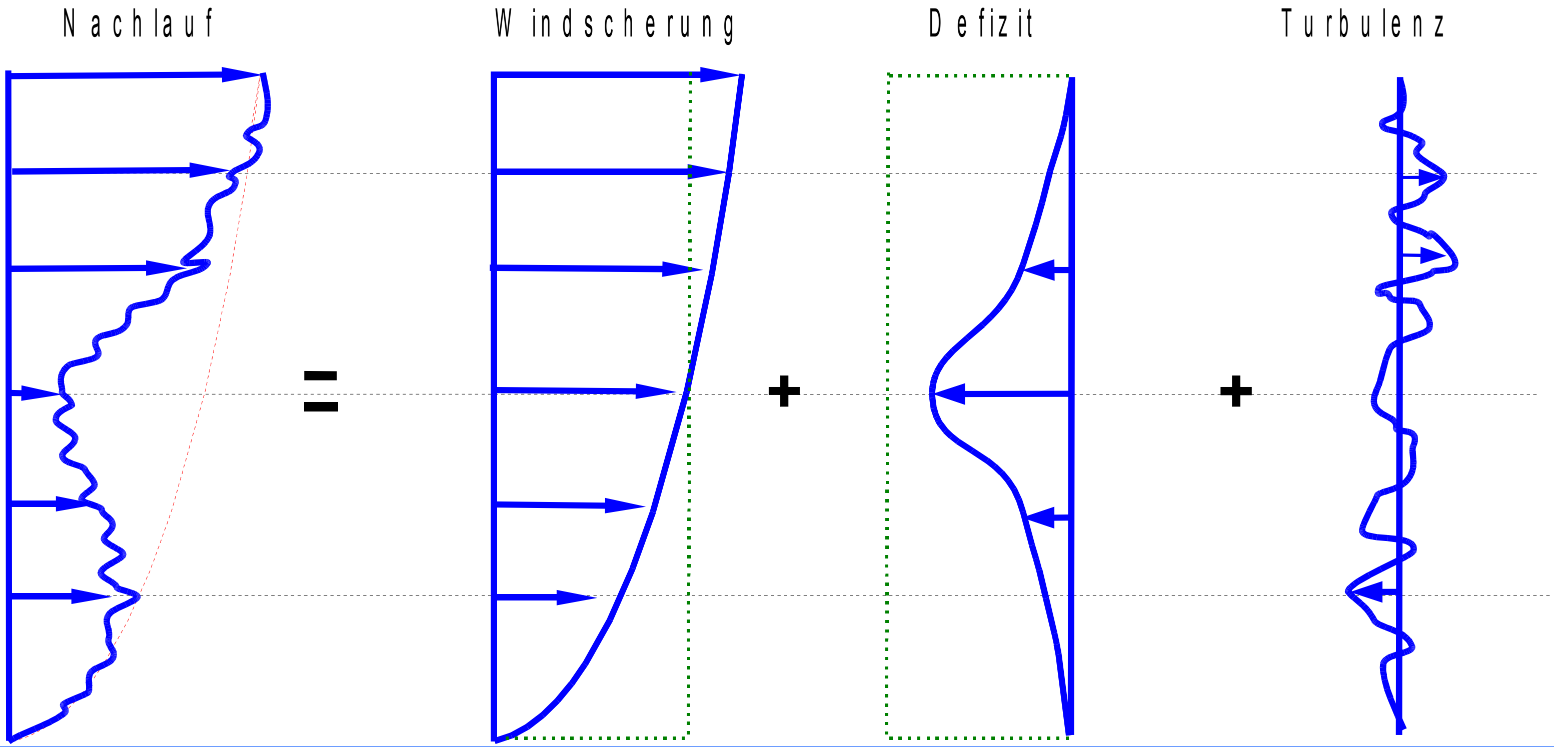
Qualitative description of the mean wind speed in wake



Mean wind speed in wake

Wake as linear superposition of wind shear, wind speed deficit and turbulence





Mean wind speed in wake

Empirical model for estimation of the wi
speed at wake center dependent on
downstream distance

$$\frac{\Delta V}{V_{\text{hub}}} = A\left(\frac{D}{x}\right)^{n}$$

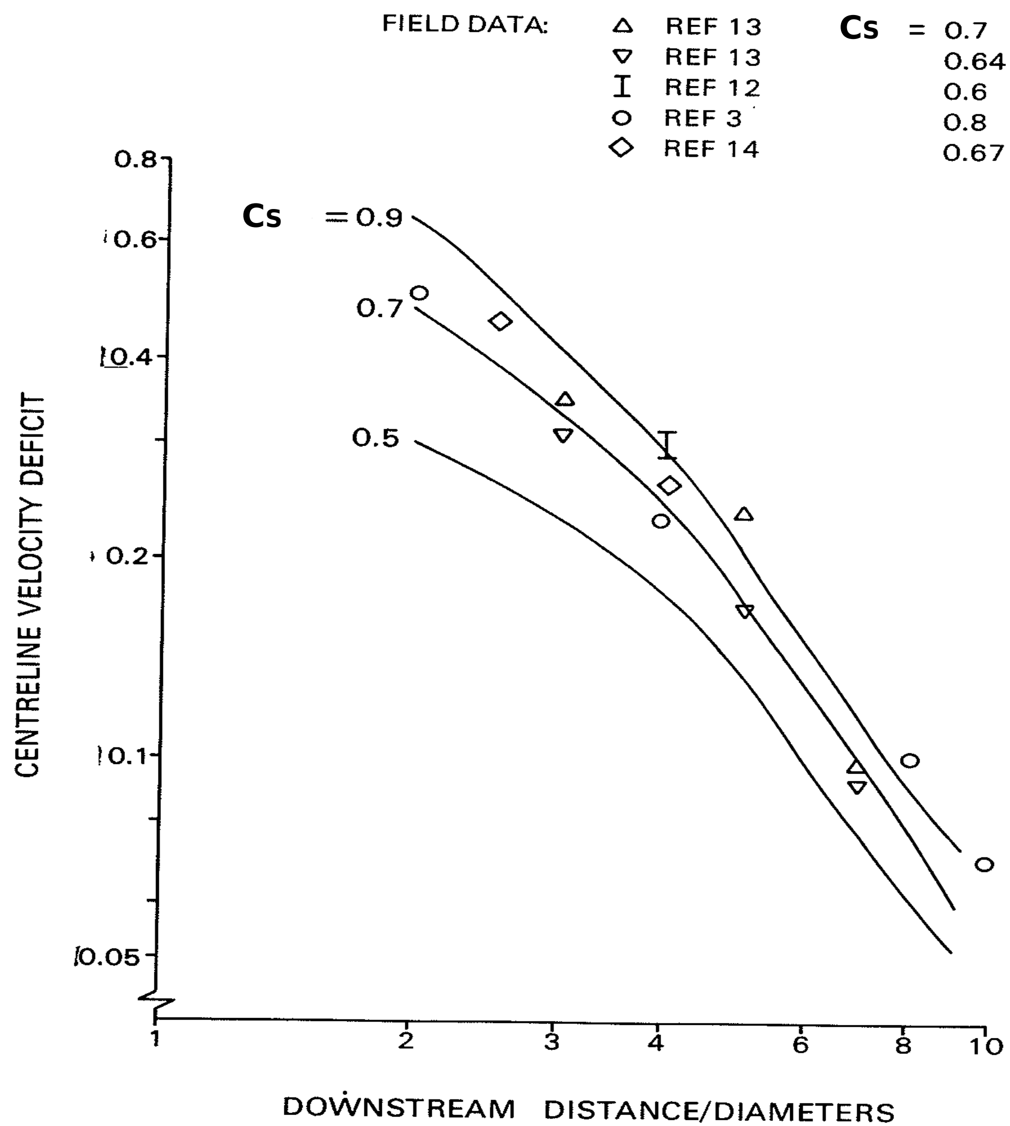
A : dependent on C_S

$1 < A < 3$

n: dependent on turbulence

$0{,}75 < n < 1{,}25$

Vermeer 2003



Ainslie 1988

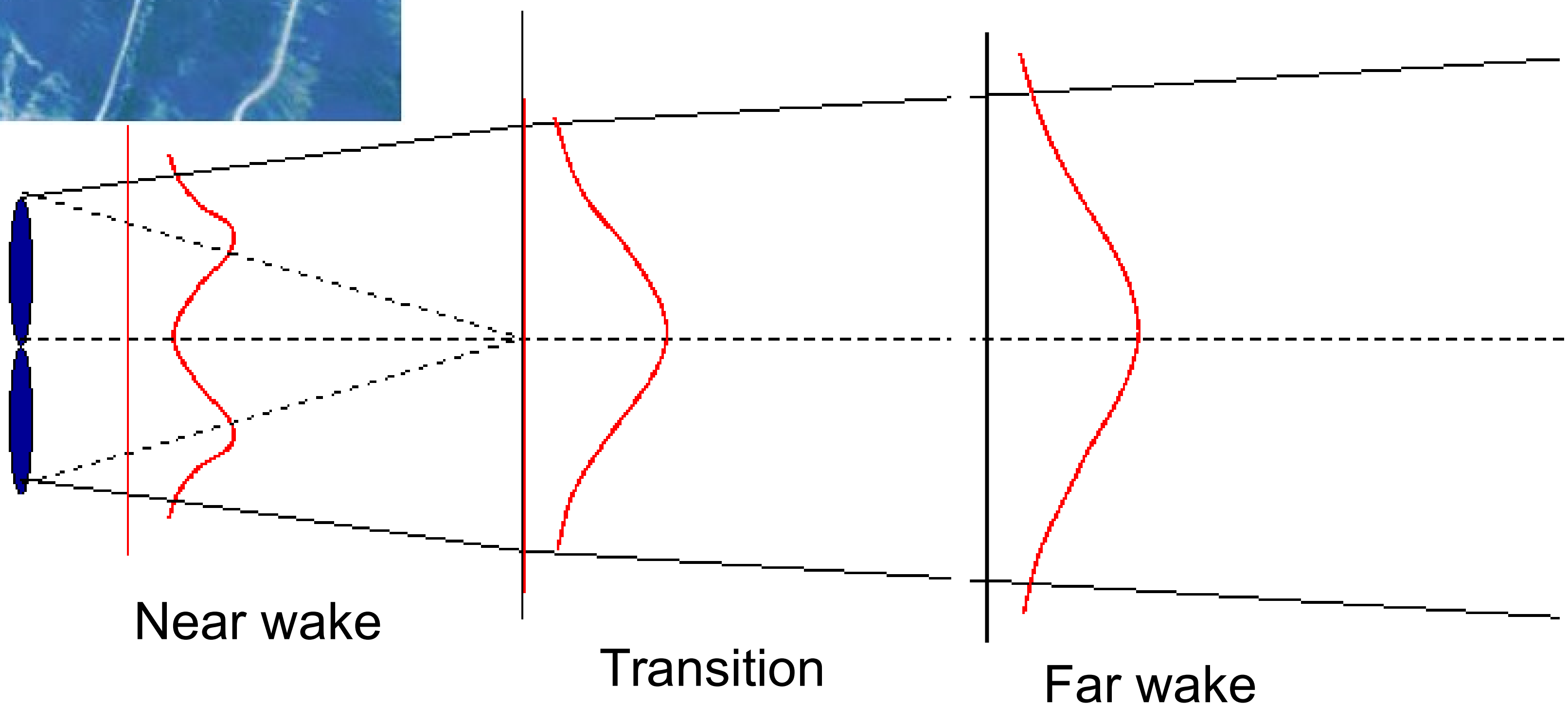
Turbulence intensity in wake

Risoe

Steady complex structures in the near wake develop into Gaussian-like profiles in the far wake

Turbulence intensity

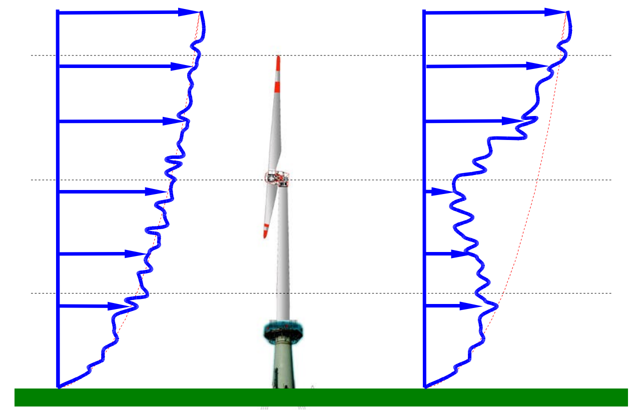
$$I = \frac{\sigma_u}{\bar{u}}$$



Turbulence in wake

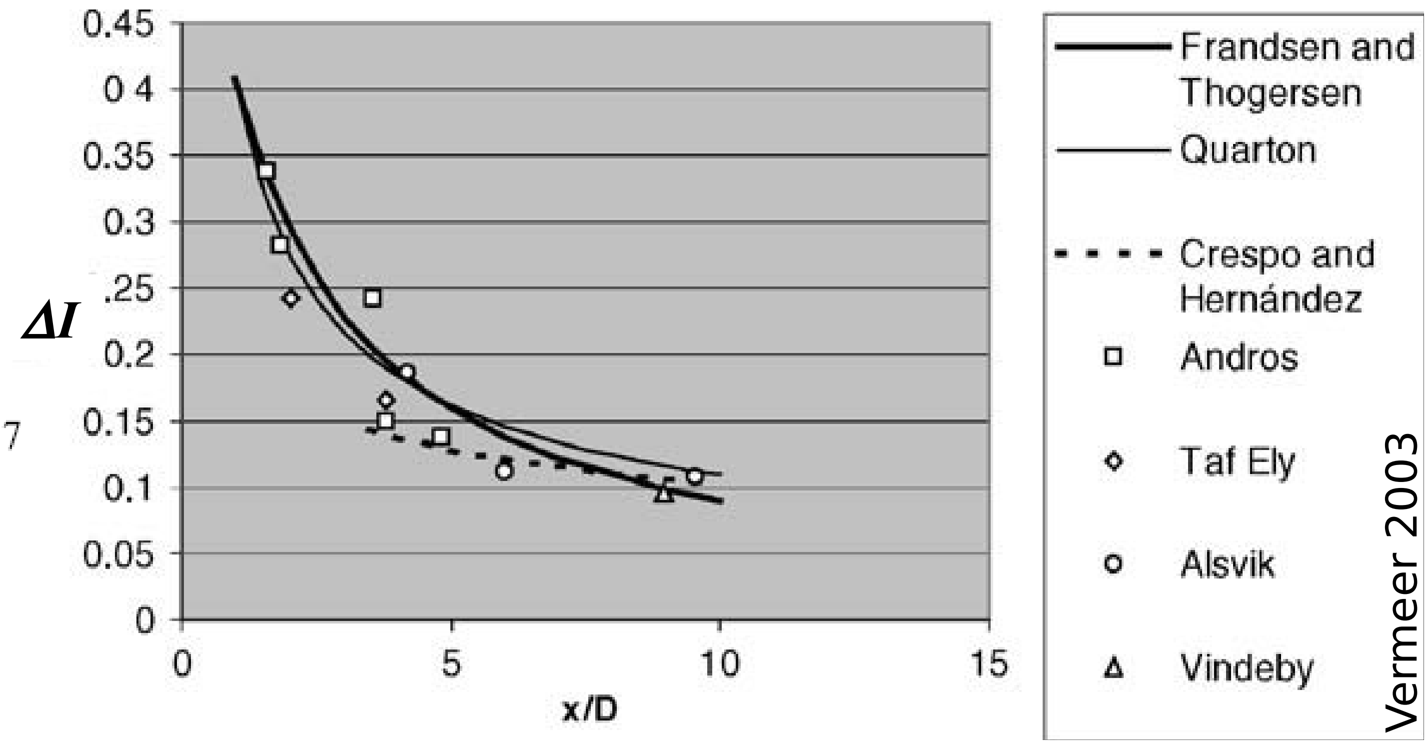
Wind turbines generate additional turbulence (ΔI) to ambient turbulence (I_∞)

$$\Delta I = \sqrt{I^2 - I_\infty^2}$$



Example: Empirical Turbulence decay at the center of the wake nach Quarton

$$\Delta I = 4.8\, C_T^{0.7} I_\infty^{0.68} \left(\frac{x_N}{x}\right)^{0.57}$$



Vermeer 2003

Wake modelling

PARK Wake model (Risø)

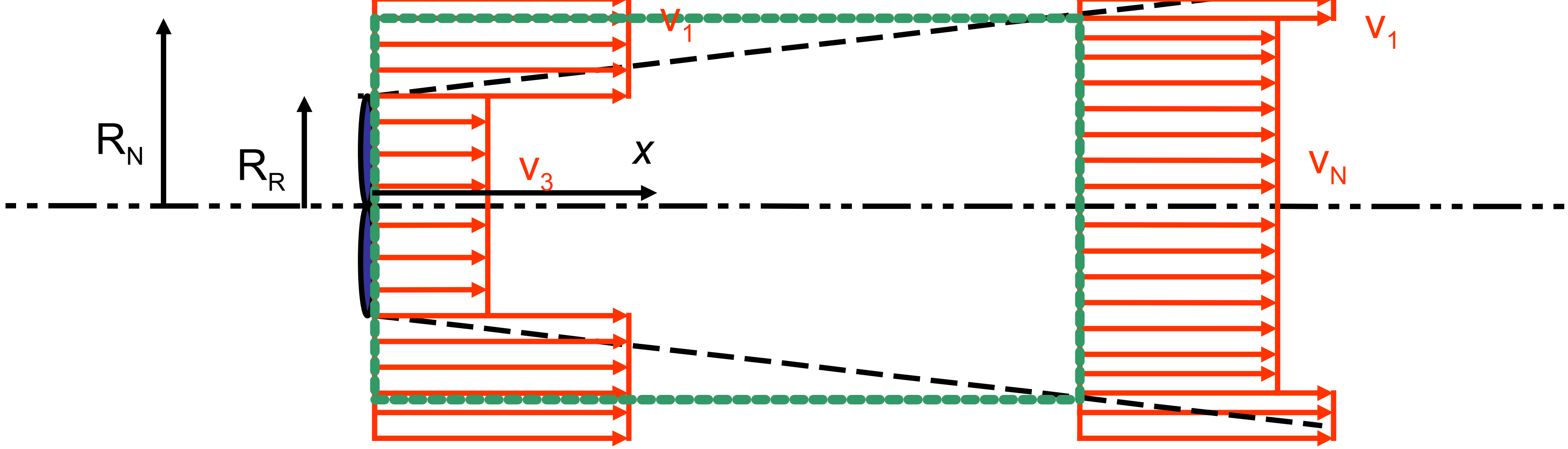
- PARK-Model of N.O. Jensen assumes a linear expansion of the wake

$$R_N = R_R + kx$$

- Mass conservation

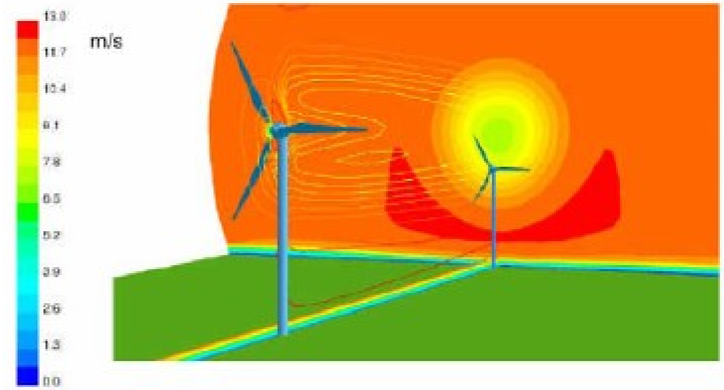
$$v_N = \left(v_3 - v_1 \right) \frac{R^2{}_R}{R^2{}_N} + v_1$$

- Implemented in commercial wind farming software

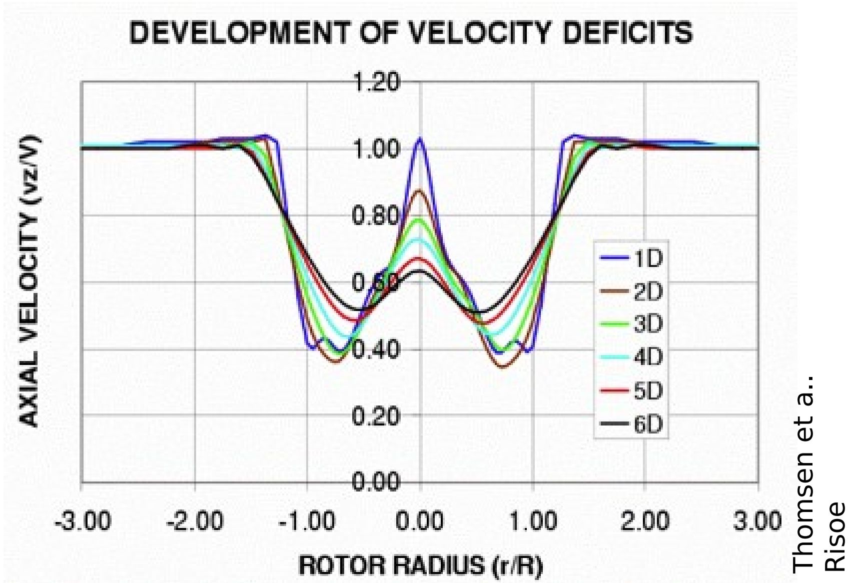


Numerical models
Steady wake characteristics

- *Ainslie* : 2D CFD
  Actuator disk
  Far wake
  Turbulence -> Eddy viscosity *GH Windfarmer®, WindPRO ®*

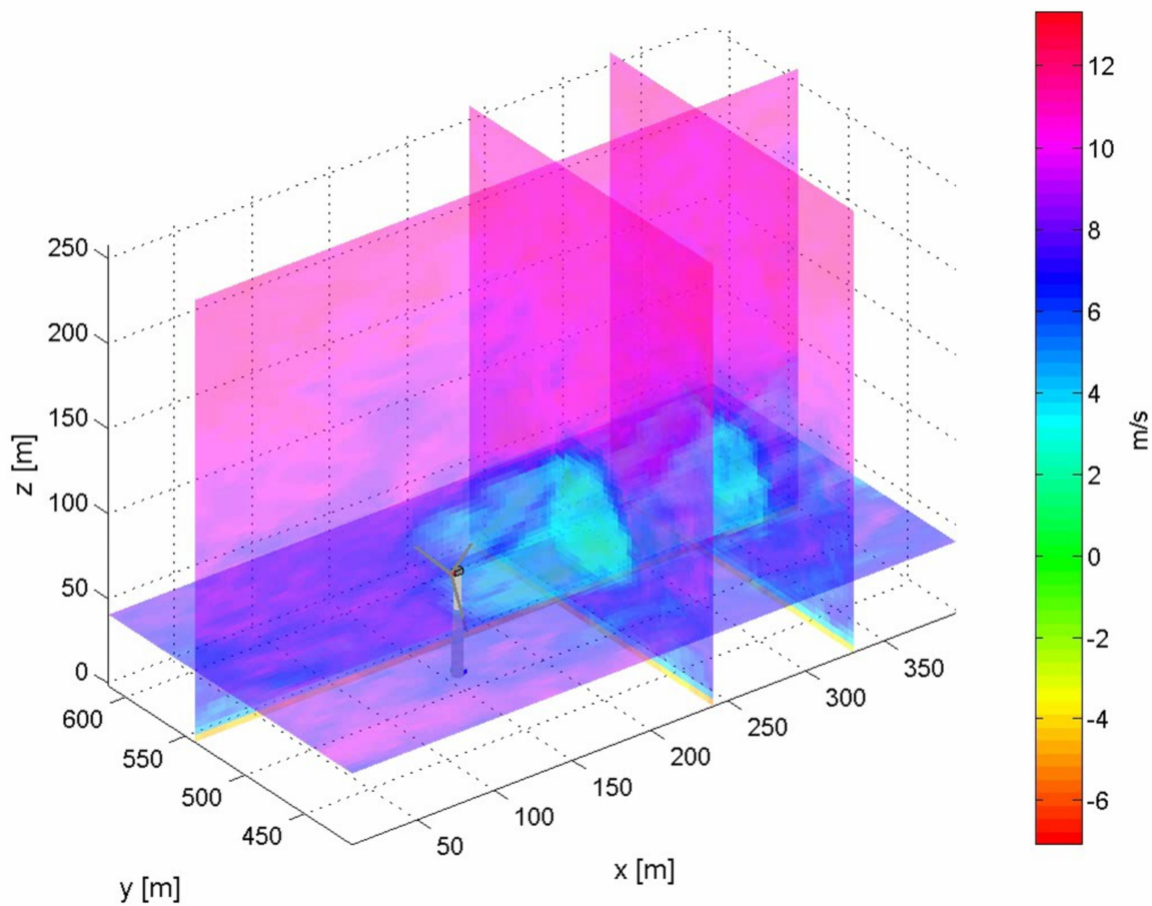


- *UPMWAKE:* 3D CFD
  Actuator disk
  Full wake
  Turbulence k-ε



Numerical models
Unsteady wake characteristics

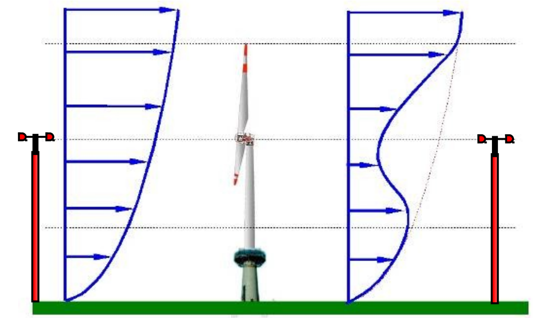
- *Large eddy simulation* : Actuator line with PALM (ForWind)

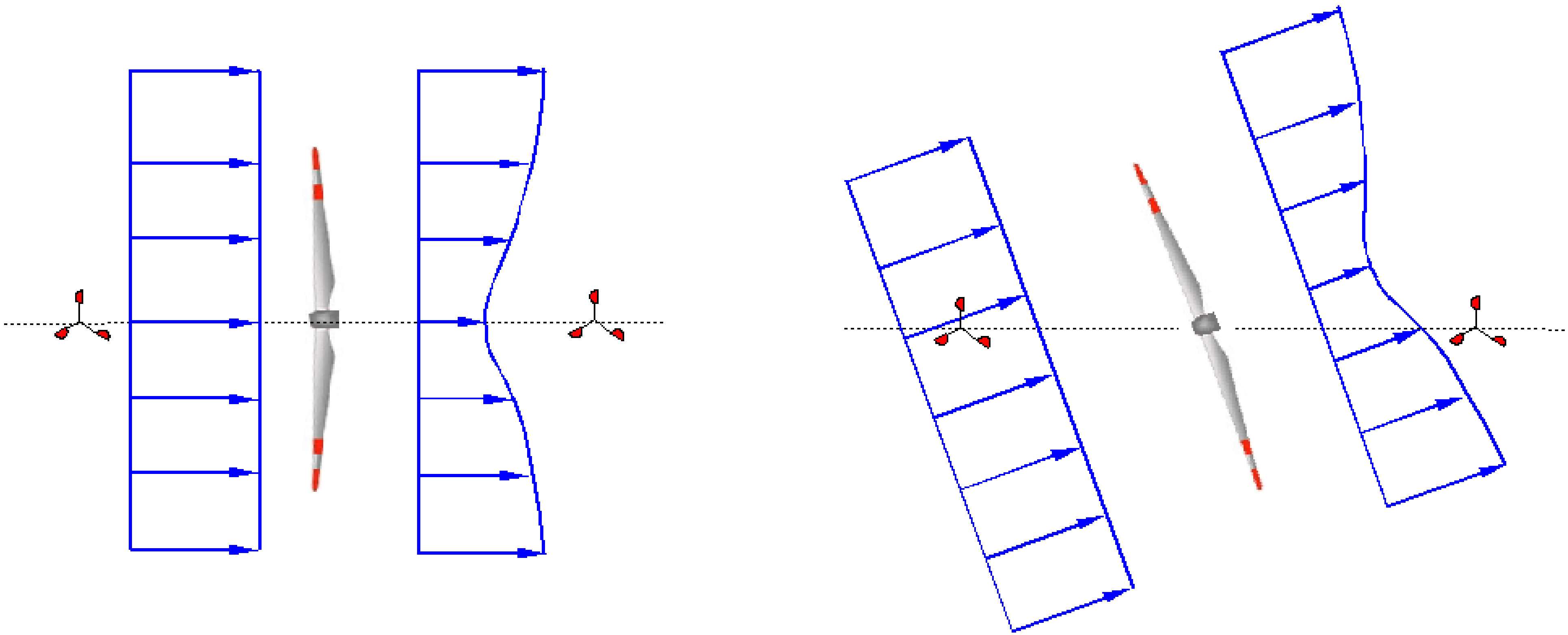


Wake measurement

Standard wake measurement

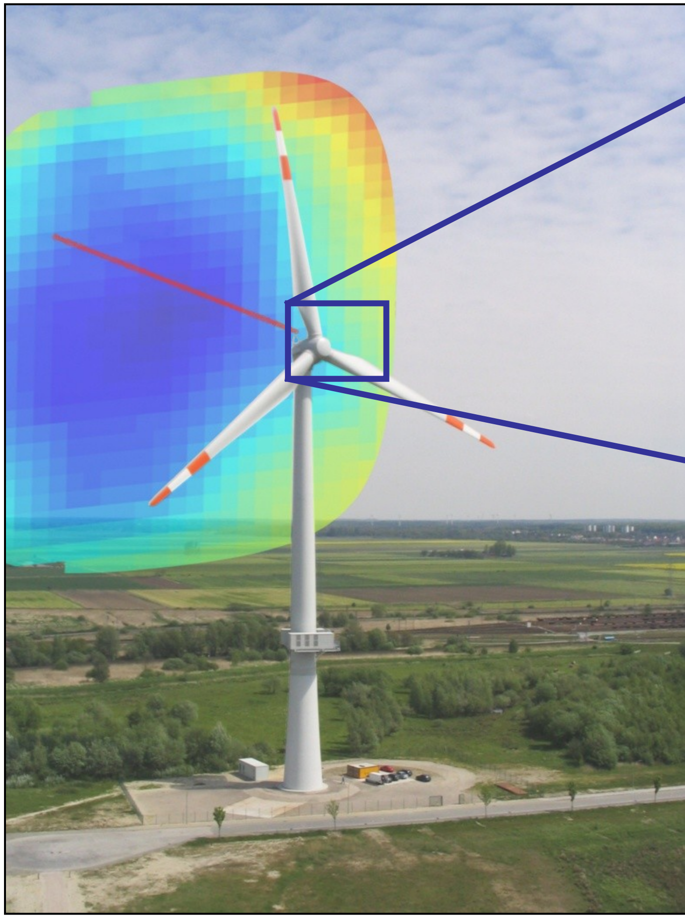
Mean horizontal profiles obtained with standard anemometers on meteorological masts



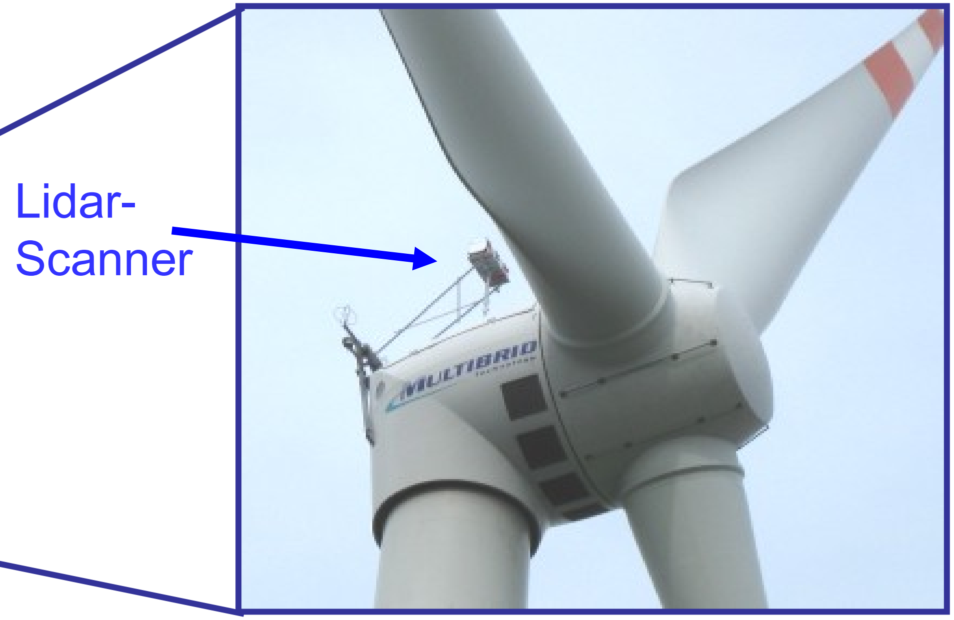


Measurements of Multibrid Prototype

Experiment setup



SWE - University of Stuttgart



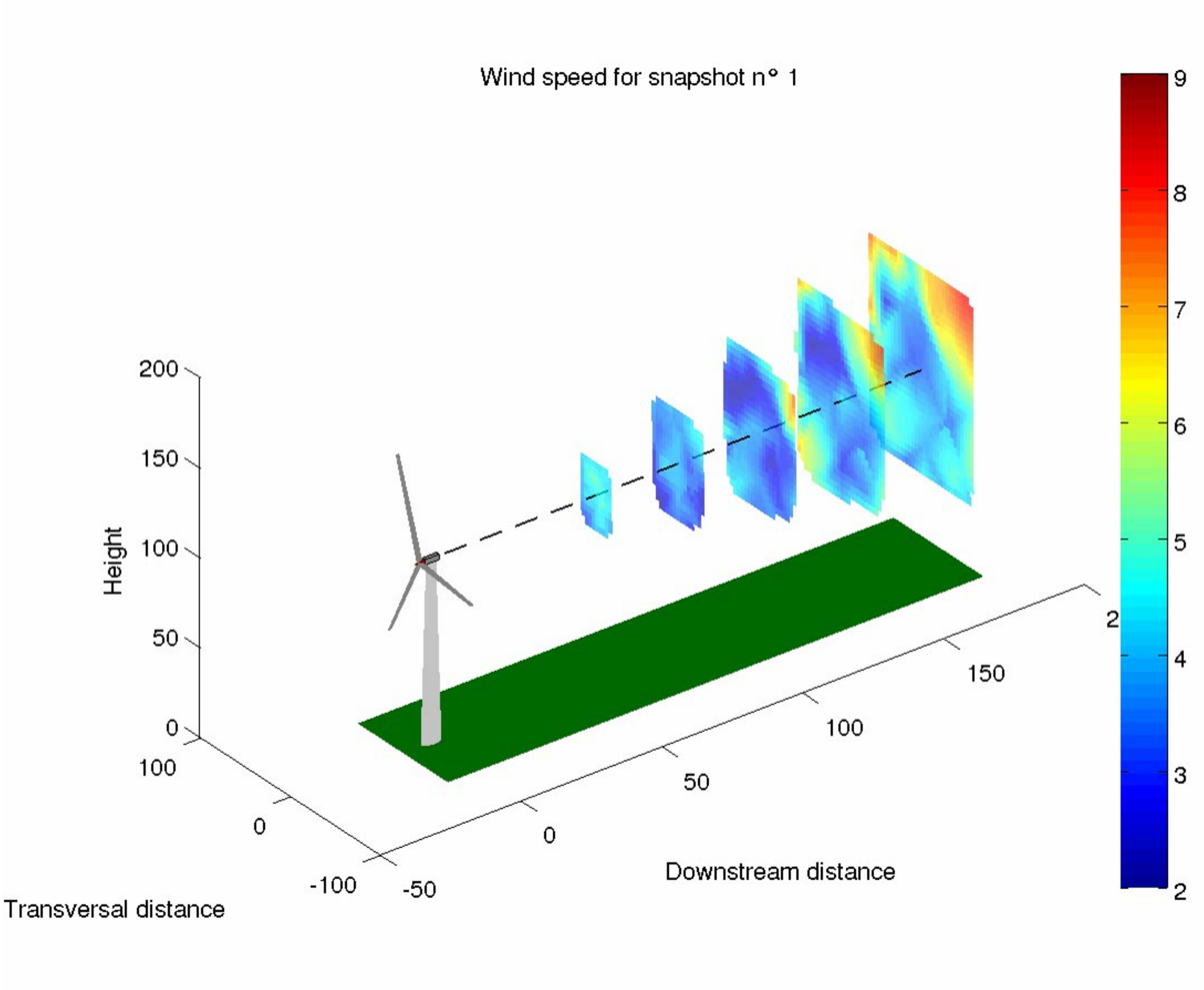
SWE – University of Stuttgart

Multibrid M5000 prototype

- 5 MW with 116m rotor diameter
- 102m hub height
- Heavily equipped with sensors
- Met mast
- Mounted Lidar-Scanner SWE

Measurements of Multibrid Prototype

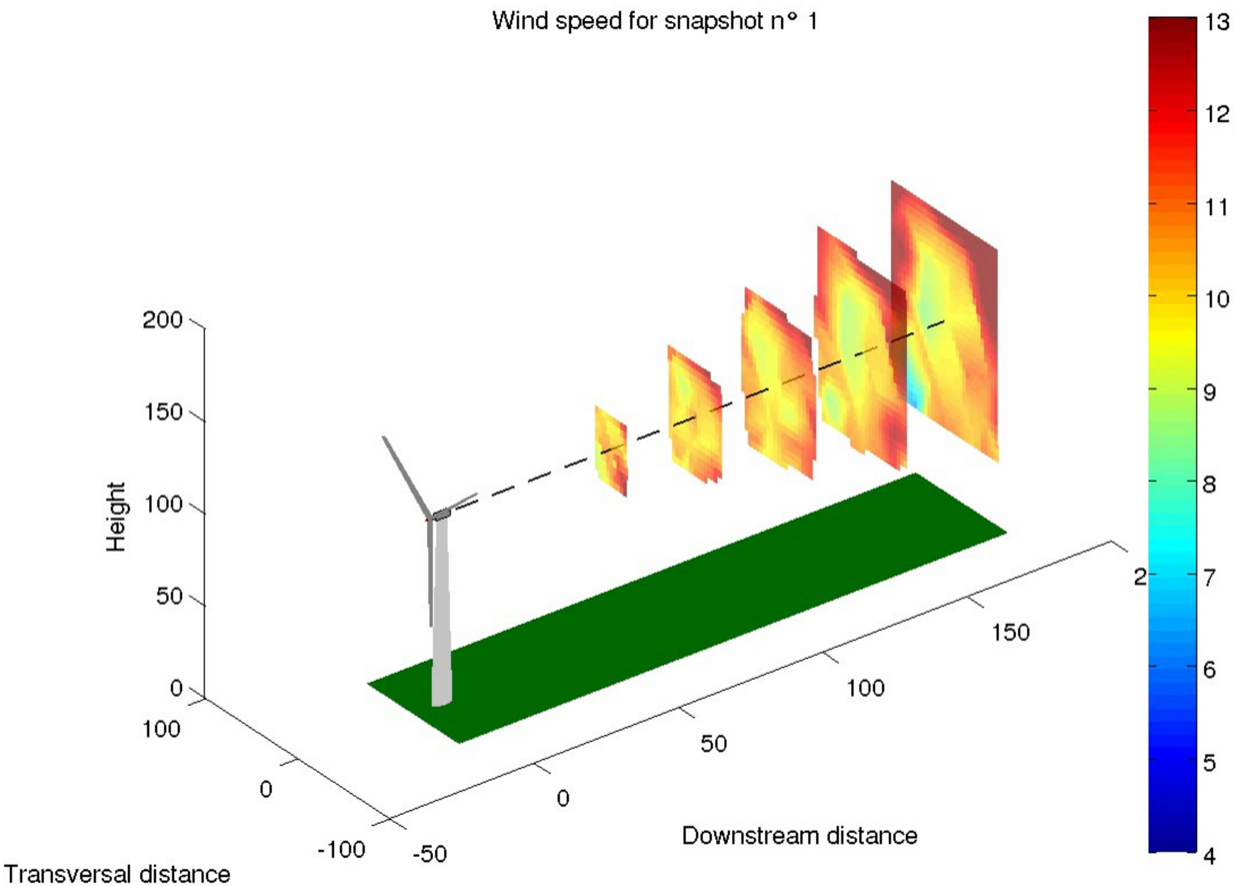
early morning (stable)



Wind speed [m/s]

Measurements of Multibrid Prototype

midday (unstable)



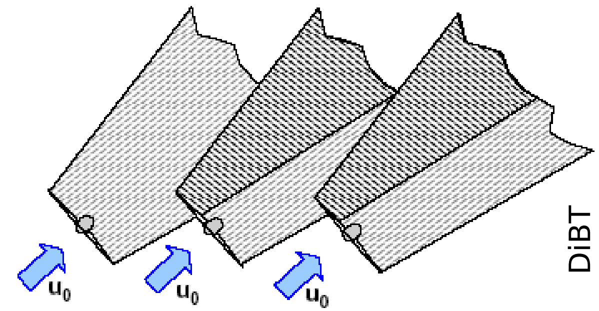
Wind speed [m/s]

Wind farms

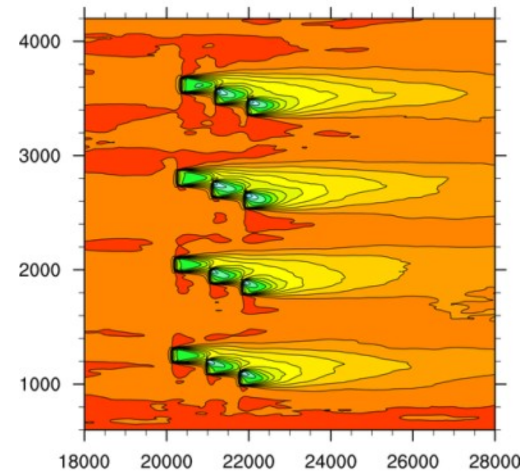
III. Wind farm modelling

Wind farm models

- **Single wake superposition**
  - Assumptions for flow simplification
  - Low computational cost
  - FLaP, WindPRO, GH Windfarmer



- **Wind farm CFD/LES simulation**
  - More detail of the physics
  - High computational effort
  - Commercial and research



LES Simulation von »alpha ventus«

Wind turbine separation onshore

Typical separations of minimum 5D

Wikimedia (CC)

Example

„ …for optimal „harvesting“ of the wind it is suggested to have a turbine separation of 8 diameters in the mean wind direction +/- 30°, in the other directions a separation of 4 diameters is suggested...“

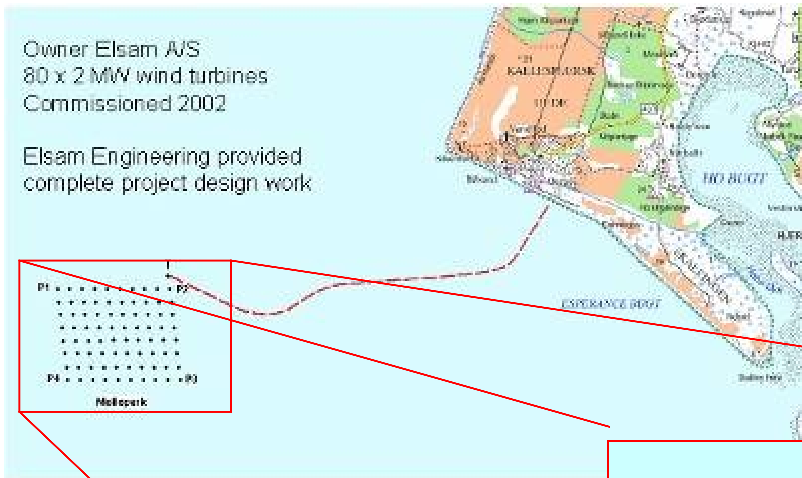
[Windenergieerlass NRW, www.IWR.de]

Wind turbine separation offshore

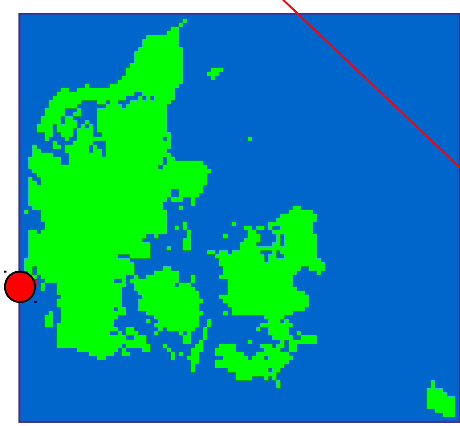
Typical separations of minimum 8D

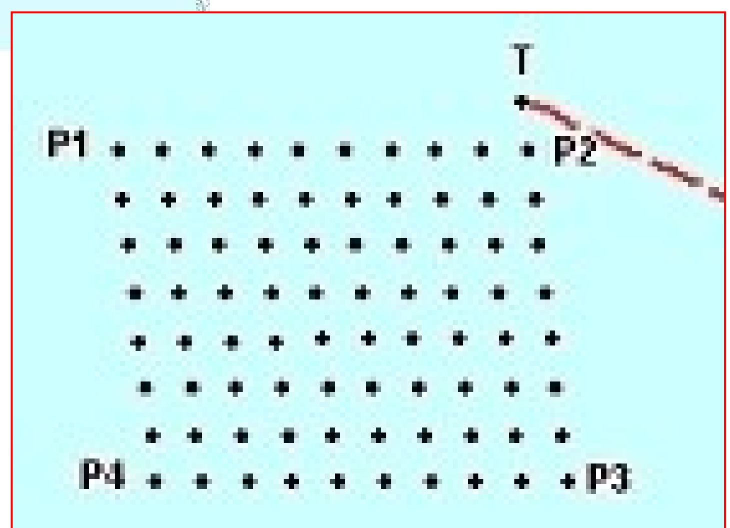
Vattenfal & DONG

IV. Example wind farm Horns Rev



80 wind turbines
2MW nominal power
14-20 km from the coast





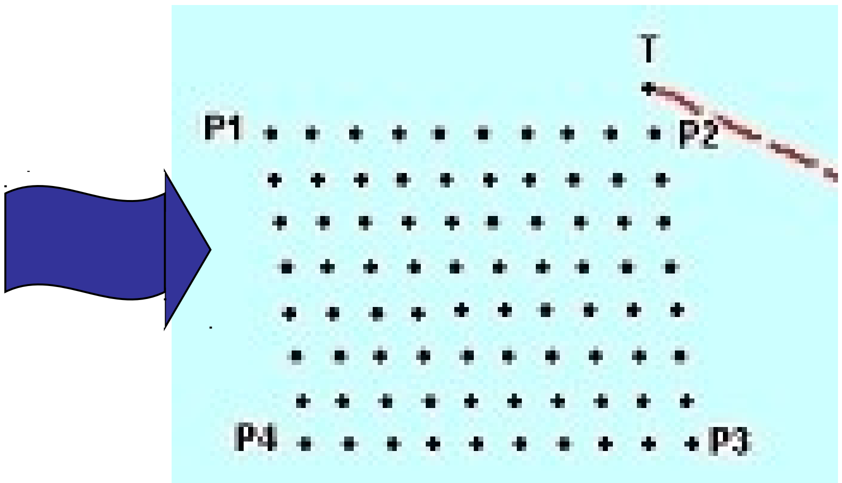
Horns Rev

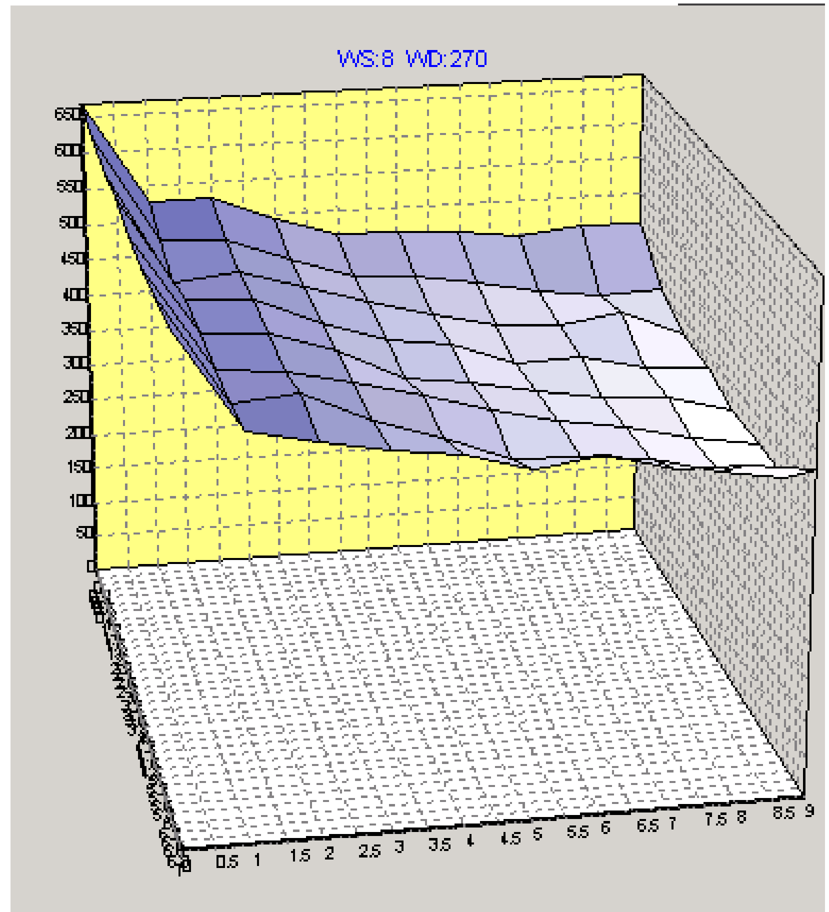
DONG Energy

Horns Rev Measurement: wind farm effects

Electrical power westerly wind

(10Min mean values)





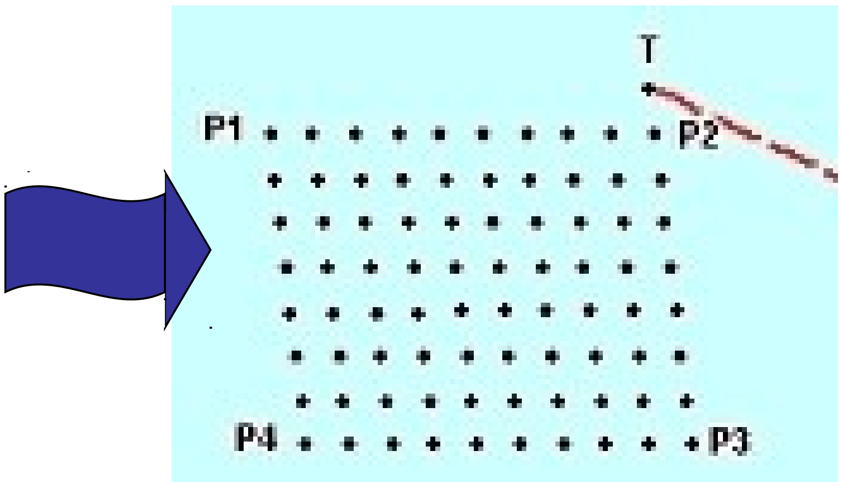
Leo Jensen, ELSAM A/S

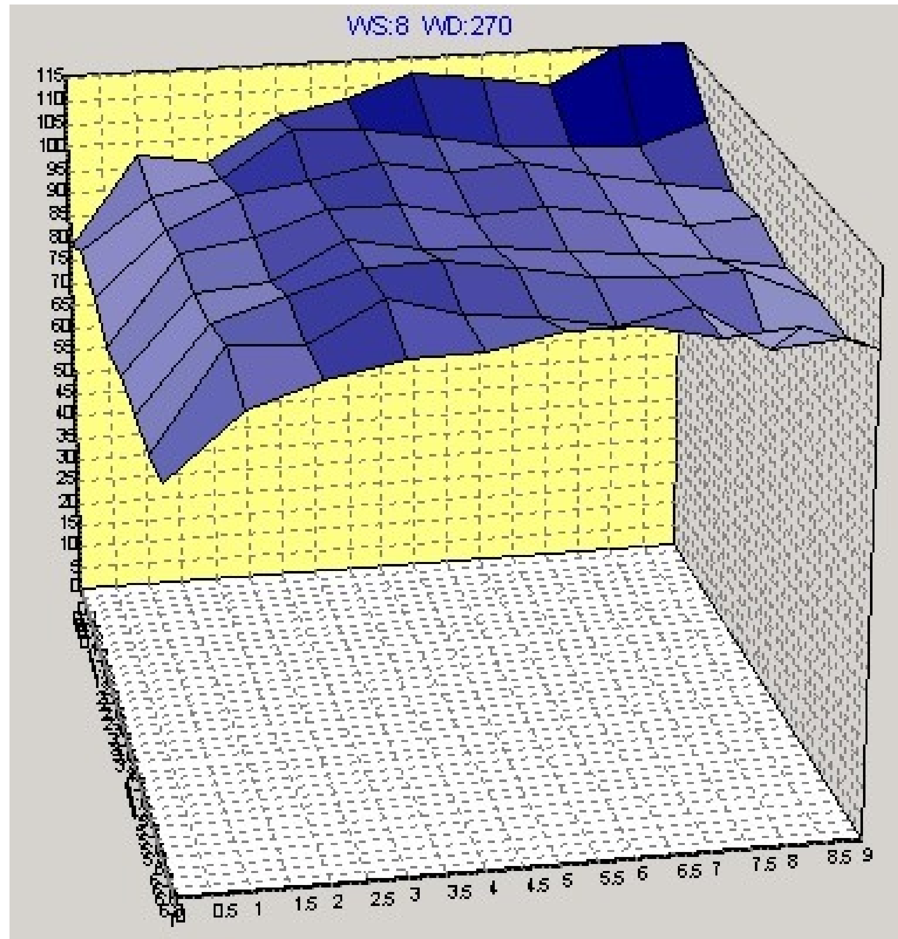
Largest power loss between 1st and 2nd row

Horns Rev Measurement: wind farm effects

Standard deviation of electrical power westerly wind

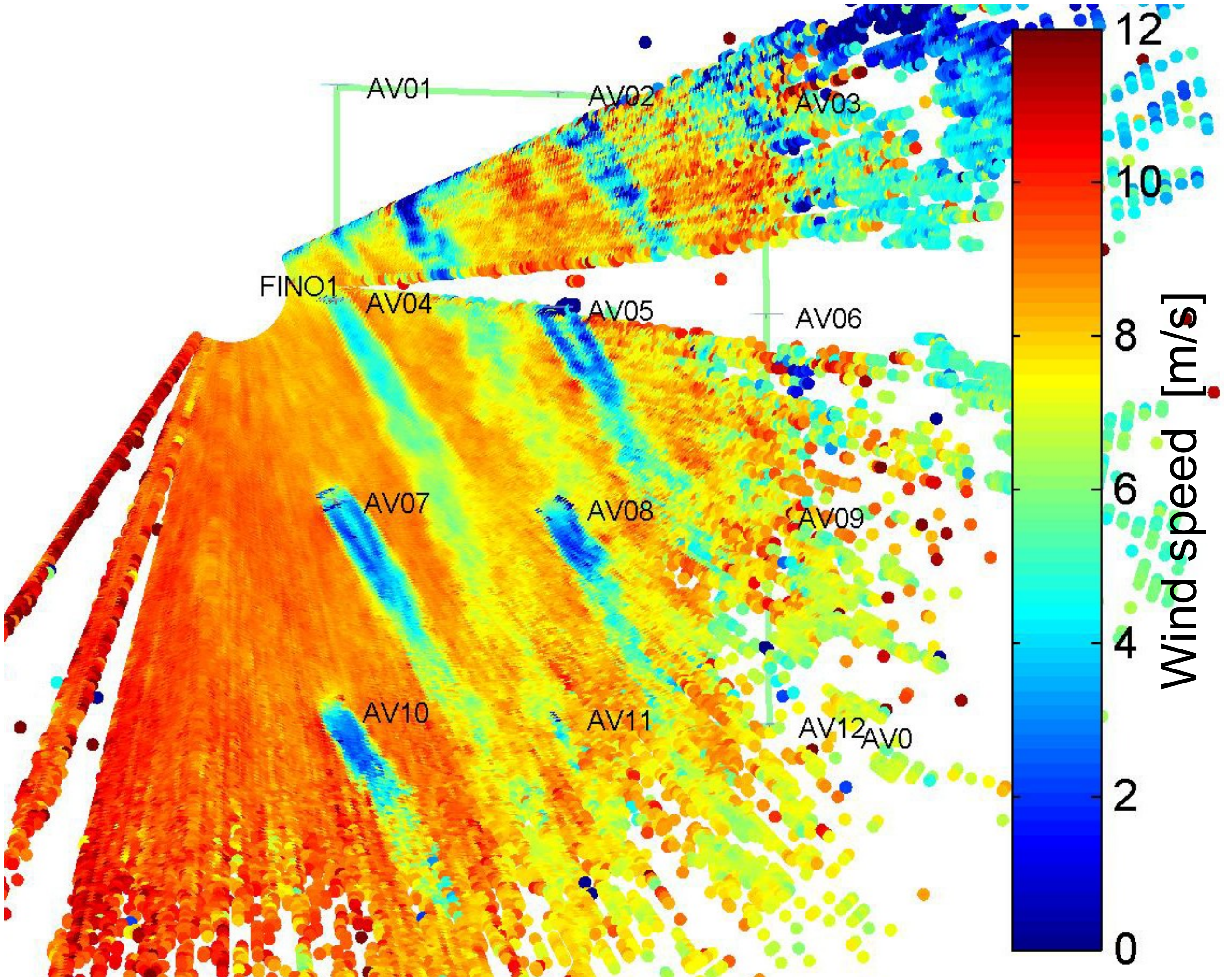
(10Min mean values)





Leo Jensen, ELSAM A/S

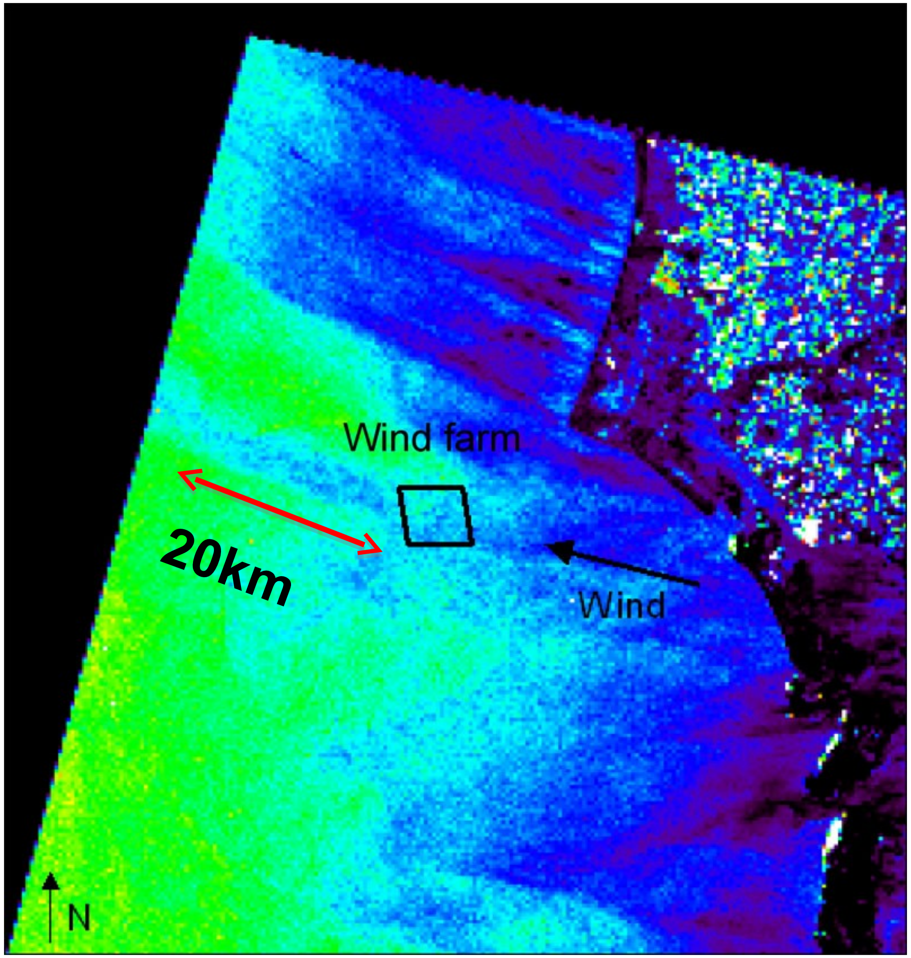
Lidar measurements at wind farm alpha ventus



Far wake of windfarms

- Satellite measurement at Horns Rev

- Reduction of wind speed still visible at 20km downstream

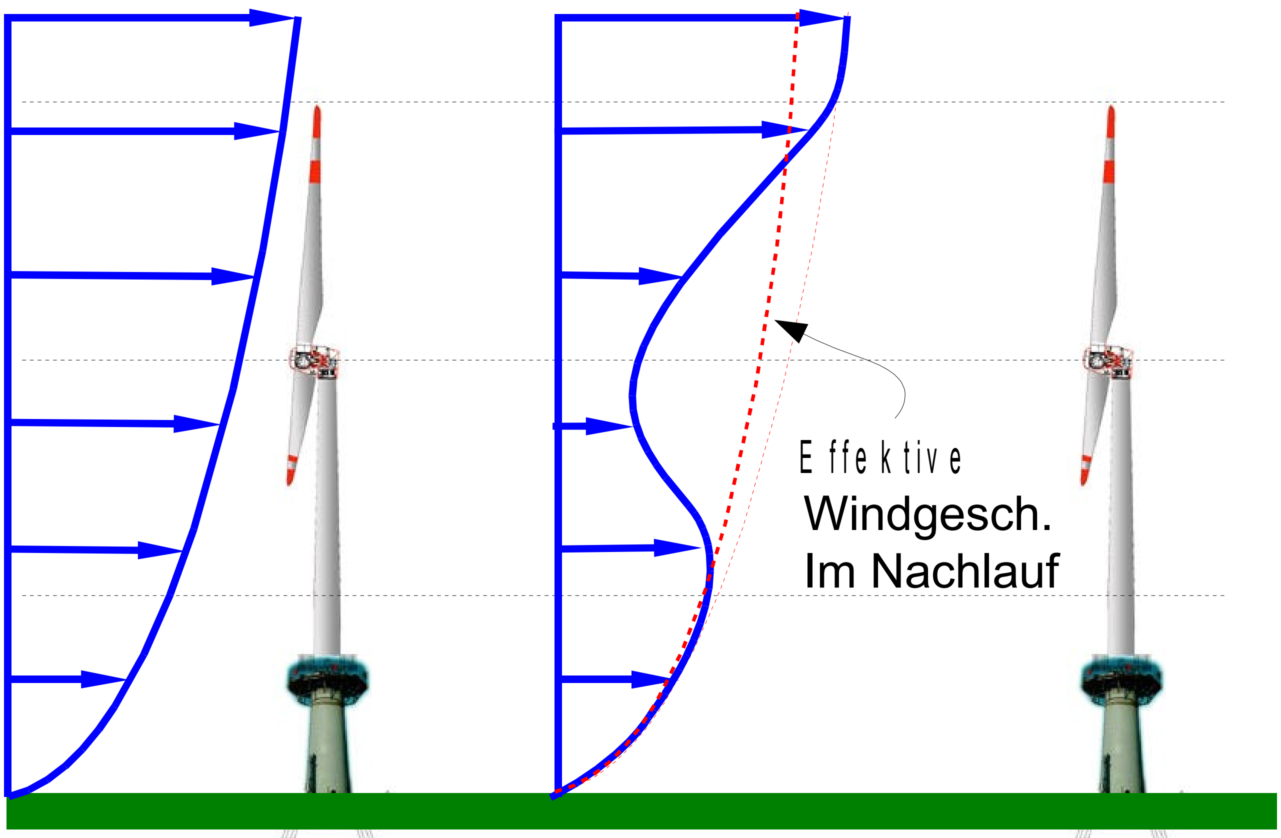


[ERS SAR / Risø]

Wake effects on wind turbines

Power in wake

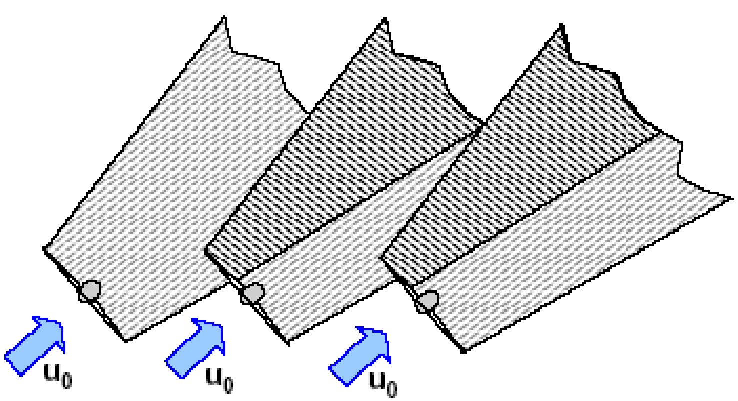
The estimation of the power in wake is typically based on the freestream **power curve** and an **effective wind speed**

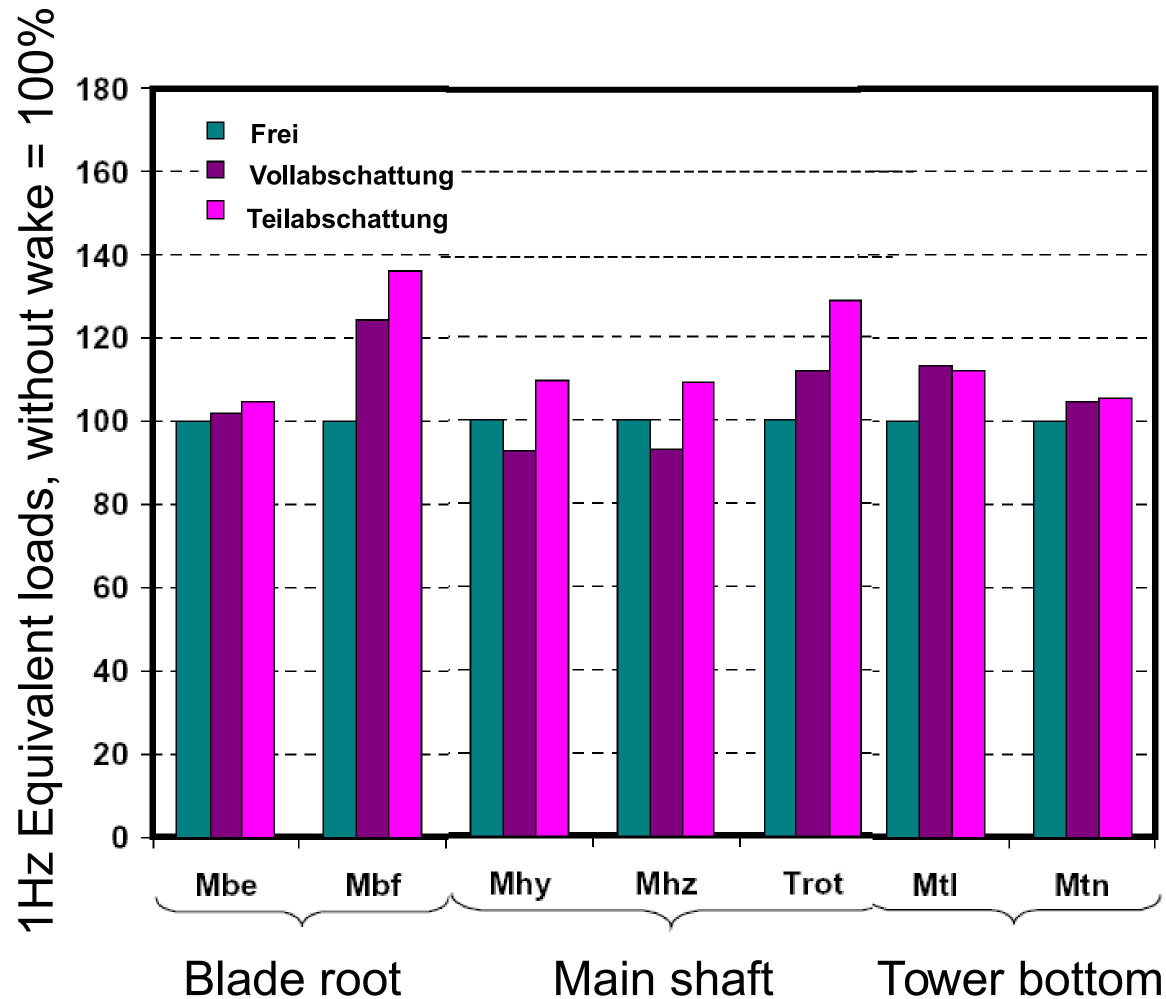


Wind farm effects on mechanical loads
Partial and full wake

Partial loading

- Inhomogeneous wind field
- Large changes in
  - Flap-wise bending moments
  - Bending and torsional moments of the main shaft
- Large mean and from of yaw and roll moments

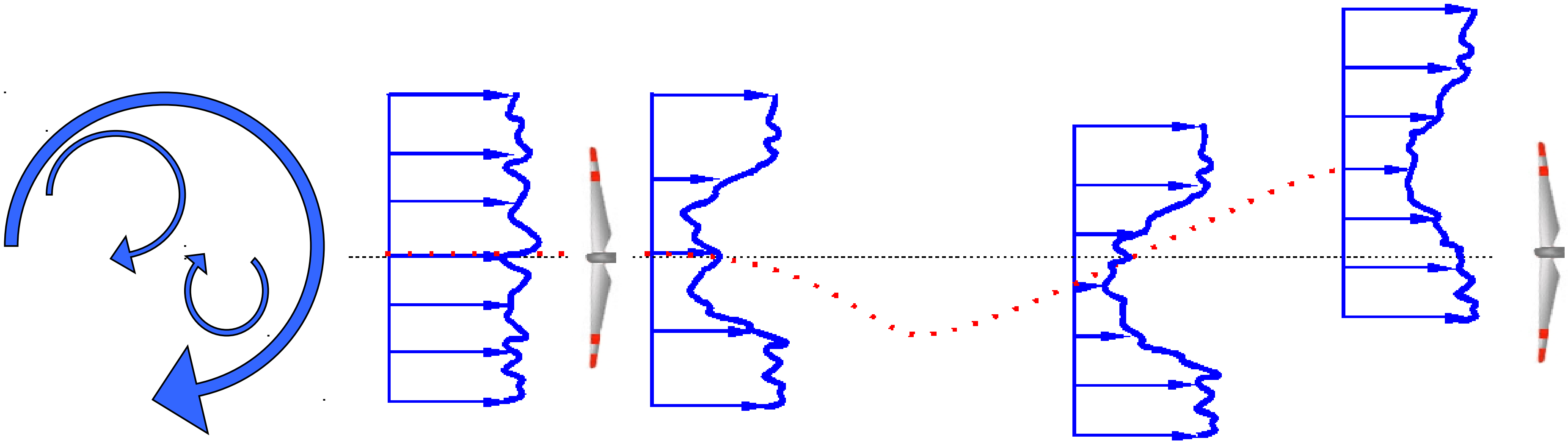




[DIBt]

Wakes are very dynamic …

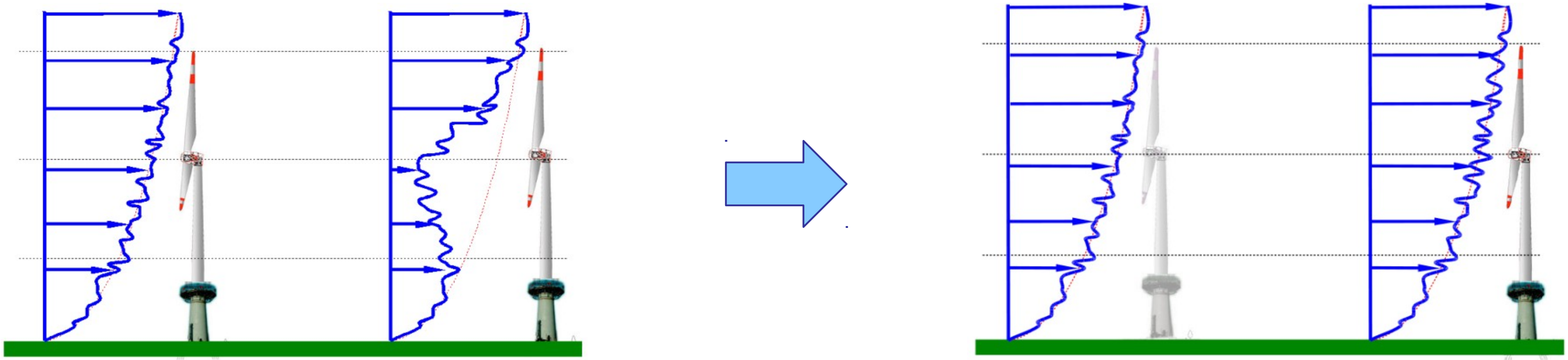
- **Wind speed and turbulence**
- **Meandering** large scale transversal movement



Present engineering models

IEC Standard recommendation

- Effective turbulence

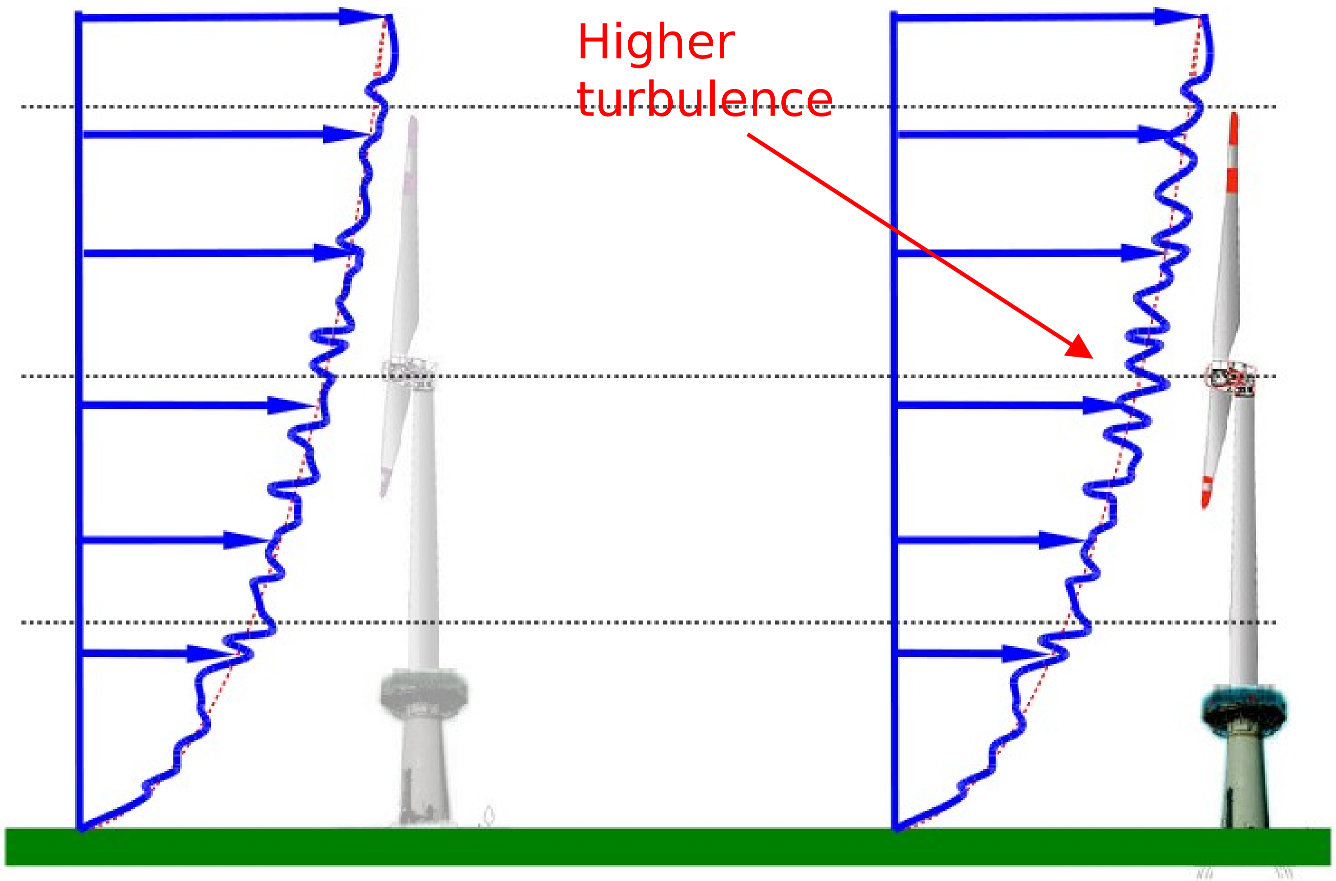


Simplified models

- Dynamic Wake Meandering (Larsen et al. DTU Wind Energy)
- Disk-Particle Model (Trujillo et al., Universität Oldenburg)

Estimation of fatigue loading in wake

Effective turbulence (Frandsen 2003) is a procedure recommended in the IEC 61400-1



Estimation of fatigue loading in wind
Effective turbulence from IEC 61400-1

- If separation of WEC´s is larger than 20 rotor diameters, wake effects are not important. (Empirical)
- If separation lower than 20 rotor diameters, consider this formula:

Prob. Wake Condition

Wöhler Curve Exponent

Separation in Rotors Diam. To neighbor WEC

$$I_{eff} = \left[(1 - N \cdot p_w) I_0^m + p_w \sum_{i=1}^{N} I_T^m(s_i) \right]^{1/m}$$

Effective TI

No. Neighboring WEC´s

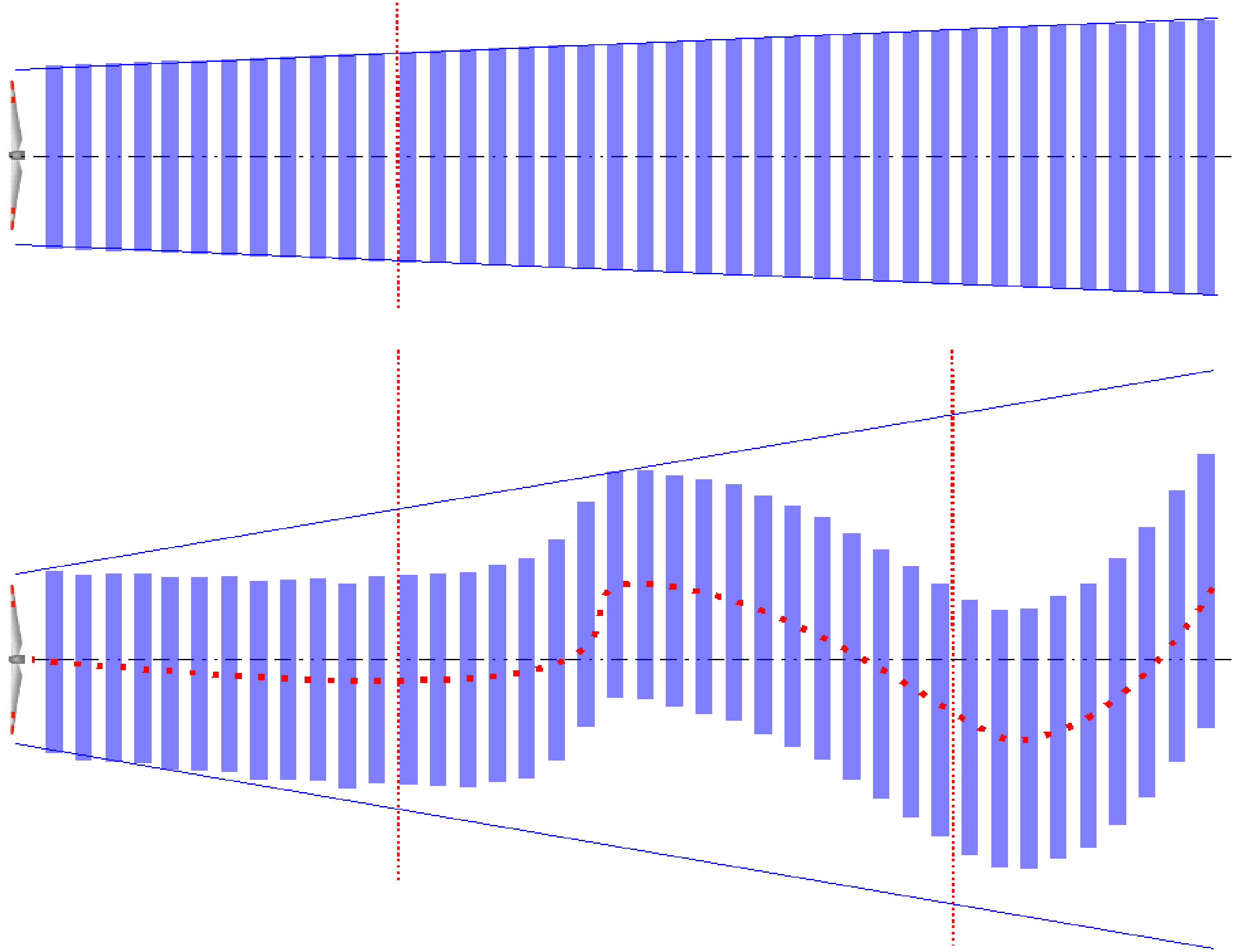
Mean TI

Total TI

Wake modelling as emitted passive disks

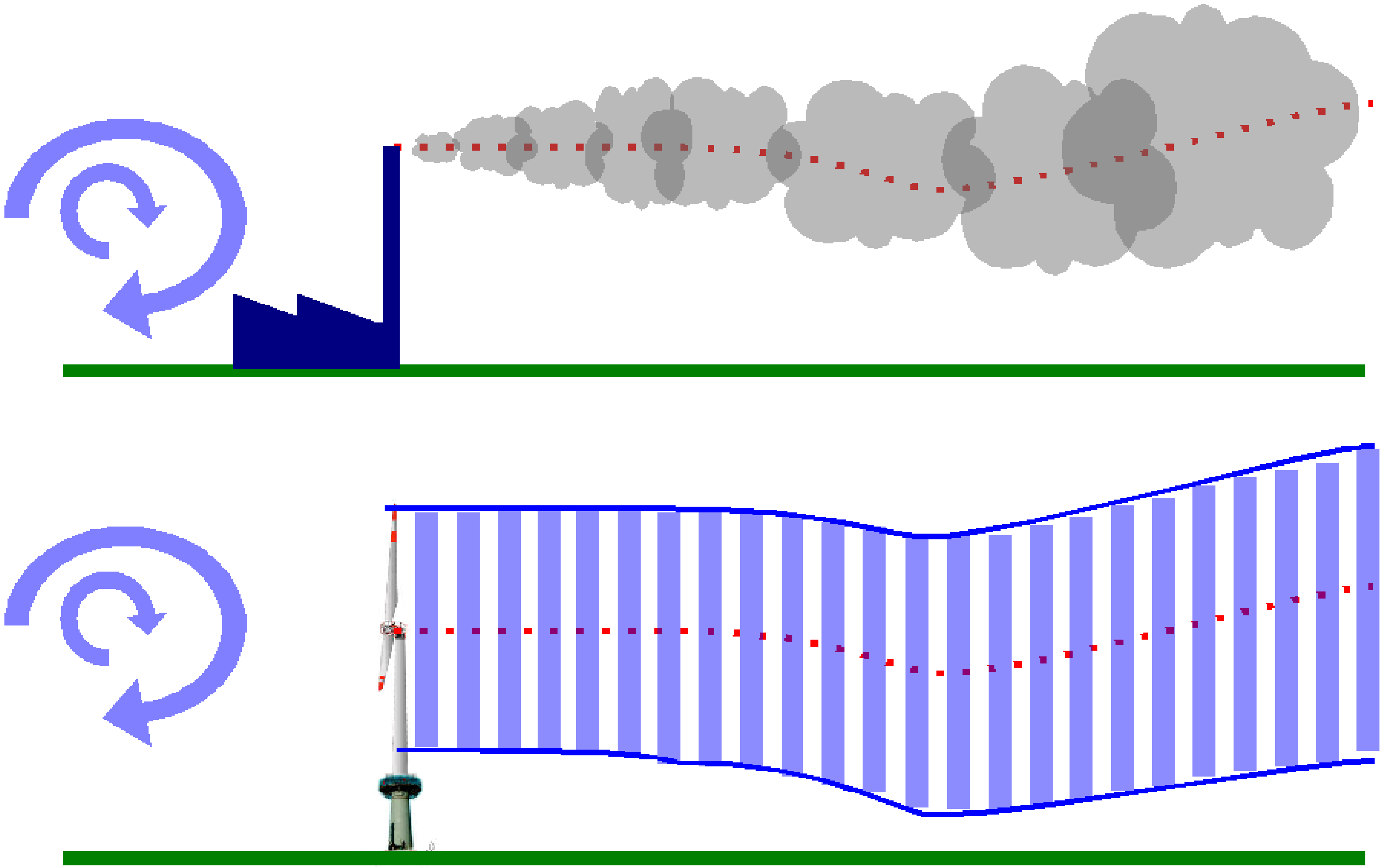
Steady wake
Without effect of large scale atmospheric turbulence

Meandering wake
Wake *meandering* driven by large scale turbulence in the atmosphere



Main assumption

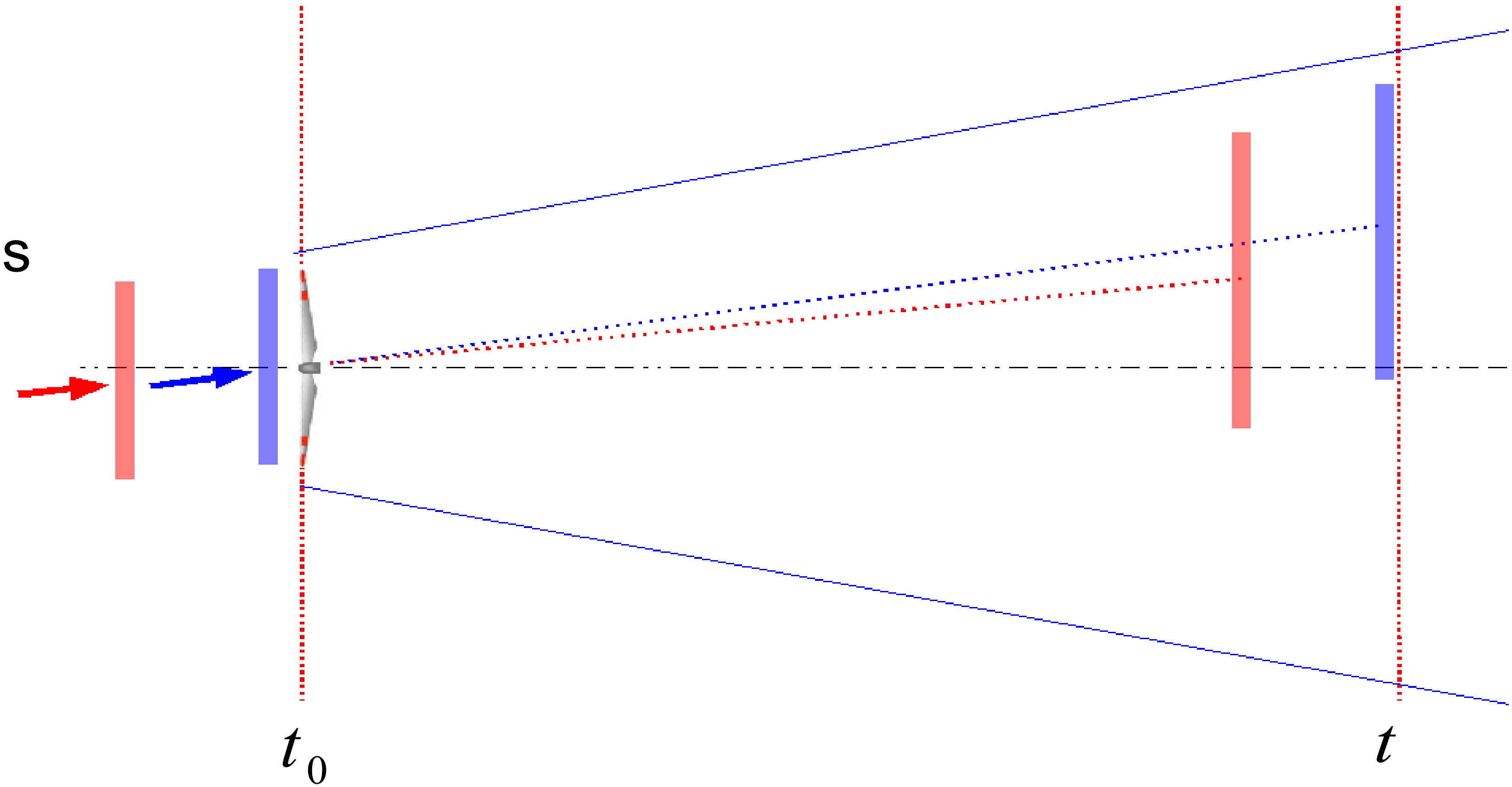
Wind turbine wake meanders similar to passive tracers



Simplified approach

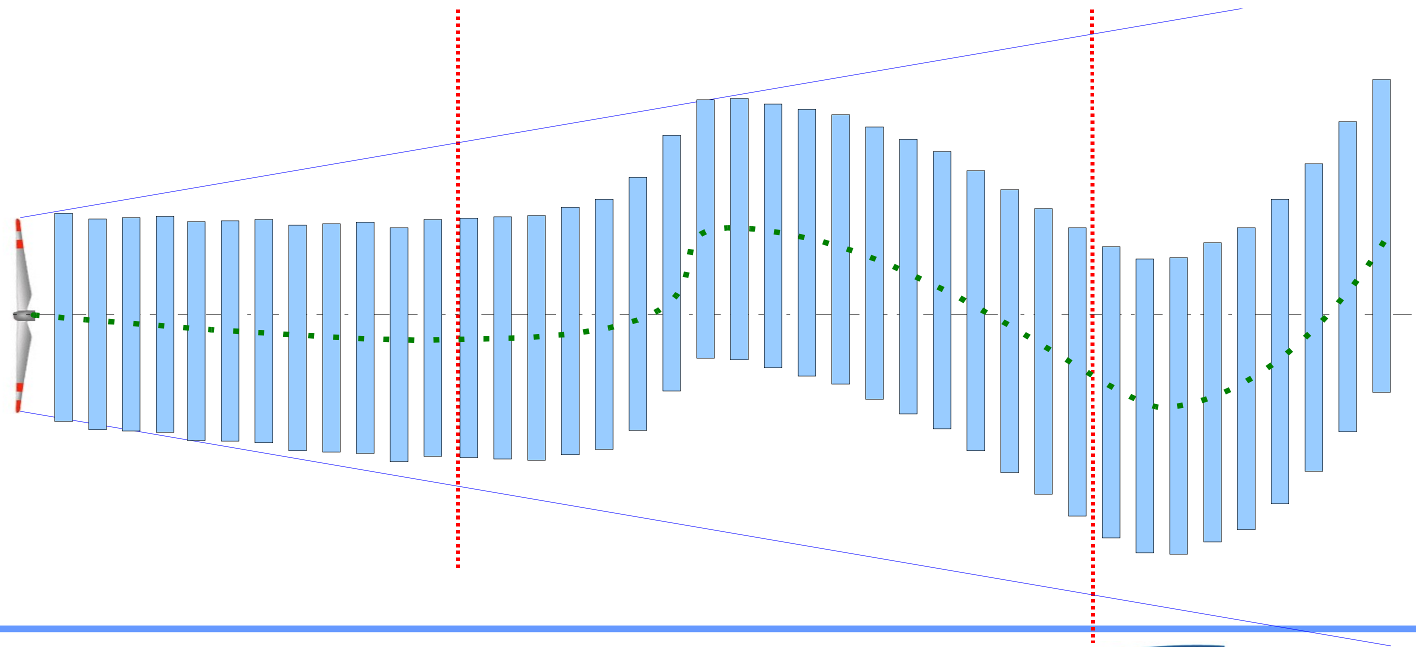
Constant passive disk advection

Low-pass filtered wind direction



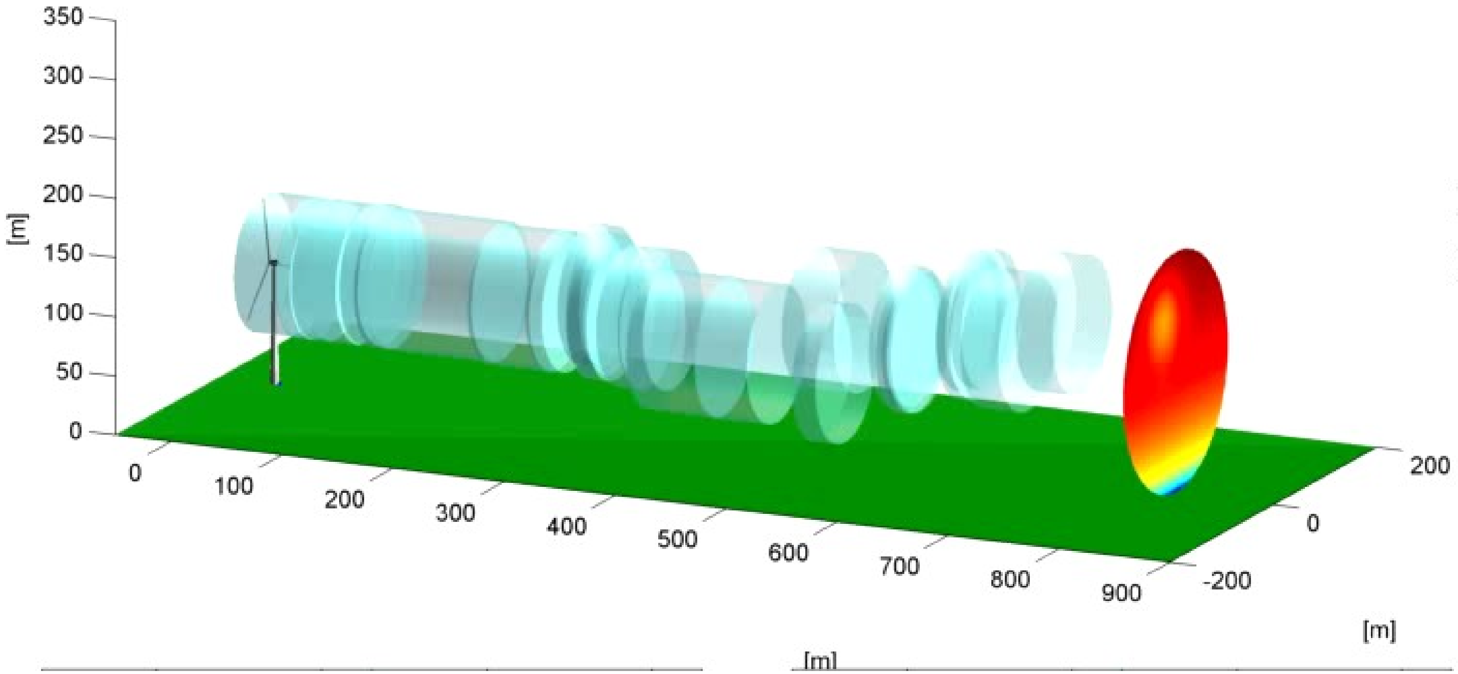
Dynamic Wake Meandering (DWM)

- Developed at DTU Wind Energy (Larsen et al.)
- Assumption of „passive“ wake advekcion
- Strutures greater than the rotor diameter are filtered out
- „Moving“ wake profile superimposed with a stochastic wind field
- Implementiert im GL-Bladed



Extended Disk-Particle Model (EDPM)

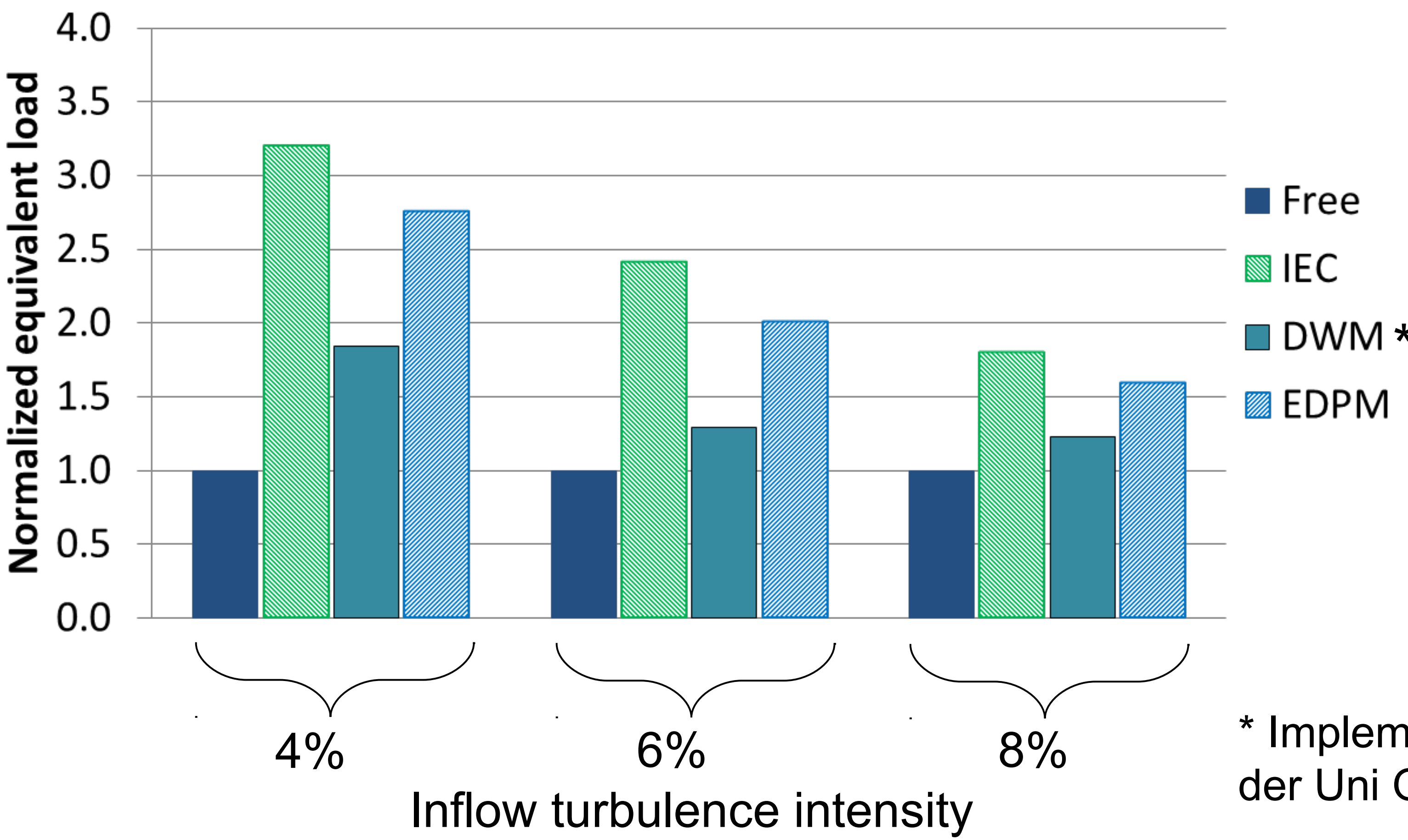
- Developed at Uni Oldenburg (Trujillo et al.)
- Assumption of „passive“ wake advection
- Enables inclusion of atmospheric convective conditions



Example of comparison of models

„Fore-aft“ tower bottom bending moment

NREL 5MW at 7 rotor diameters downstream and 7 m/s inflow



* Implementierung der Uni Oldenburg