Detection of Wake Impingement in Support of Wind Plant Control

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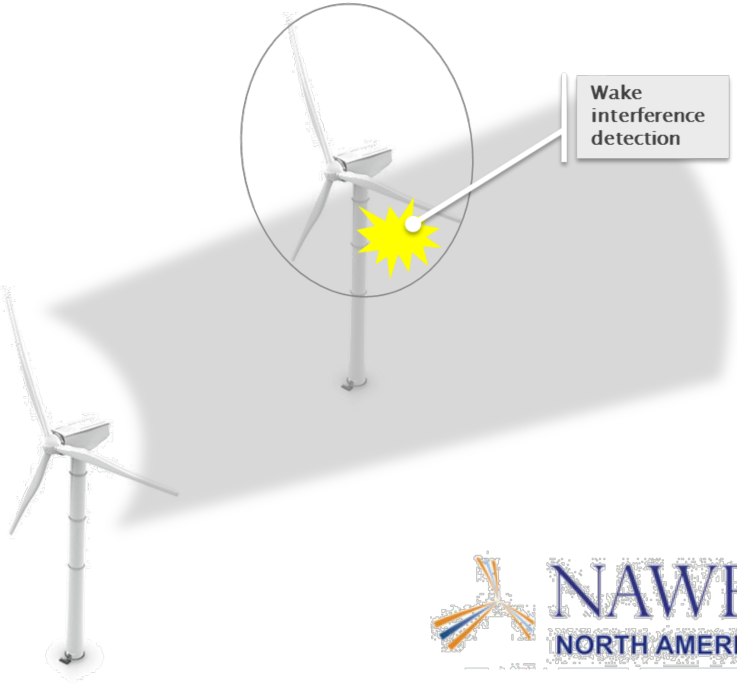

NAWEA
NORTH AMERICAN WIND ENERGY ACADEMY

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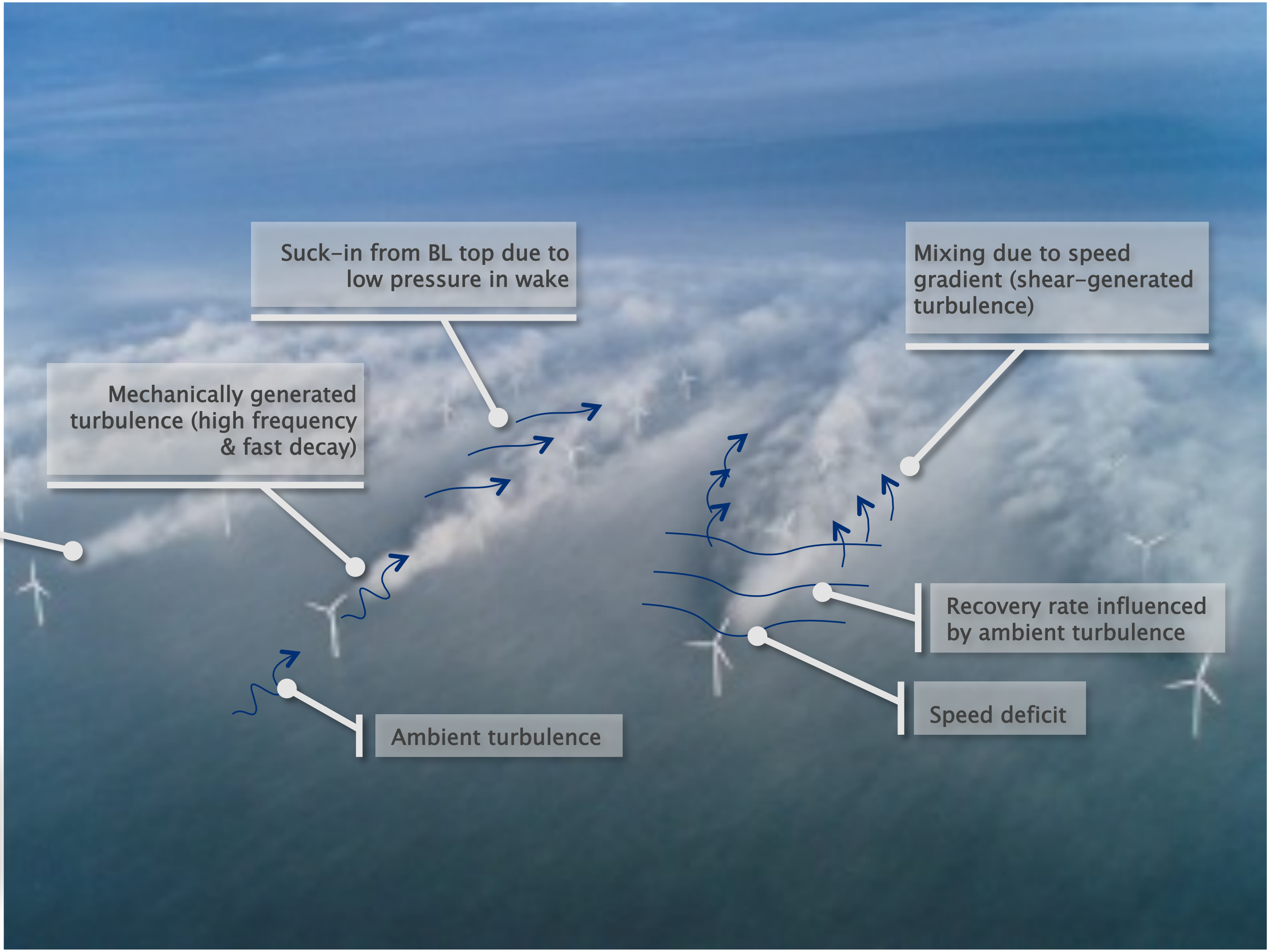
Flow Physics: Wakes and Turbulence



Suck-in from BL top due to low pressure in wake

Mixing due to speed gradient (shear-generated turbulence)

Mechanically generated turbulence (high frequency & fast decay)

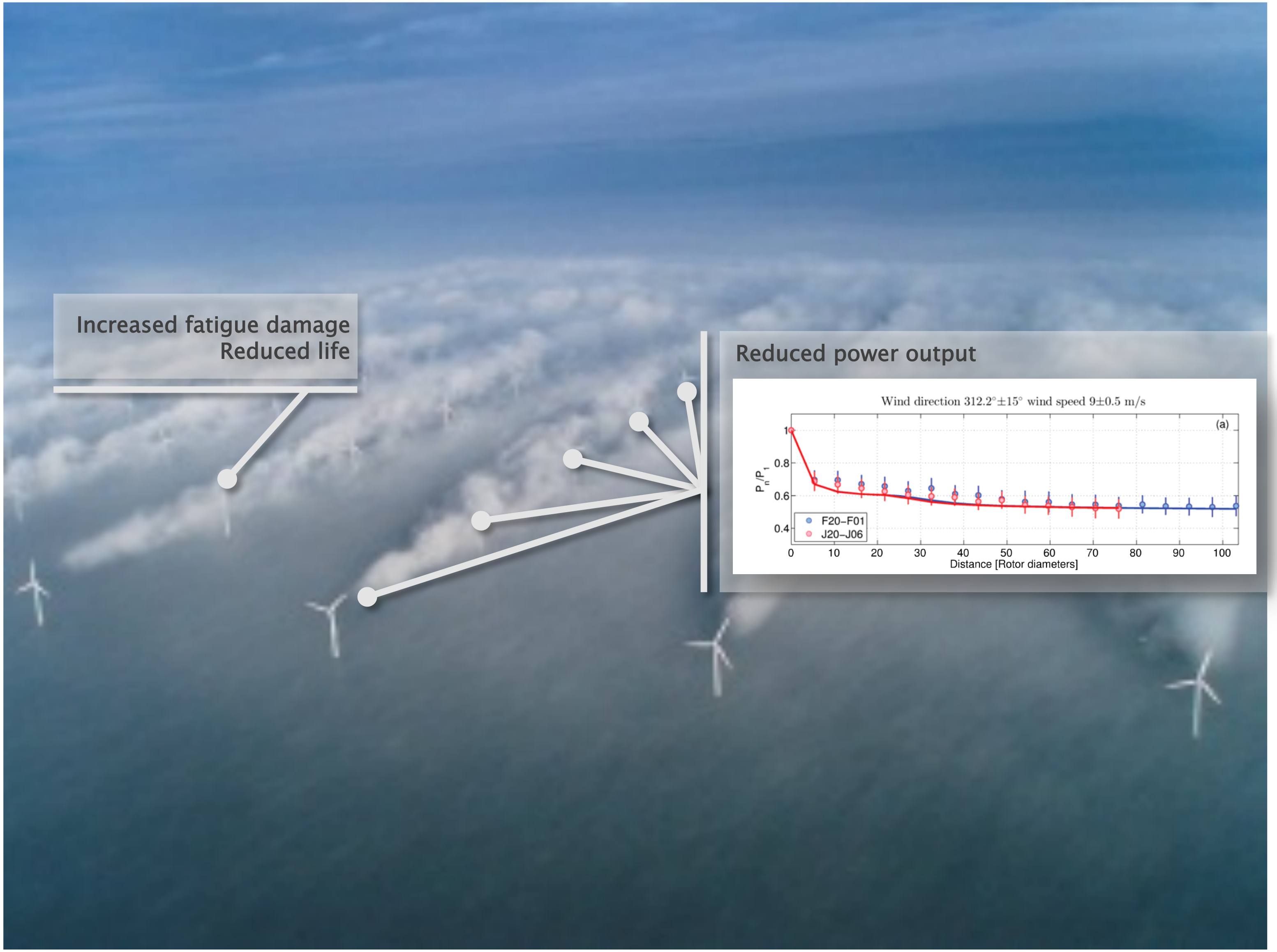
Recovery rate influenced by ambient turbulence

Speed deficit

Ambient turbulence

Vortex breakdown

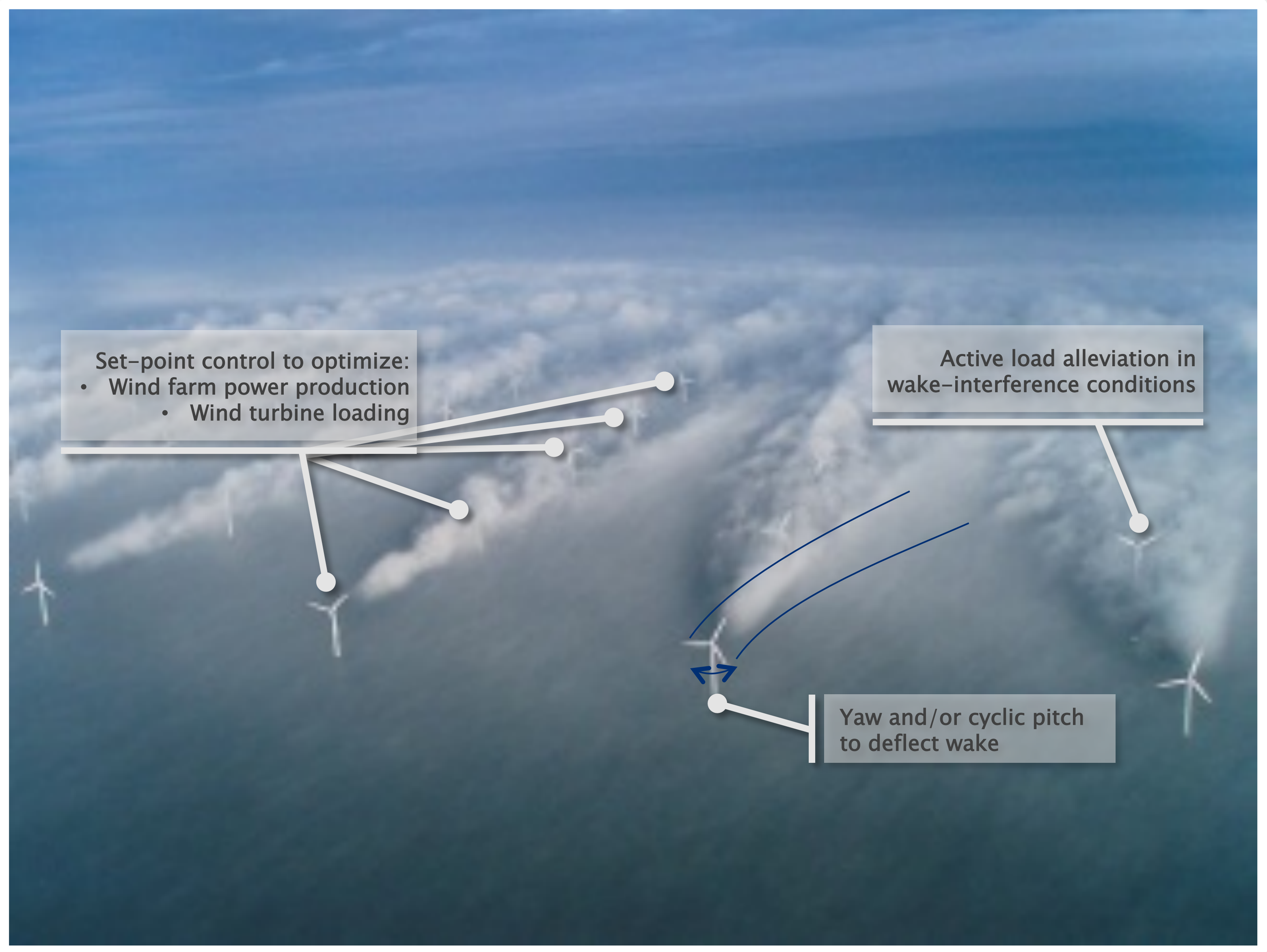
Wind Farm Effects



Increased fatigue damage
Reduced life

Reduced power output

Wind Farm Control



Set-point control to optimize:
- Wind farm power production
- Wind turbine loading

Active load alleviation in wake-interference conditions

Yaw and/or cyclic pitch to deflect wake

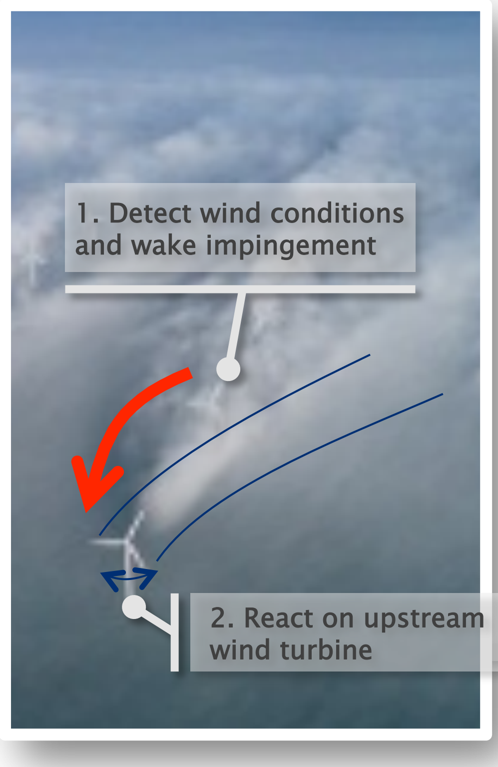
Wind Farm Control

Cooperative control of wind farms, a **vast and complex problem**:

- Understand/measure flow conditions
- Control algorithms:
  - Model based: accuracy/complexity of models?
  - Model free: convergence time?
  - Robustness in real operating conditions
  - …
- Testing and verification of performance

The **rotor as a wind sensor**:

1. Wake interference detection (**this presentation**) ▶
2. Reaction & wake redirection



Outline

- Local wind estimation from blade loads
- Field validation
- Wake impingement detection
- Simulation studies in waked and meandering conditions
- Conclusions and outlook

Wind Speed Estimation from Blade Loads

Out-of-plane bending (cone) coefficient:

$$C_m(\lambda_{RE},\beta,V_{RE})=\frac{1}{2\pi}\int_{\varphi=0}^{2\pi} m_i \,\mathrm{d}\varphi \Big/ \frac{1}{2}\rho A V_{RE}^2 R$$

Local effective wind speed:

$$V_{LE}(\psi)=\frac{1}{A_B(\psi)}\int_{A_B(\psi)} V \,\mathrm{d}A_B(\psi)$$

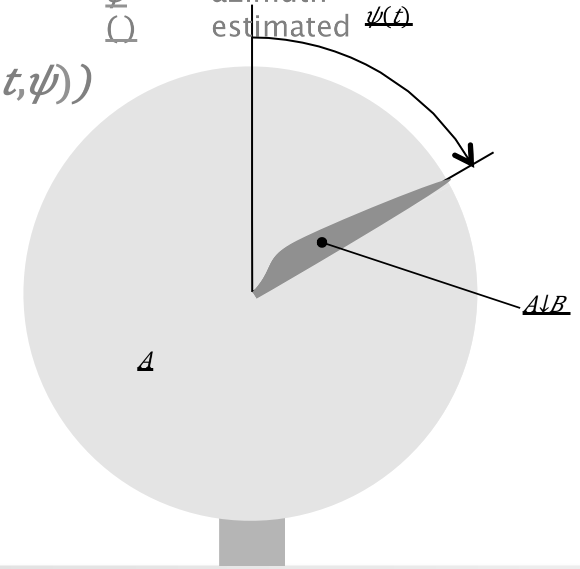
Local effective wind speed **estimation** from blade i:

$$m_i(t)=\frac{1}{2}\rho A V_{LE}^2(t,\psi) R C_m(\lambda_{LE}(t,\psi),\beta(t),V_{LE}(t,\psi))$$

(Refs. Bottasso et al. 2009-2010)

Nomenclature:

λ_{RE}	rotor eff. tip speed ratio
m_i	out of plane bending moment of blade *i*
V_{RE}	rotor eff. wind speed
V_{LE}	local eff. wind speed
V_{SE}	sector eff. wind speed
ρ	air density
A	area of wind turbine
A_B	area of rotor blade
A_S	area of sector
t	time
ψ	azimuth
$\hat{(\ )}$	estimated



Sector Effective Wind Speed Estimation

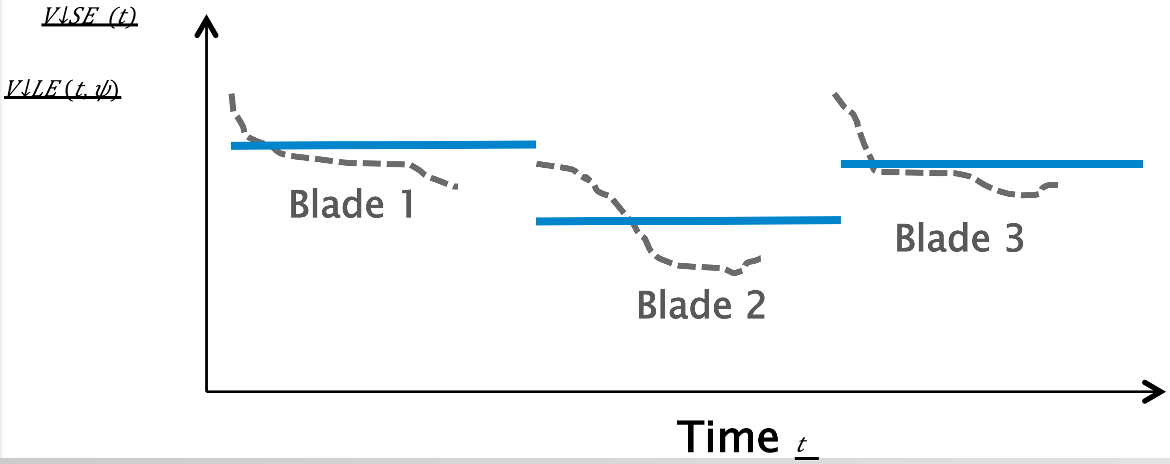
Nomenclature:	
λ_{RE}	rotor eff. tip speed ratio
m_i	out of plane bending moment of blade i
V_{RE}	rotor eff. wind speed
V_{LE}	local eff. wind speed
V_{SE}	sector eff. wind speed
ρ	air density
A	area of wind turbine
A_B	area of rotor blade
A_S	area of sector
t	time
ψ	azimuth
$\hat{( )}$	estimated

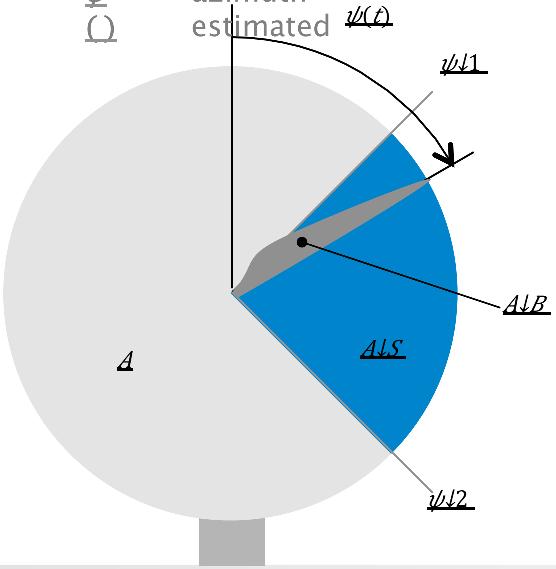
Sector effective wind speed (SEWS):

$$V_{SE}(\psi)=\frac{1}{A_S}\int_{A_S} V\,\mathrm{d}A_S$$

Calculate $\hat{V}_{SE}(t)$ after a blade leaves a sector:

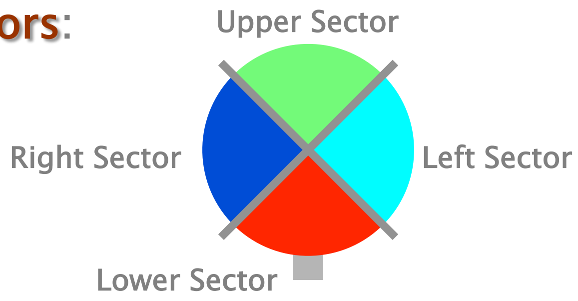
$$\hat{V}_{SE}(t)=\frac{1}{A_S}\int_{A_S}\hat{V}_{LE}(t,\psi)\,\mathrm{d}A_S$$





Simulation Results (3MW HAWT)

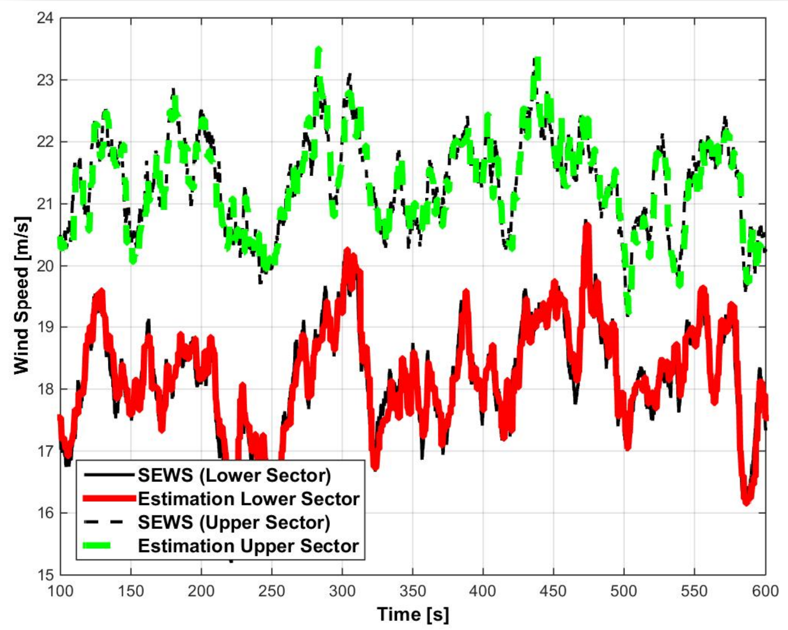
Define **four sectors**:



Wind turbine:
Rated power: 3 MW
Rotor radius: 47 m
Hub height: 80 m

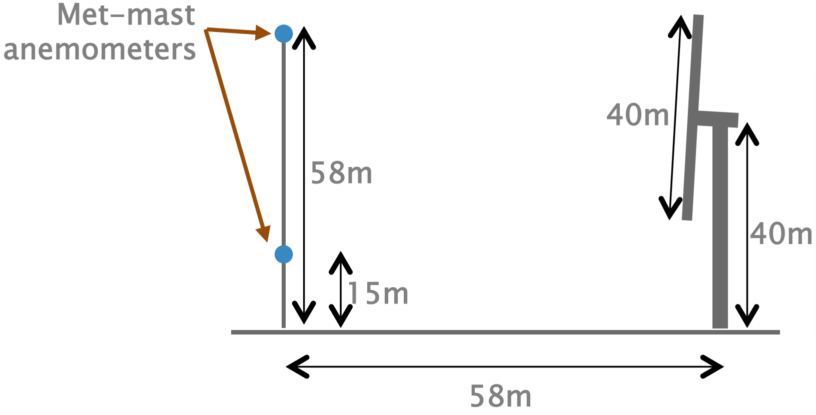
Simulation results:

Shear (α=0.2),
Turbulence (5%)



Field Data (CART 3)

Setup:

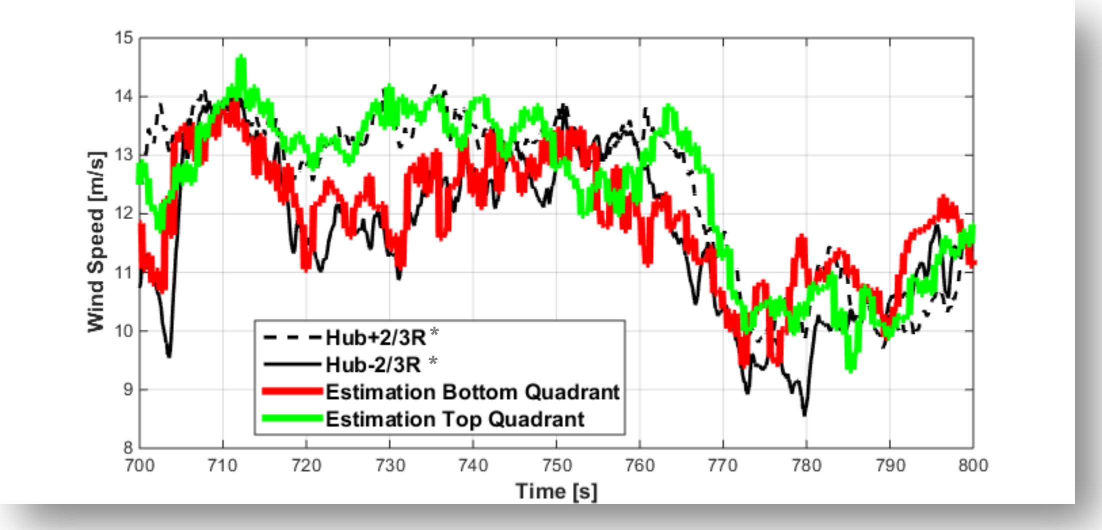



https://maps.google.com/maps?q=39.909045,-105.222741

Met-mast


Photo: Fleming et al., 2011

Field test results:



Wind turbine:
NREL Controls Advanced Research Turbine CART 3
3-bladed
Rated power: 600kW
Rotor radius: 20 m
Hub height: 40 m

*) Met-mast anemometer interpolation assuming linear shear

Rotor Effective Wind Speed Estimation

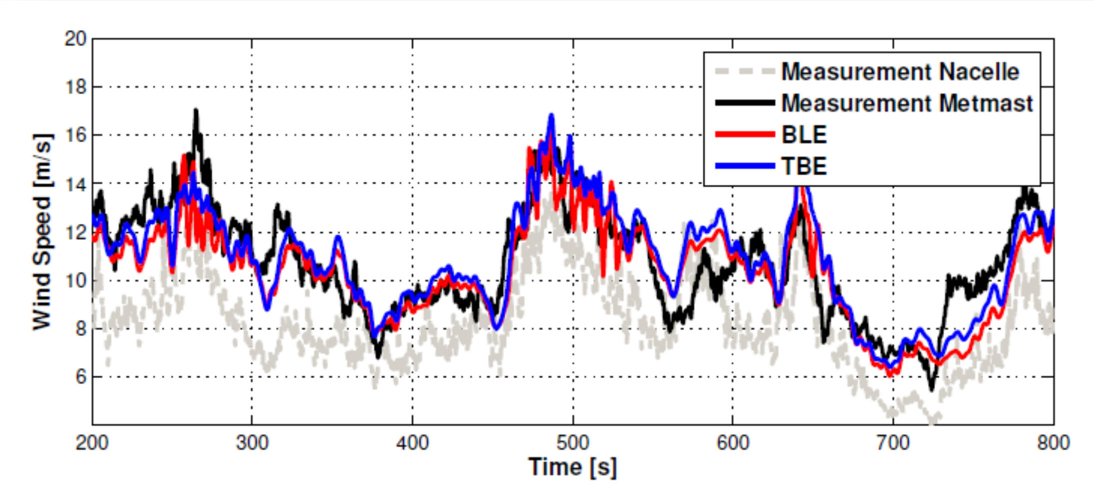
Rotor effective wind speed:

$$V_{RE} = \frac{1}{A}\int_{A} V \, \mathrm{d}A$$

Rotor effective wind speed **estimation** from all blades:

$$\frac{\sum_{i=1}^{B} m_i(t)}{B} = \frac{1}{2}\rho A V_{RE}^{2}(t,\psi) R C_m(\lambda_{RE}(t,\psi),\beta(t),V_{RE}(t,\psi))$$

Field test results:



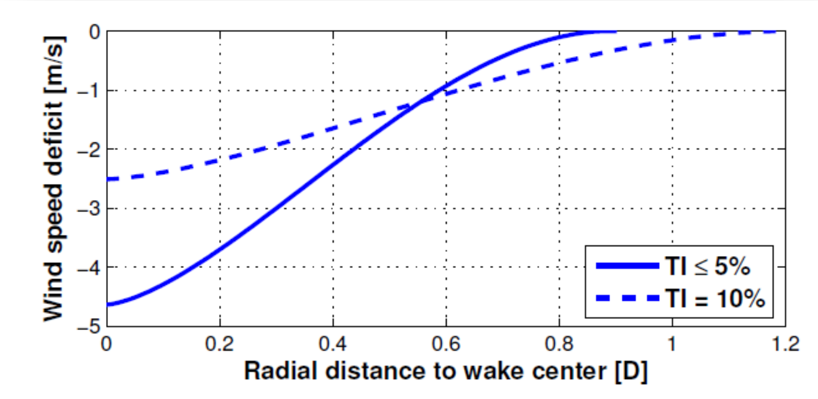
Wake Modeling

Superposition of **Mann's turbulent wind** field with **Larsen wake model**

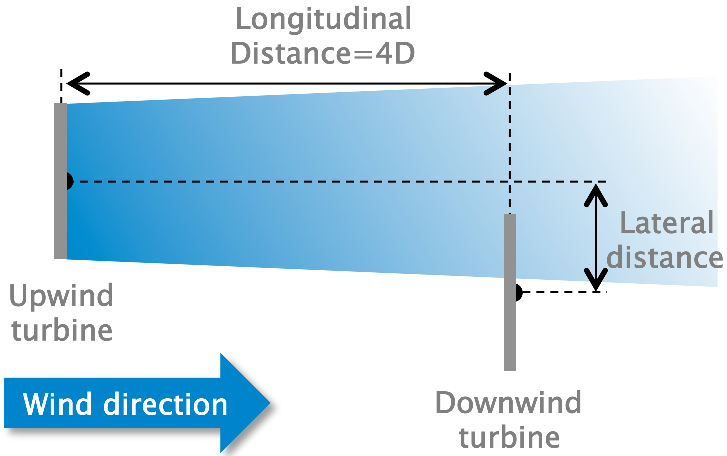
Larsen wake model (1st order appr.):

- Deterministic
- Prandtl's mixing length theory
- Stationary, axisymmetric
- Parameters (C_{thrust}, V, turbulence, geometry)

Wind speed deficit for ambient wind speed of 8m/s and 4D longitudinal distance:



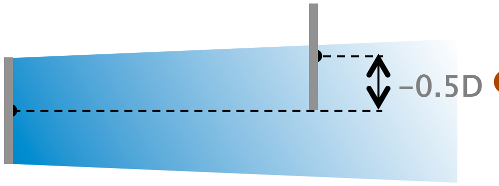
Wind farm layout:



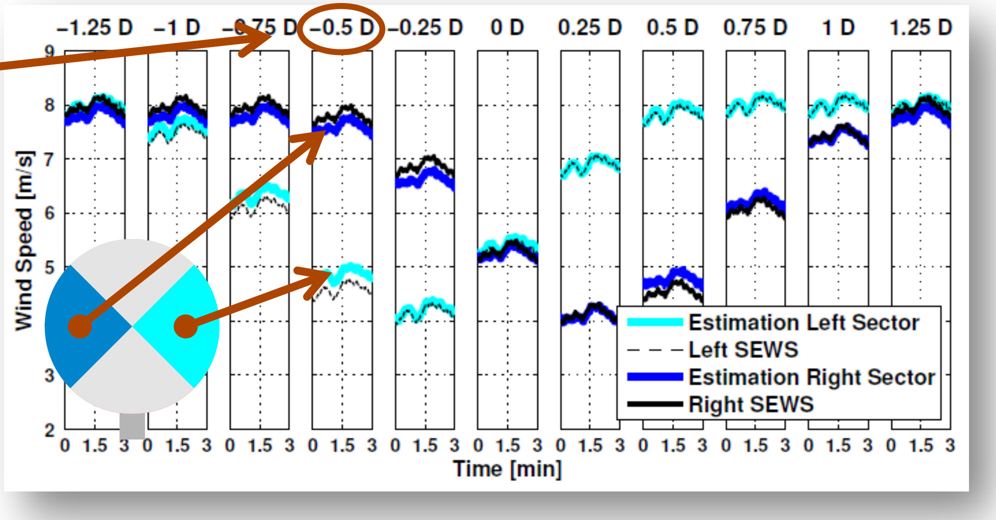
Wind turbines:

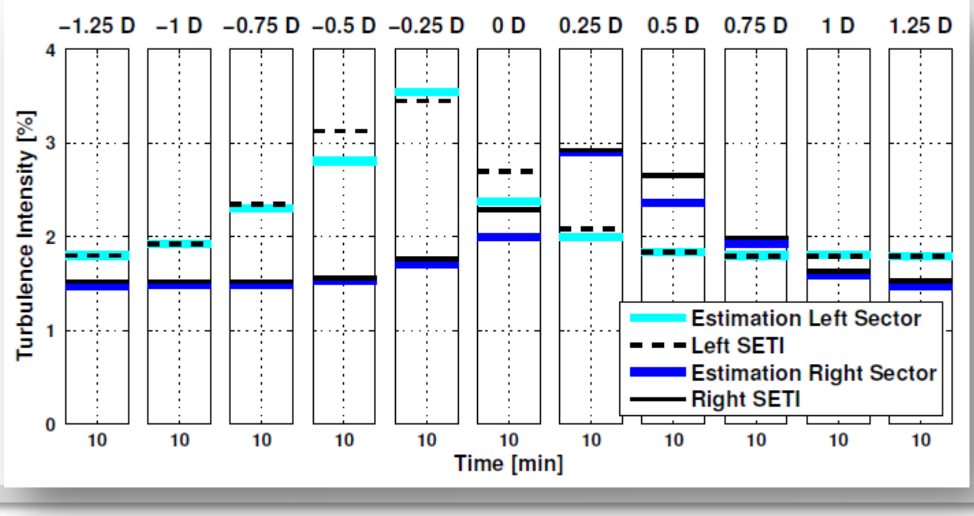
Rated power:	3 MW
Rotor radius:	47 m
Hub height:	80 m

Simulation Results in Wake Interference



Each subplot represents a different wake overlap indicated by the **lateral distance** between rotor and wake center ▶





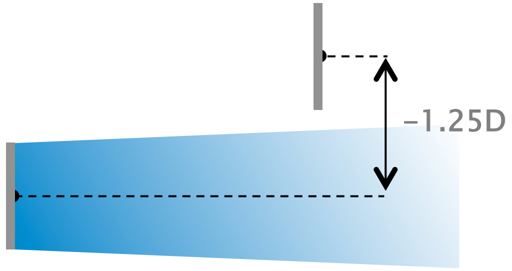
The estimator can also detect an **increase in turbulence** intensity ▶

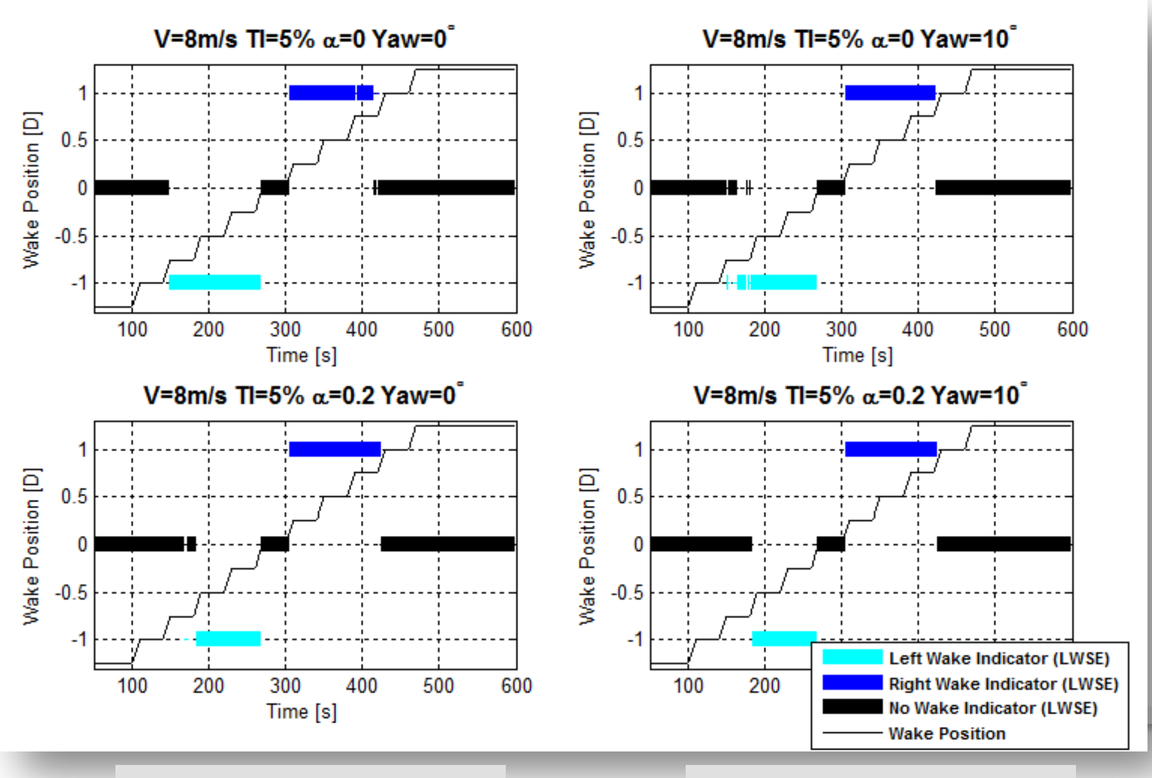
Wake Impingement Detection Based on SEWS

Wake detection criteria:

Left wake: $V_{SE,left} - V_{SE,right} / V_{RE} < threshold + offset$

Right wake: $V_{SE,left} - V_{SE,right} / V_{RE} > -threshold + offset$





Shear exp. = 0.0

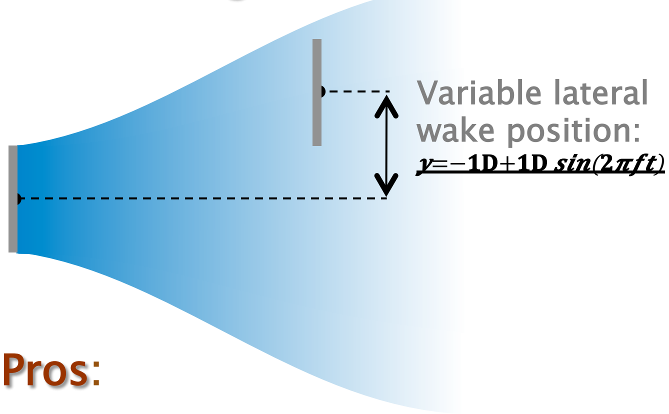
Shear exp. = 0.2

Yaw Misalignment = 0°

Yaw Misalignment = 10°

Wake Impingement Detection Based on SEWS

Meandering wake between far out-of-wake and full-waked conditions:



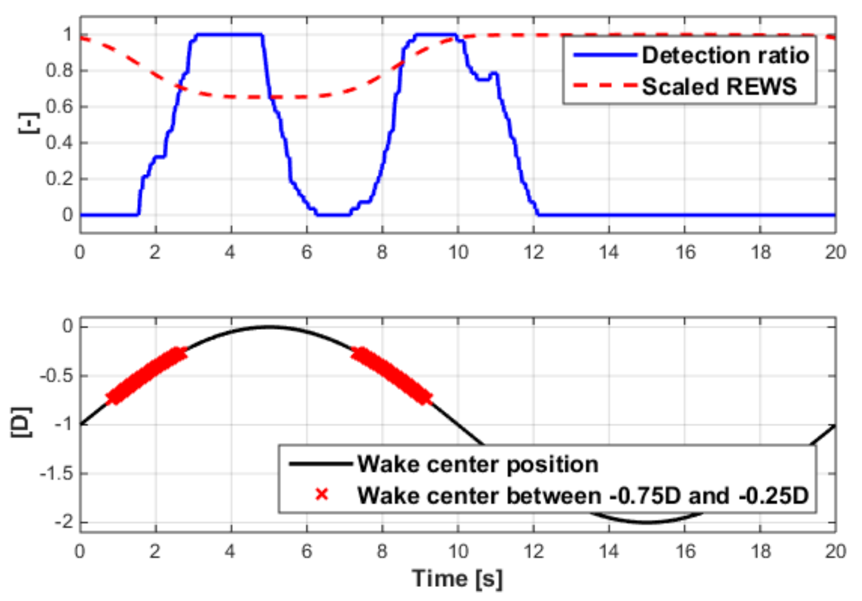
Variable lateral wake position: $y = -1D + 1D\ sin(2\pi f t)$

Pros:

- Simple, robust (in simulation)
- Small delay of 2 sec (~1/3 of a rotor rev.)

Cons:

- Unable to estimate lateral distance to wake center
- Detection of full-wake requires wind direction wrt farm layout



▲ Frequency f=0.05Hz, shear (α=0.1), turbulence (5%), 28 oscillations

Remark: possible effect of wake model on results

Conclusions

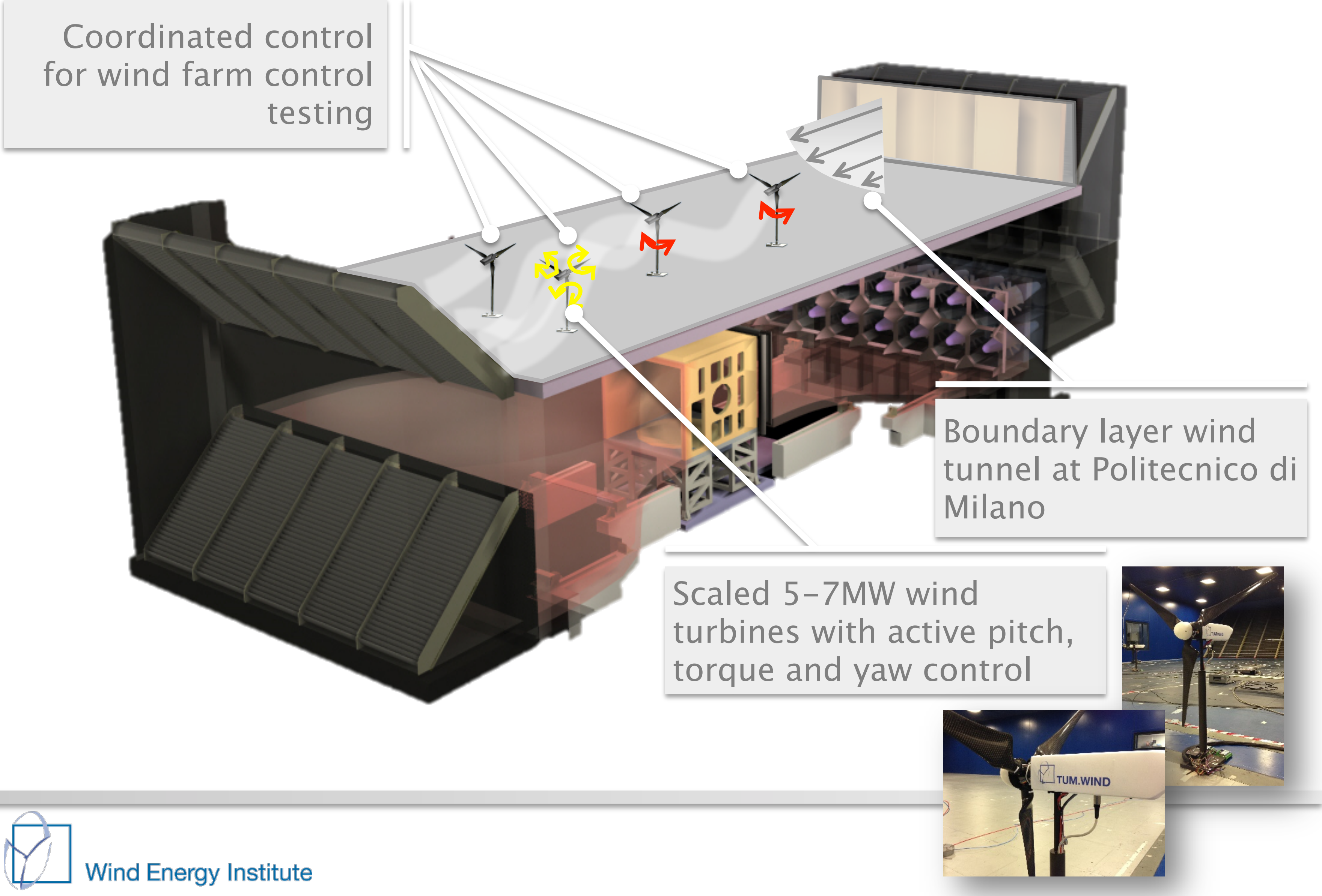
Local wind speed estimation from rotor loads:

- Simple and free (if load sensors are available)
- Concept validated in the field with CART3
- Wake impingement: very promising results in simulation, can also handle dynamically meandering wakes

Outlook:

- Validation using TUM scaled wind farm facility

TUM Scaled Wind Farm Facility

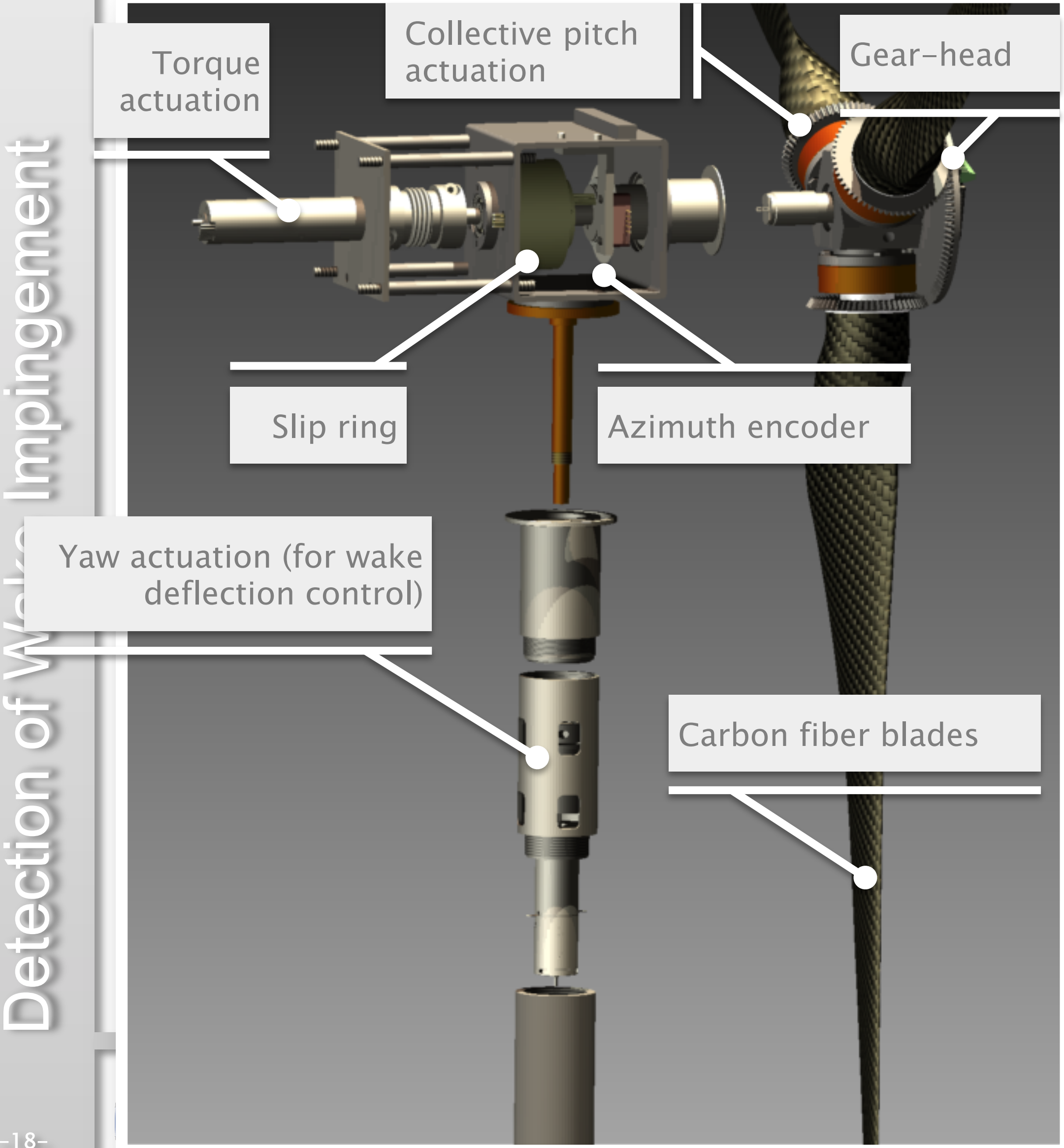


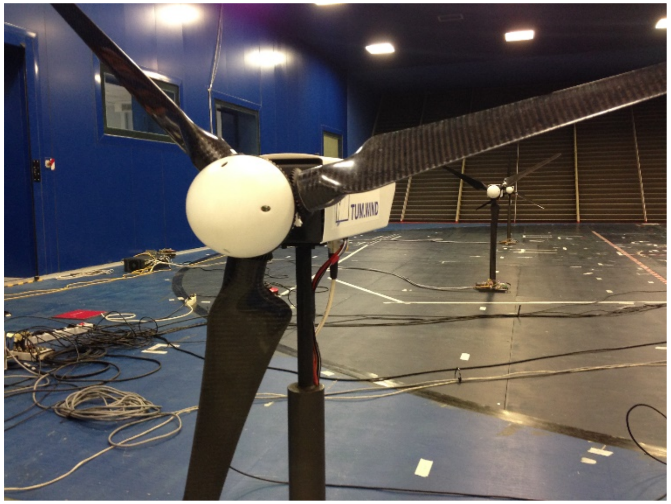
Coordinated control for wind farm control testing

Boundary layer wind tunnel at Politecnico di Milano

Scaled 5-7MW wind turbines with active pitch, torque and yaw control

Scaled Wind Turbine Models





Outlook

- A comprehensive set of experiments is planned for 2015-16
  - Wake detection
  - Wake redirection by active yawing and IPC
  - Induction control
  - Load mitigation in wake interference conditions
  - …
- Supporting LES simulations using NREL's SOWFA

Check back soon …

Thank you for your attention and…

TORQUE 2016

Munich, Germany, 5-7 October 2016

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