SUPERGEN Wind
2011 General Assembly

Wind tunnel simulations of wind turbine wakes

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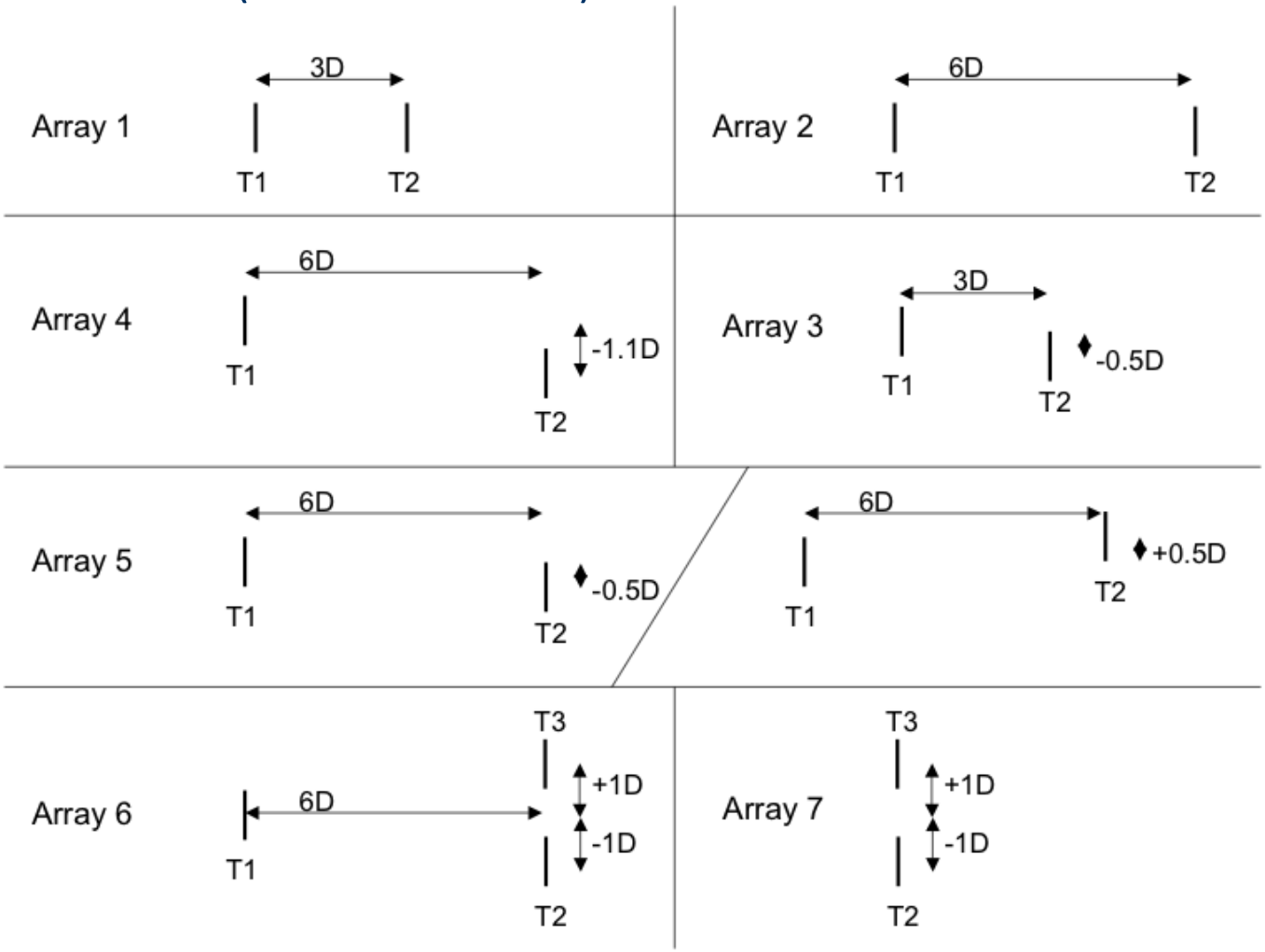
20th March 2011, Durham University

Supergen 1, in outline:

- **Set up wind tunnel simulations**
  - physics of wakes; test-case data sets
  - **suitable model wind turbines (5MW, 1:300 scale)**
  - **atmospheric boundary layer (ABL) simulations**
    - **on-shore rural, off-shore** - both neutral
    - **off-shore - stable stratification**
- **Wake development investigations**
  - baseline single wakes - on-shore, off-shore
  - wake interactions (7 cases)
  - database data (> 180 profile-sets of data + number of full planes)
  - turbines in forested regions

Wake interactions (2 turbines so far)

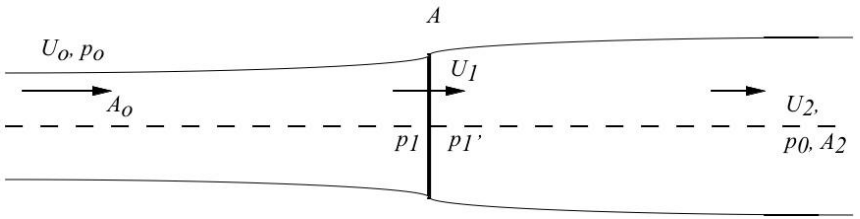


Supergen 2, in outline (key points):

- **wind tunnel investigations**
  - more comprehensive test cases (but selective!)
    - **multiple-machine arrays**
    - **unstable ABL cases, stable ABL cases**
  - effect of a turbine on the impinging-flow, especially the turbulence, how it is changed by the turbine and how it affects wake development
  - test-case database
- **wake modelling**
  - physical models - simple and 'high level'

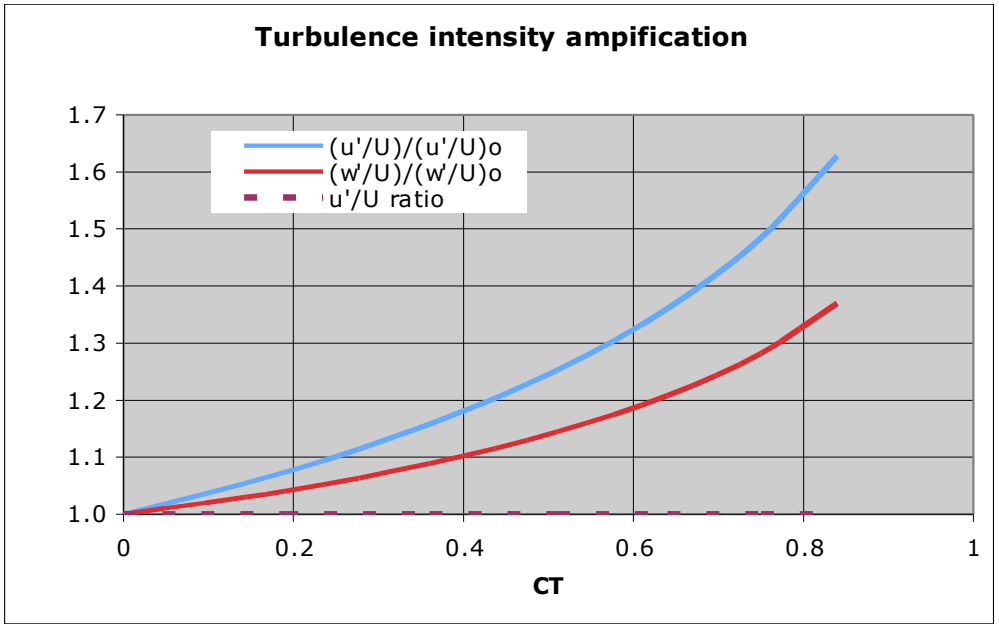
Effects on upstream flow and turbulence

Deceleration and streamline divergence causes
u'/U, *v'/U* and *w'/U* to increase.



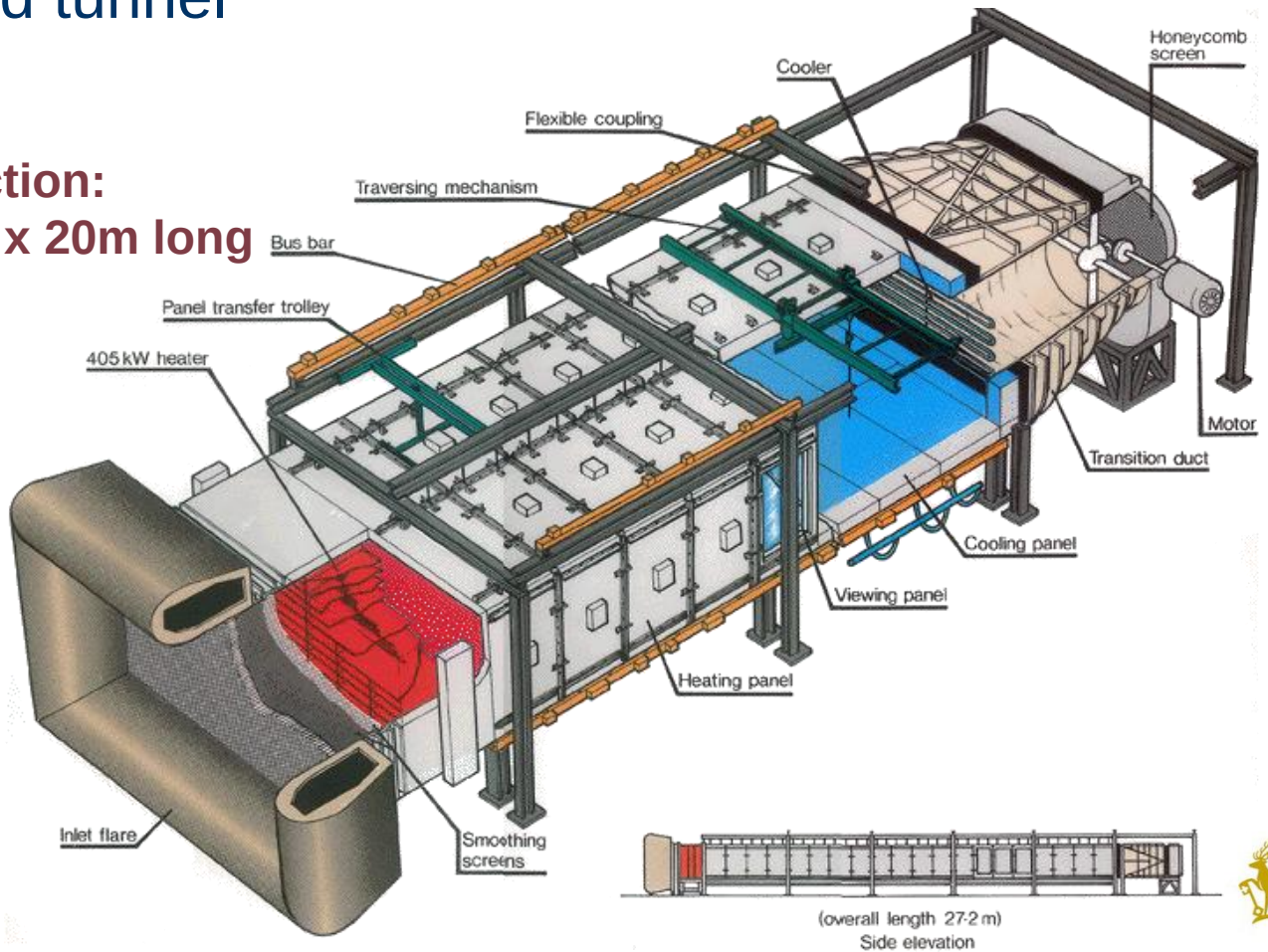
Implications for
i) blade loading,
ii) development of turbine wake

Effect will depend on upstream turbulence characteristics - ABL or upstream wake



Simulation of the atmospheric boundary layer - the EnFlo wind tunnel

Working section:
3.5m x 1.5m x 20m long



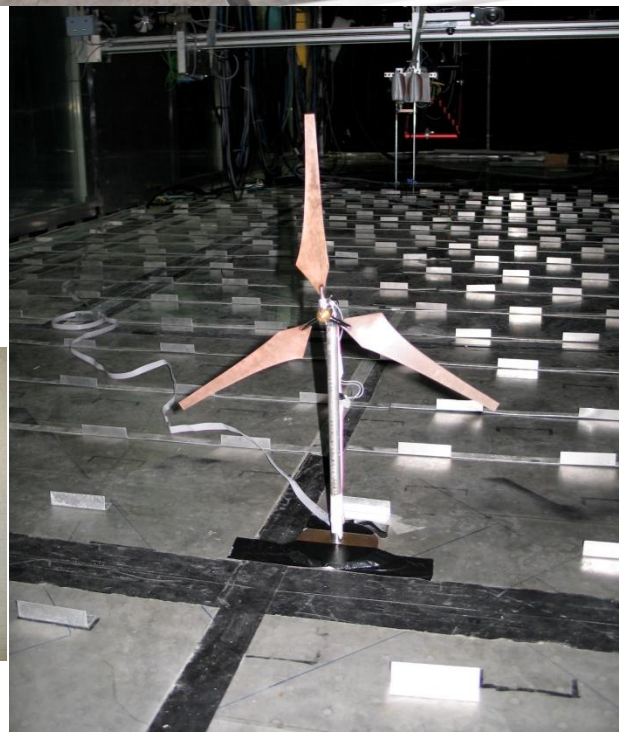
ABLs off- and on-shore

Rotor diameter$_{model}$ = 416mm (1:300)

Scaling: require special blades
that don't look 'normal'.

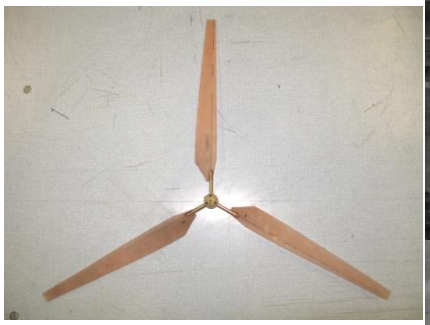
Design TSR = 6

Blade B2



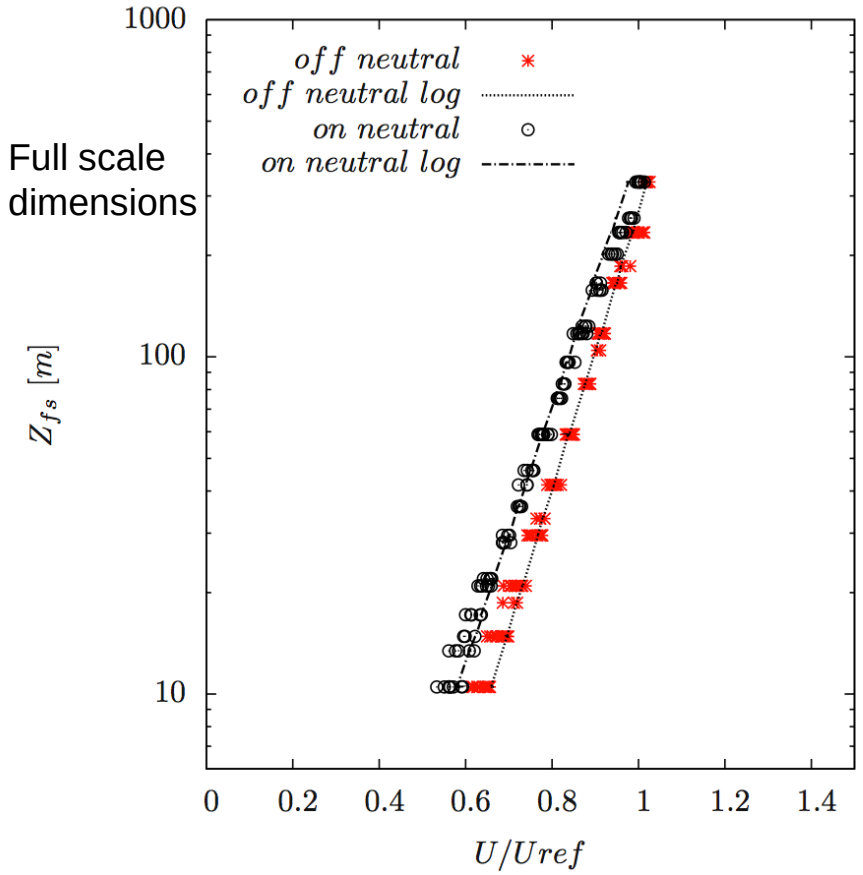
Instrumentation:
2-component Laser-Doppler Anemometry:
mono PIV;
hot-wire anemometry;
heat flux measurement for stratified flows,
phase locked capability, etc..

Blade B1



Neutrally-stable cases:

(off shore and rural onshore)



Full scale dimensions

Velocity profile -

the “logarithmic law of the wall” (log law):

characterised by

a velocity scale, the friction velocity

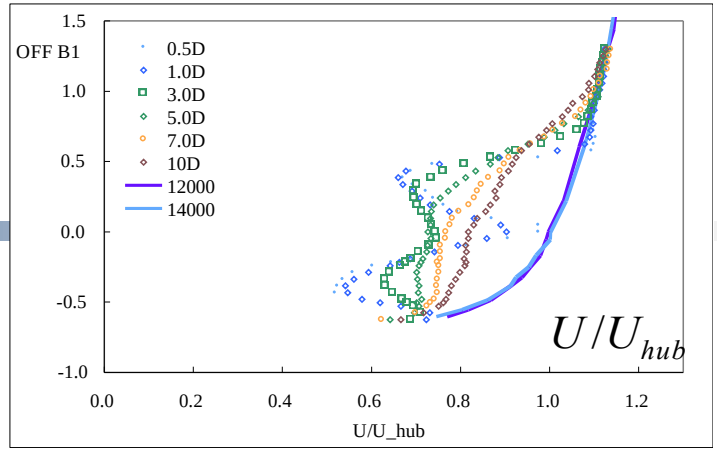
and a roughness length.

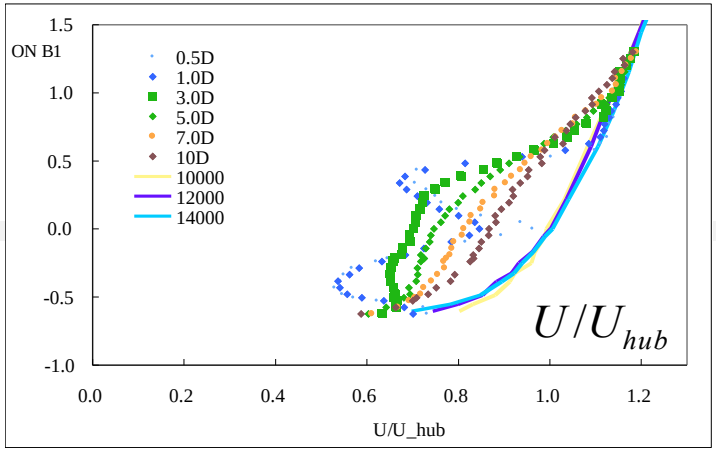
$$\overline{U}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

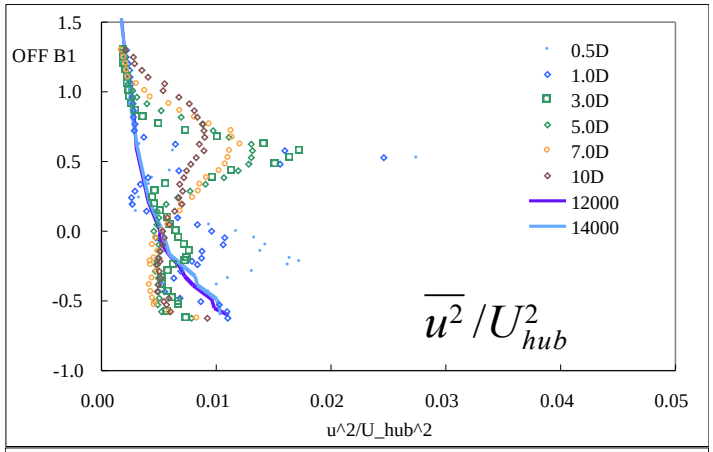
SUPERGEN WIND

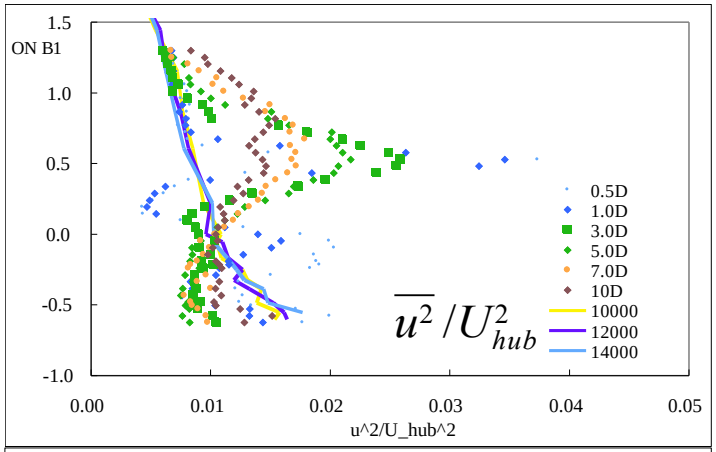
Off-shore

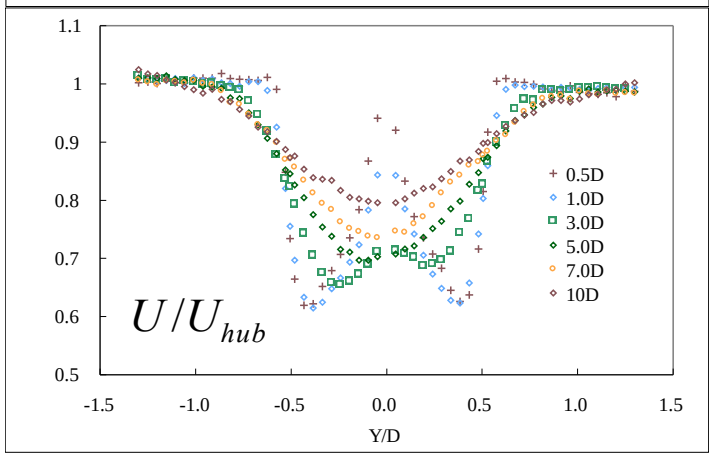
On-shore

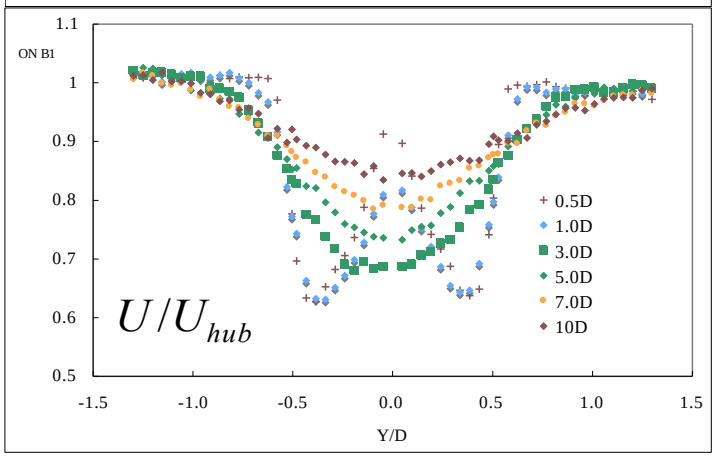












Significant differences:

- off-shore wake develops more slowly over whole length;

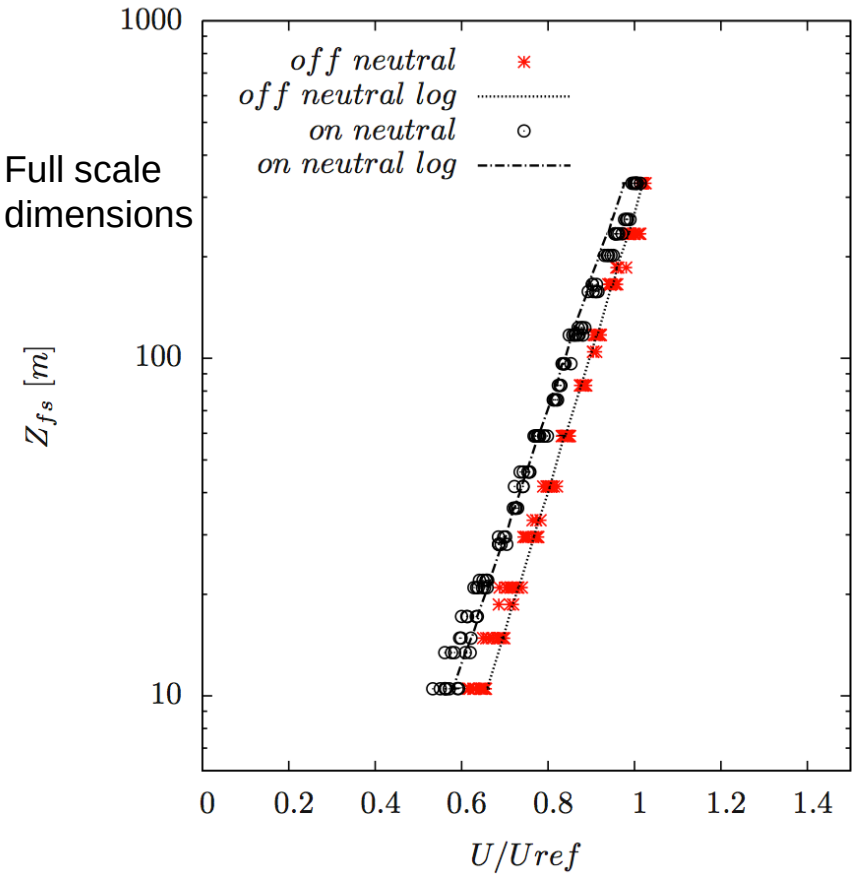
- not just superposition of ABL turbulence: there is interaction between ABL and wake turbulence

Note also, suppression of $\overline{u^2}$ below hub height.

Effect of “moderate” stable stratification - reduced turbulence.

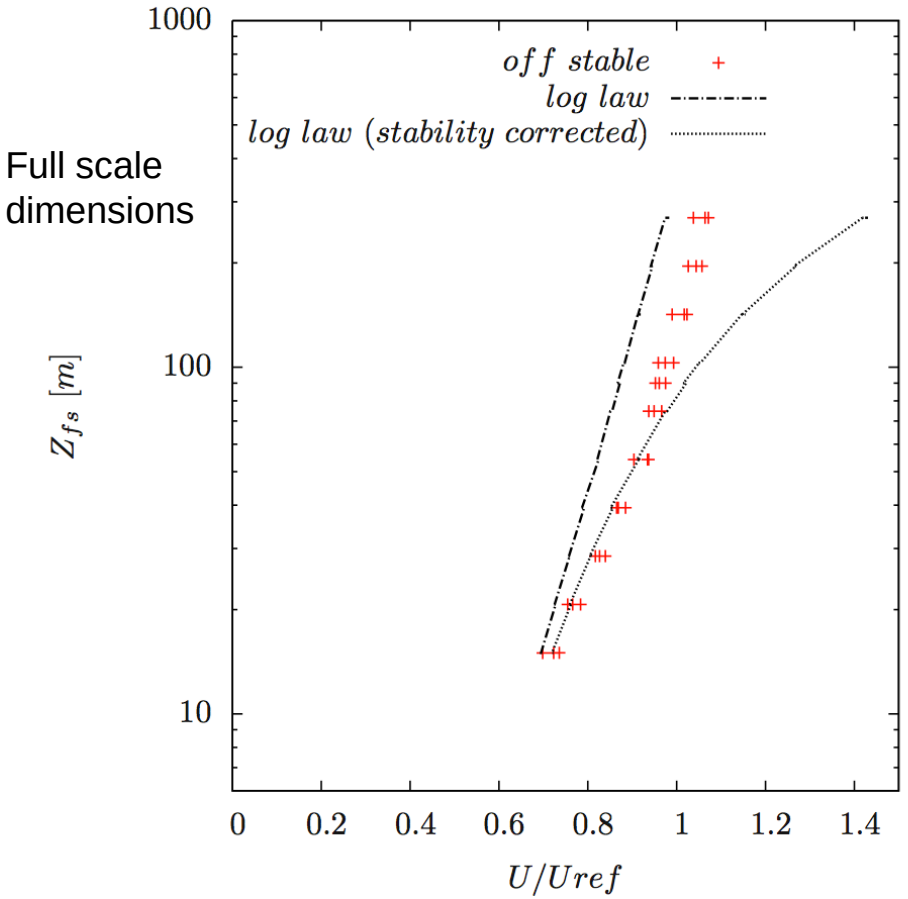
Neutrally stable cases:

(off-shore and rural on-shore)



Moderately stable stratification:

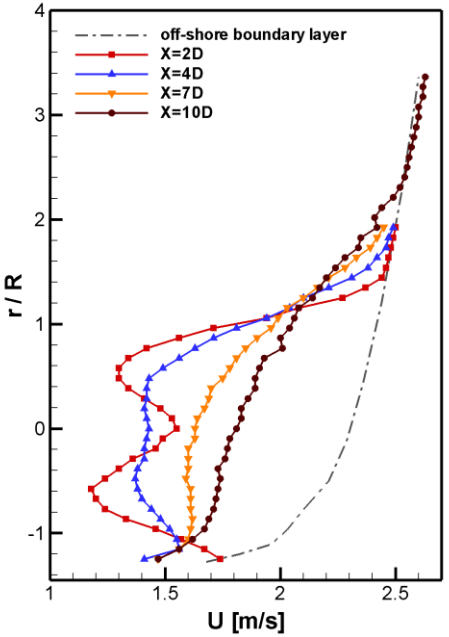
(off-shore)



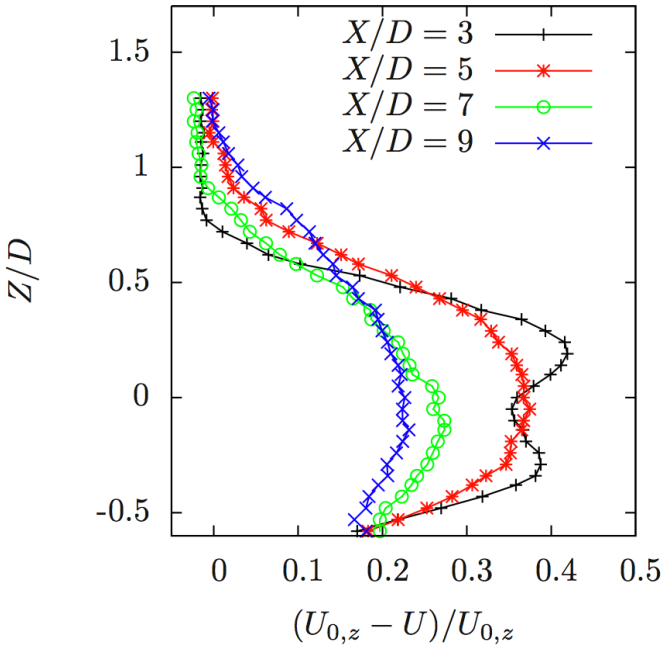
Effect of **mild** stable stratification (off-shore)

Shown here as momentum deficit profiles

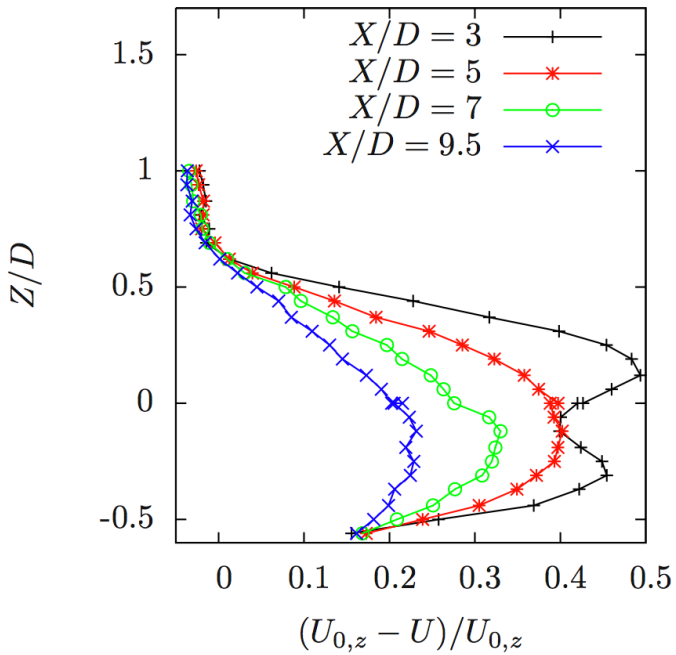
- larger, more persistent deficit
- inhibited vertical development
- maximum deficit at lower height



Neutral:

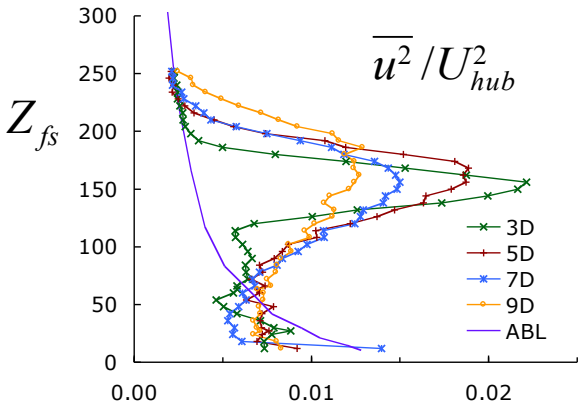


Stable:

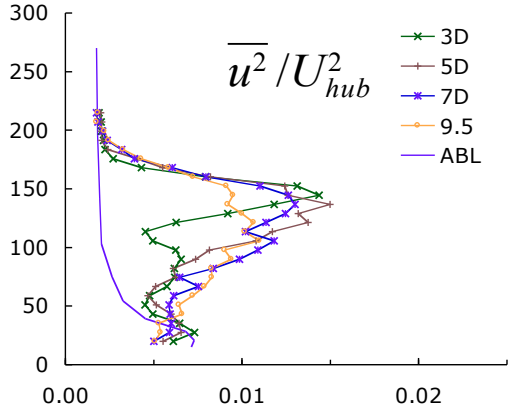


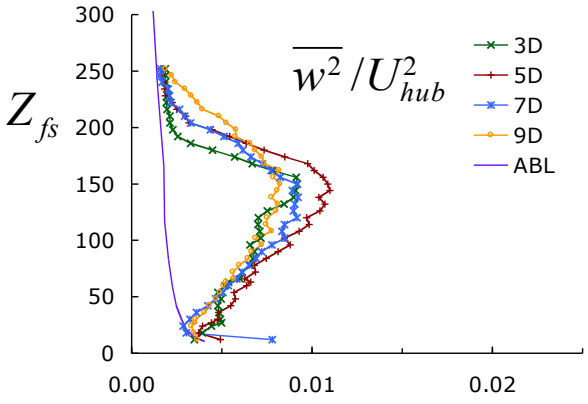
Mean-square fluctuations: $\overline{u^2}/U_{hub}^2$ and $\overline{w^2}/U_{hub}^2$

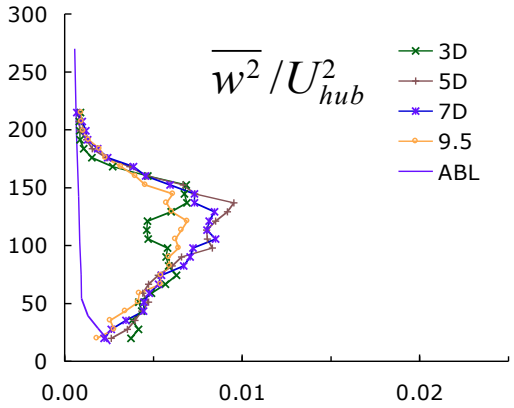
Neutral offshore:



Stable offshore:







Reduced wake height and growth rate.

Turbine ‘contribution’ smaller in stable case.

No suppressing effect on ABL turbulence near ground in stable case.

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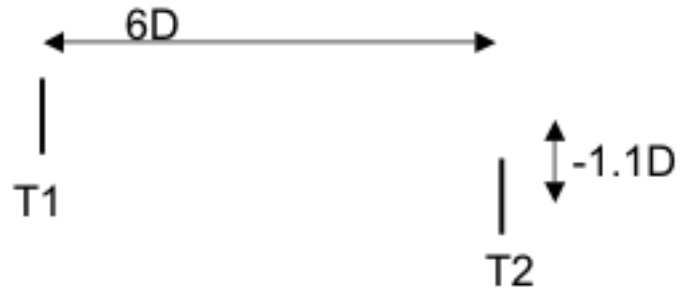
“Array”: - example of (just) two turbines

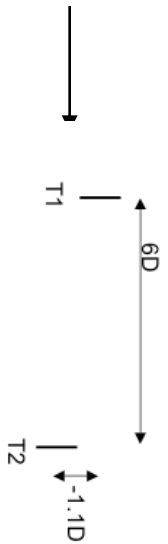
Array 4

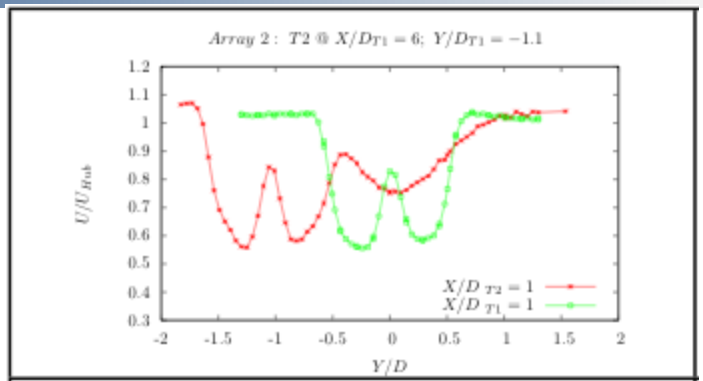


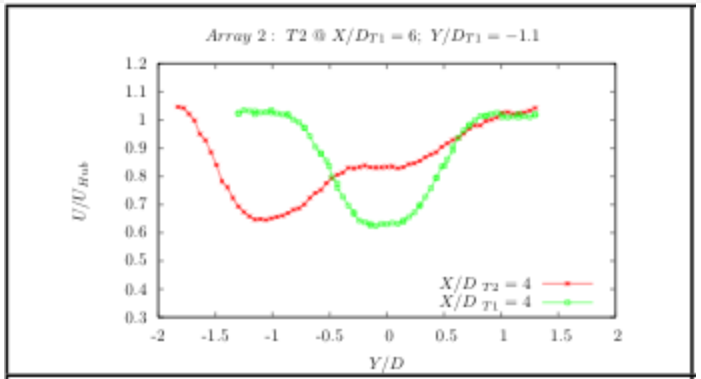
Green - downstream of 1 (single turbine)

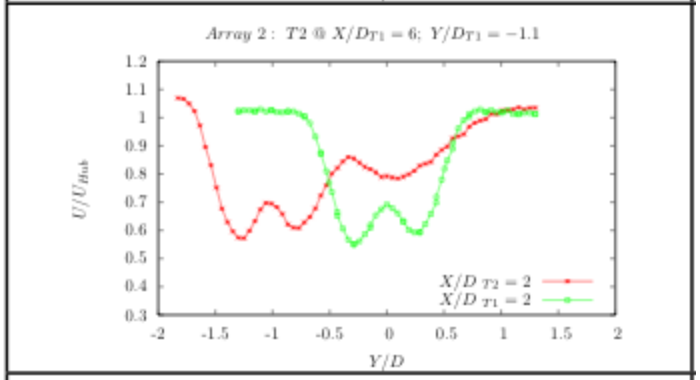
Red - downstream of 2 turbines

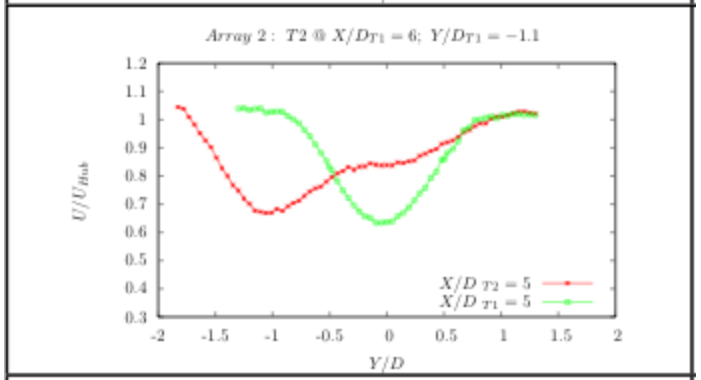
Array 4

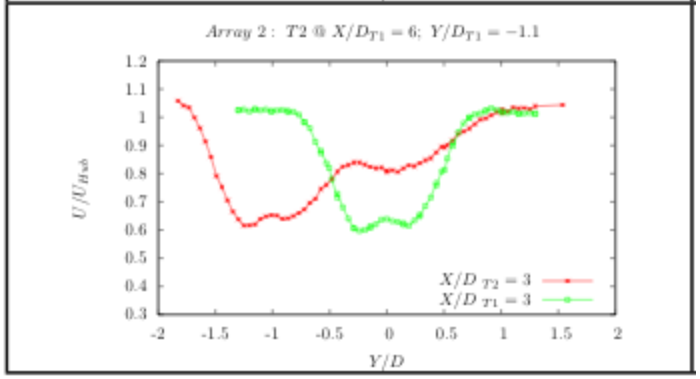


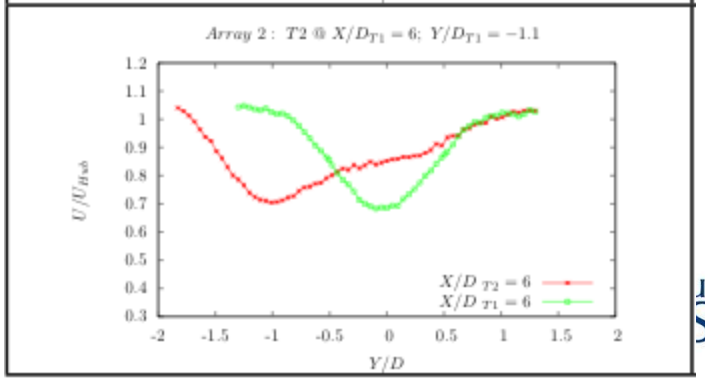








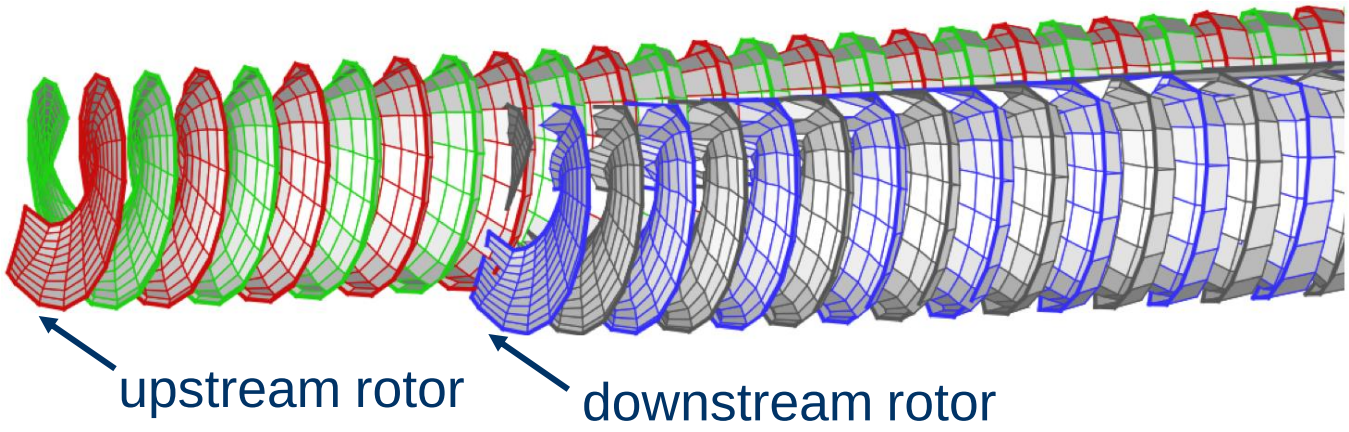




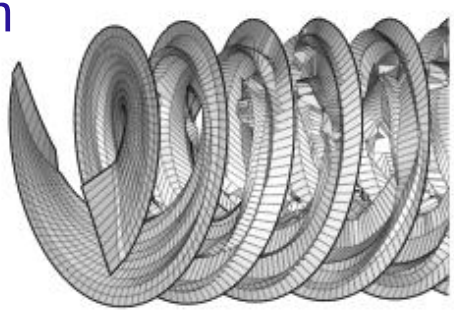
Idealised interaction: Vortex Lattice Method

- Identical rotors (2-bladed)
- Rotor distance: 2D
- Uniform flow field

Mike Graham, et al., Imperial College



Non-uniform Upstream Flow: ‘skewed’ Wake.



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Blade root bending moment (1:200 scale instrumented hub)

(Imperial College, Mike Graham, et al.)

Two cases:

a) no upstream turbine (red)

b) with upstream turbine (blue)

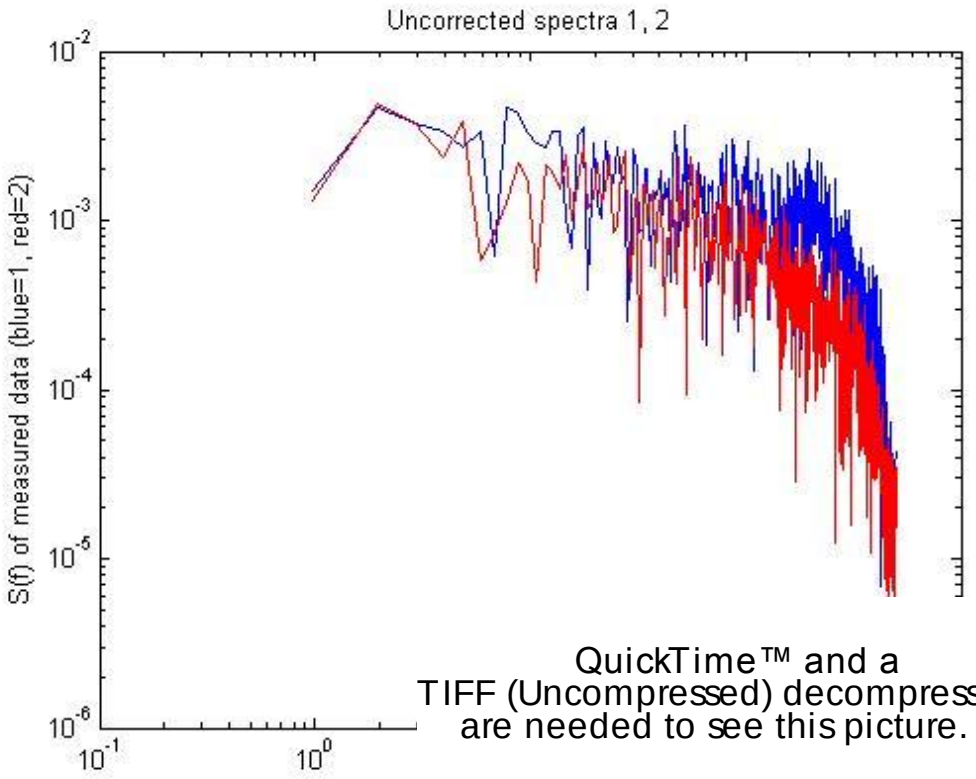
Simulated ABL

(1:200 scale)

Turbines separated by 6.5D, with 0.5D offset

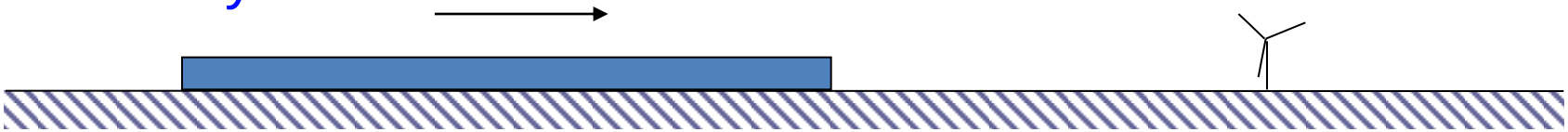
TSR of ~6: ratio of TSRs varied by factors of 2/3 to 3/2.

Upstream wake leads to broader band of turbulence seen by second turbine.



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

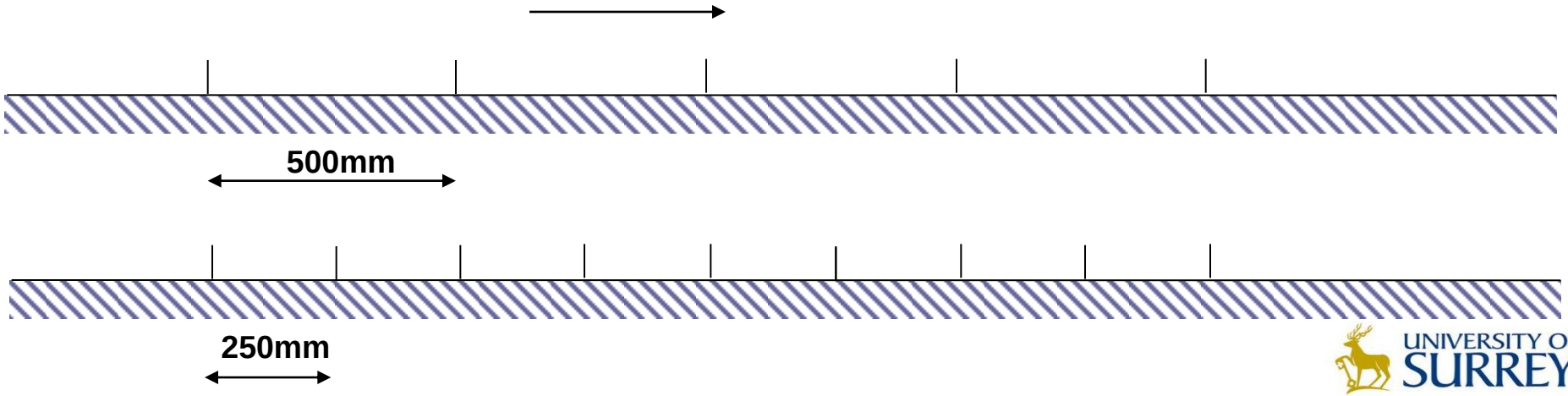
Forestry



Porous fence simulation of trees

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Canopy height 21m i.e. 70mm at 1:300 scale



Mean velocity and turbulence intensity