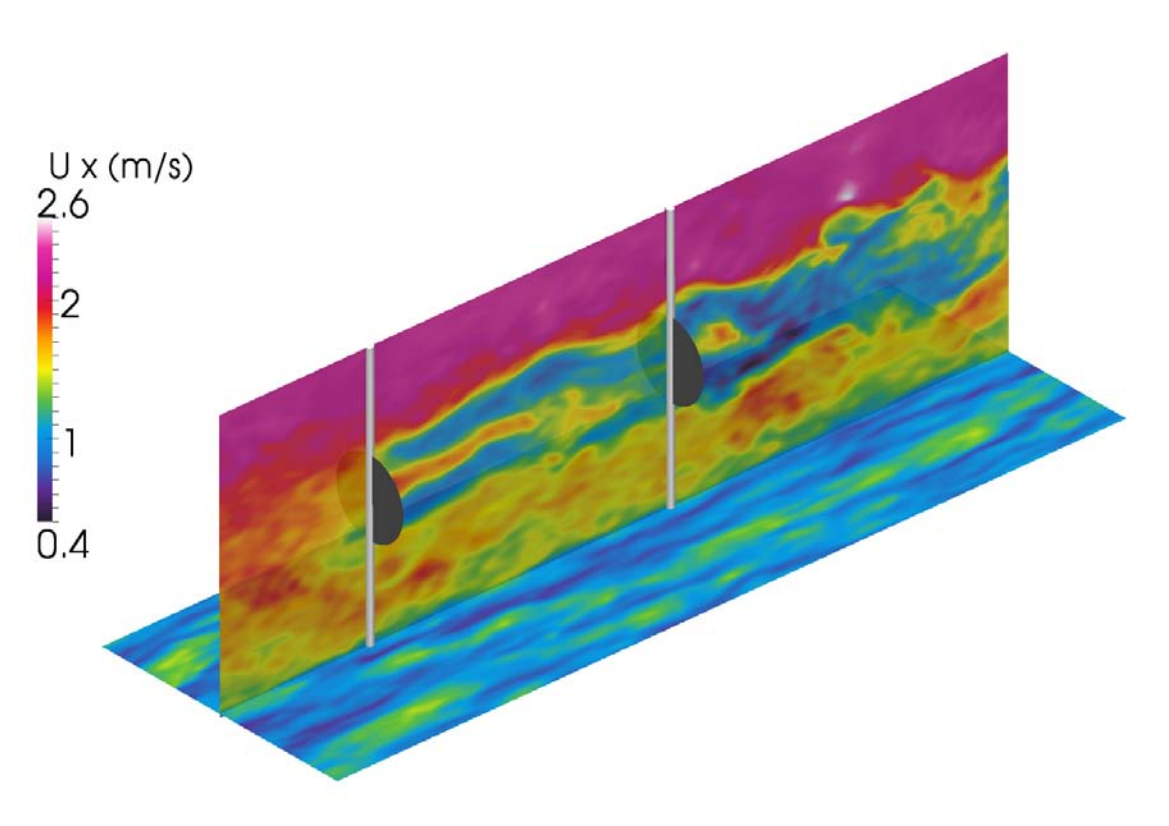
NATIONAL RENEWABLE ENERGY LABORATORY

# Preliminary Work in Tidal Turbine Farm Computational Fluid Dynamics Simulations




**Matthew J. Churchfield**

**1st NREL MHK Modeling Meeting**

**March 1, 2011**

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Objectives

**Extend wind farm computational fluid dynamics (CFD) experience to tidal turbine farms**

- **Use large-eddy simulation (LES)**

**Create a preliminary framework for tidal turbine farm large-eddy simulations**

Eventually, use this framework to examine:

- Tidal turbine farm power production and loads
- Interaction of tidal turbine wakes with:
  - other turbines and their wakes
  - tidal channel turbulence

Knowledge gained could lead to lower-order, faster engineering tools

# What is LES?

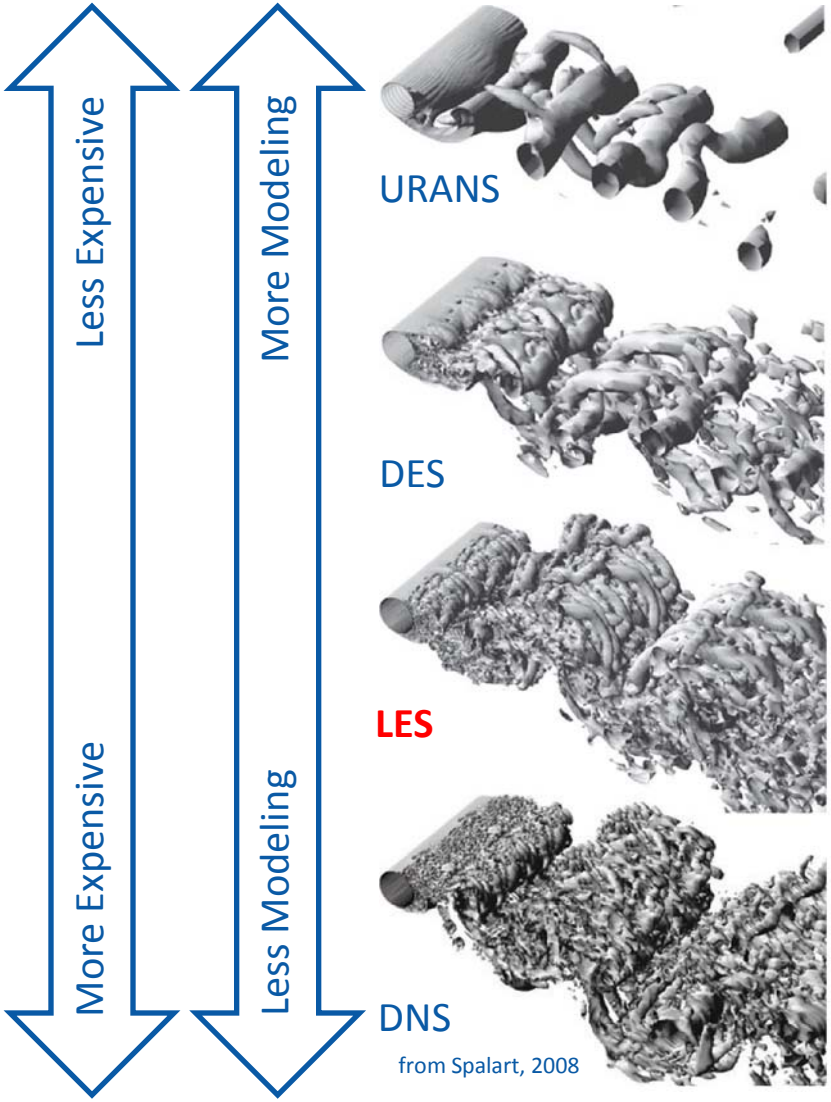
Resolve the larger "energy-containing" turbulent scales

Model the smaller scales

Less computationally expensive than DNS, more detail than URANS

What about near solid surfaces?

- Wall model (channel surface)
- Actuator line (turbine blades)



from Spalart, 2008

# Why use LES?

Captures relevant scales of turbulence

- “relevant” = down to blade chord scale

Gives a non-averaged picture of the flow and fluid-turbine interaction

- Captures power/load fluctuations

Modeling of small scales maintains computational tractability

Research tool used to better understand physics

# The OpenFOAM CFD Toolbox

**Open F**ield **O**perations **A**nd **M**anipulations

Open-source, freely-available toolbox

Not a canned CFD solver!  A set of C++ libraries meant for solving complex partial differential equations using an unstructured finite-volume formulation

“Easy” to modify code to be problem specific

Have run OpenFOAM on 1024 processors of NREL’s RedMesa

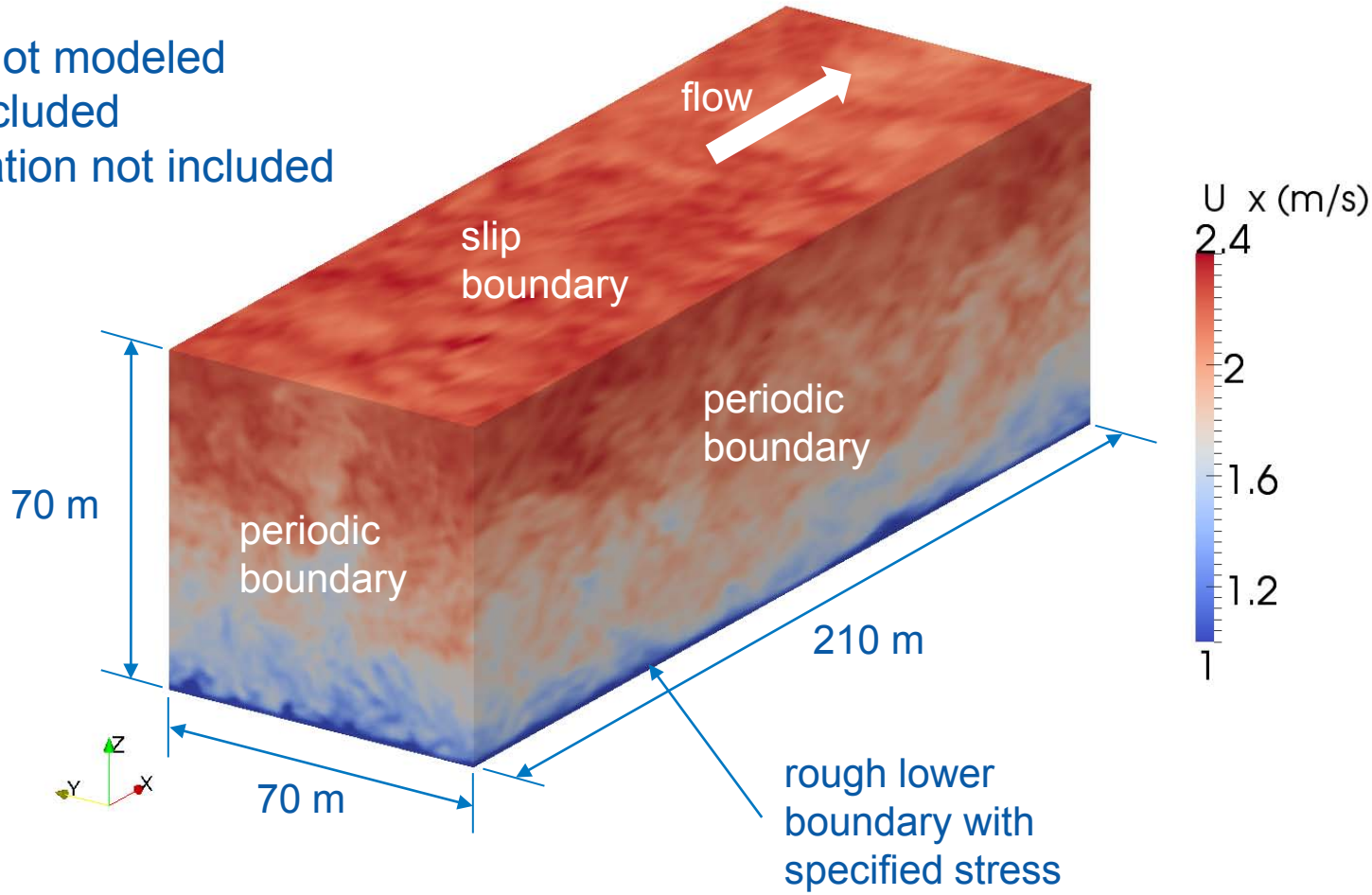
- Scales well when greater than 40K cells/processor

# Methodology: Tidal Flow Generation

simulation time: 6000 s

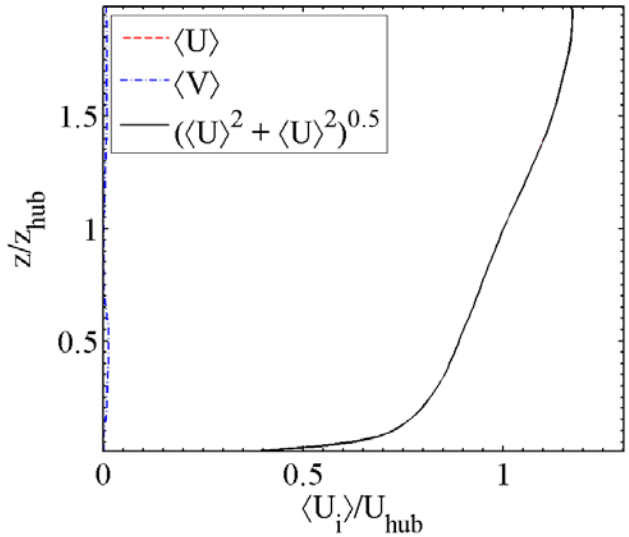
**NO TURBINES, YET!!!**

simplifications:
- free surface not modeled
- salinity not included
- ebb/flow variation not included

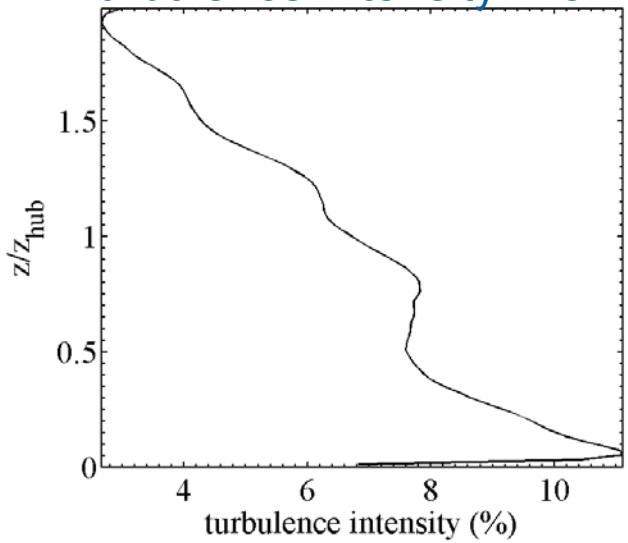


# Methodology: Tidal Flow Generation

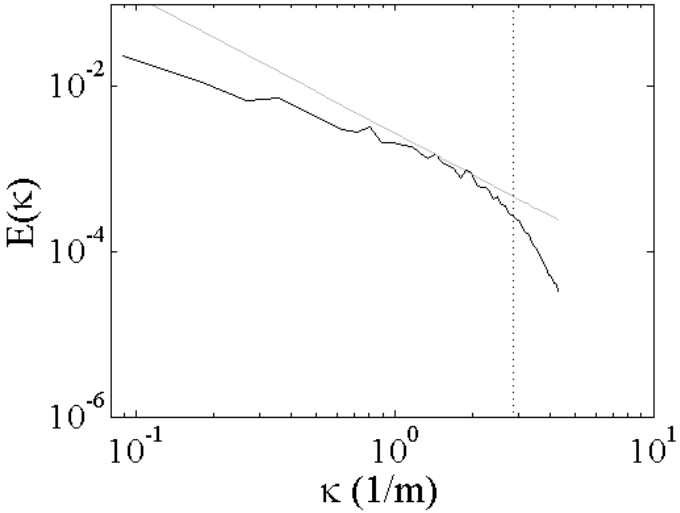
## Mean Flow Profile




## Turbulence Intensity Profile



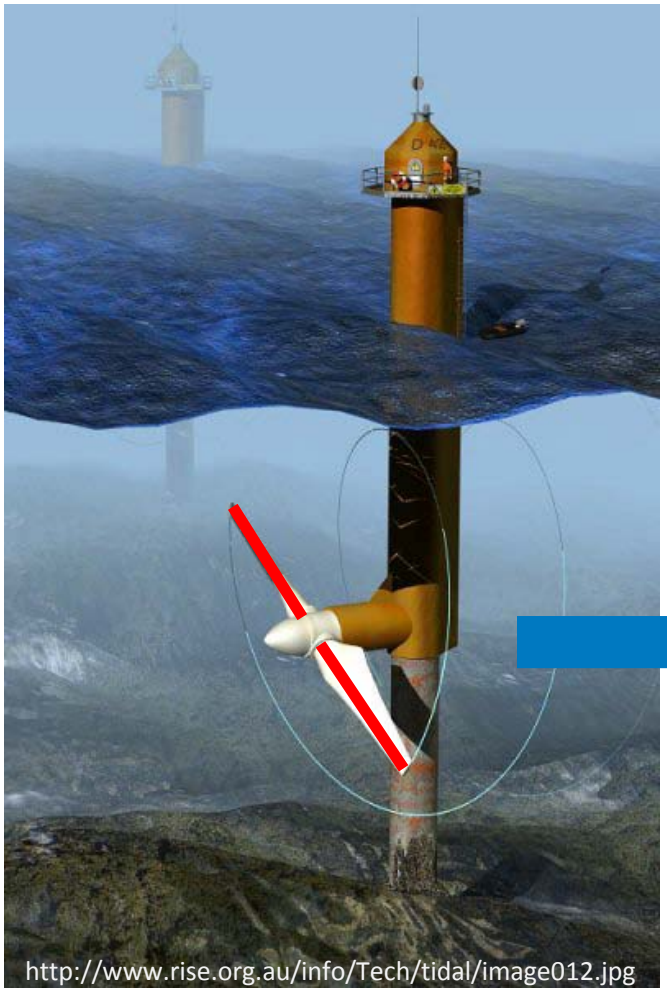

## 2D Velocity Spectrum at Hub Height

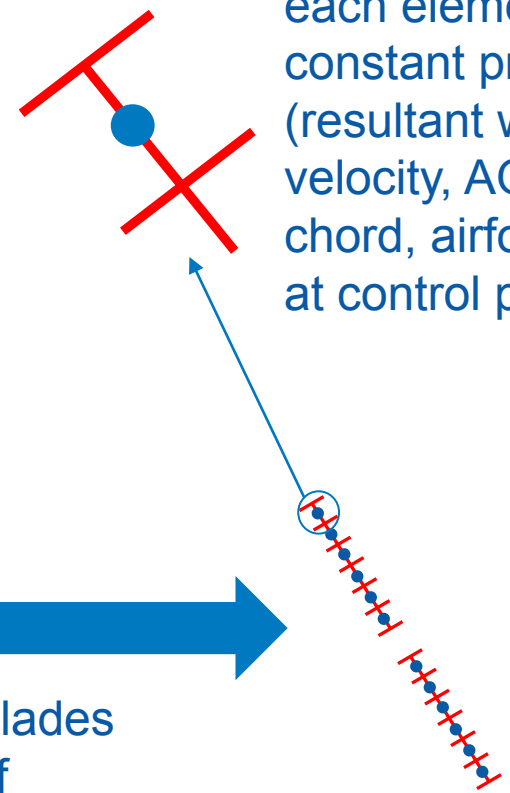



$U_{hub}$ = 1.9 m/s
$Z_{hub}$ = 35 m
$TI_{hub}$ = ~6%

# Methodology: Turbine Modeling

## Actuator Line Model (Søresen & Shen, 2002)



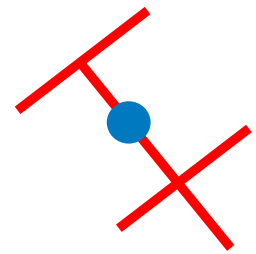



each element has constant properties (resultant wind velocity, AOA, chord, airfoil) taken at control point

break the blades into a set of blade elements

# Methodology: Turbine Modeling

## Actuator Line Model (Søresen & Shen, 2002)



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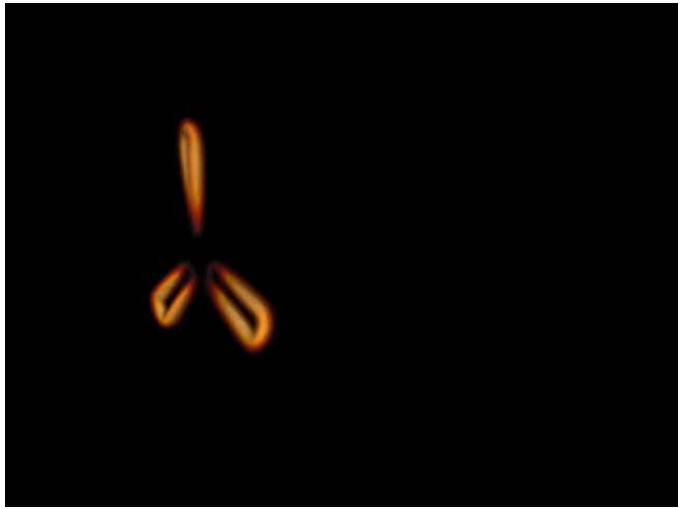


High resolution actuator line simulation in uniform, non-turbulent flow. Isosurfaces of second-invariant of velocity-gradient tensor (highlights bound, starting, tip, and root vortices)

like blade element mometum (BEM) theory, but "momentum" theory part replace with CFD

CFD naturally accounts for axial/tangential induction

returns a body force to CFD domain created by each blade element

# Methodology: Tidal Farm Simulation

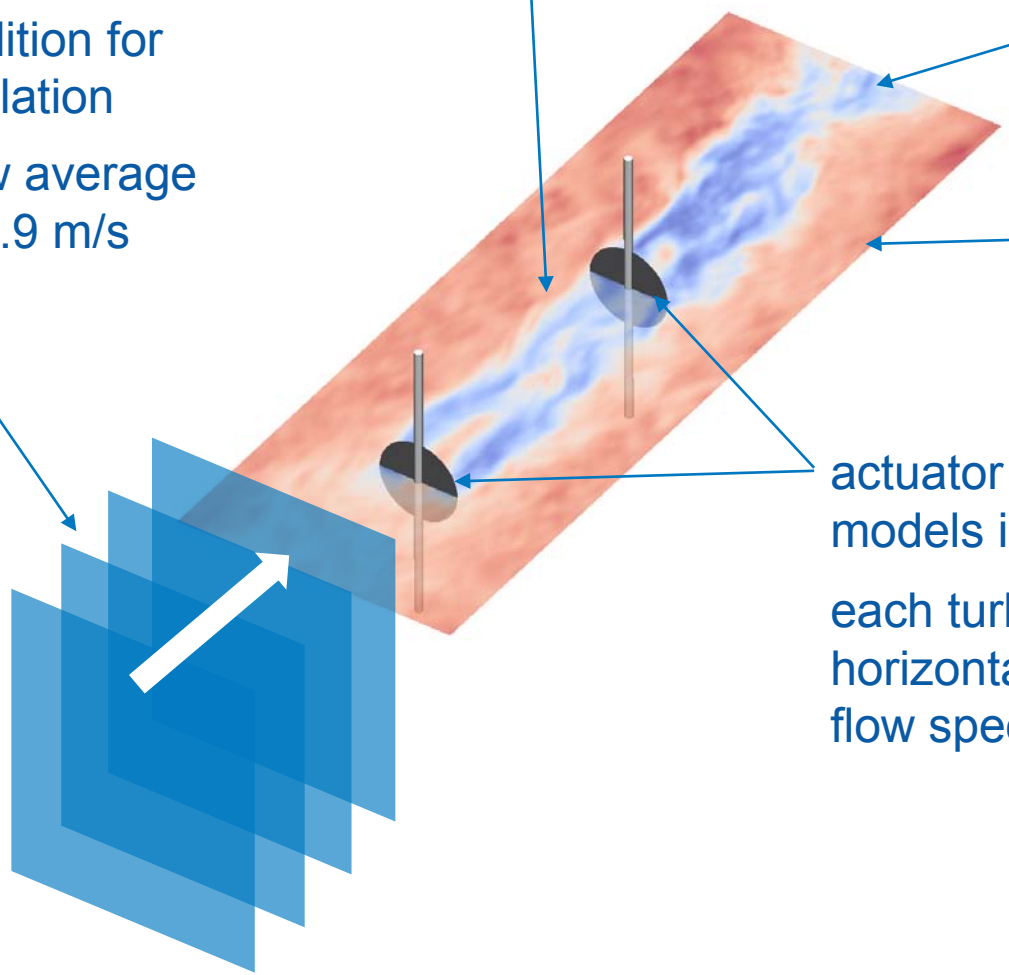
planes of data saved from tidal flow precursor simulation used as inflow boundary condition for tidal farm simulation

hub height flow average flow speed = 1.9 m/s

turbulent flow field initialized from tidal flow precursor simulation

outflow boundary:
dU/dn = 0
pressure = 0

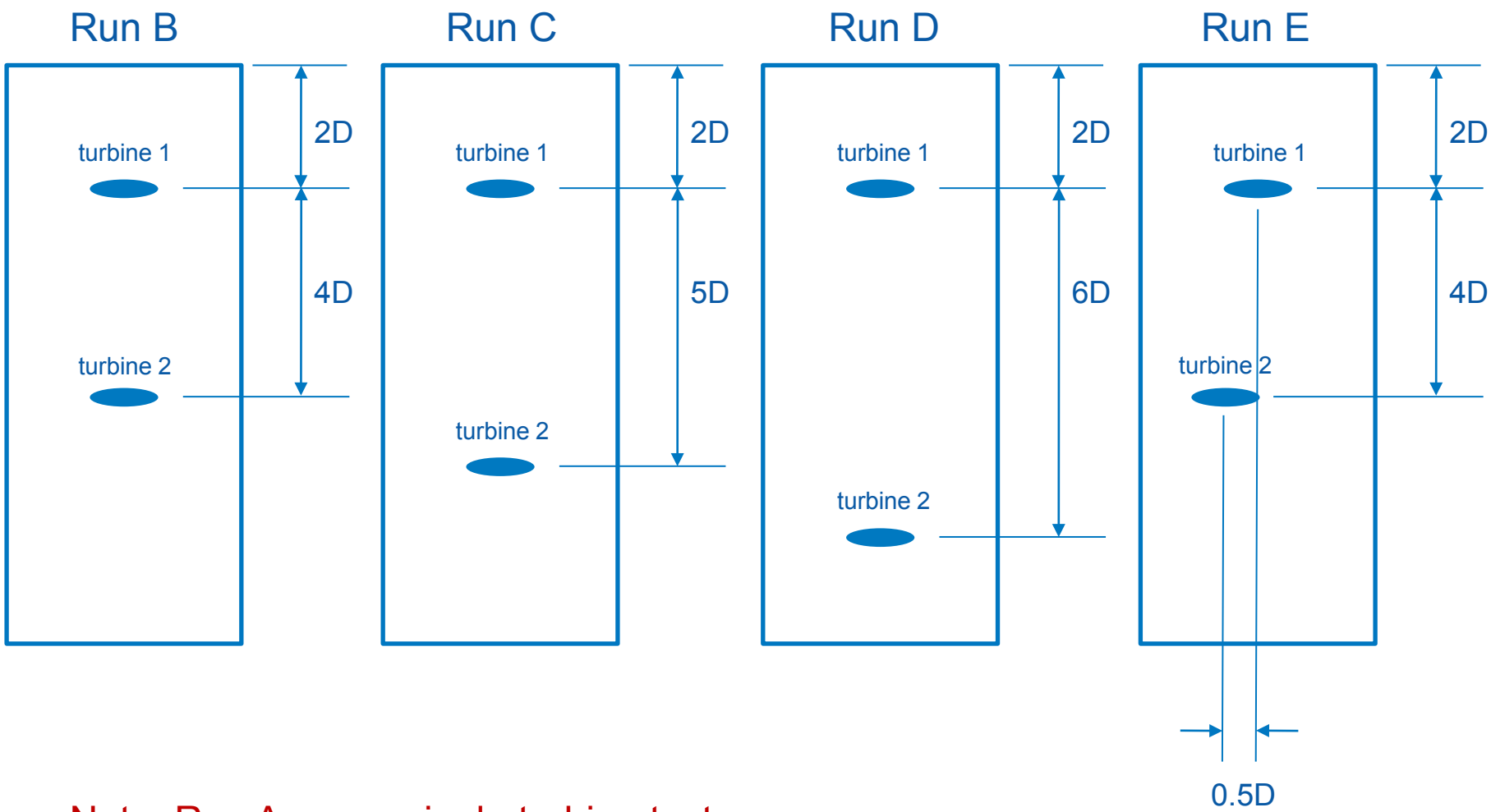
periodic side boundaries



actuator line tidal turbine models inserted into domain

each turbine is a 550 kW horizontal axis turbine (rated flow speed is 2 m/s)

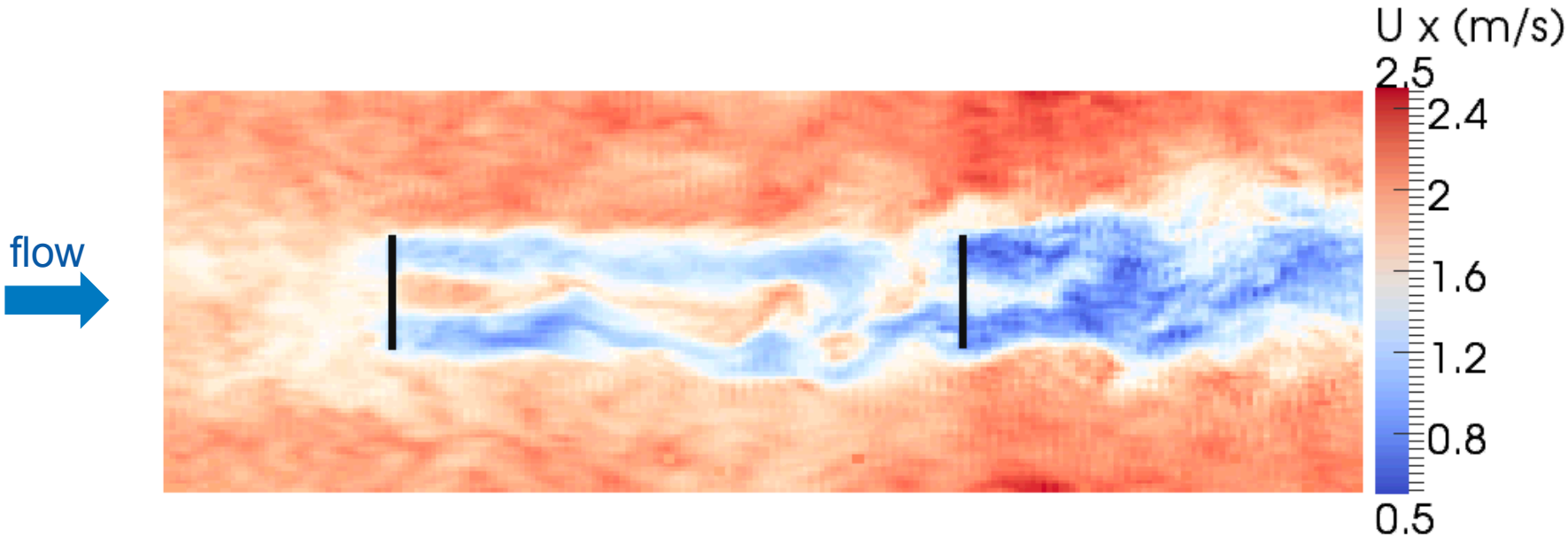
# Simulation Layouts




Note: Run A was a single turbine test case

# Results: Overview

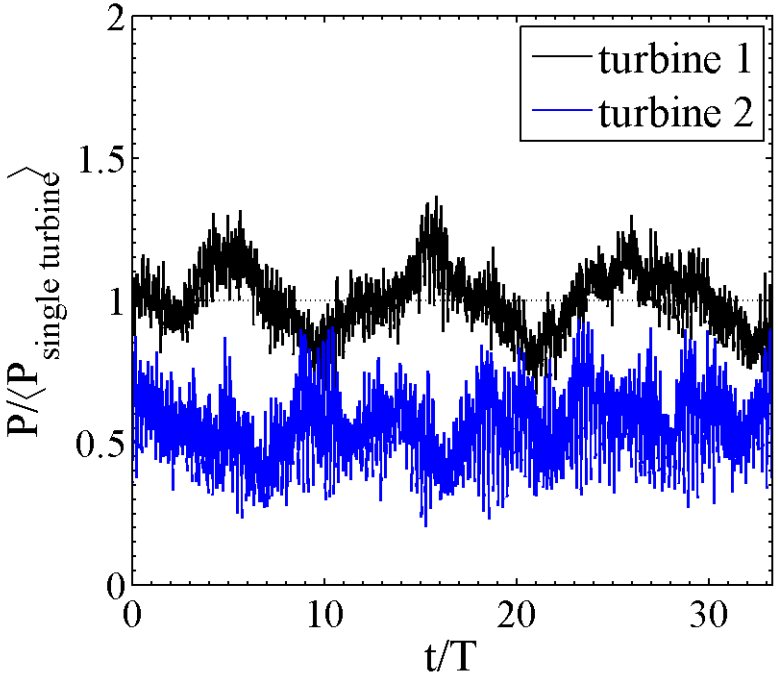
A view from **above** the farm of streamwise resolved velocity (5D separation)



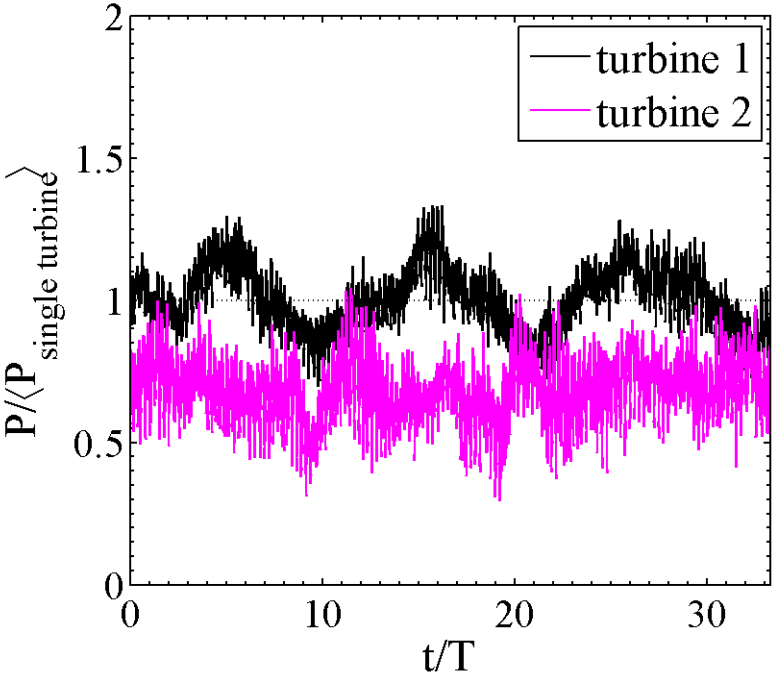

These oscillations are a concern!
They occur when using precursor inflow data
Outflow velocity needs to be scaled to match mass flow rate of inflow?

# Results: Power Production

4D separation




6D separation




T = time for hub height flow to travel 1 rotor diameter = 10.53 s

$\langle P_{\text{single turbine}} \rangle$ = time averaged power produced by standalone turbine

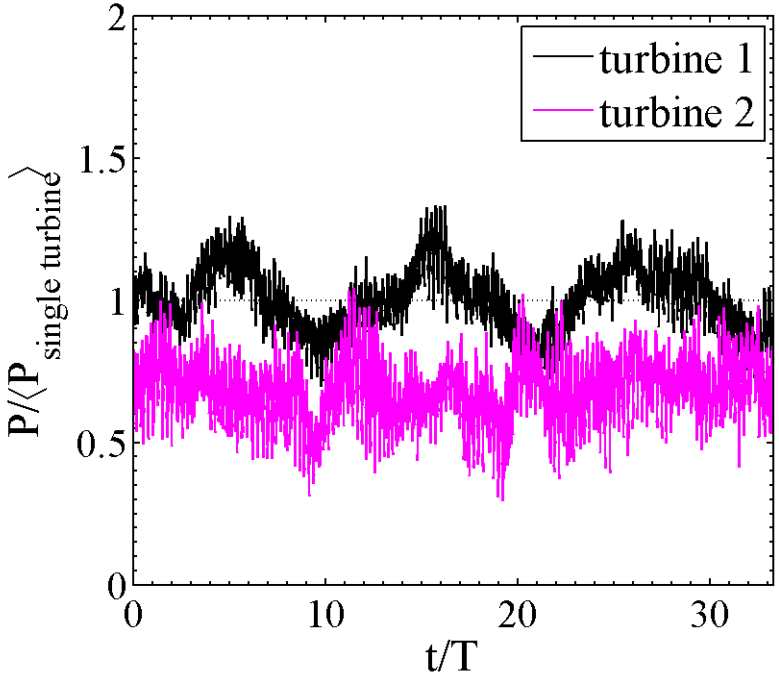
Noisy power production. Why?

Low frequency oscillation due to turbulence and meandering wake

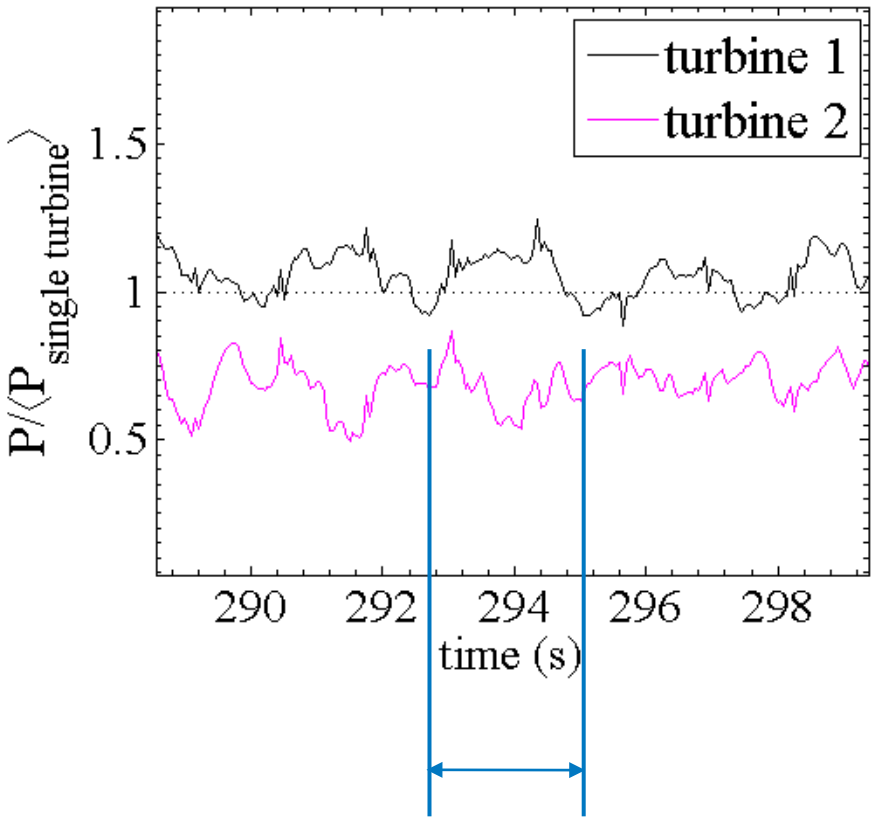
High frequency…

# Results: Power Production

6D separation




6D separation (zoomed)

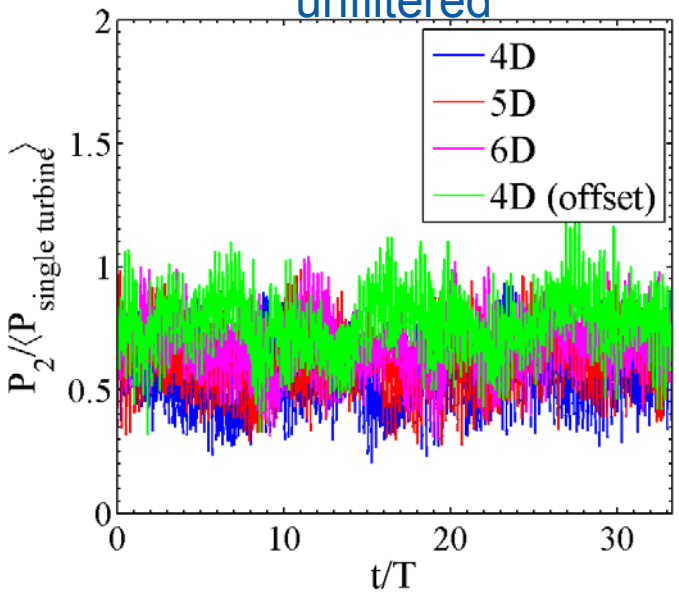



**half blade revolution time = 2.6s**

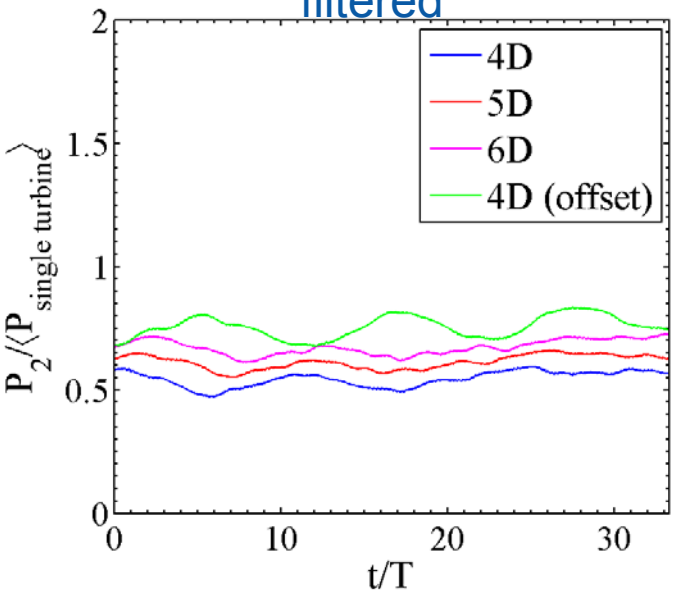
Noisy power production. Why?
High frequency: corresponds to blade passage of 2-bladed rotor

# Results: Power Production

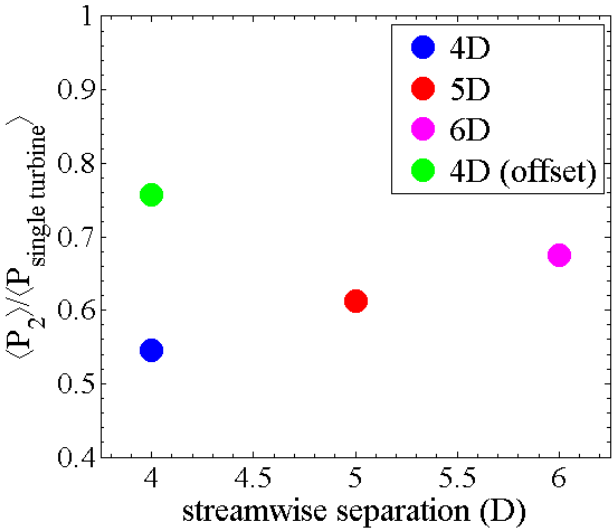
unfiltered




filtered



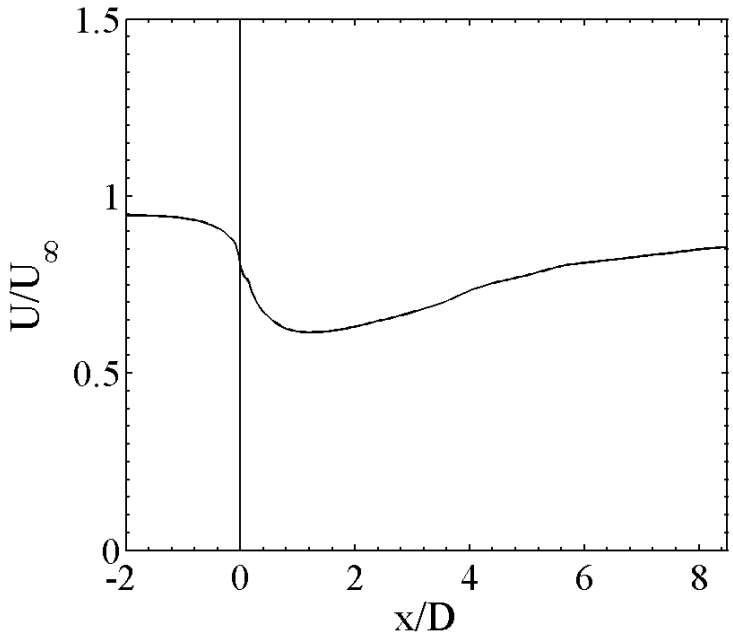

If flow direction is known, offsetting turbines offers greater advantage than increased spacing



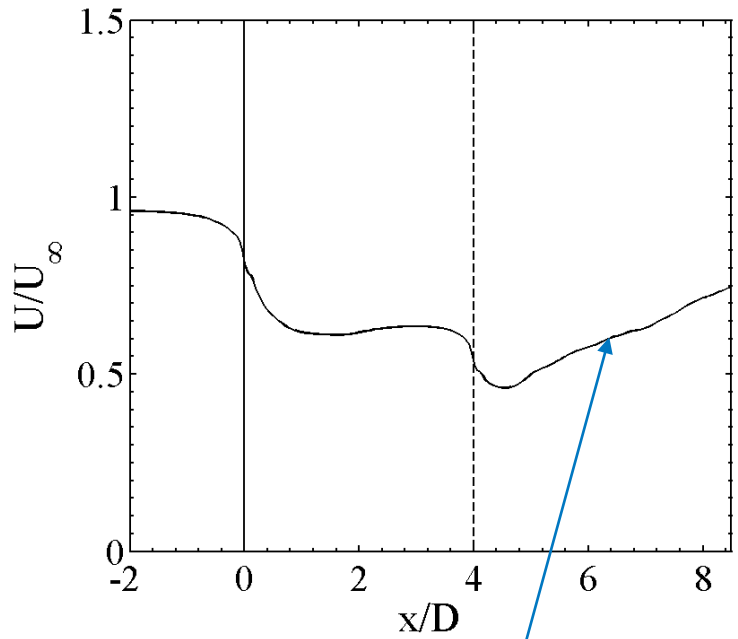

$\langle P_2 \rangle$ = time averaged power produced by downstream turbine

# Results: Wake Streamwise Profiles

single turbine



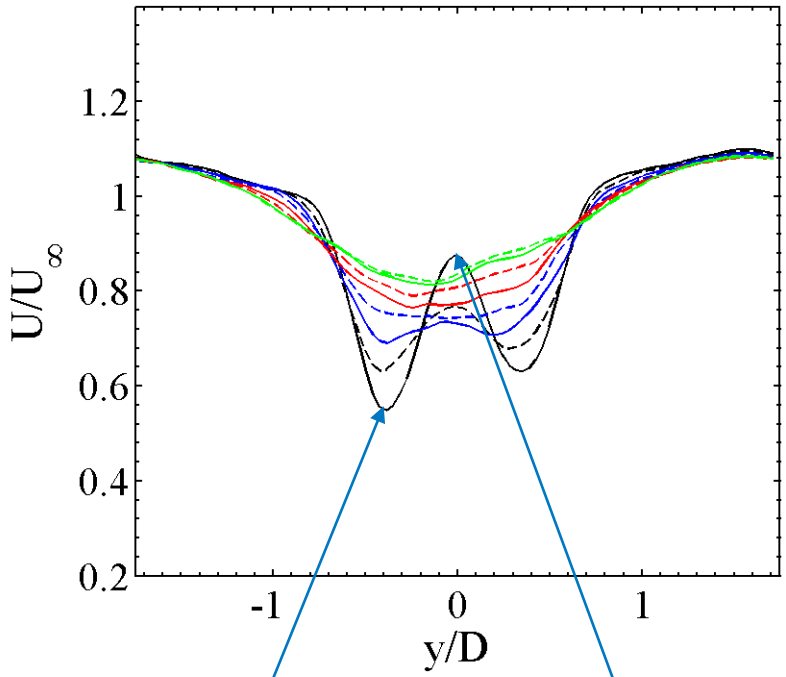

two turbine - 4D separation



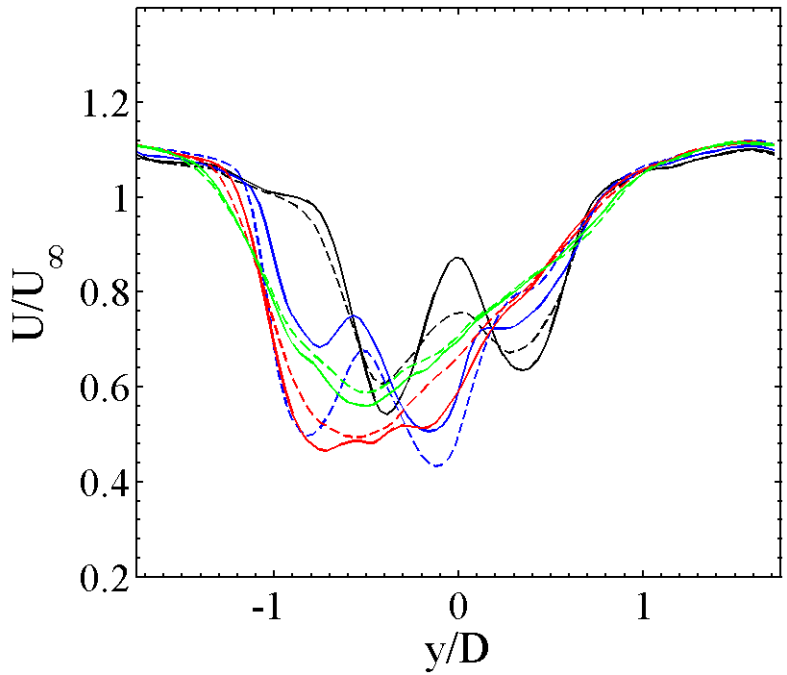

increased wake recovery behind second turbine due to increased turbulence there

# Results: Wake Spanwise Profiles

single turbine




two turbine - 4D separation with lateral offset




need to model hub and nacelle!

wake asymmetry due to wake rotation and vertical shear

distance behind turbine 1

- 1D
- 2D
- 3D
- 4D
- 5D
- 6D
- 7D
- 7.5D

# Area for Refinement

Add equation for salinity

- Buoyancy effects caused by salinity have important effects on turbulence suppression or enhancement

More resolved grid to better resolve wake and tip/root vortices

Investigate velocity oscillations

Model free surface

Better tidal channel modeling in general

# Conclusions

Successfully applied experience in wind farm large eddy simulation to tidal channel turbine farm

Laid out a framework for performing this type of simulation

Initial results seem reasonable

**Need data for comparison!**

Present results at European Wave and Tidal Energy Conference 2011