Marine Hydrokinetic Turbine Array Optimization and Wake Characteristics

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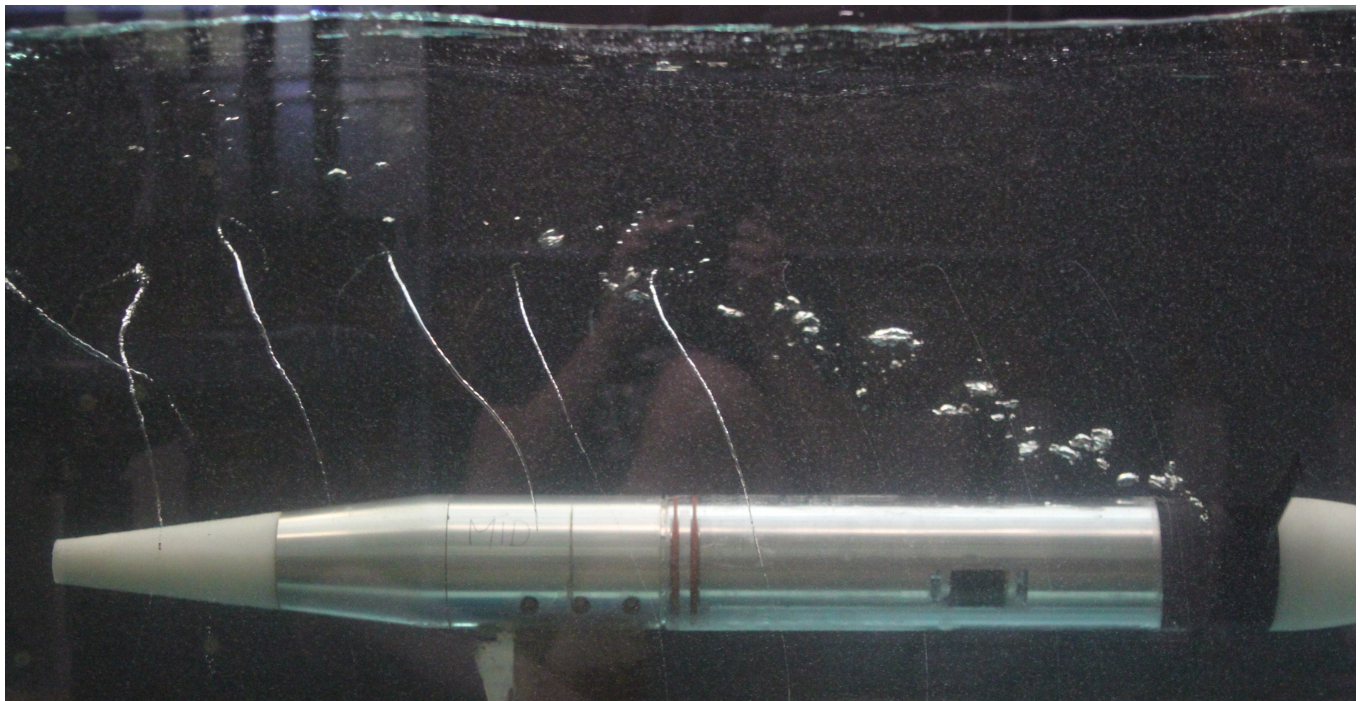
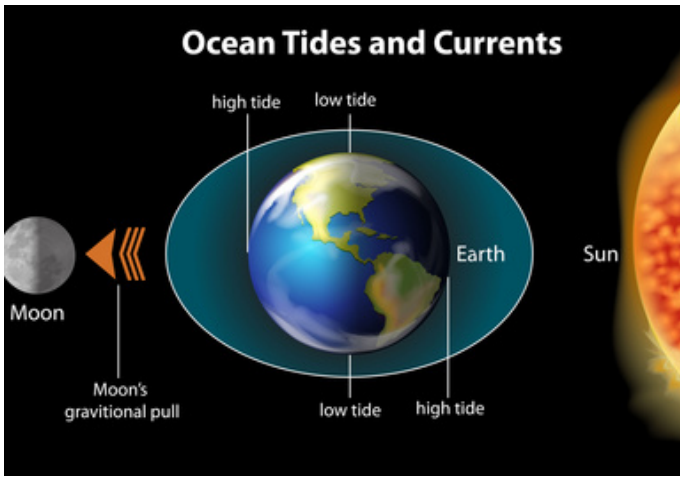
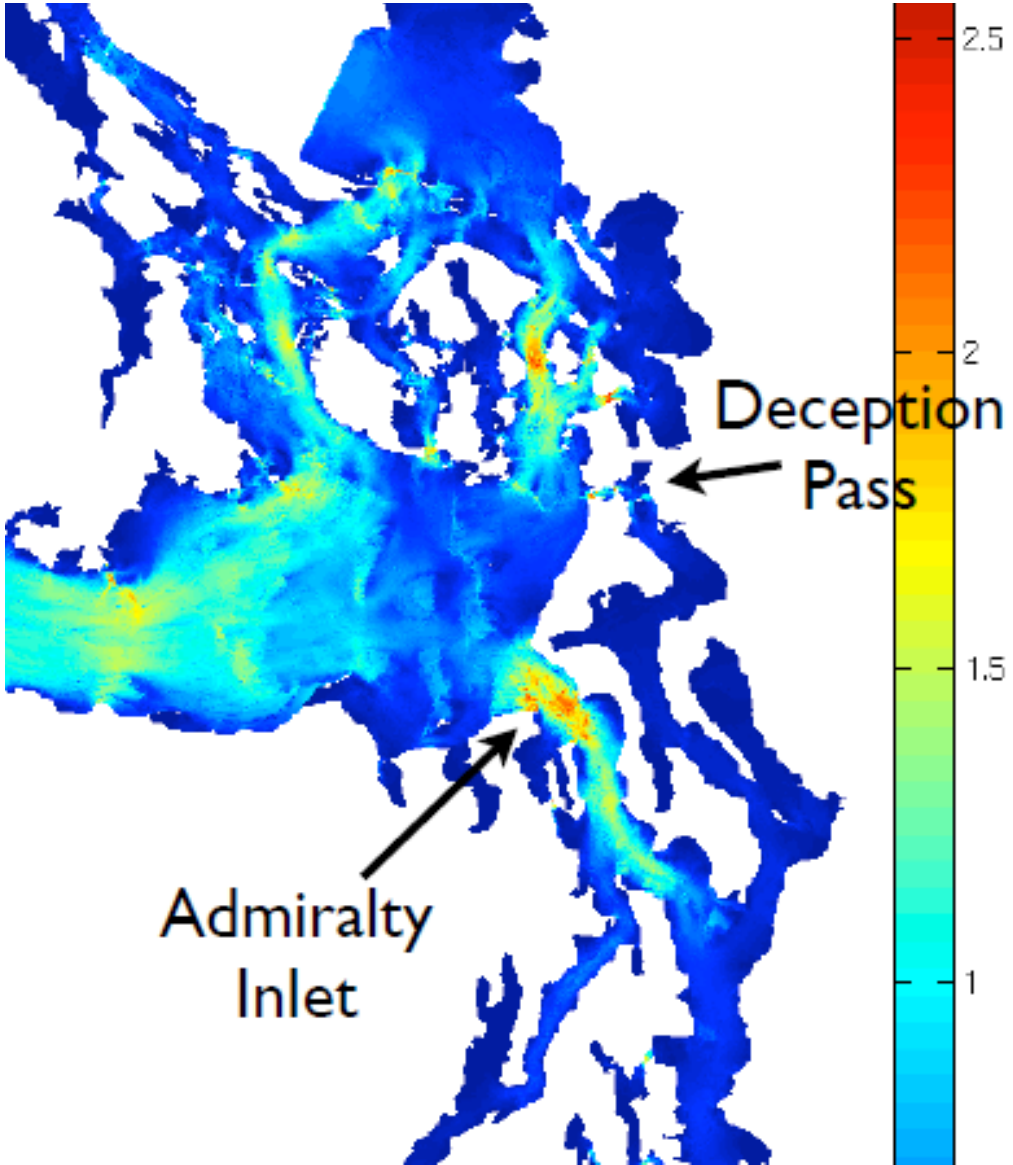
Northwest National Marine Renewable Energy Center
University of Washington



What is Tidal Energy?

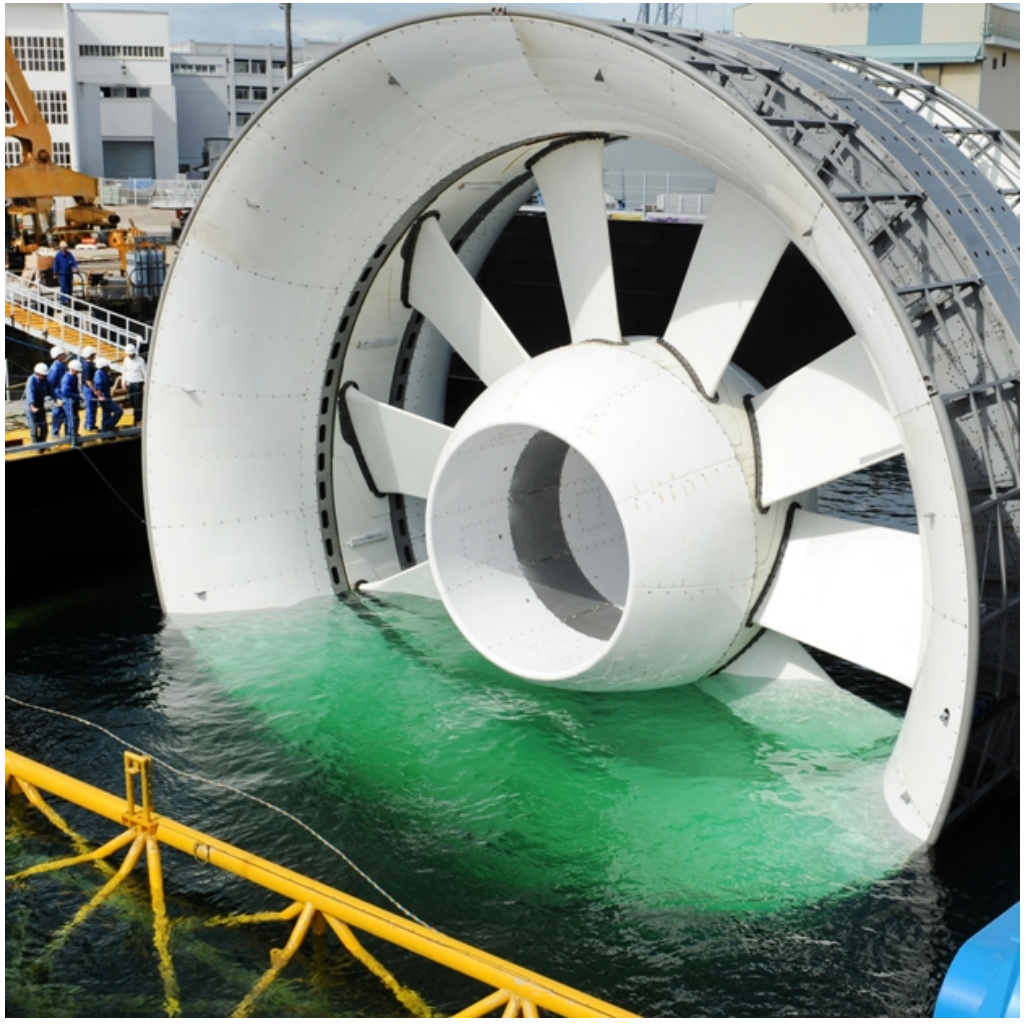




Extracting power from tidal currents

Marine Current Turbine

Extracting power from tidal currents



OpenHydro

Extracting power from tidal currents

Ocean Renewable Power Company

The Big Picture

Tidal energy advantages:

- Source of renewable energy
- Small-scale project are possible for remote communities
- Regularity and predictability of tidal currents a key advantage

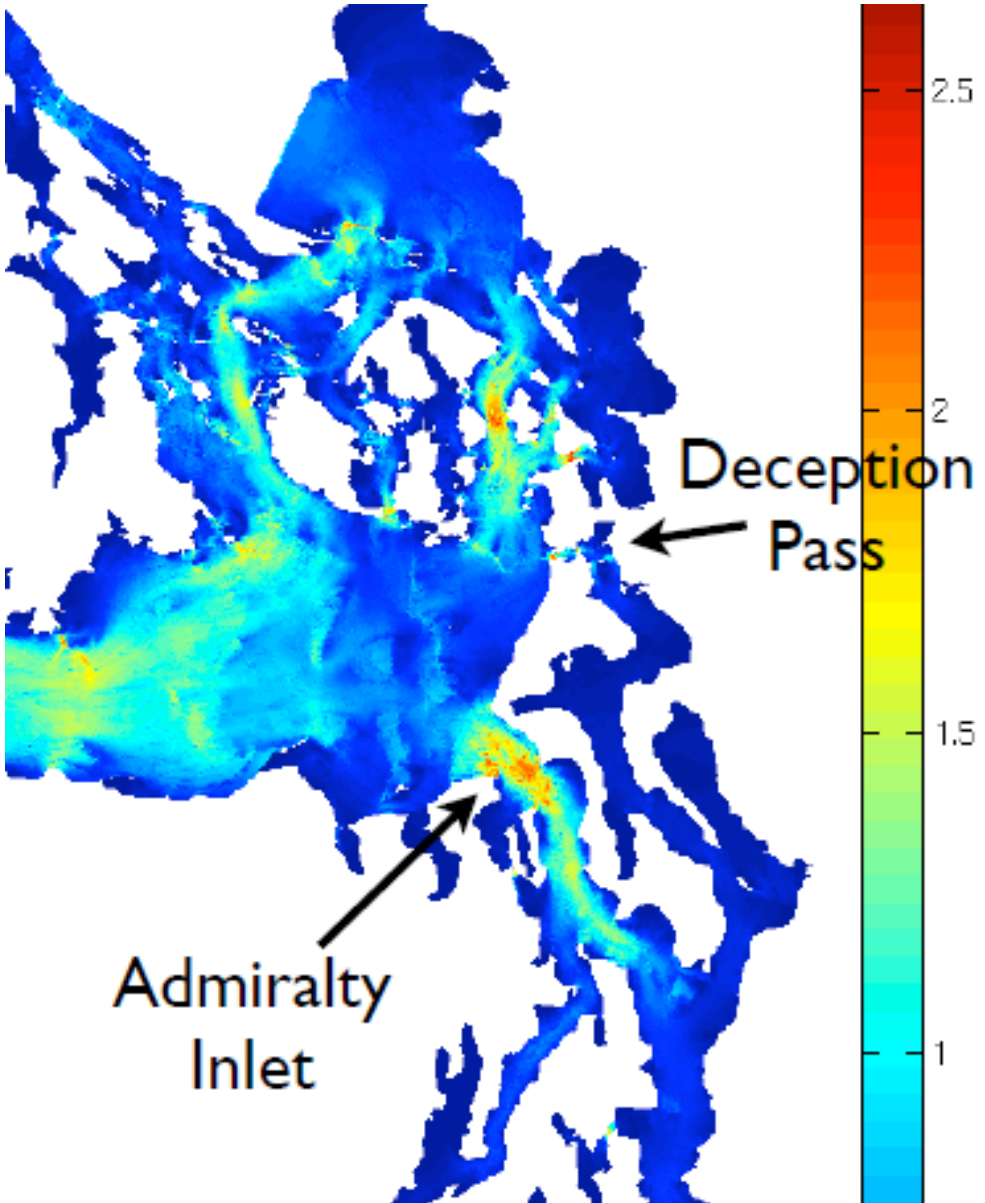
Possible disadvantages:

- Unknown environmental consequences
- Harsh operating conditions
- Spatially limited resource

PROJECT MOTIVATION

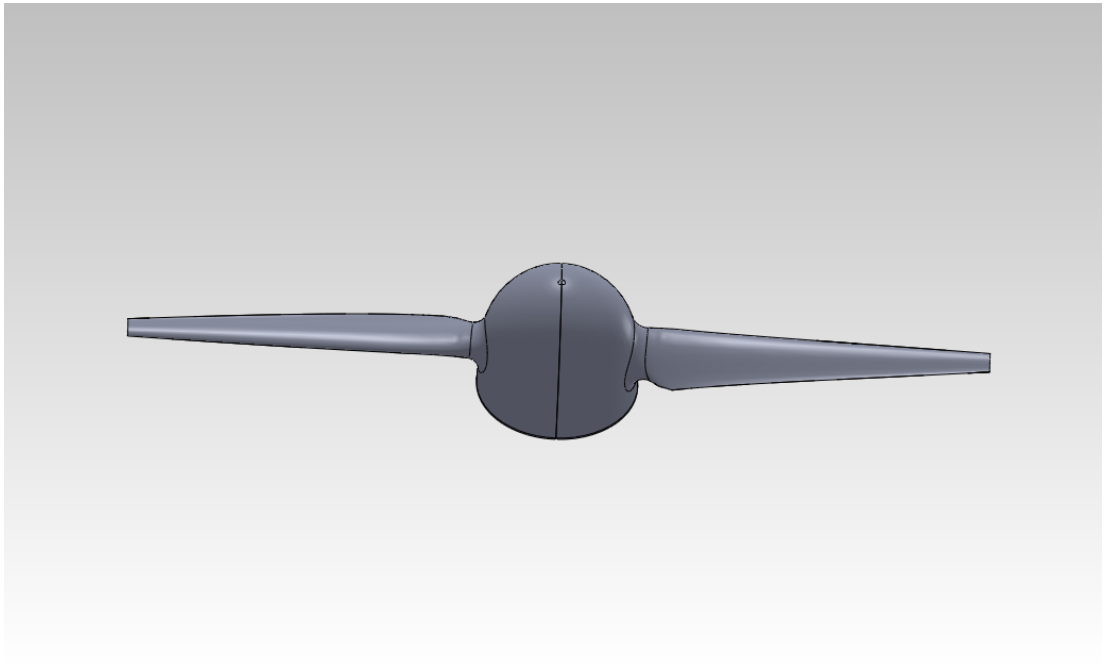
Kinetic power of the flow

$$P \propto V^3$$



PROJECT MOTIVATION

Department of Energy Reference Model 1



DOE Reference Model 1 (solid model)

RESEARCH GOALS

- Design and test a scale model turbine with similar performance characteristics to full-scale Department of Energy Reference Model 1 tidal turbine
- Create a database of experimental measurements for validating numerical methodologies
- Explore the effect of spacing on turbine array performance and wake development

NON-DIMENSIONAL PERFORMANCE AND ROTATIONAL SPEED

$$TSR = \frac{\omega r}{V}$$

$$C_p = \frac{P}{0.5\rho\pi r^2 V^3}$$

ω = Rotational speed

r = Rotor radius

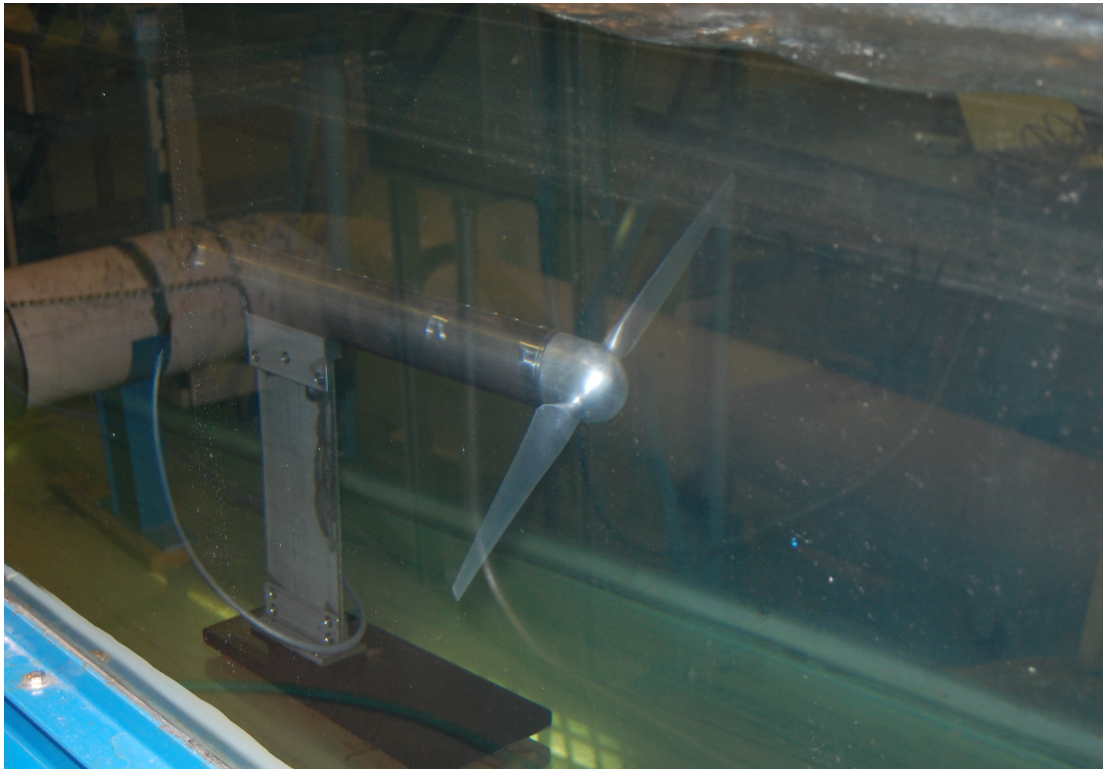
V = Freestream velocity

P = Power extracted by turbine

ρ = Fluid density

C_p = Coefficient of performance, or efficiency

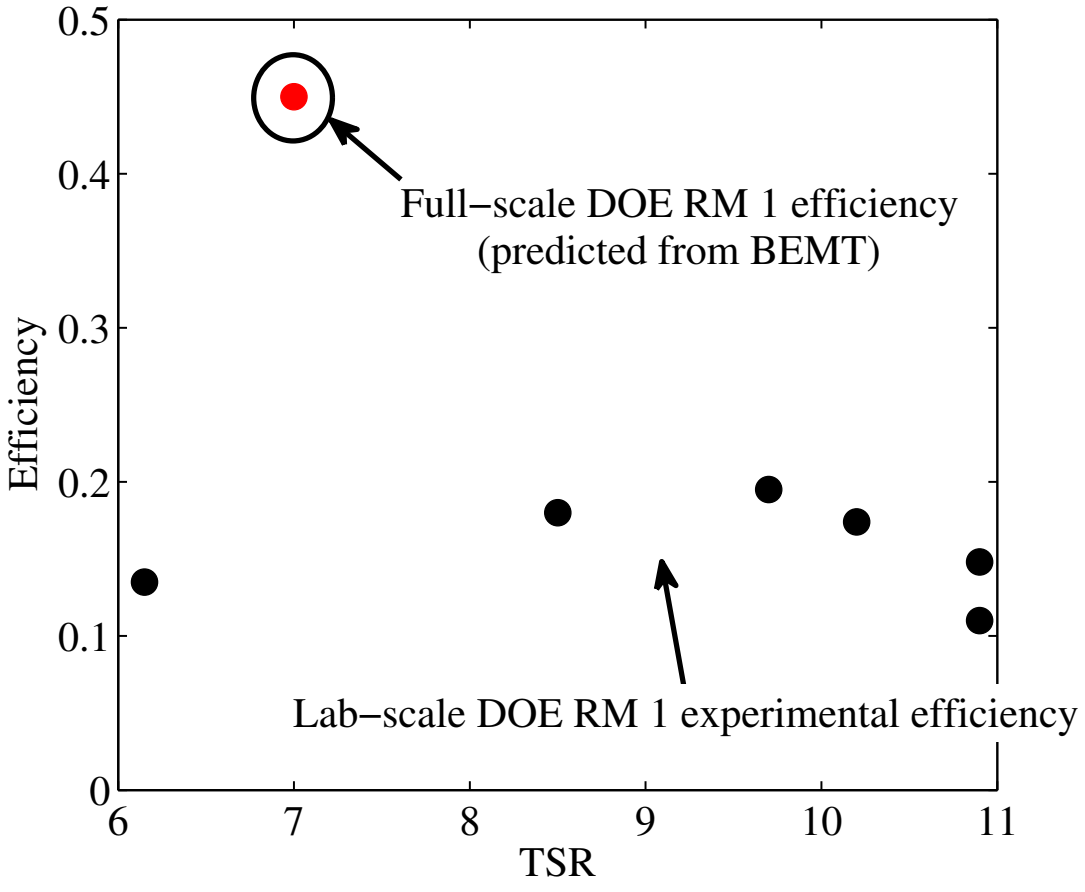
Department of Energy Reference Model 1



Photograph of the laboratory-scale DOE reference model 1

- Created to standardize experimental and numerical results
- Full-scale diameter of 20 m
- 45:1 scaling $\rightarrow$ 45cm diameter experimental scale
- Foils are NACA 63-424 chosen for cavitation prevention
- Experiments encountered Reynolds number effects
- Poor performance required rotor redesign

Department of Energy Reference Model 1



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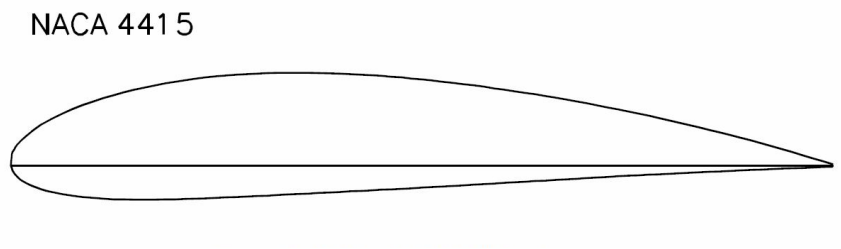
Laboratory-scale rotor geometry

- Maximize chord-based Reynolds number
- Choose foil to minimize Reynolds number effects
- Match performance and optimum tip speed ratio with blade-element momentum design code
- Attempt to match power extraction and wake characteristics at scale, not geometry



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REYNOLDS NUMBER DEPENDENCE

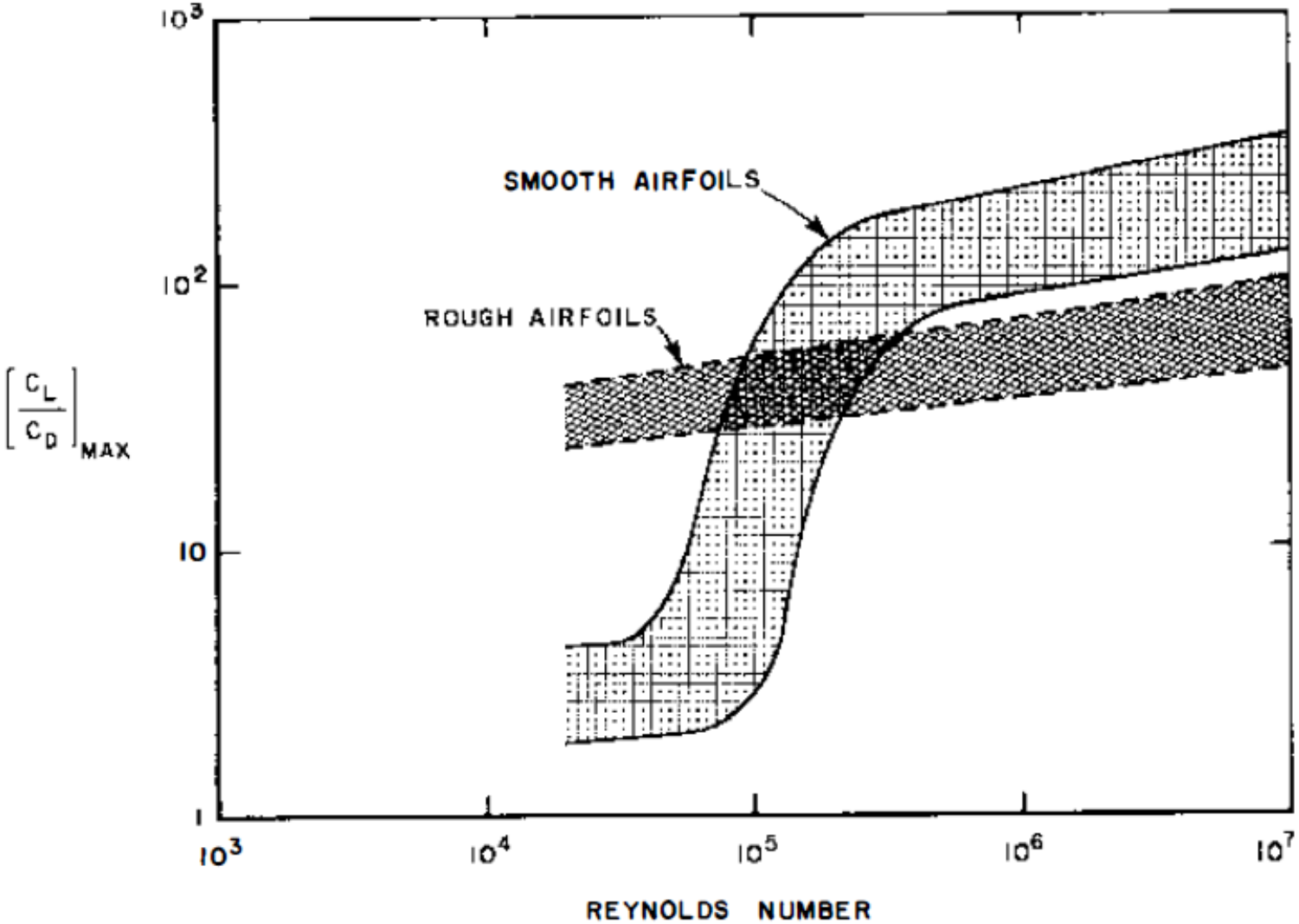
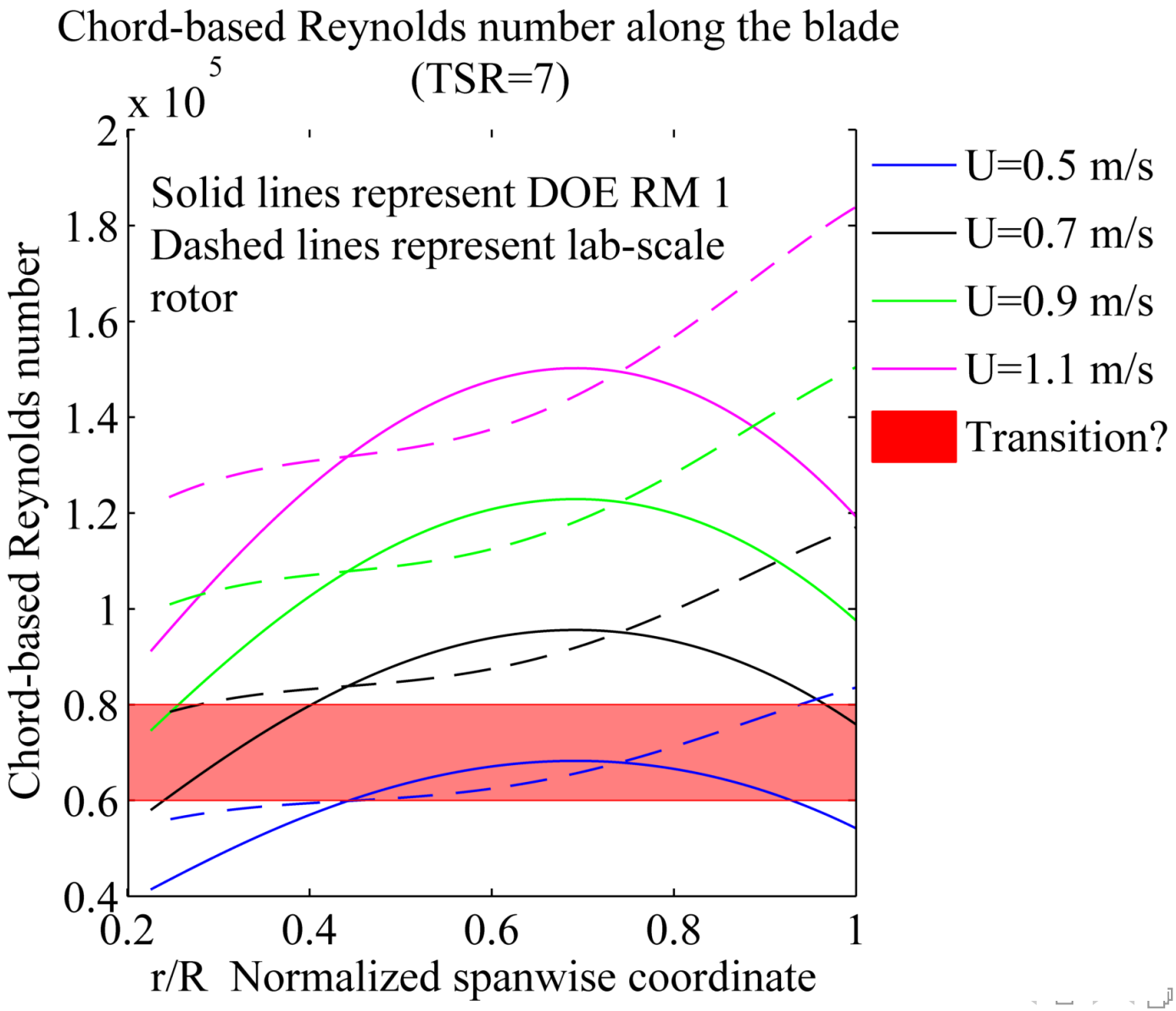
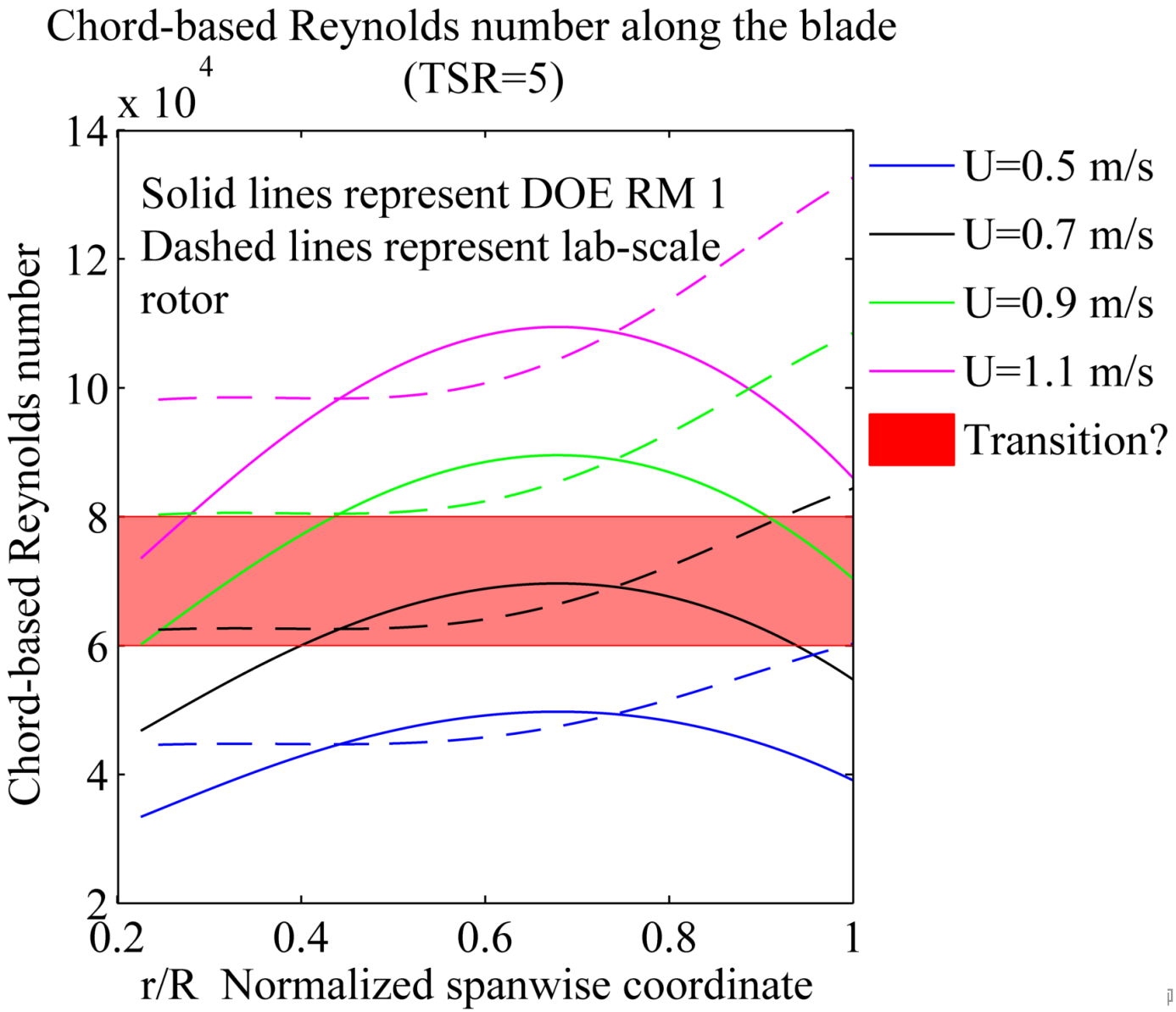


Figure 2 Low-Reynolds-number airfoil performance.

Chord-based Reynolds number

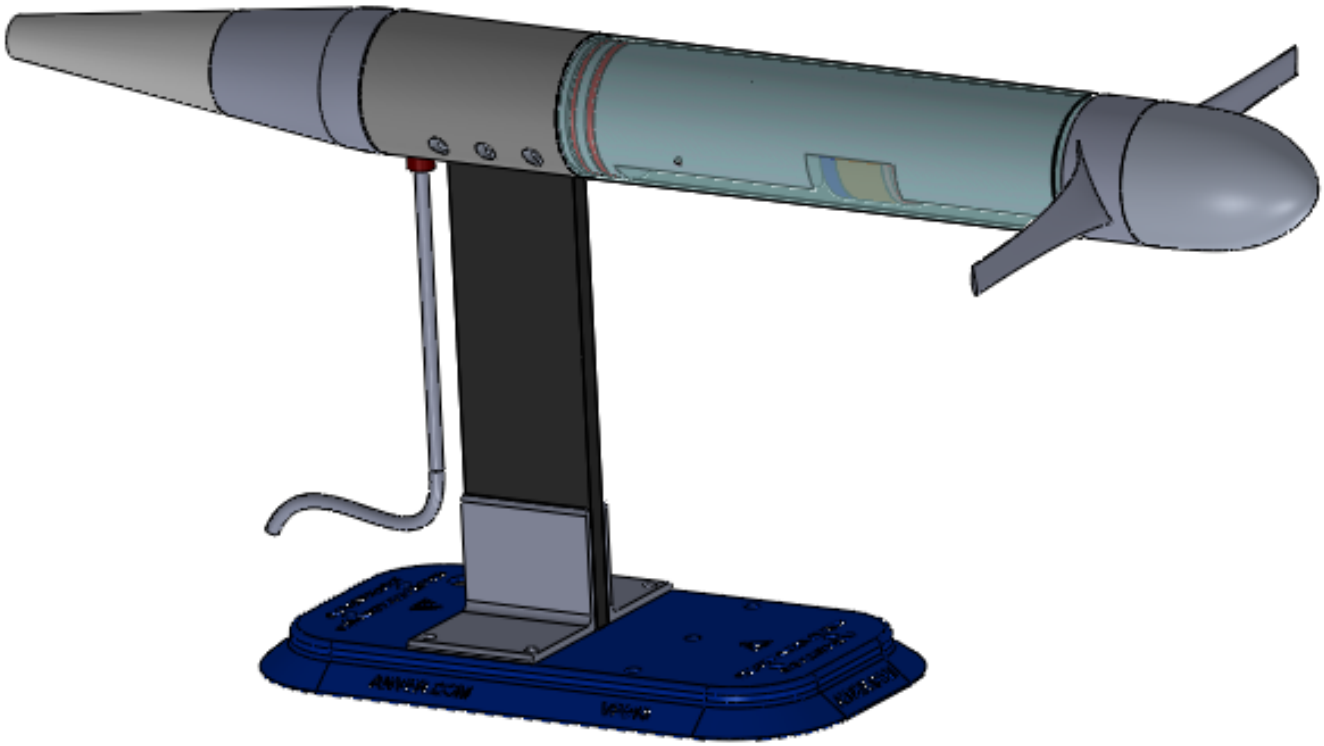


Chord-based Reynolds number



LABORATORY-SCALE TURBINE

45 cm diameter rotor



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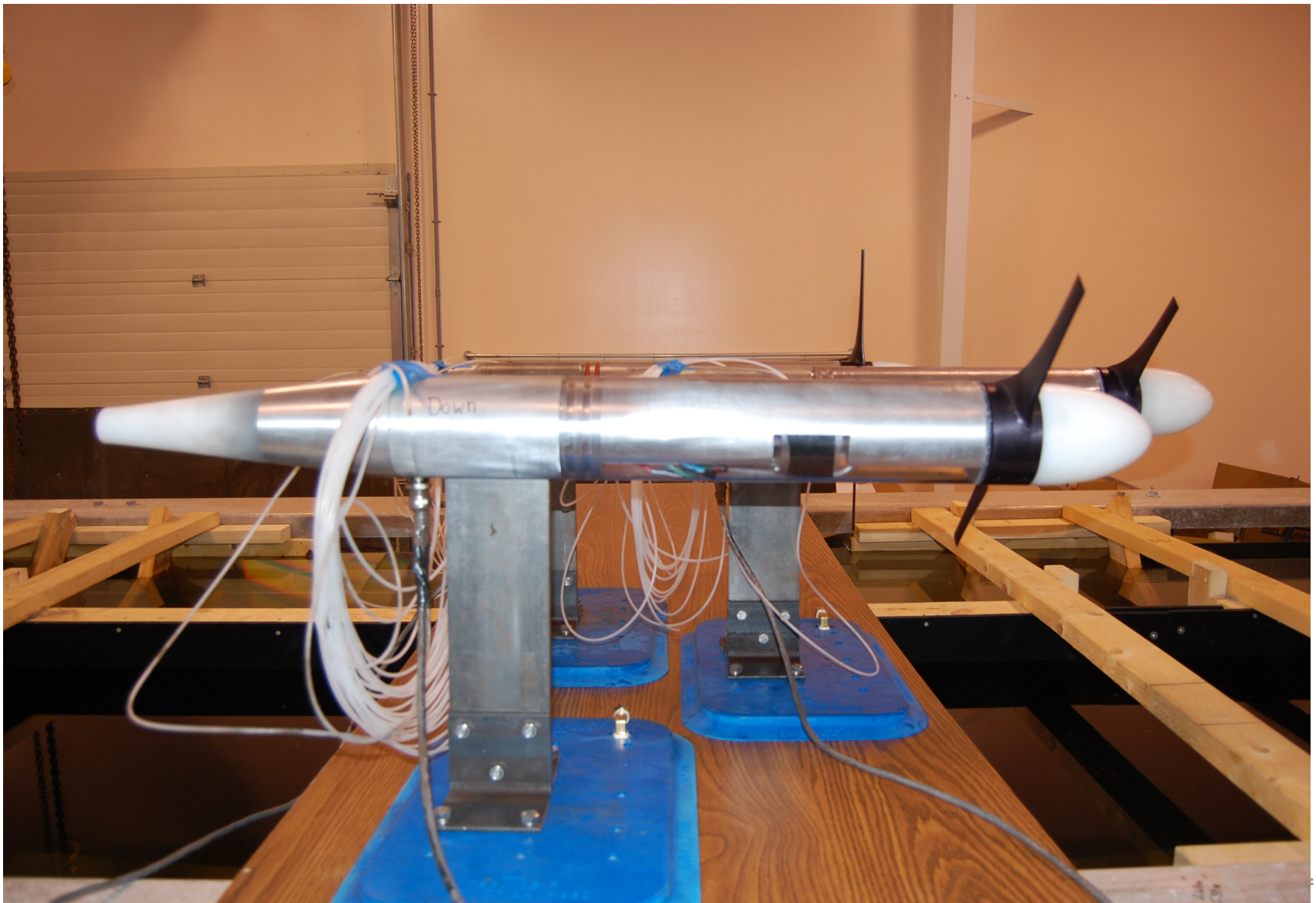
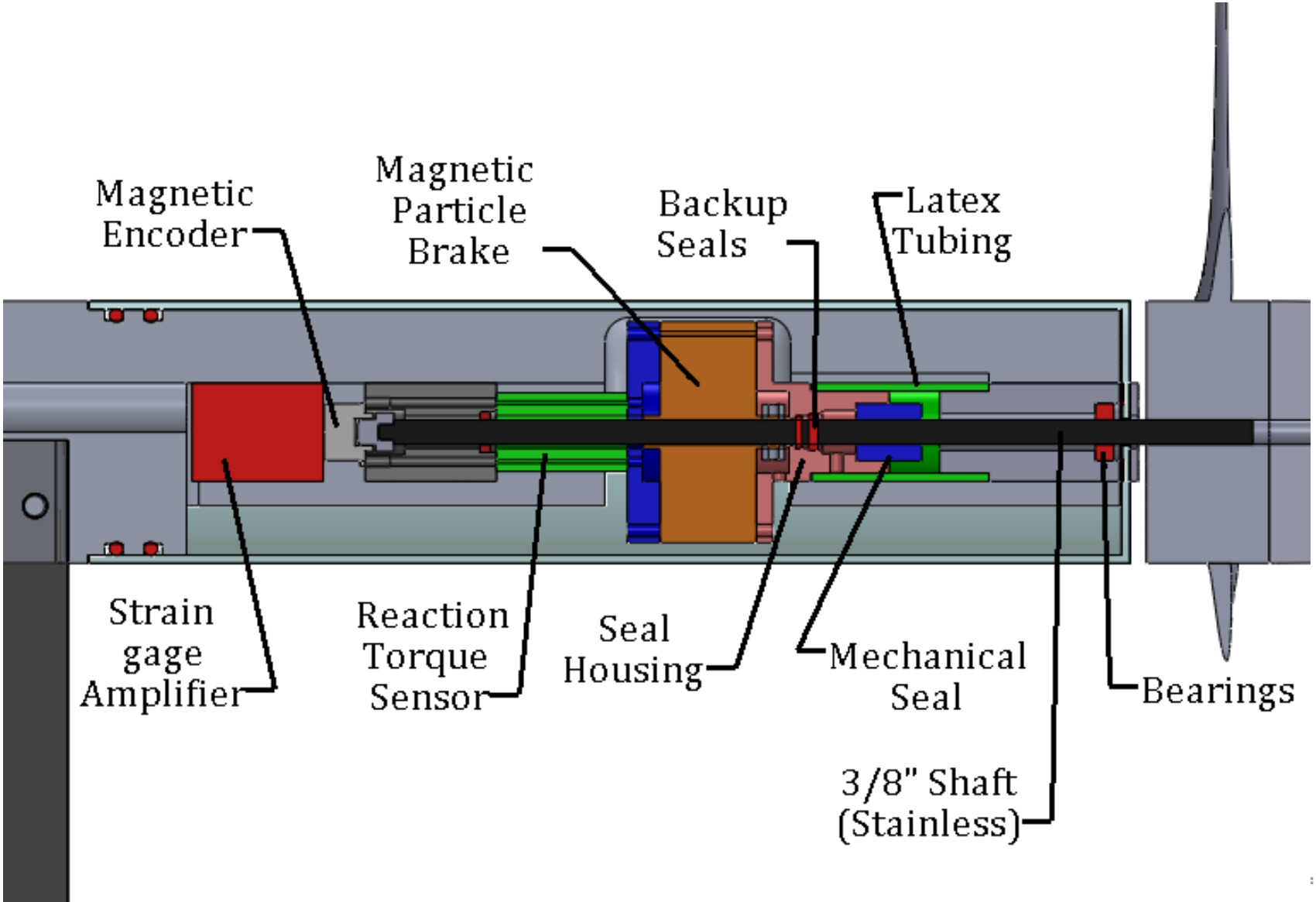
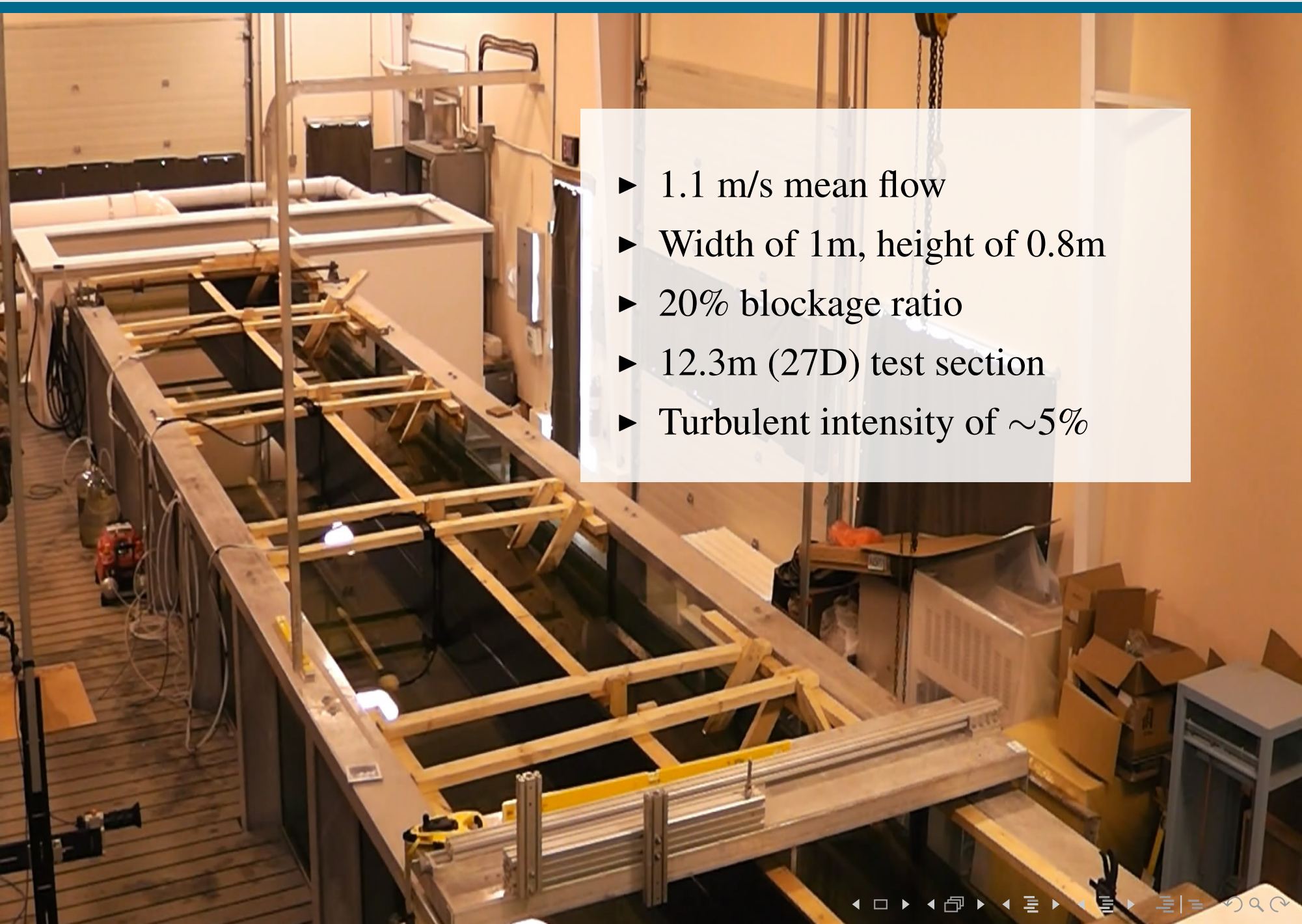


Laboratory-scale turbine

Instrumentation and Seals

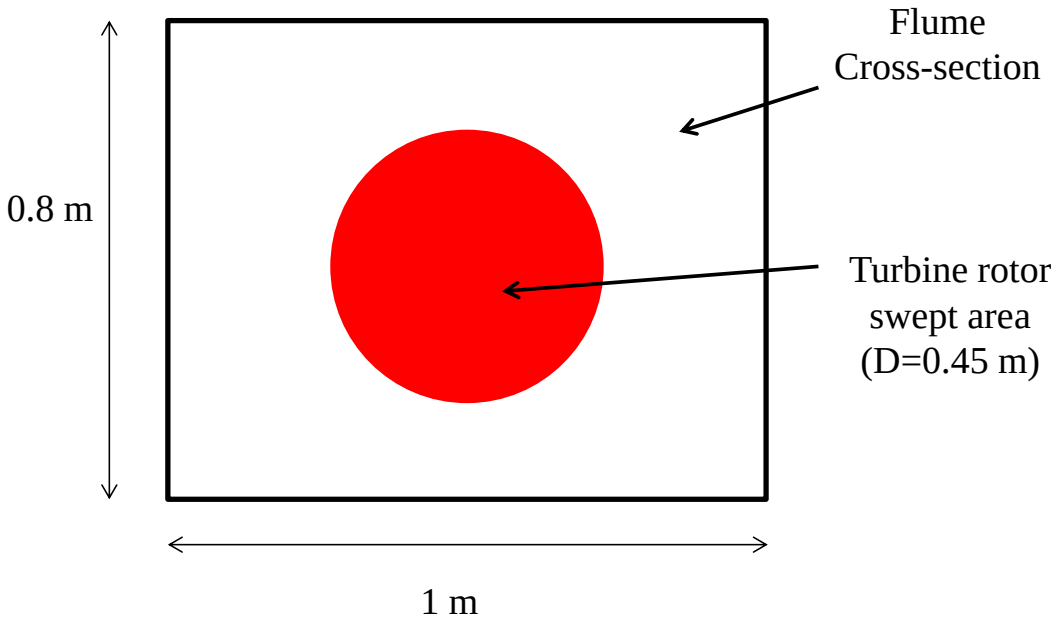




- 1.1 m/s mean flow
- Width of 1m, height of 0.8m
- 20% blockage ratio
- 12.3m (27D) test section
- Turbulent intensity of $\sim$5%

BLOCKAGE EFFECTS

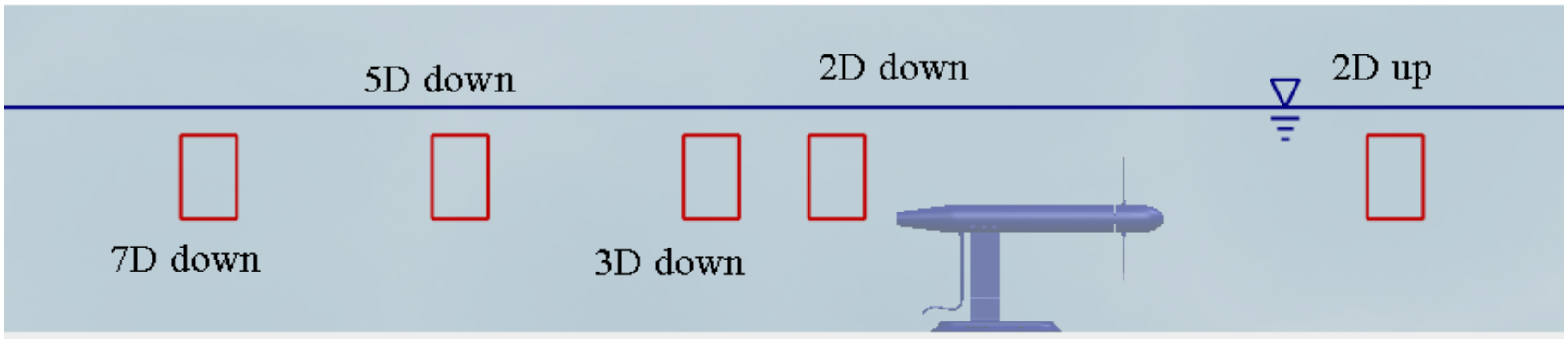
$$\text{Blockage ratio} = \frac{\text{swept area of rotor}}{\text{channel cross-sectional area}} = 20\%$$



- Blockage increases turbine performance
- Blockage restricts wake expansion
- Blockage correction methods are not settled

DATA COLLECTION

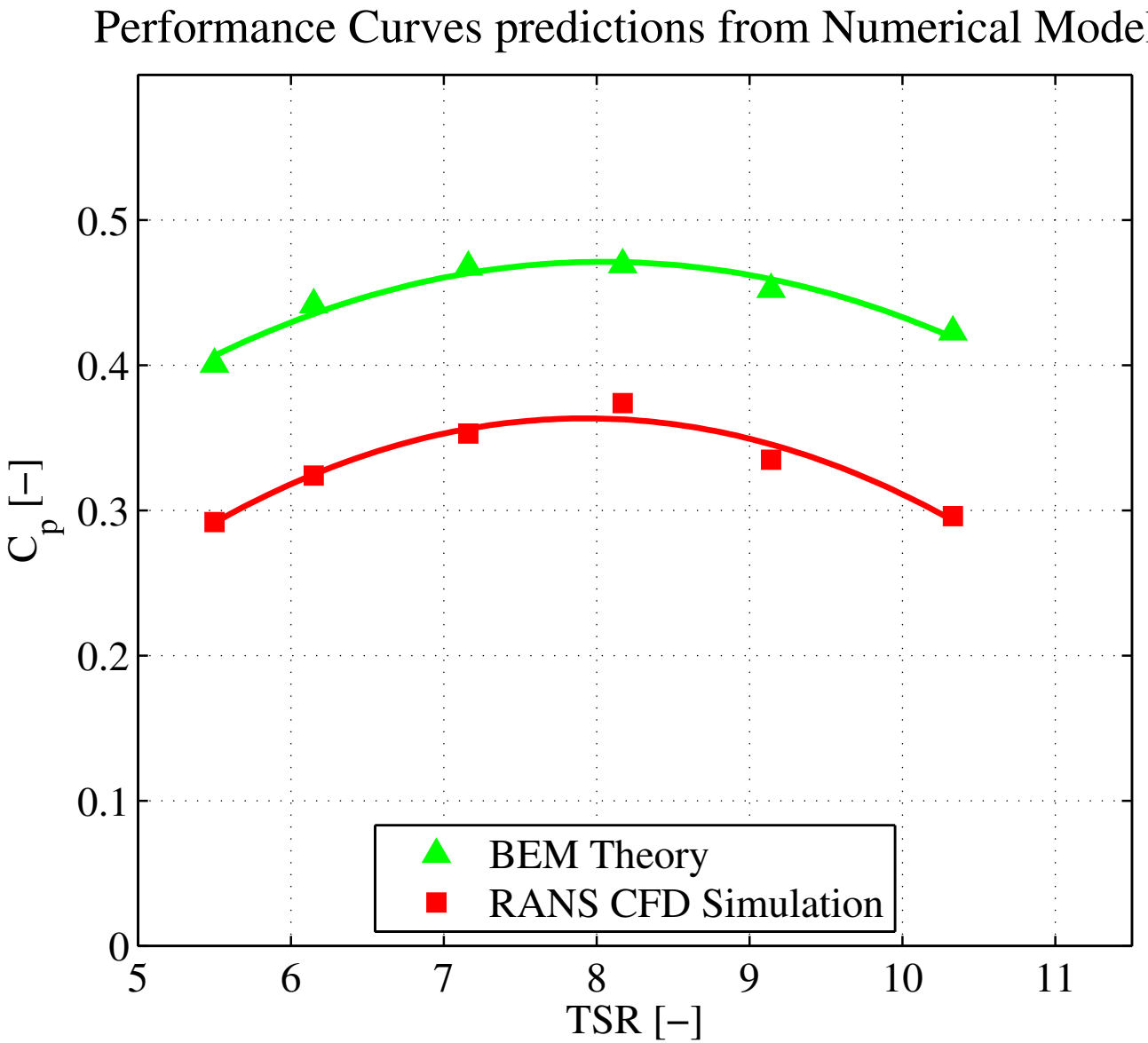
- Rotor rotational position,1000 Hz
- Developed torque, 1000 Hz



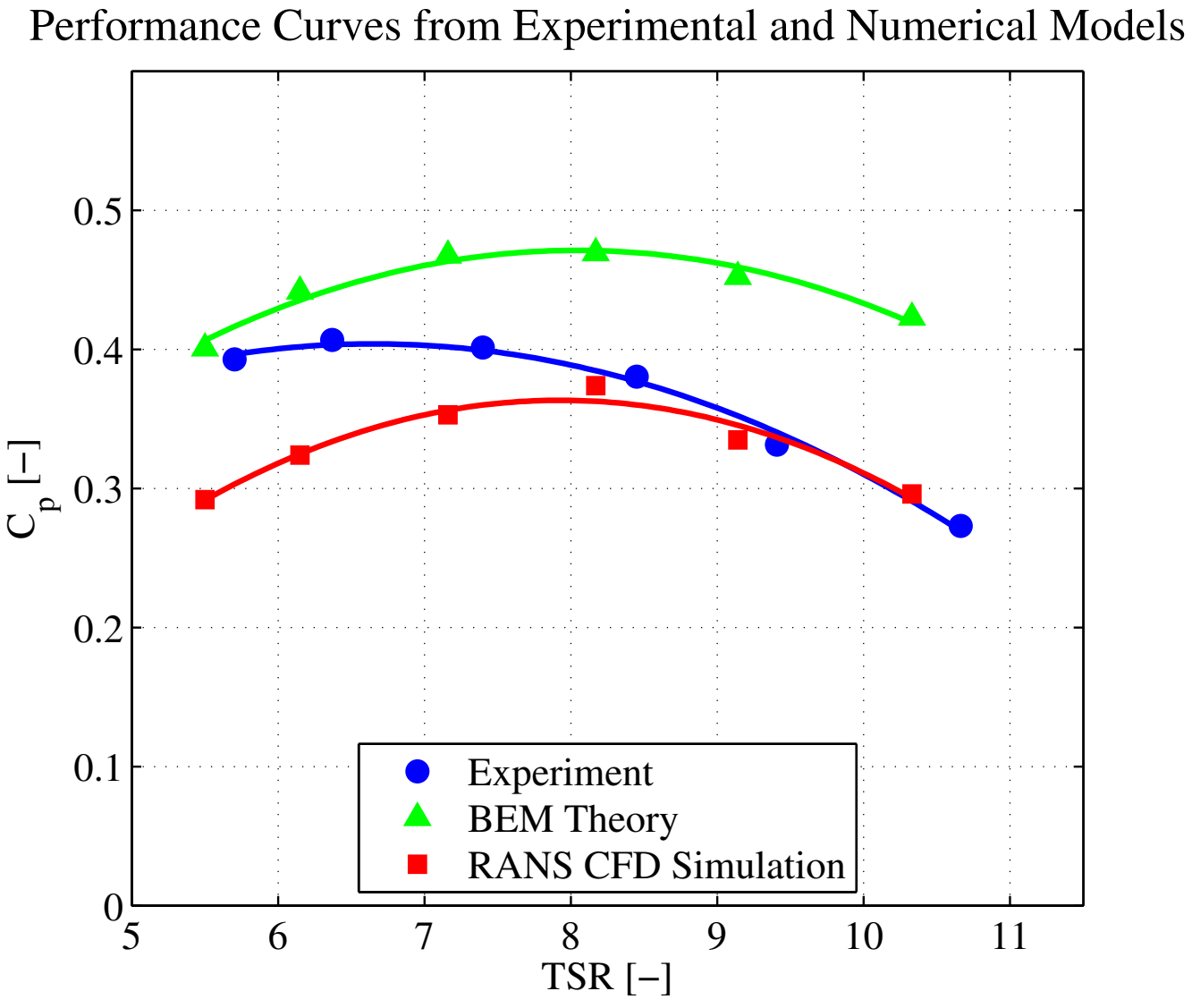
Particle Image Velocimetry (PIV):

- Interrogation windows located on turbine axis
- Only upper half of water column
- FOV is 30 cm by 20 cm
- Image acquisition rate is 5 Hz

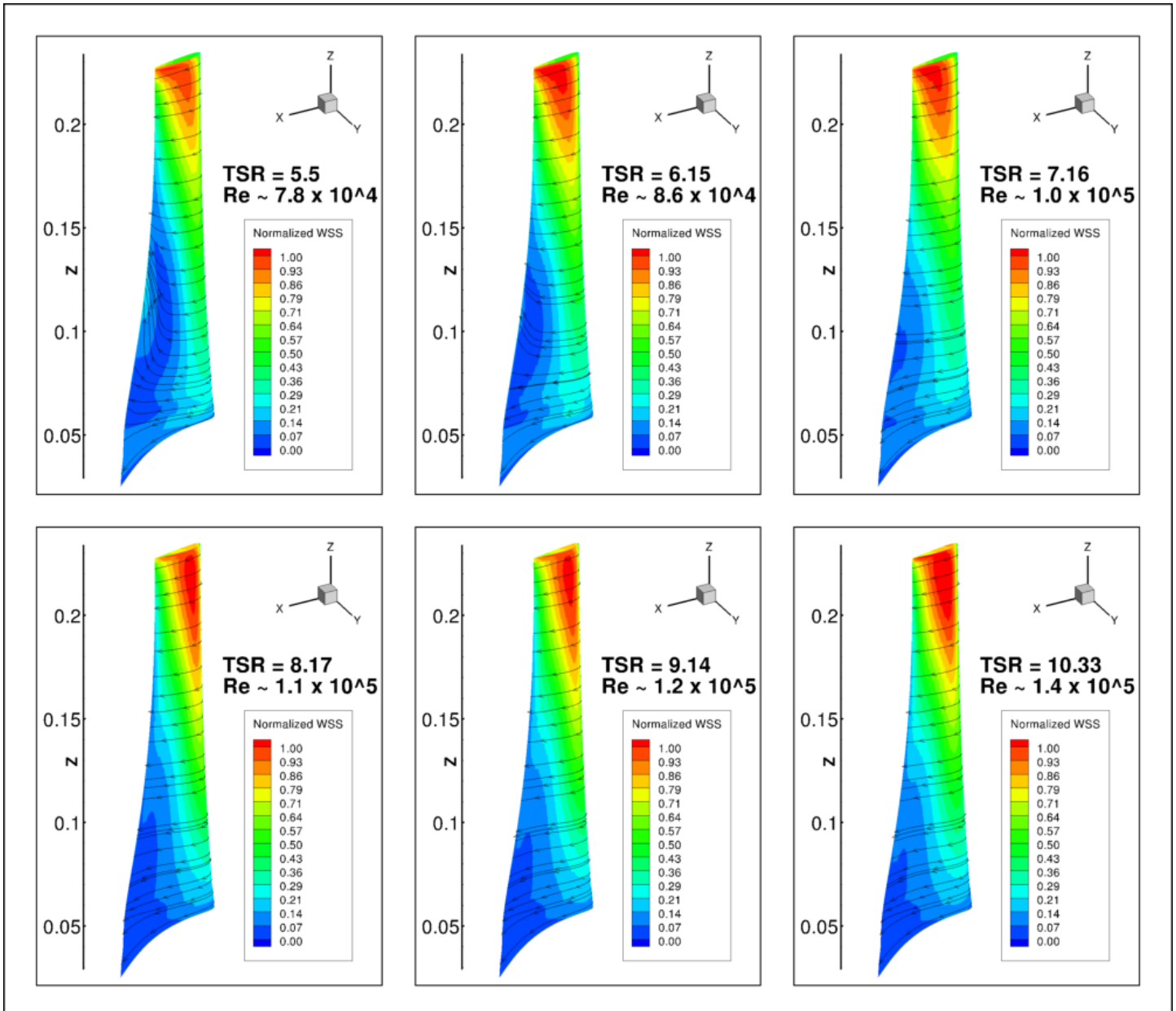
PERFORMANCE OF A SINGLE TURBINE



PERFORMANCE OF A SINGLE TURBINE



STALL IN CFD SIMULATION



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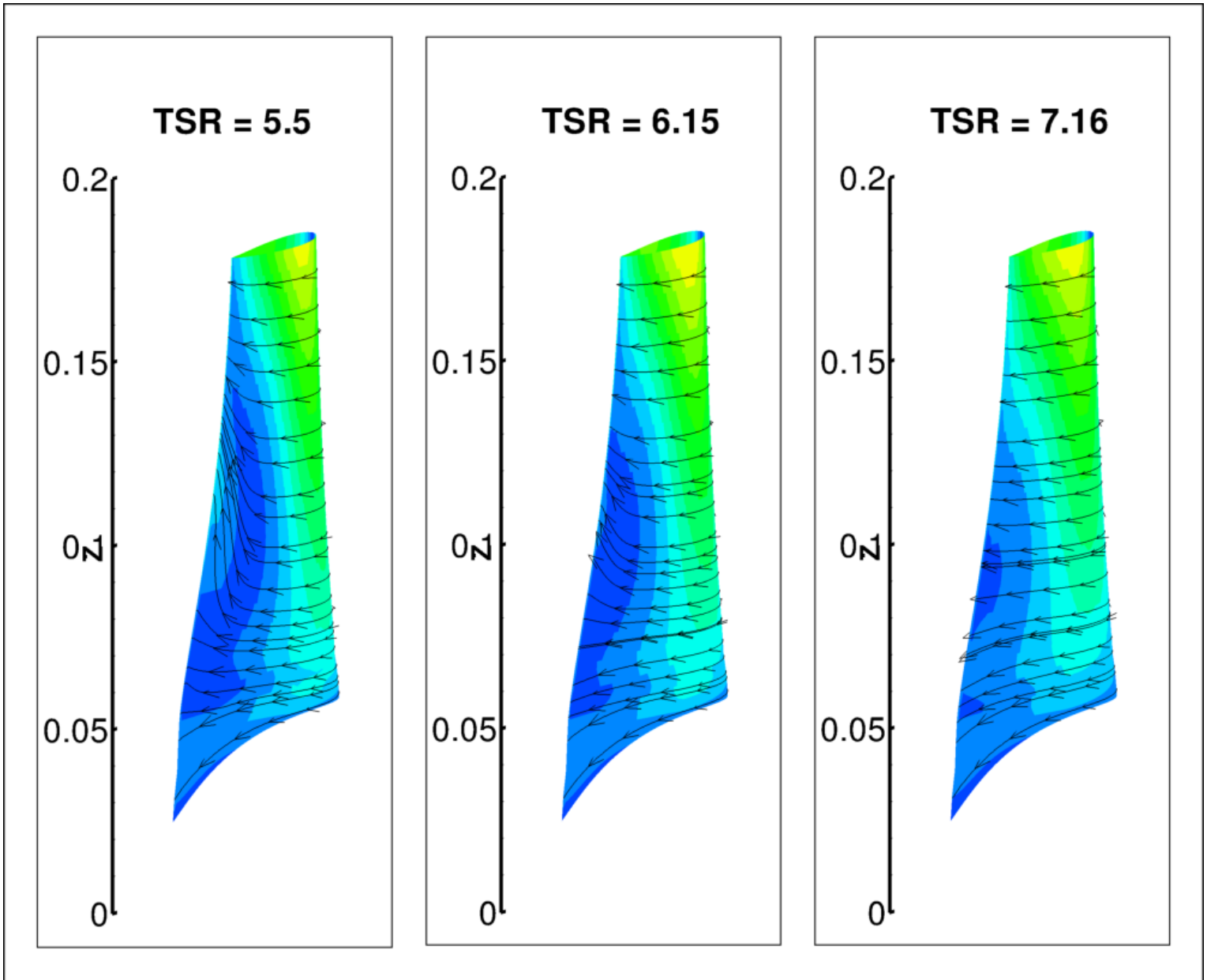
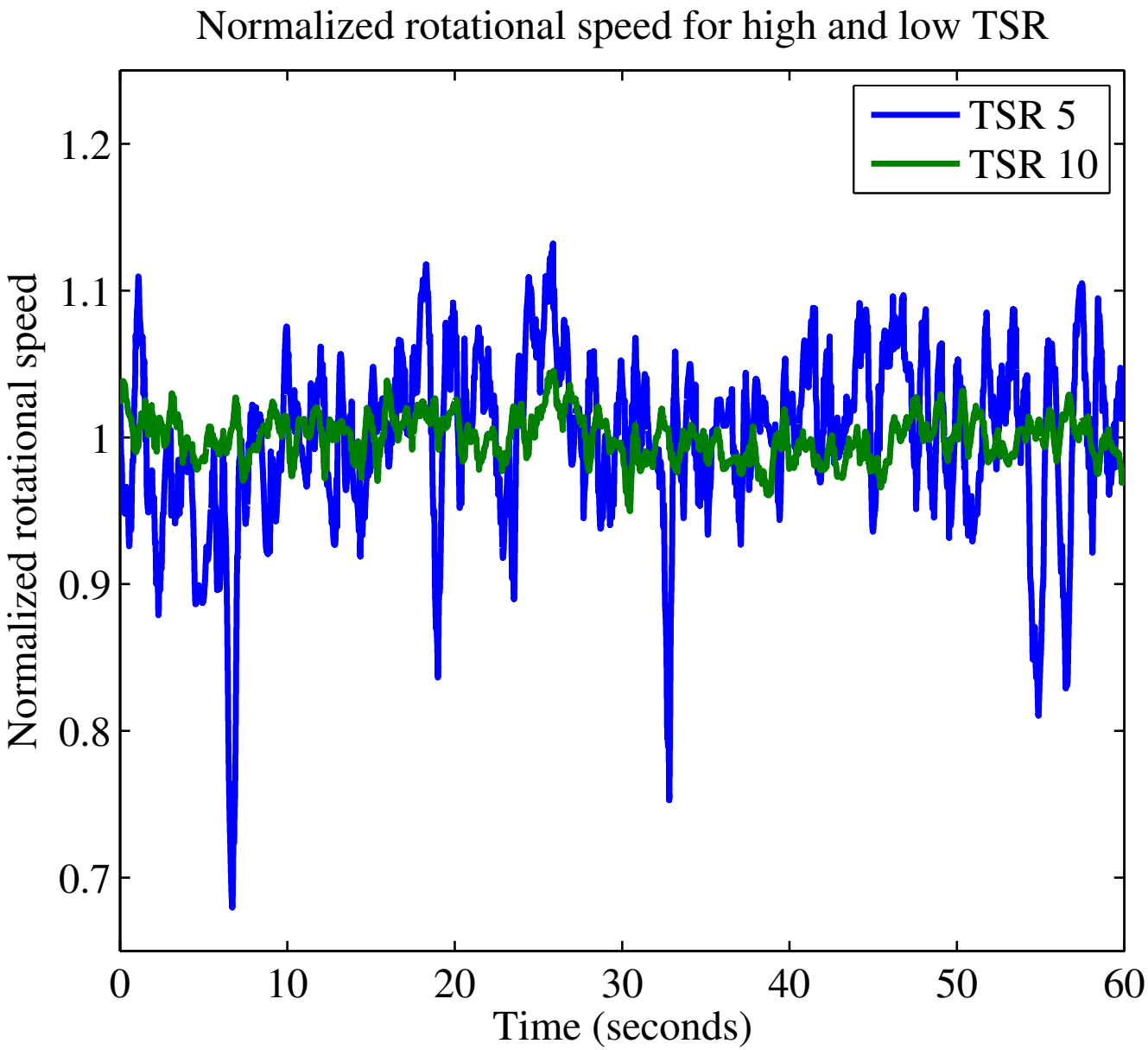
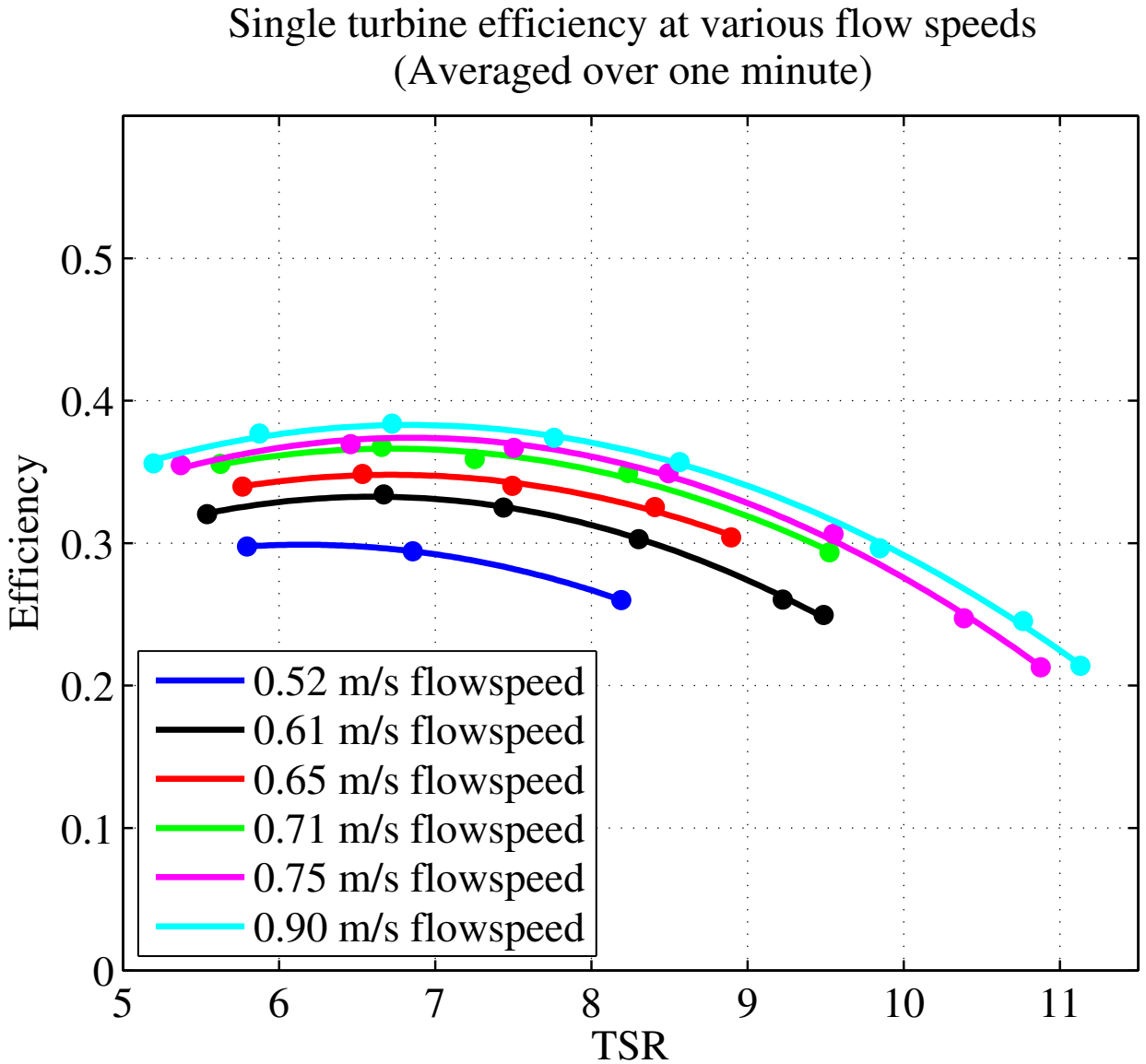


STALL DELAY AT LOW TSR?

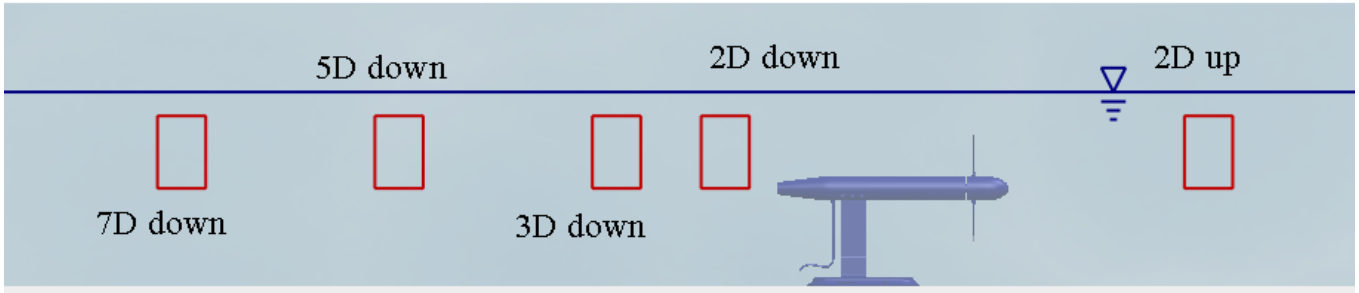


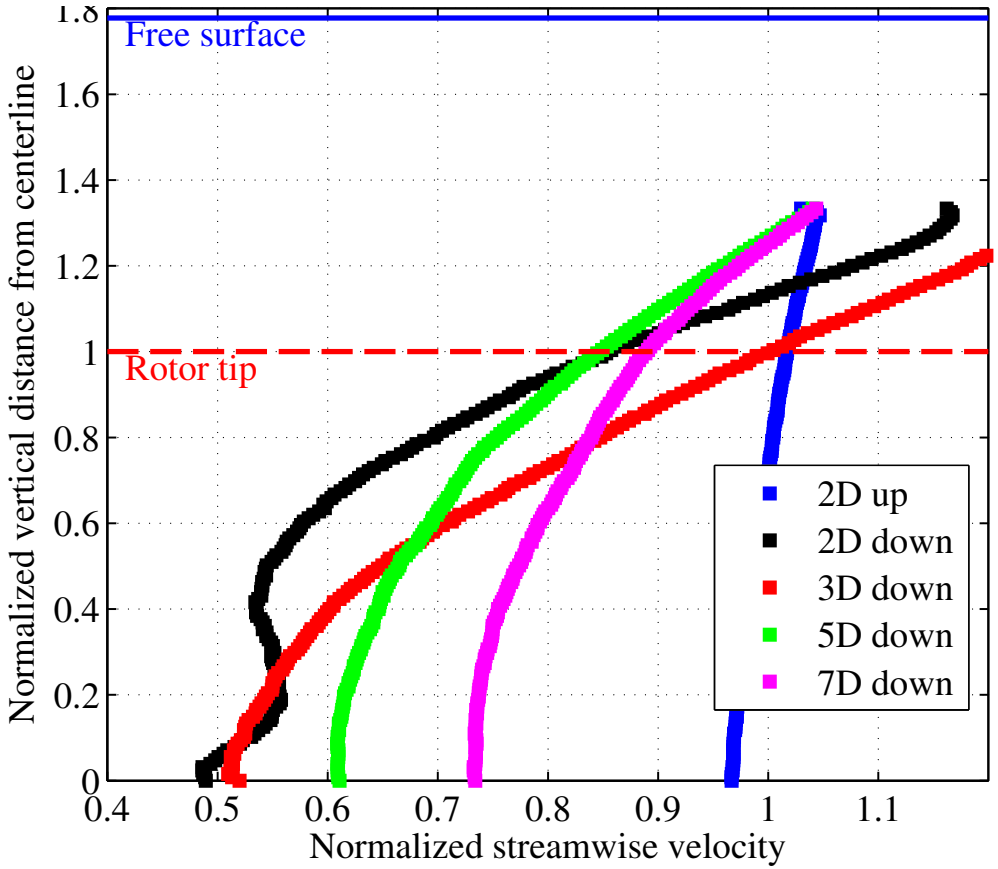
Reynolds number effects



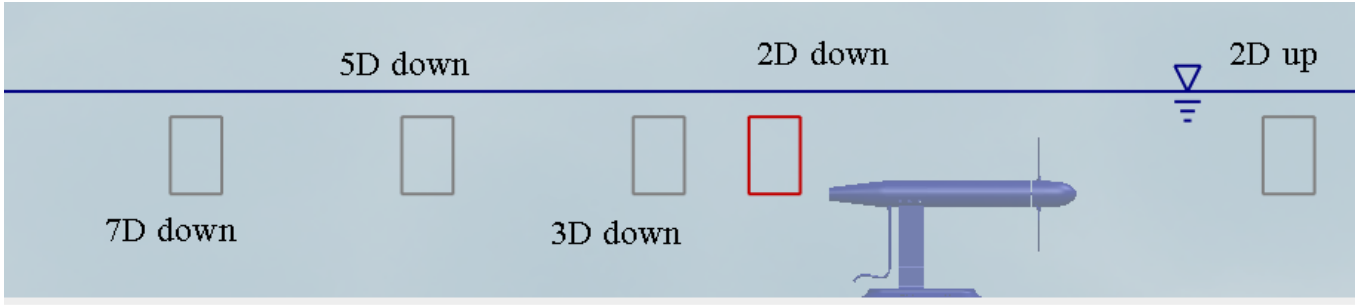
Tidal Turbine Wakes

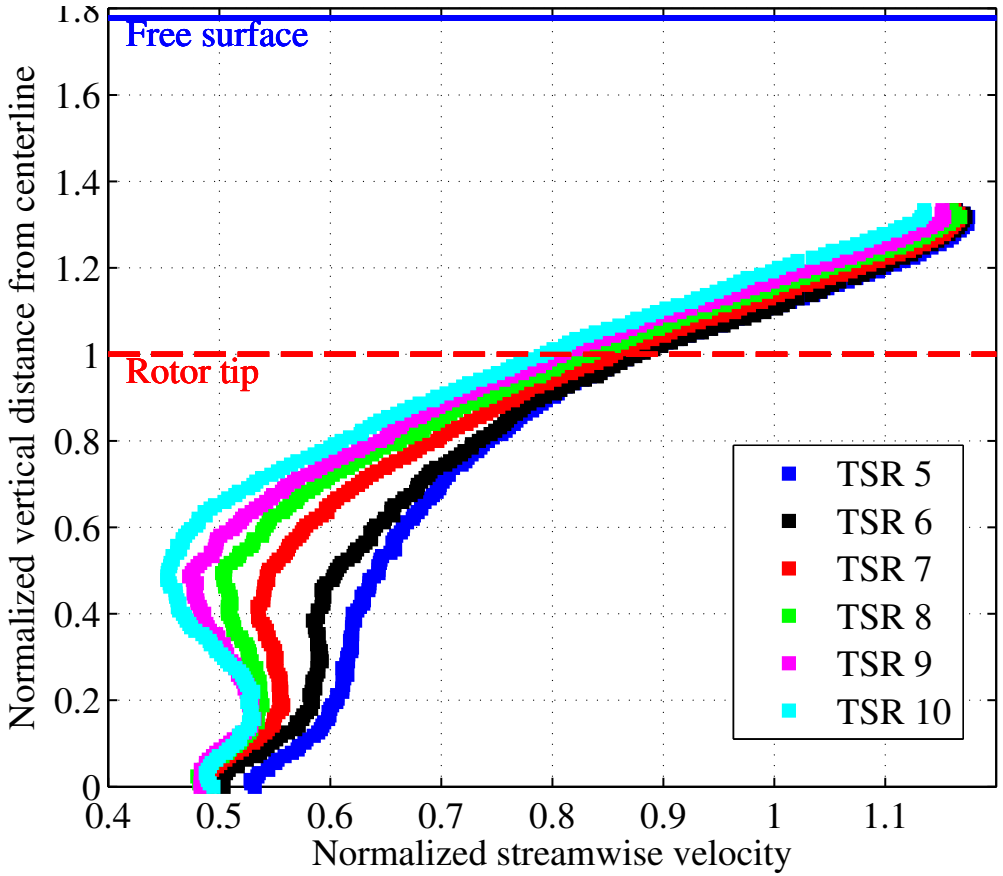
VELOCITY PROFILES IN THE WAKE





VELOCITY PROFILES IN THE WAKE AT VARIOUS TSR





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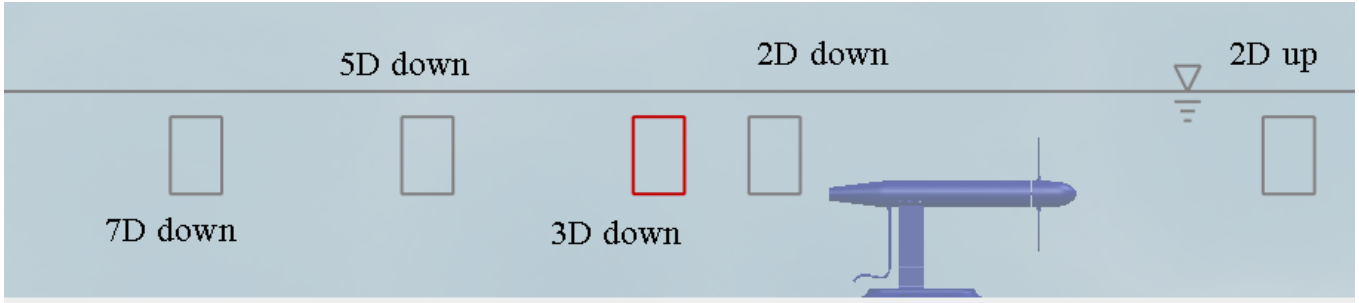

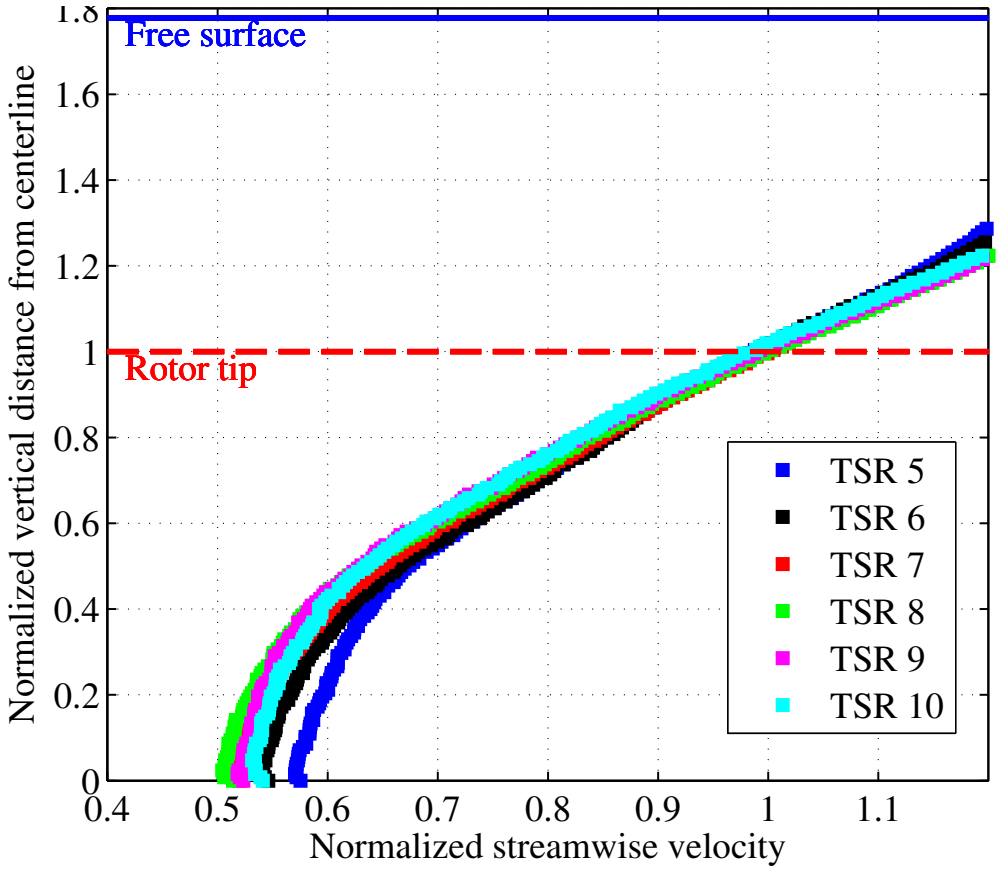

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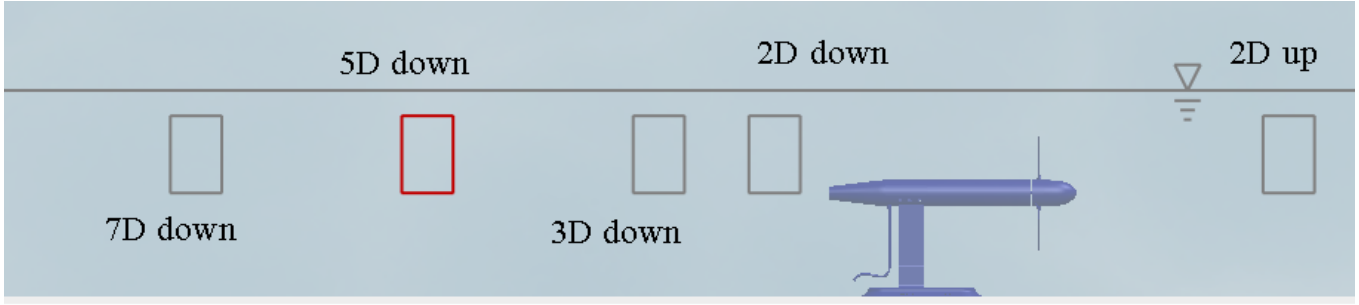

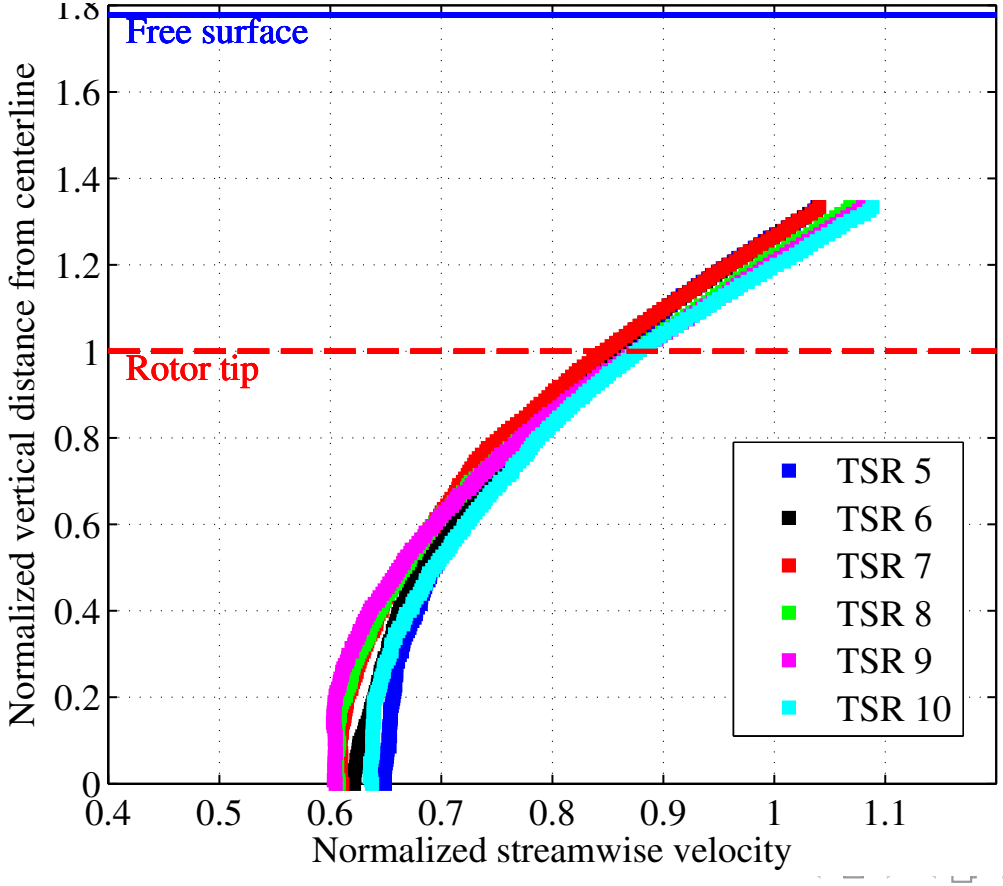

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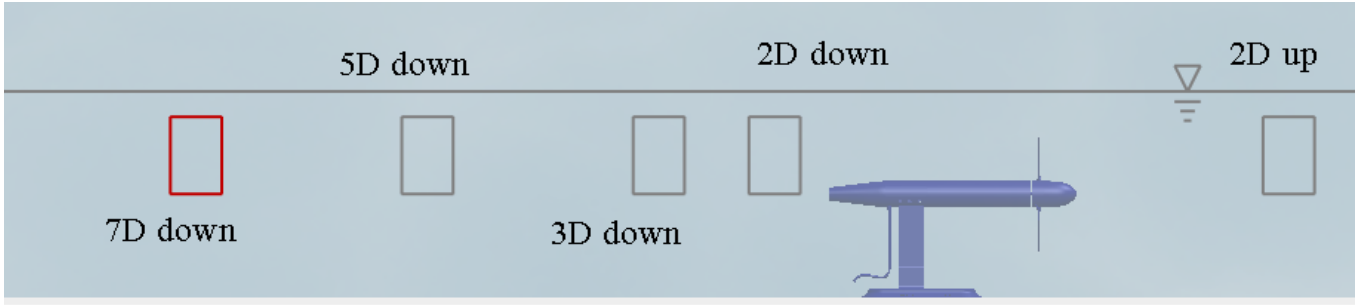
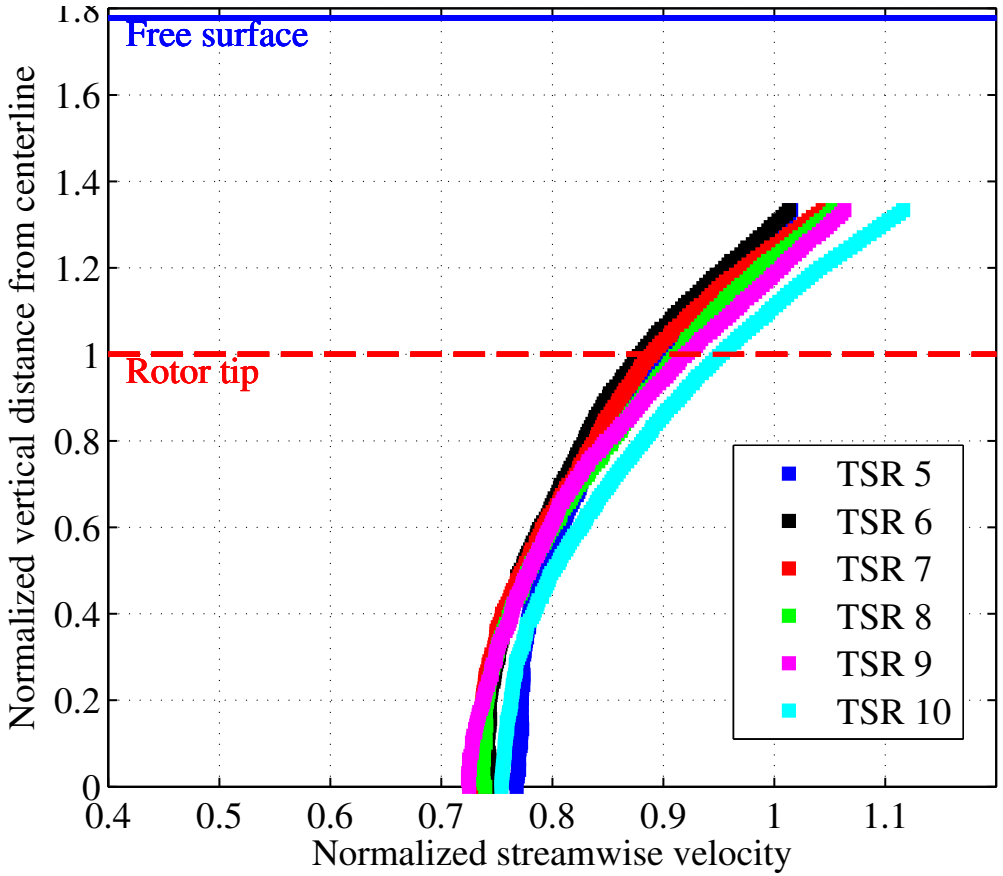
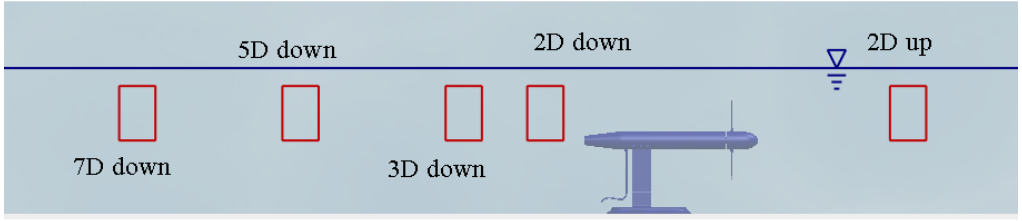
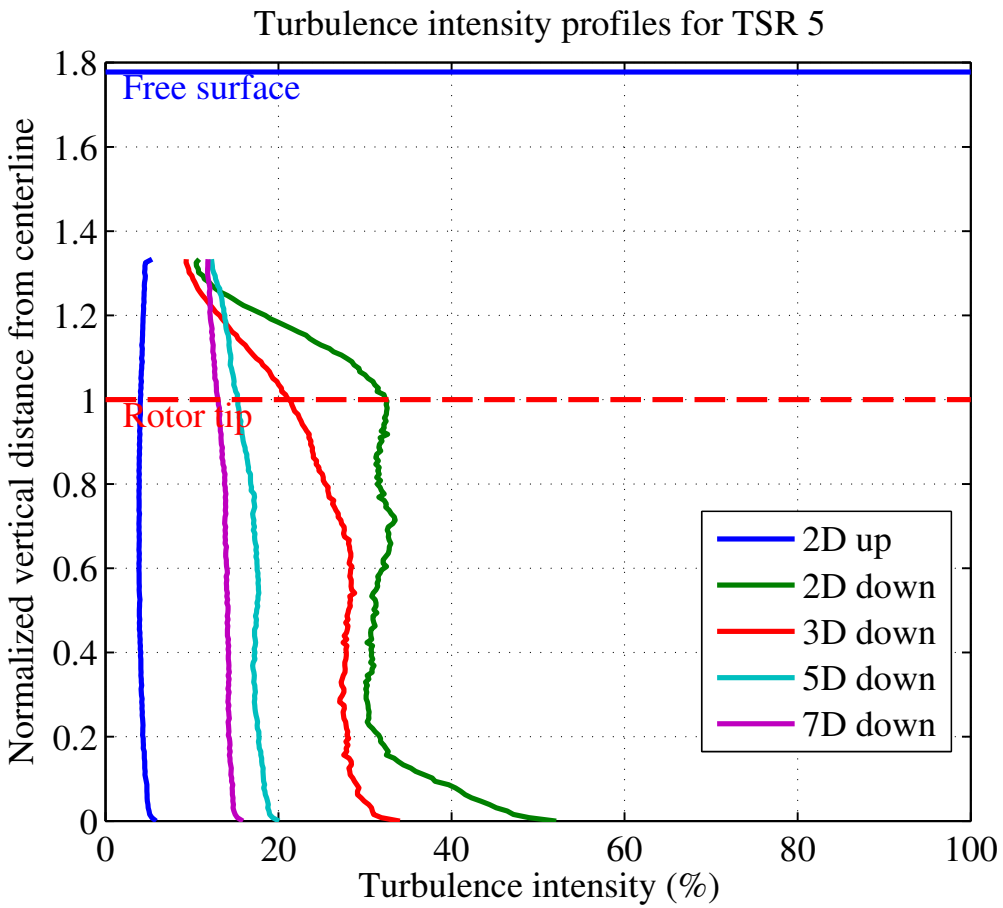




TURBULENCE INTENSITY PROFILES IN THE WAKE





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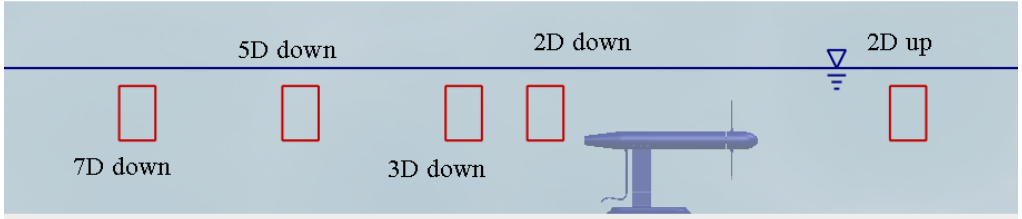

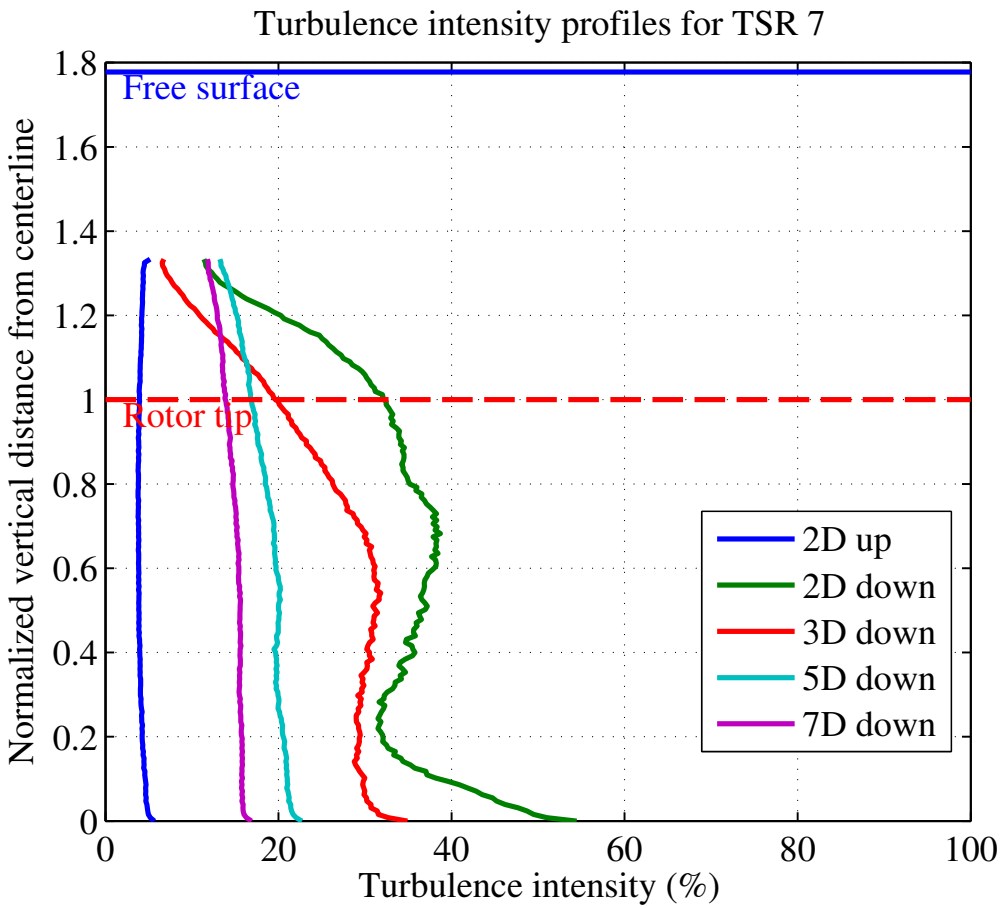

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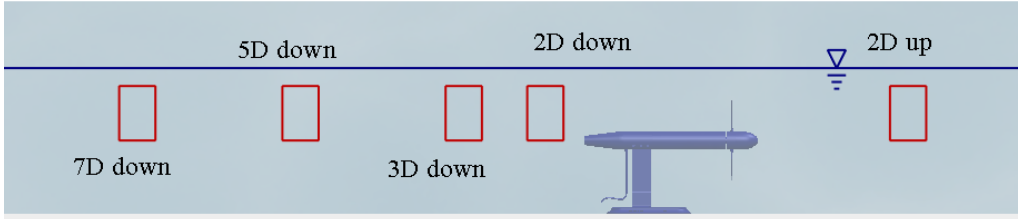
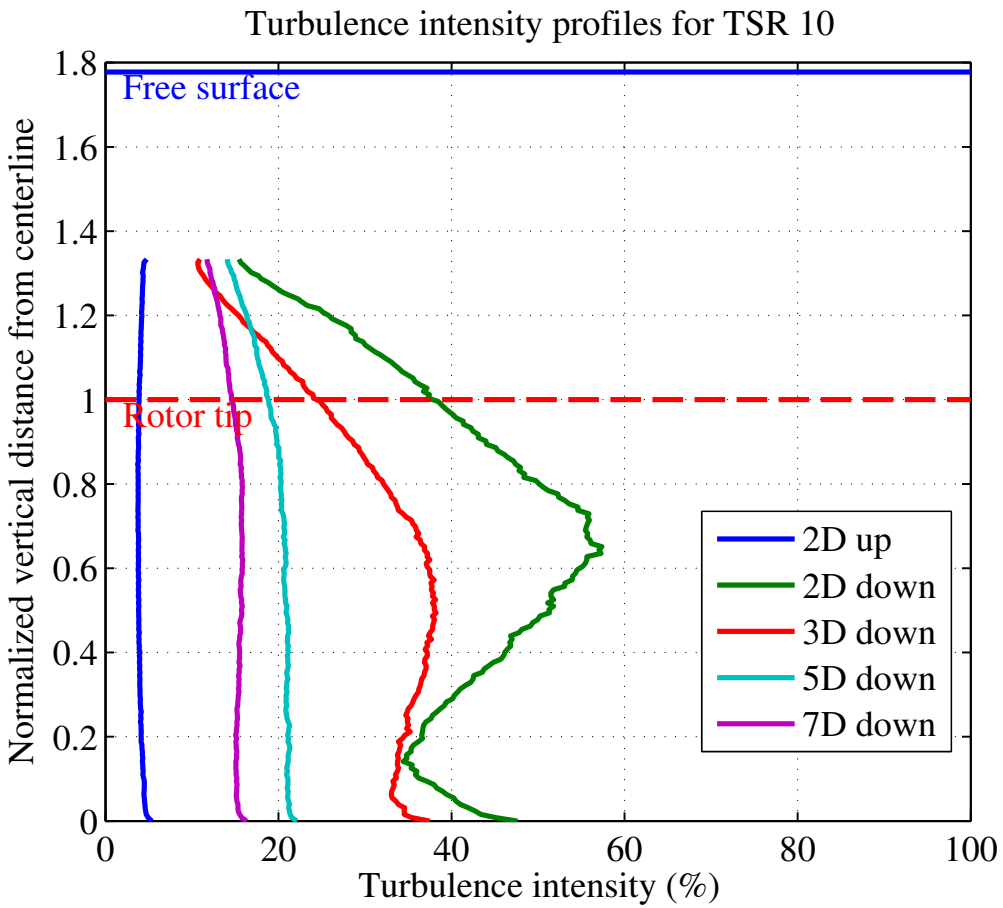
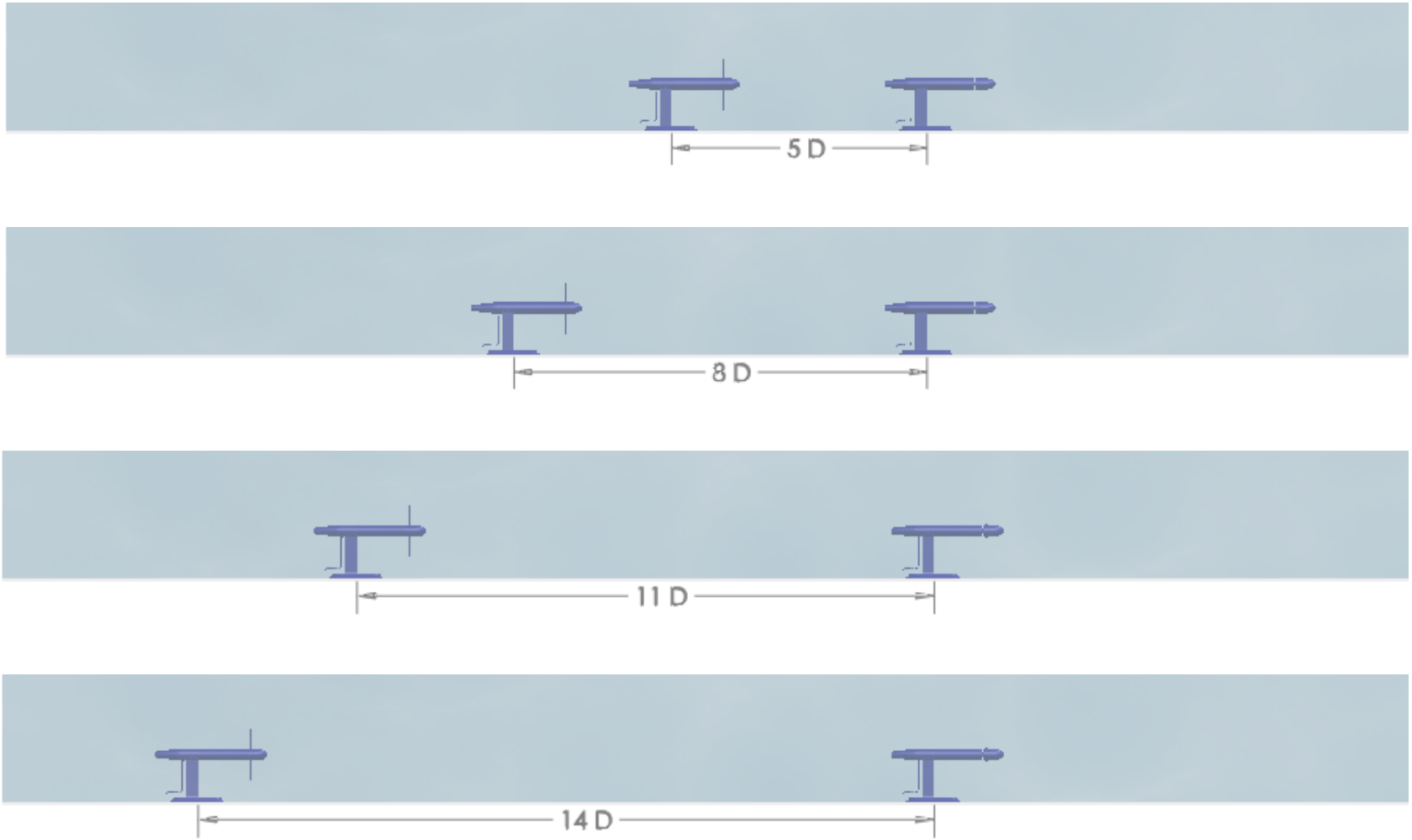
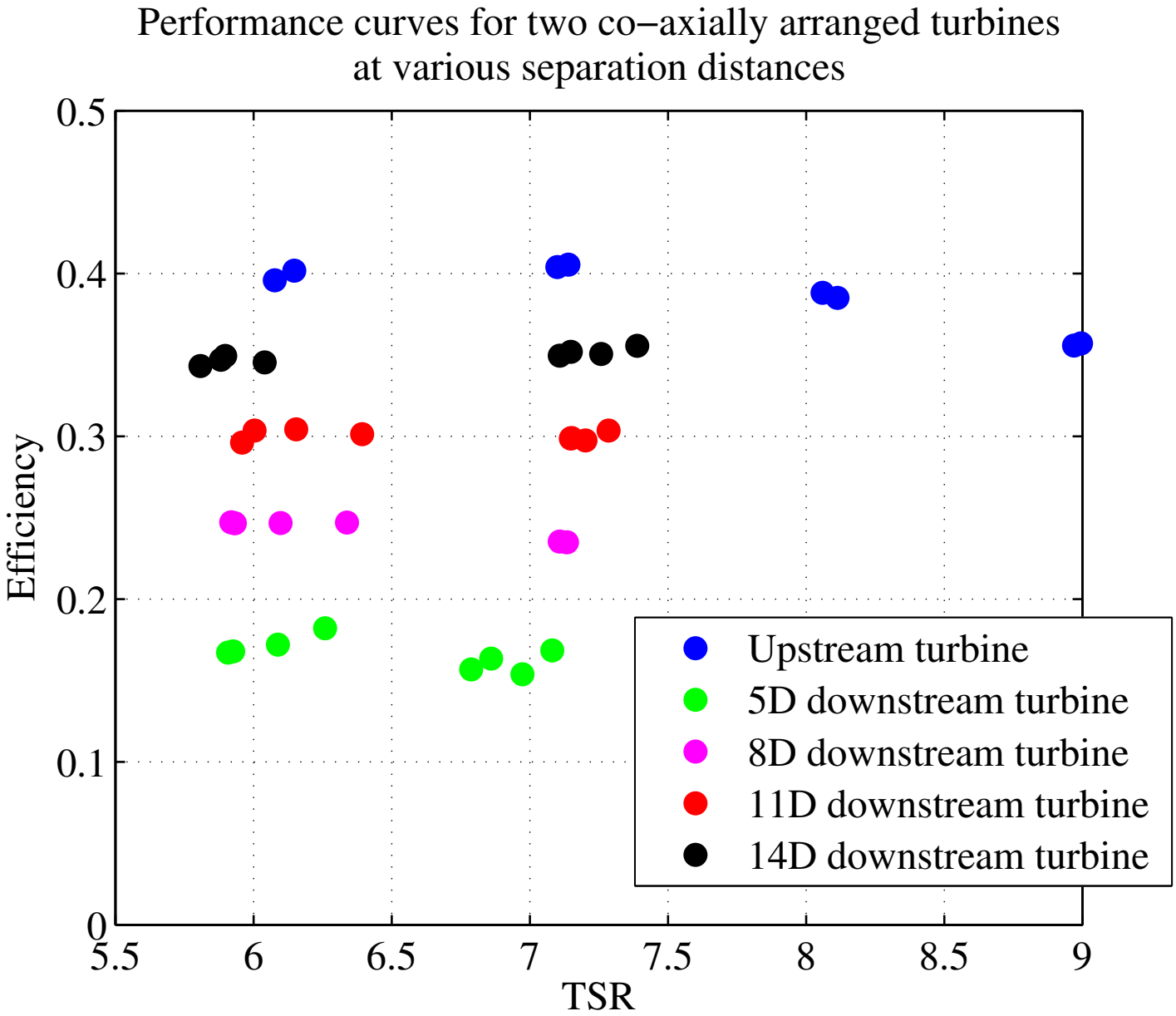




Two co-axial turbines at various spacings



TWO CO-AXIAL TURBINES PERFORMANCE



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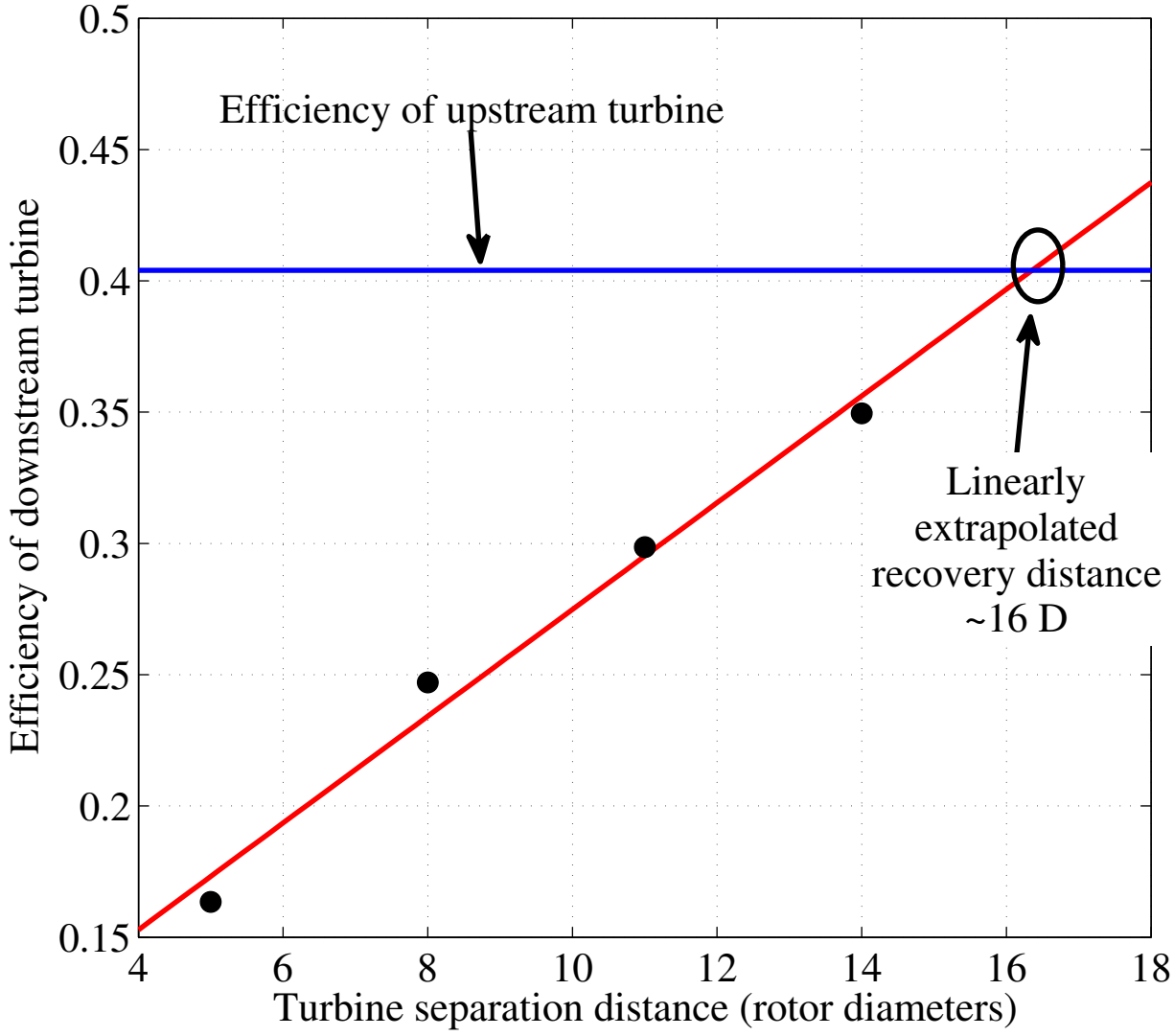
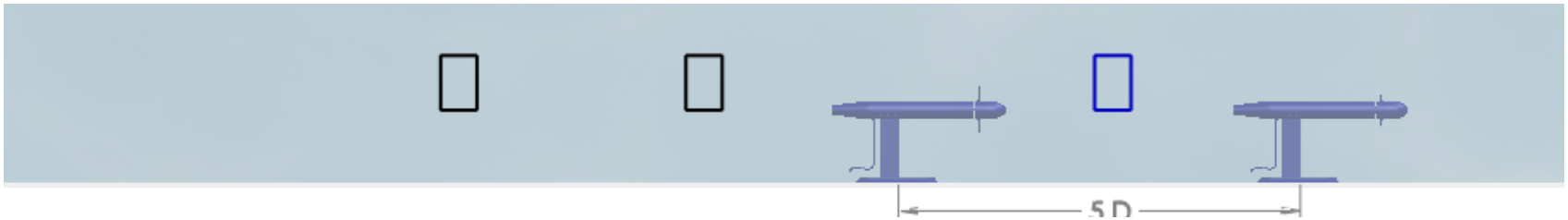
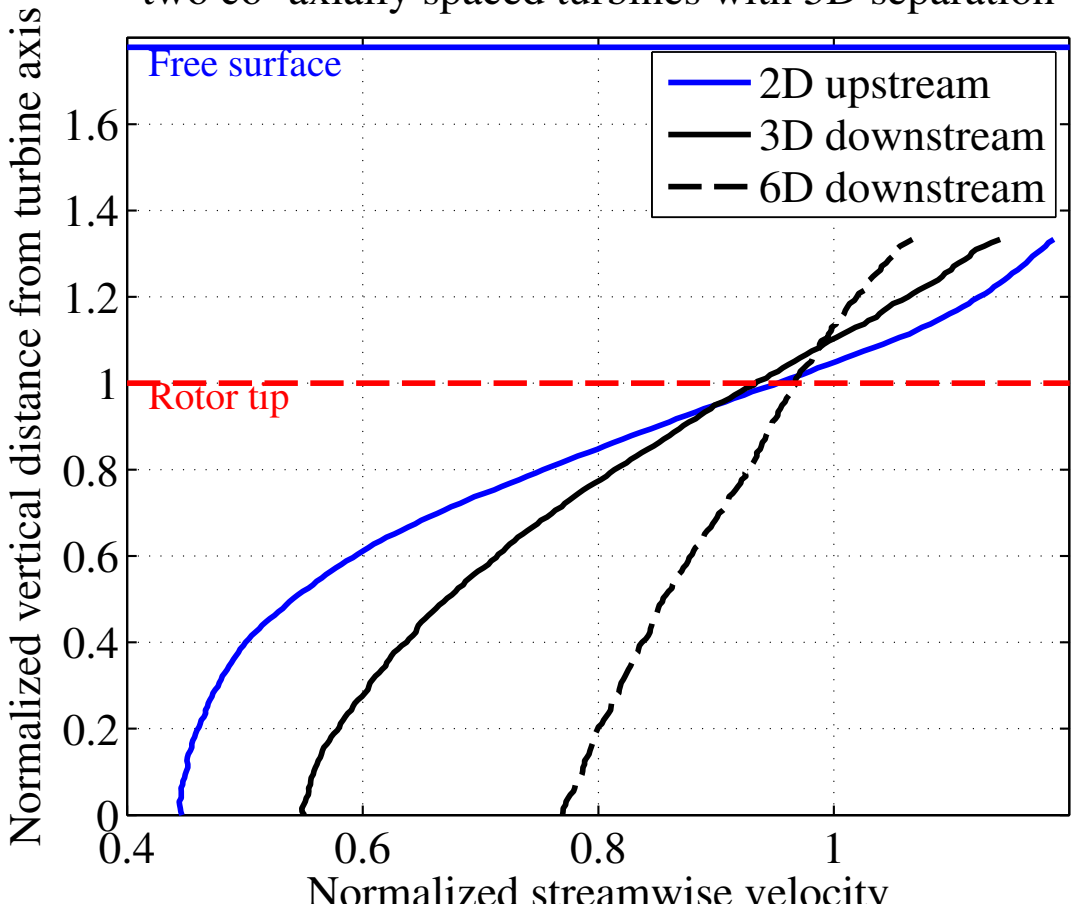


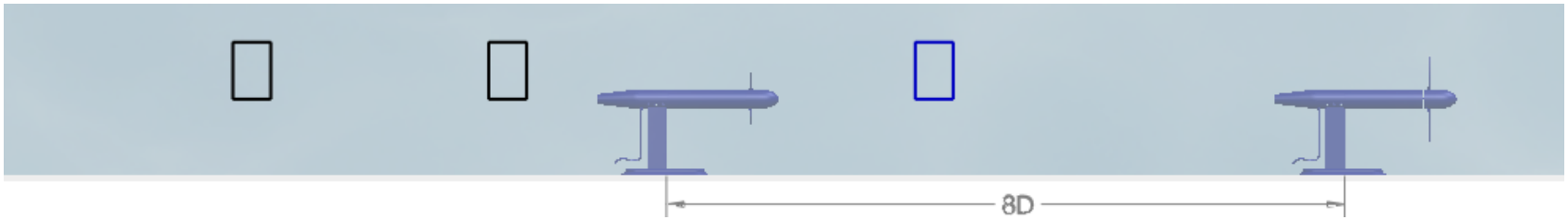
VELOCITY PROFILES



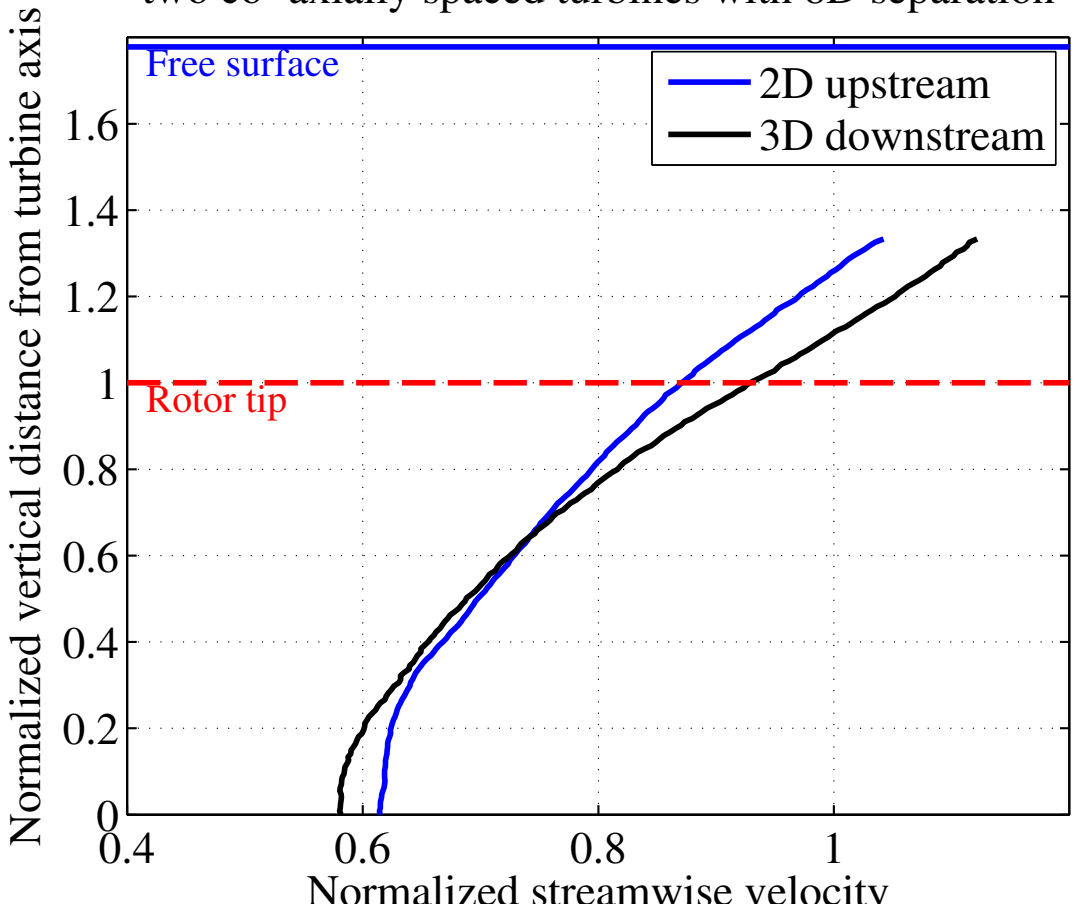
Incident flow and wake for downstream turbine in a two co−axially spaced turbines with 5D separation



VELOCITY PROFILES

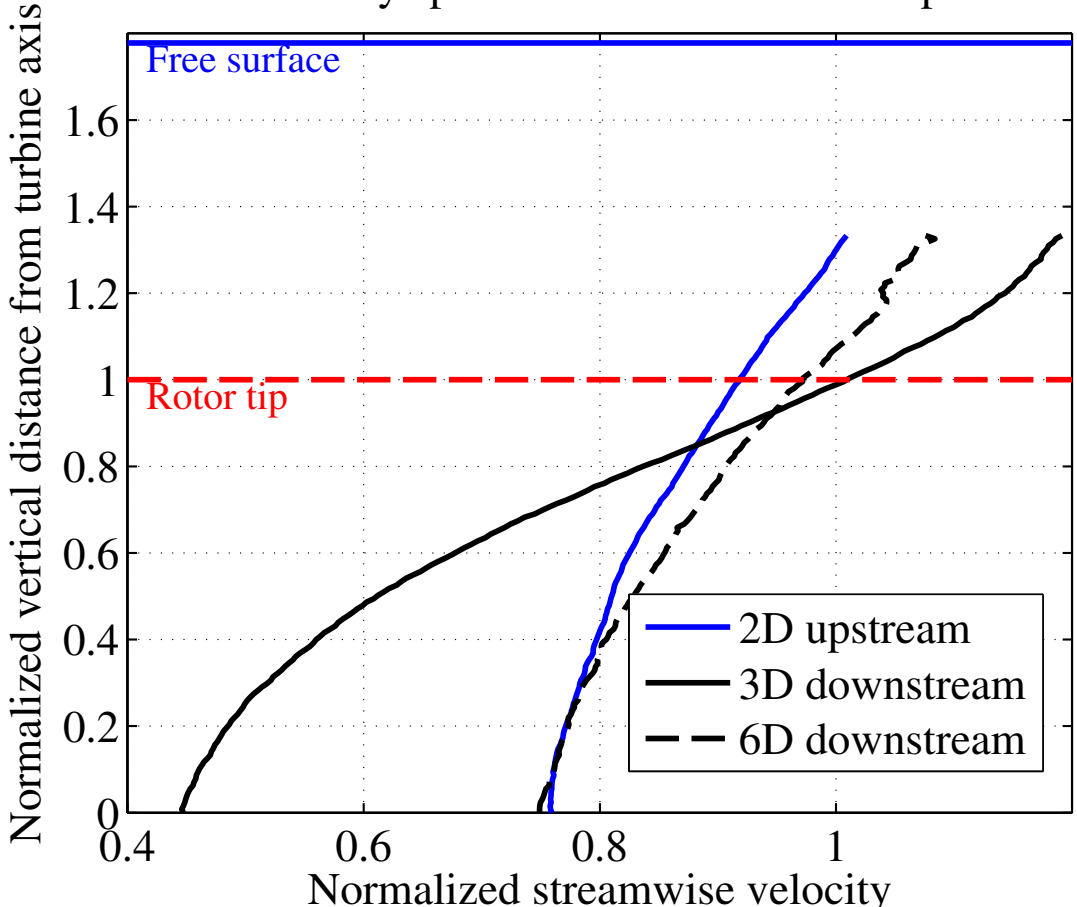


Incident flow and wake for downstream turbine in a two co−axially spaced turbines with 8D separation

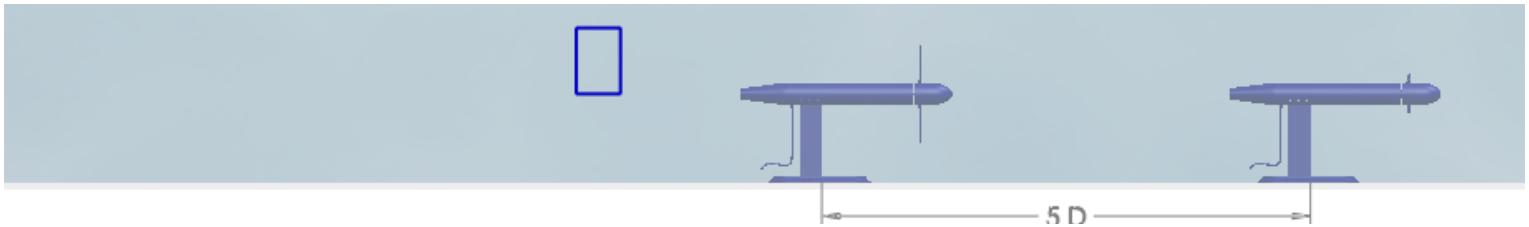


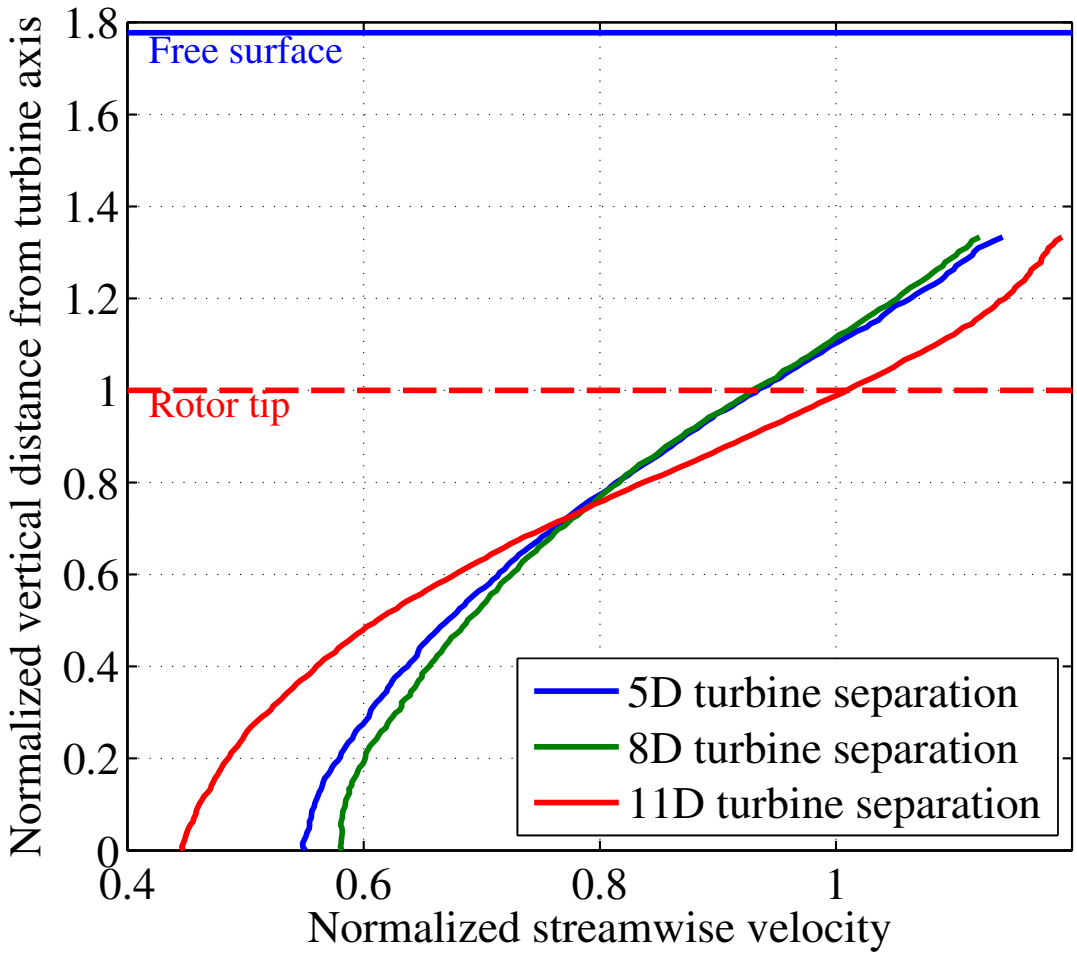
VELOCITY PROFILES

Incident flow and wake for downstream turbine in a two co−axially spaced turbines with 11D separation

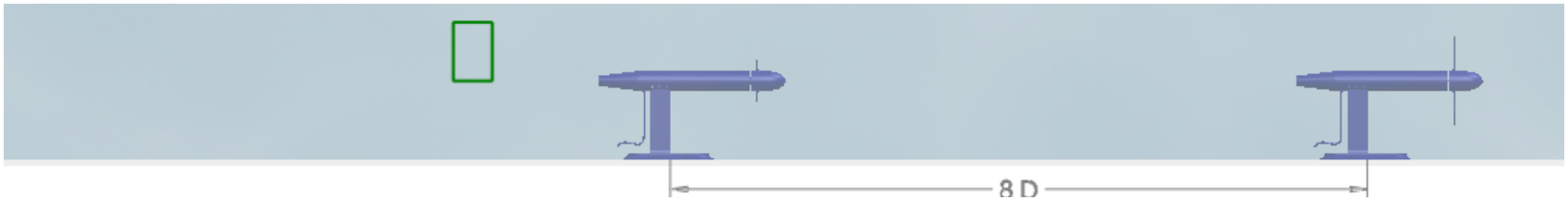


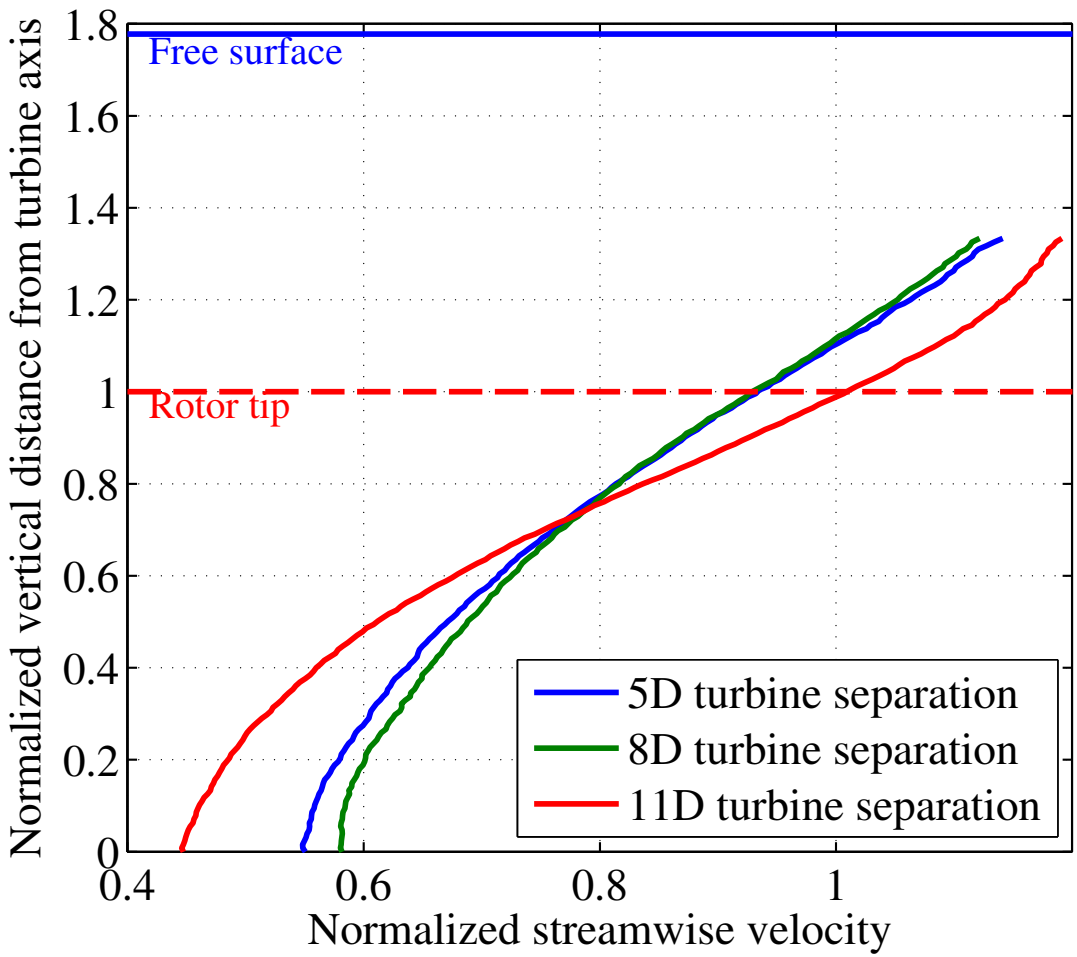
VELOCITY PROFILES AT 3D DOWNSTREAM



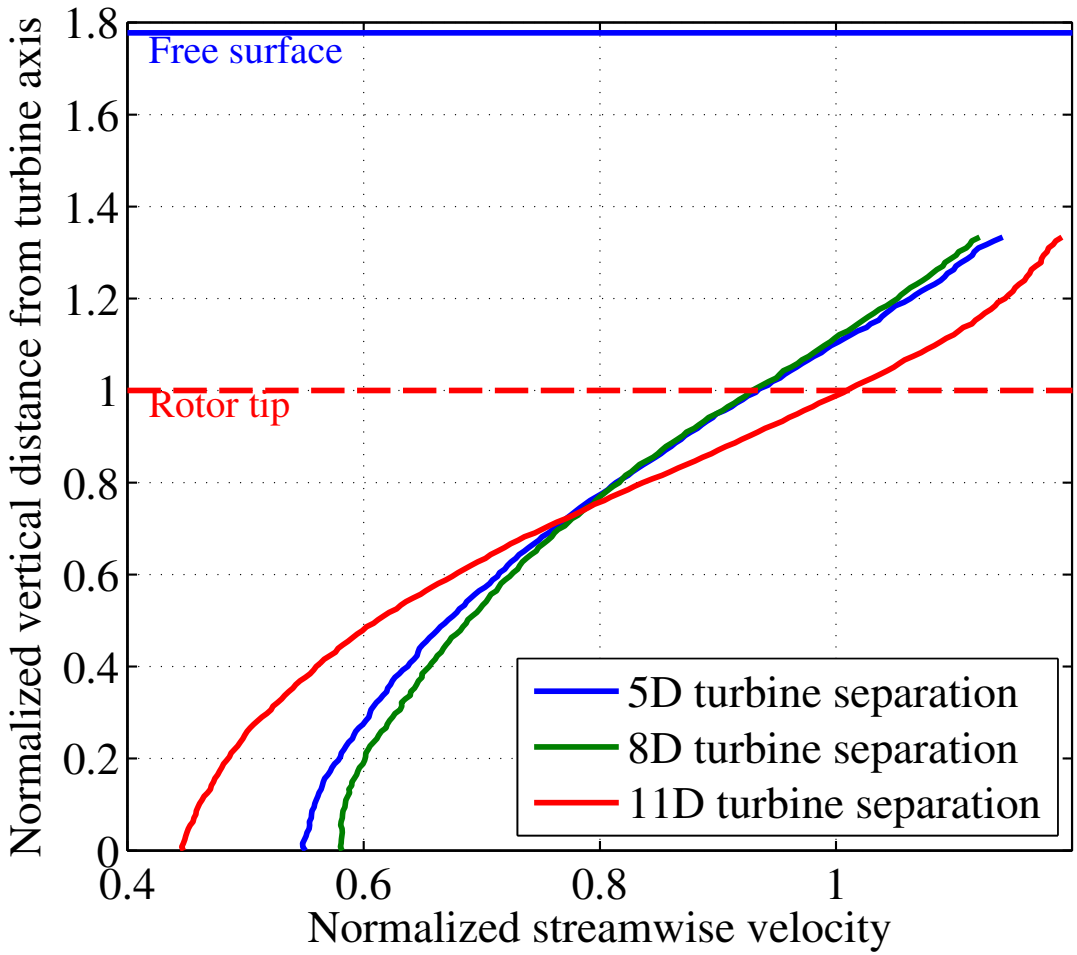


VELOCITY PROFILES AT 3D DOWNSTREAM

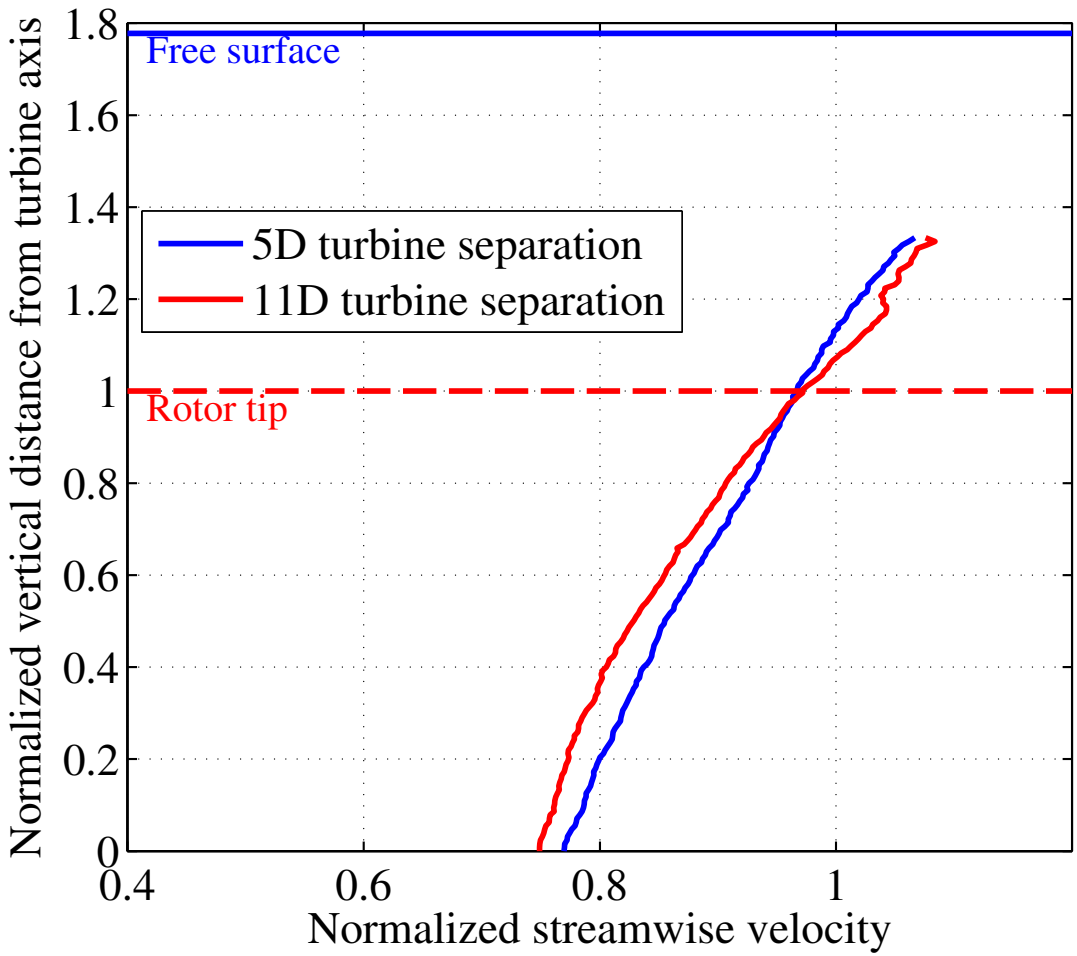




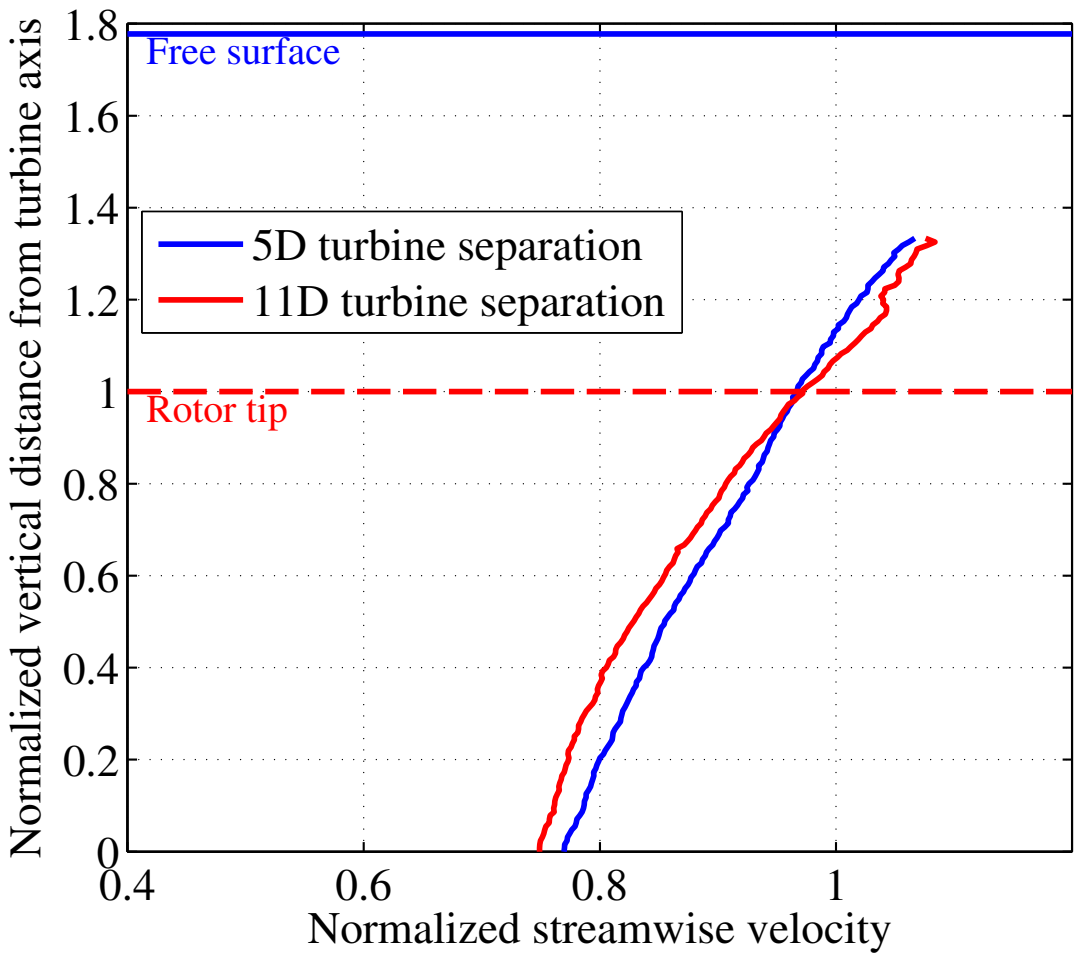
VELOCITY PROFILES AT 3D DOWNSTREAM



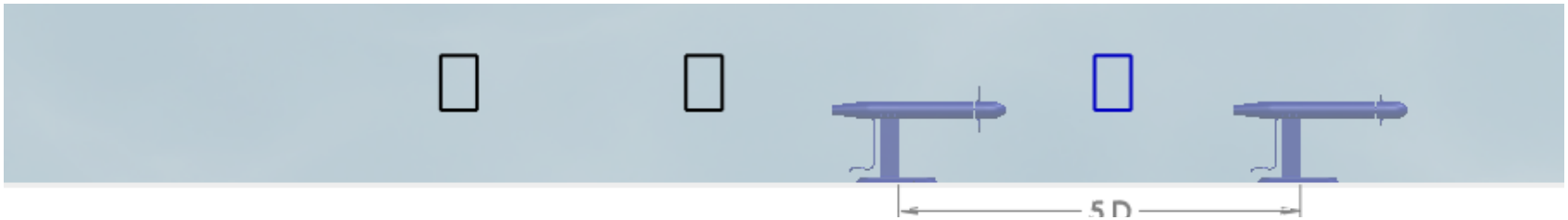
VELOCITY PROFILES AT 6D DOWNSTREAM



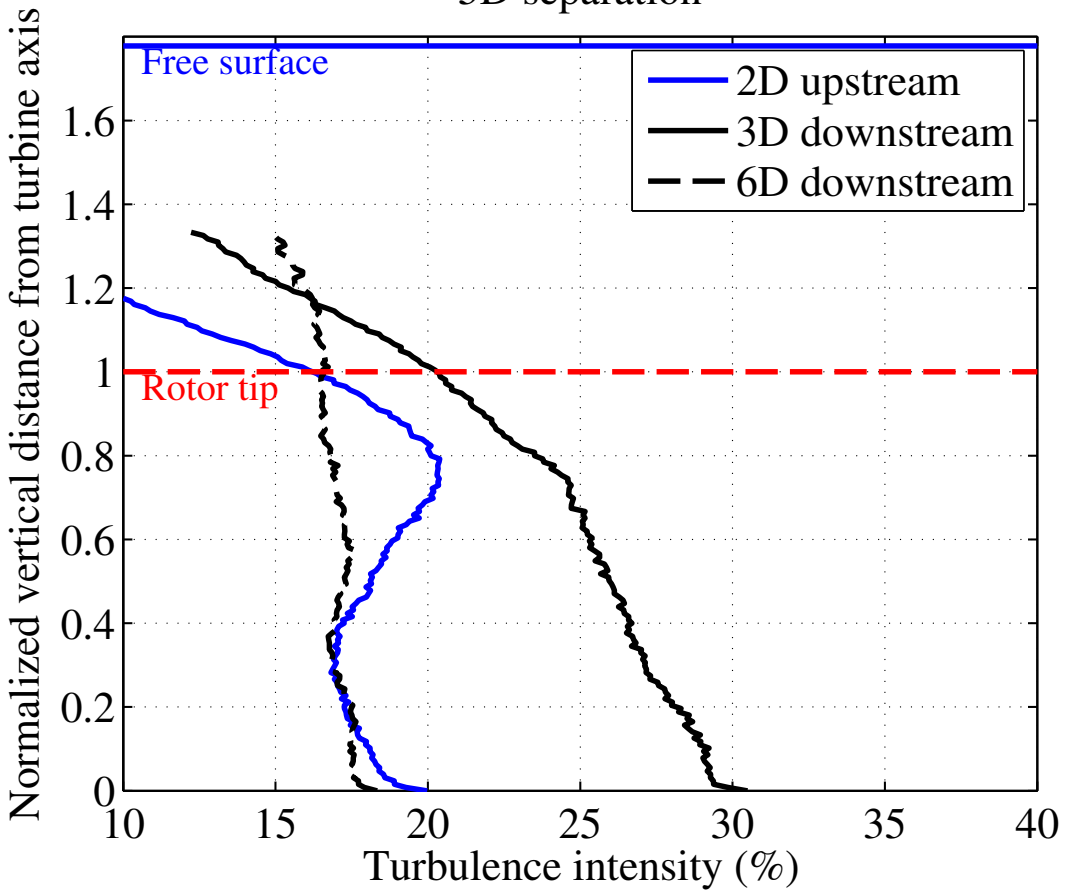
VELOCITY PROFILES AT 6D DOWNSTREAM



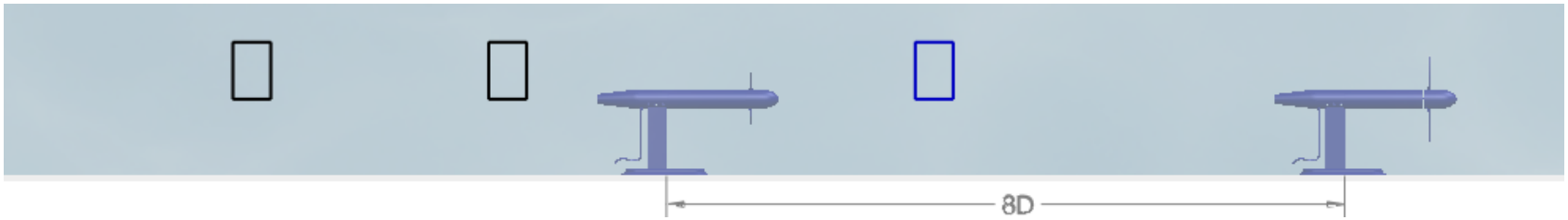
TURBULENCE INTENSITY PROFILES



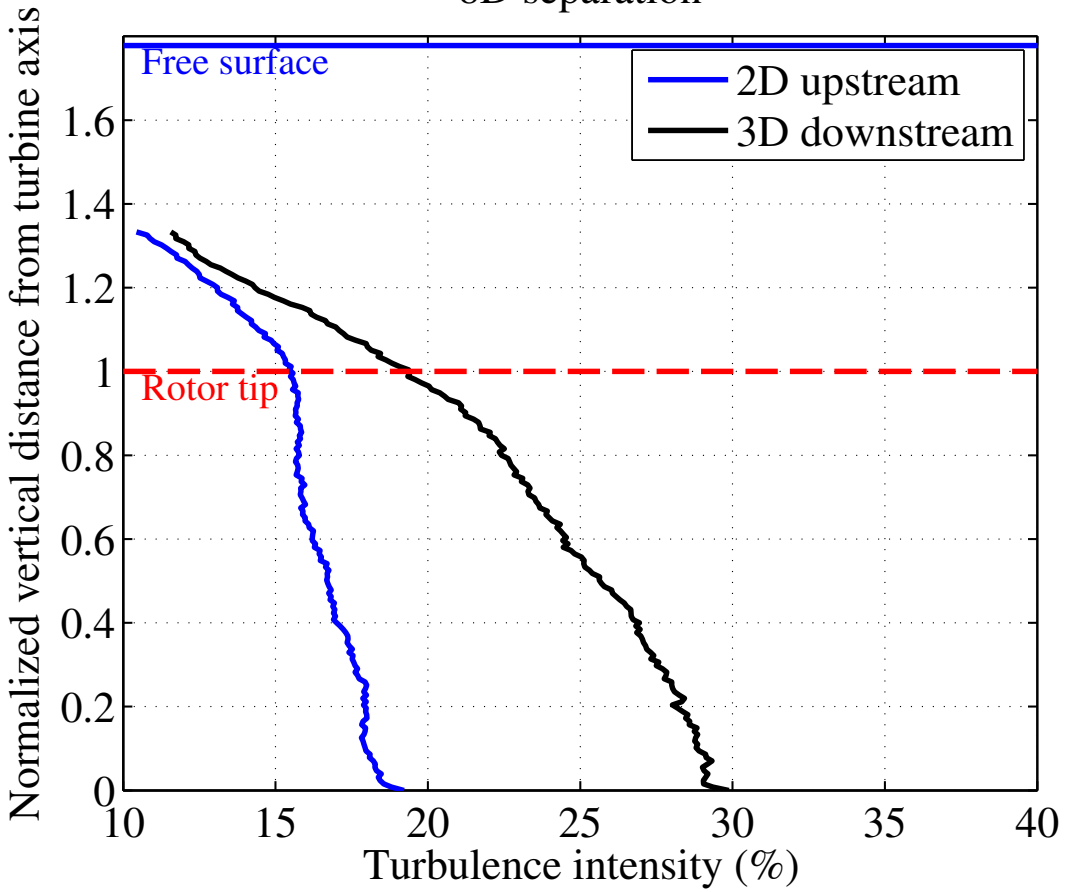
Incident TI and wake TI profiles for downstream turbine
5D separation



TURBULENCE INTENSITY PROFILES

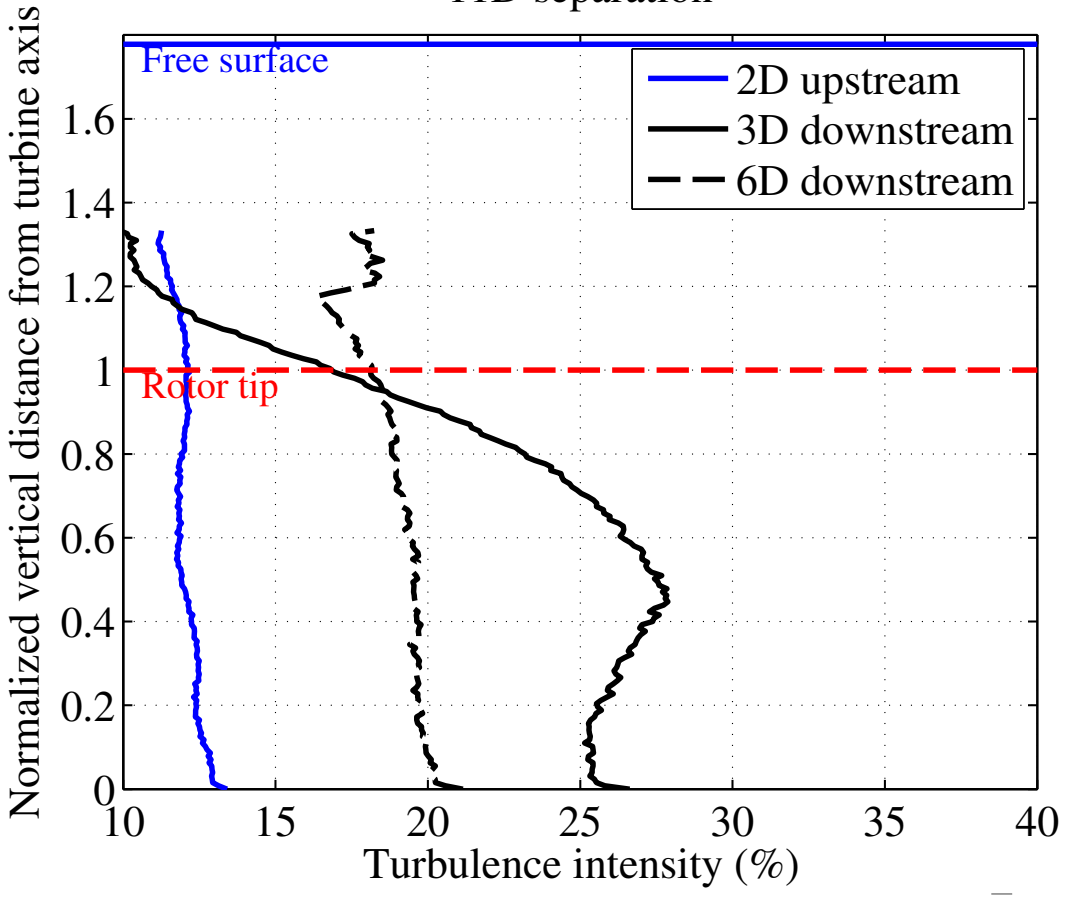


Incident TI and wake TI profiles for downstream turbine
8D separation

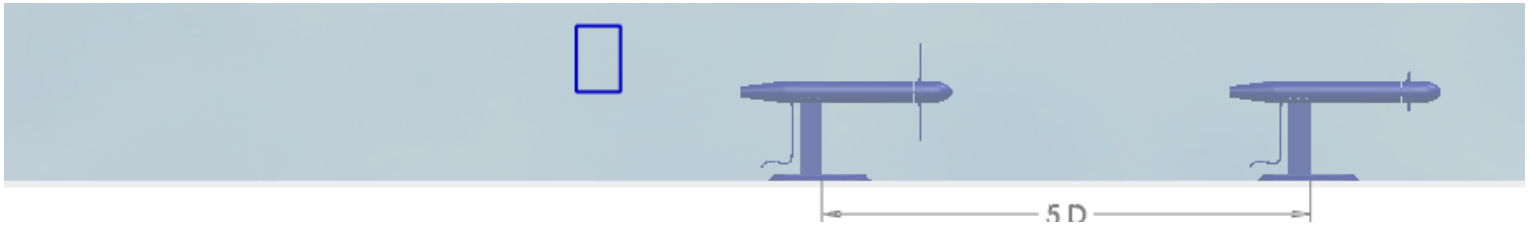


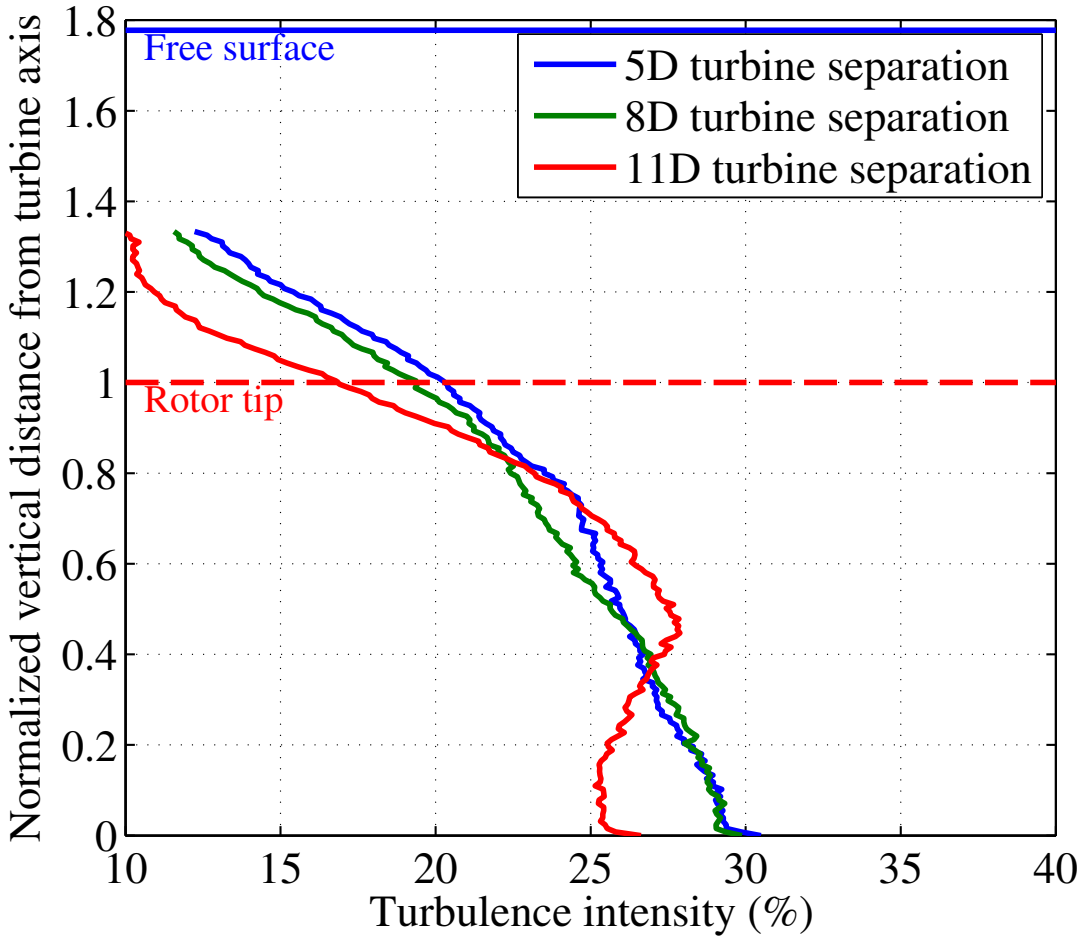
TURBULENCE INTENSITY PROFILES

Incident TI and wake TI profiles for downstream turbine
11D separation

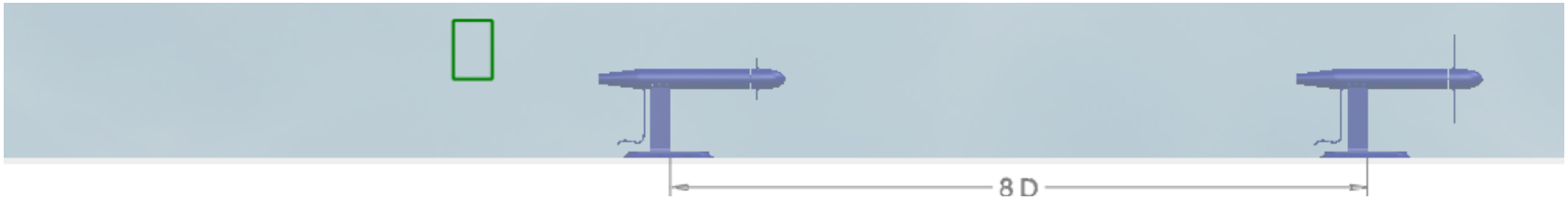


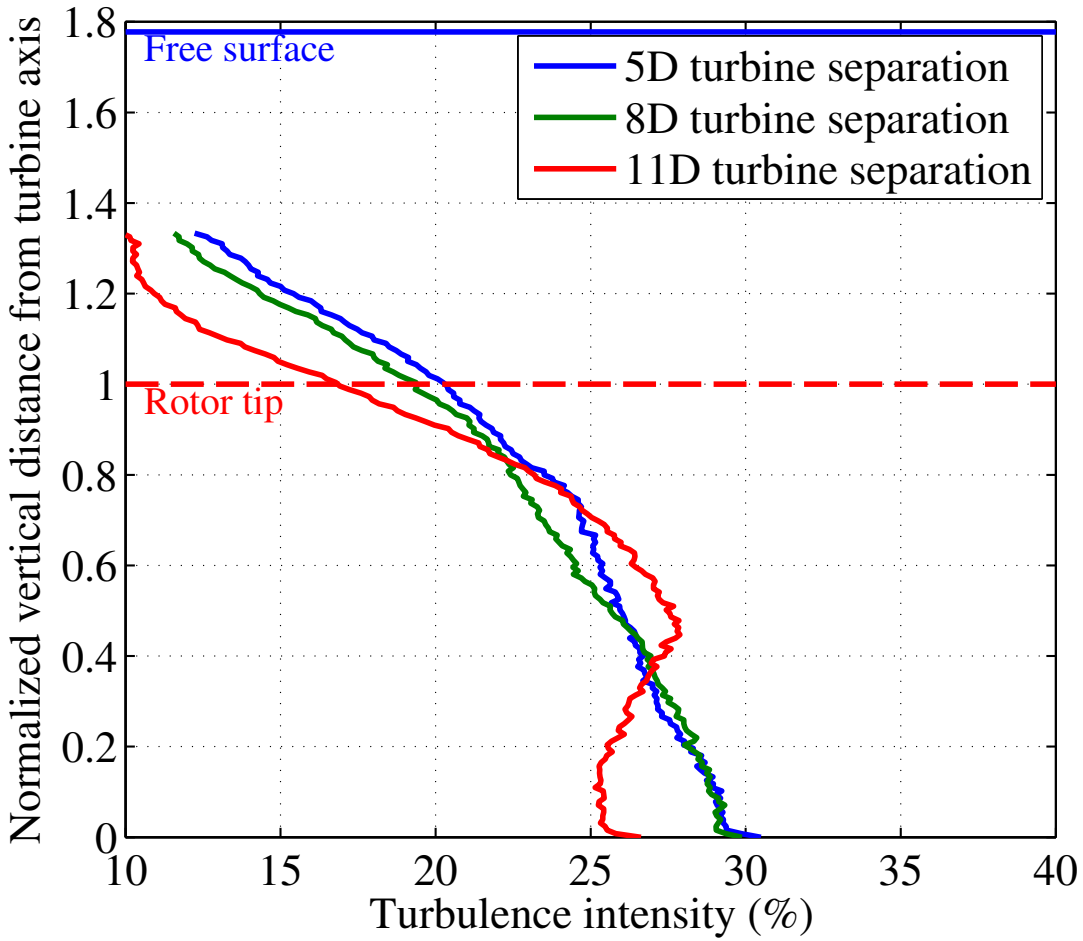
TURBULENCE INTENSITY AT 3D DOWNSTREAM



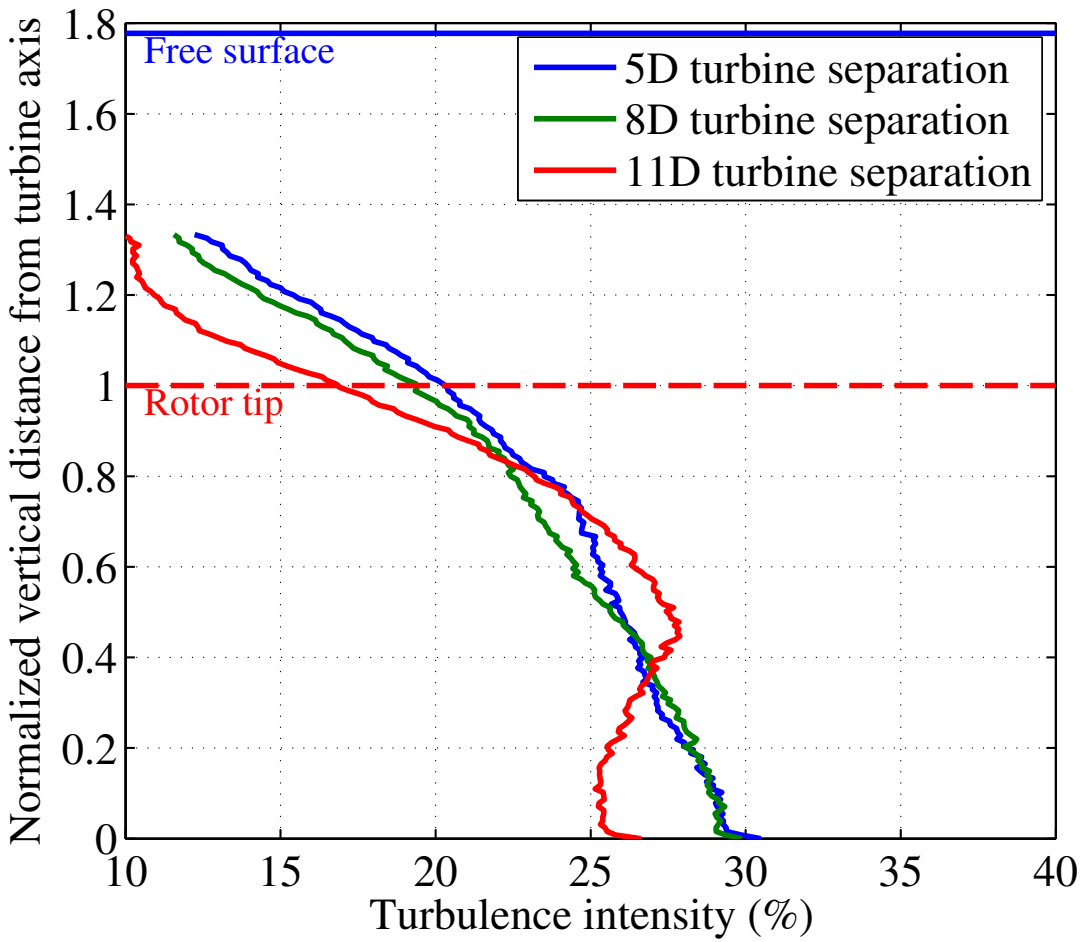


TURBULENCE INTENSITY AT 3D DOWNSTREAM

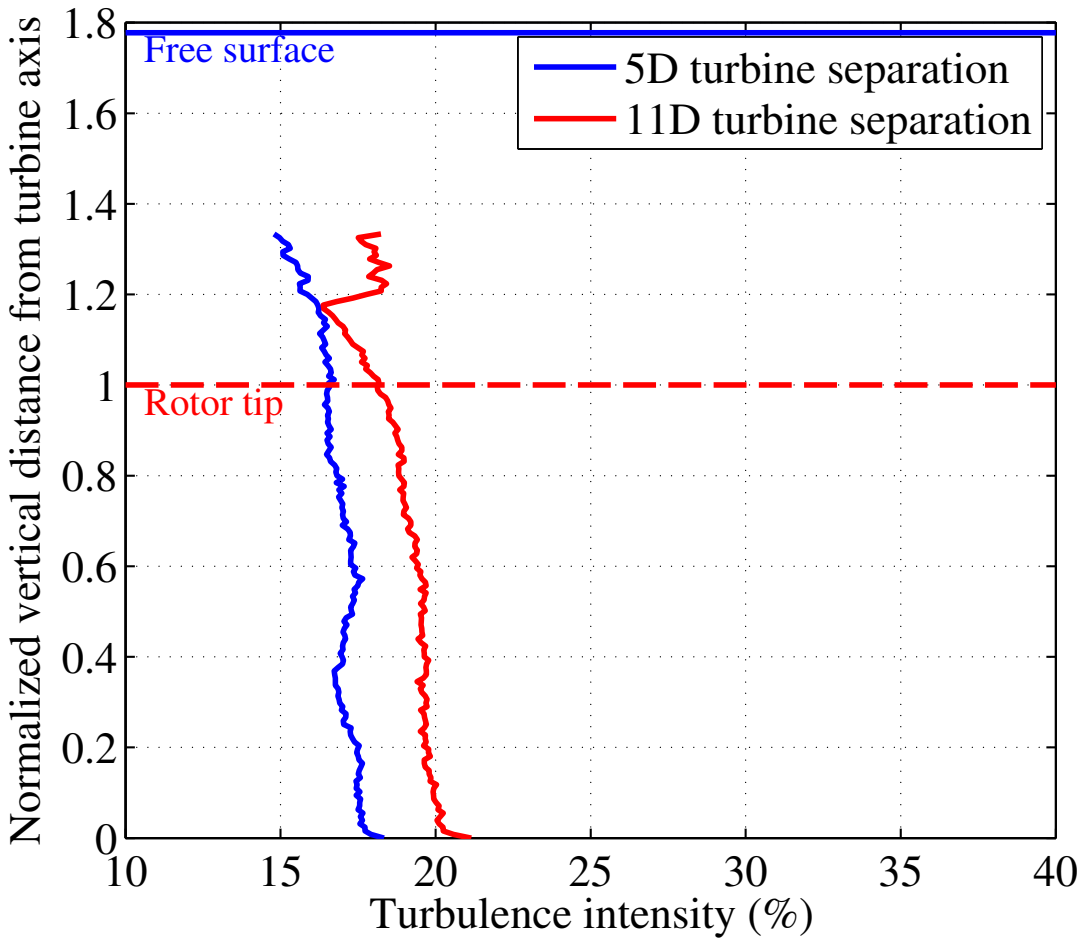




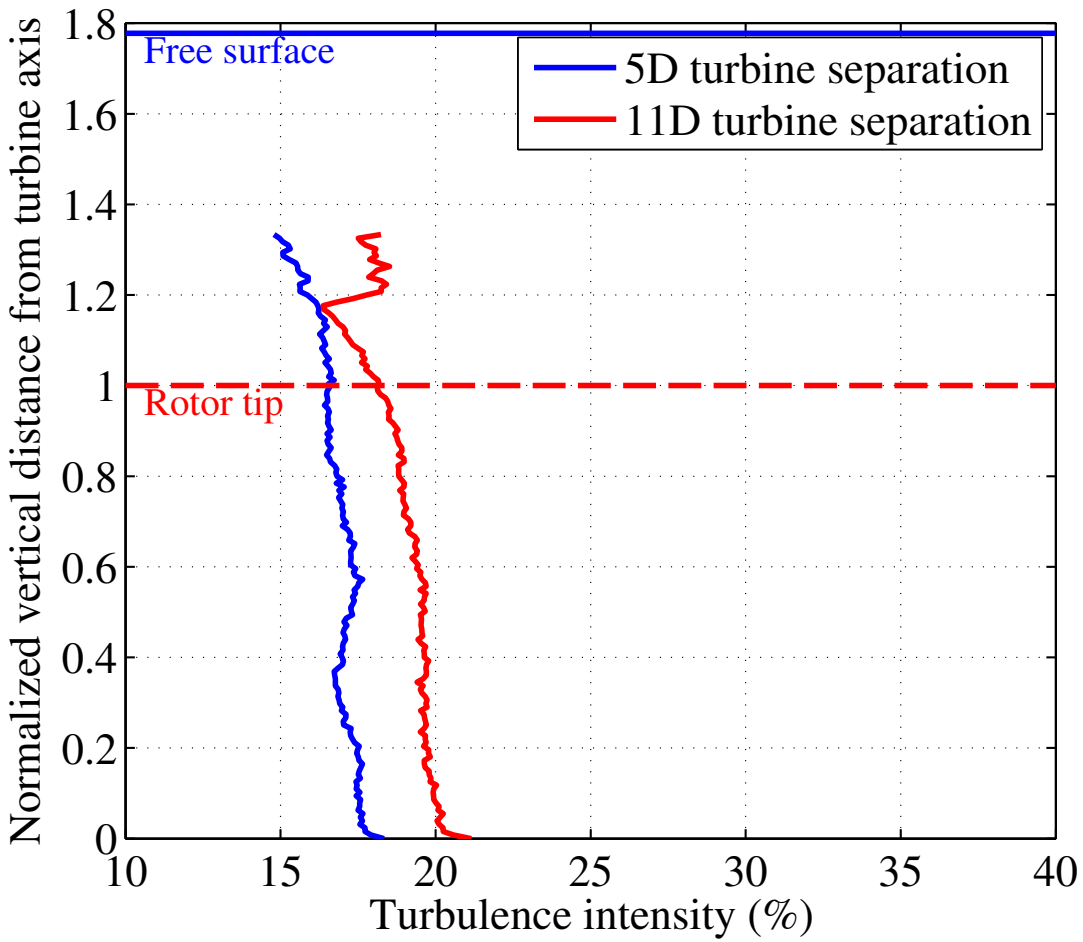
TURBULENCE INTENSITY AT 3D DOWNSTREAM



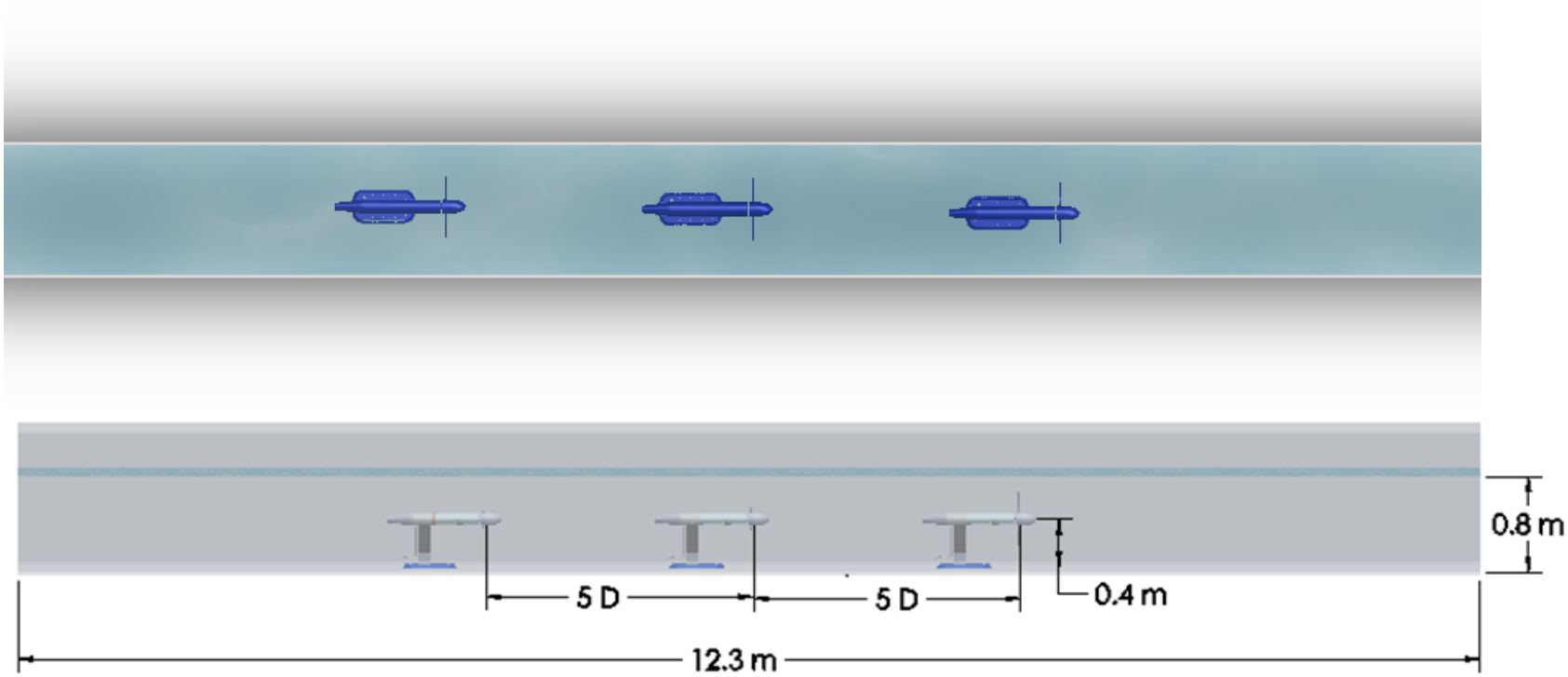
TURBULENCE INTENSITY AT 6D DOWNSTREAM



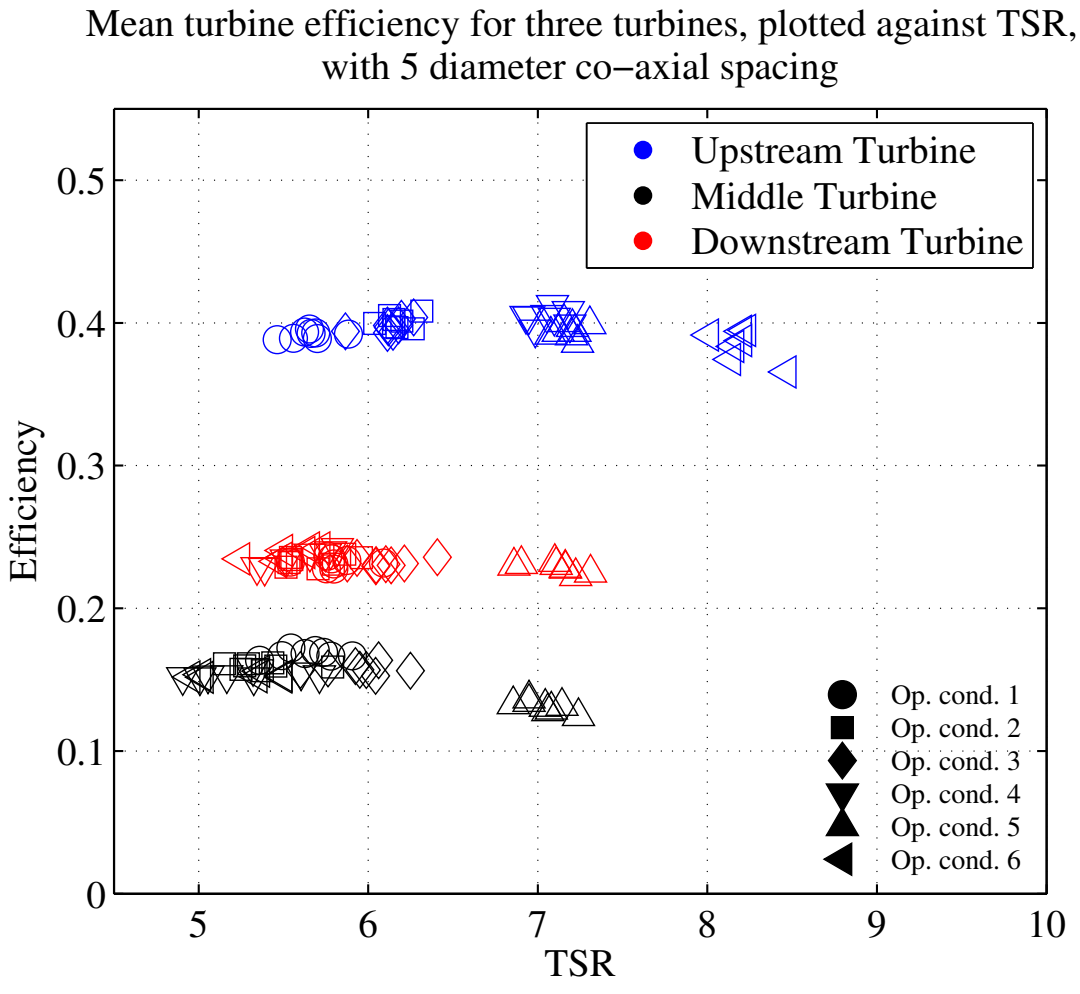
TURBULENCE INTENSITY AT 6D DOWNSTREAM



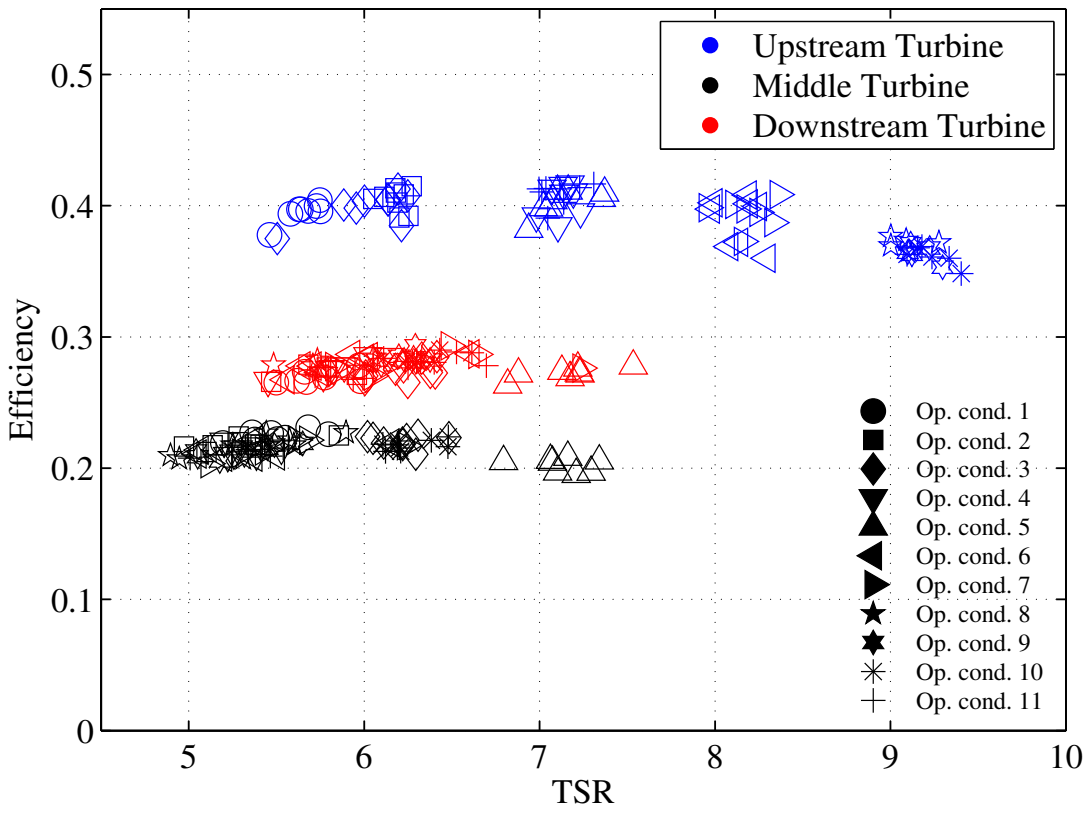
Turbine Arrays: Three co-axial turbines



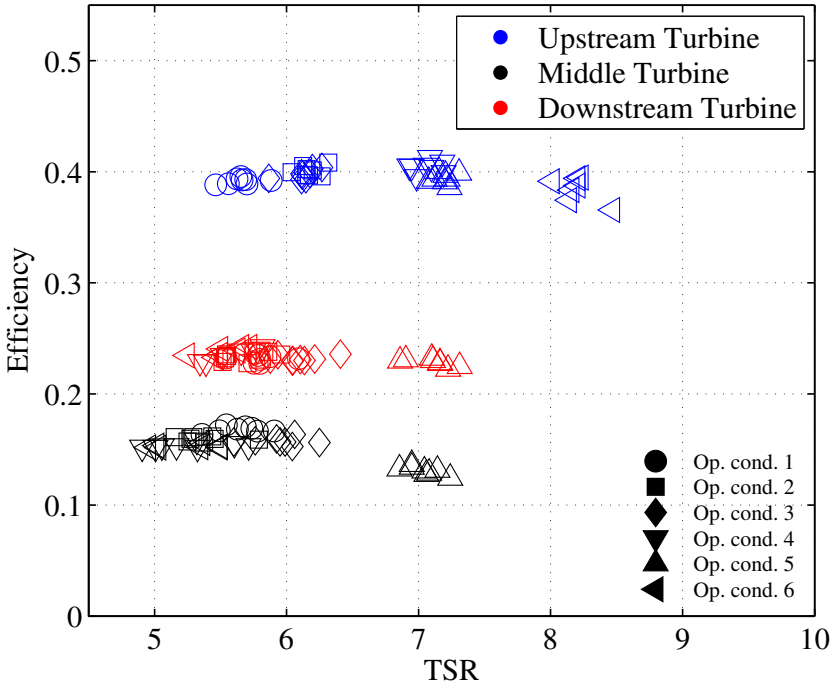
THREE TURBINES SEPARATED BY 5 DIAMETERS CO-AXIAL



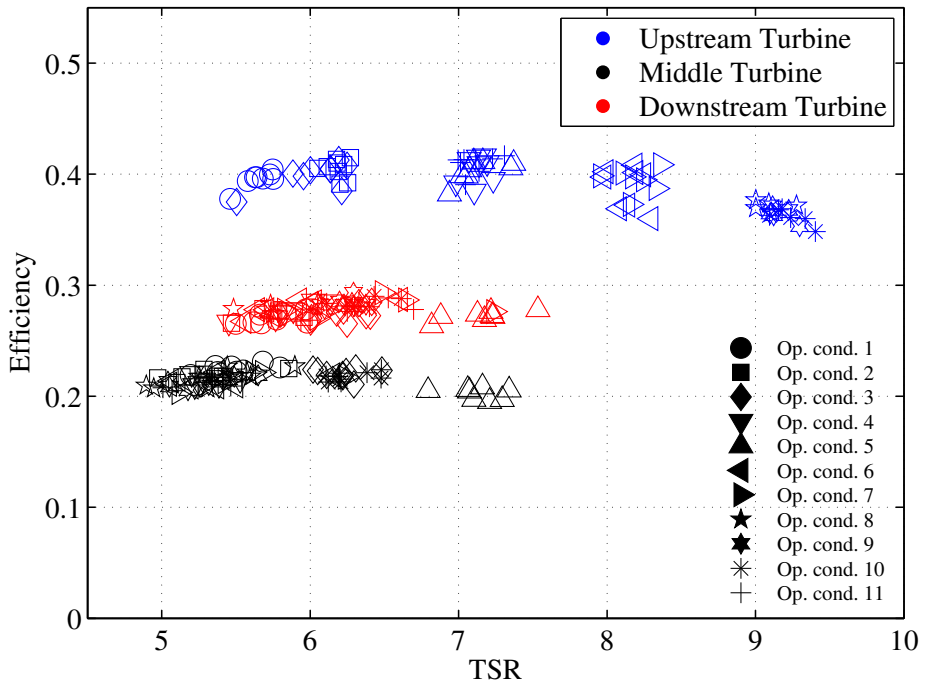
THREE TURBINES SEPARATED BY 7 DIAMETERS CO-AXIAL



COMPARISON OF THE PERFORMANCE OF THREE-TURBINE CO-AXIAL ARRAYS



5 D spacing



7 D spacing

Accomplished Research goals

- Design and test a scale model turbine with similar performance characteristics to full-scale Department of Energy Reference Model 1 tidal turbine
- Create a database of experimental measurements for validating numerical methodologies
- Explore the effect of spacing on turbine array performance and wake development

Conclusions: Rotor Design

- The DOE Reference Model 1 performs poorly at laboratory scale
- A new rotor was designed for laboratory-scale experiments
- The Reynolds number effect on performance is a key design consideration

Conclusions: Nacelle Design

- An instrumented nacelle was designed and built as an experimental test bed
- Unmeasurable shaft loading was minimized through design
- The test bed performed as designed and will be used for further rotor testing

Conclusions: Single Turbine

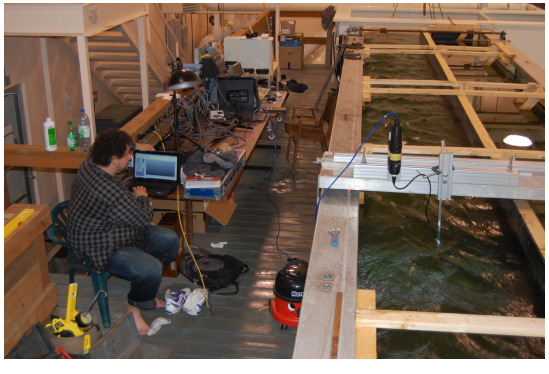
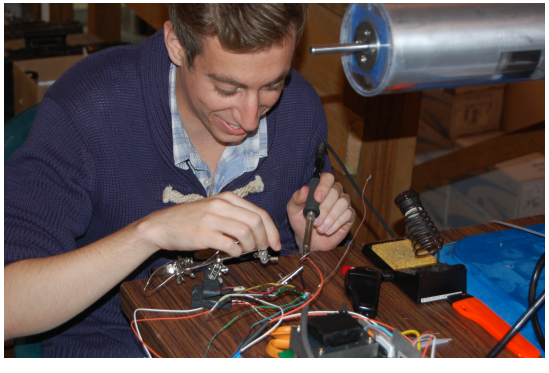
- An experimental performance curve was found to agree with numerical simulation, with some deviation at low TSR
- Stall delay was suggested a a reason for this deviation at low TSR and some evidence was found to support that hypothesis
- A Reynolds number effect on performance was shown, with evidence of a transition Reynolds number effect.
- Mean velocity profiles in the near wake were found to be highly dependent on TSR, but in the far wake no dependence was observed

CONCLUSIONS: TURBINE ARRAYS

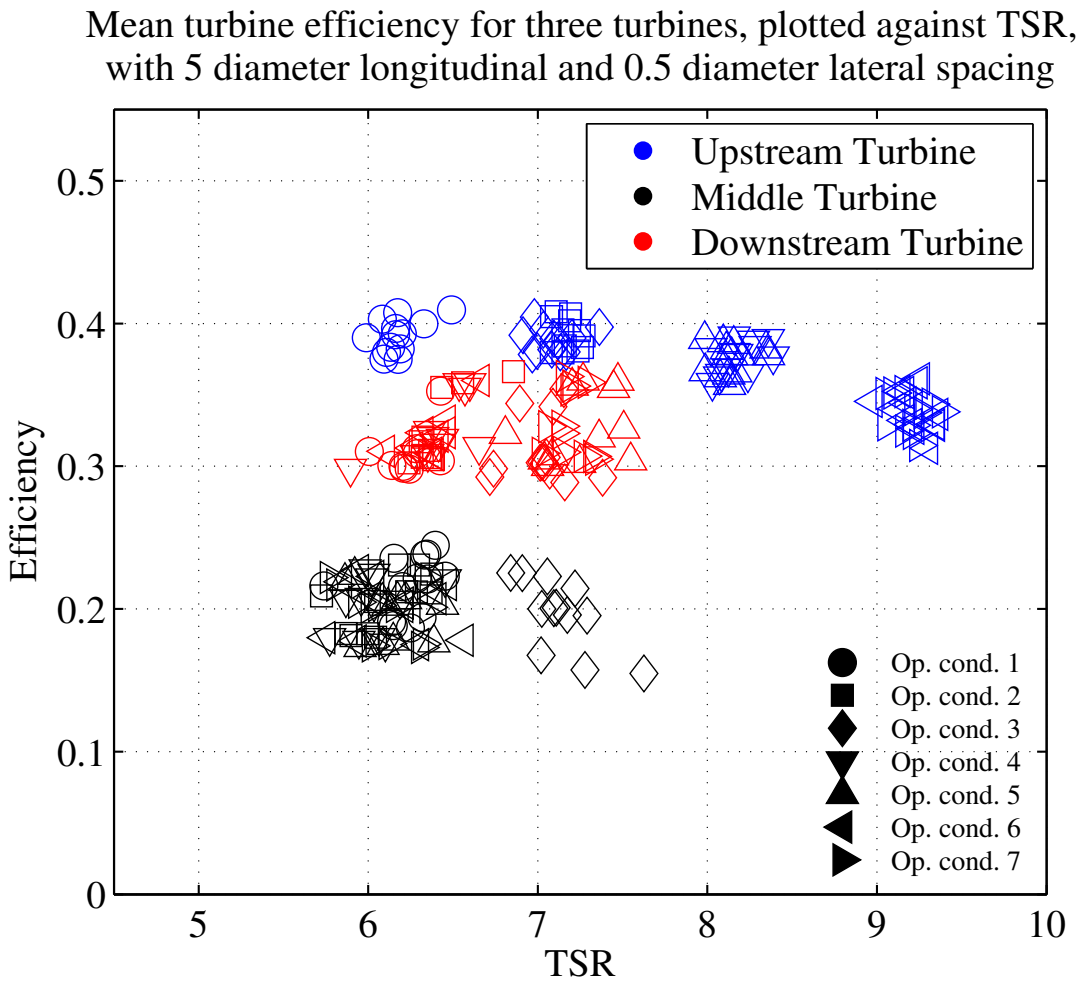
- The performance of co-axial turbine arrays of two and three turbines was characterized
- Wake recovery is faster in downstream turbine wakes
- Far wake recovery of the downstream turbine is relatively independent of separation distance
- In three-turbine arrays the downstream turbine performance is higher than that of the midstream turbine

Thank You!

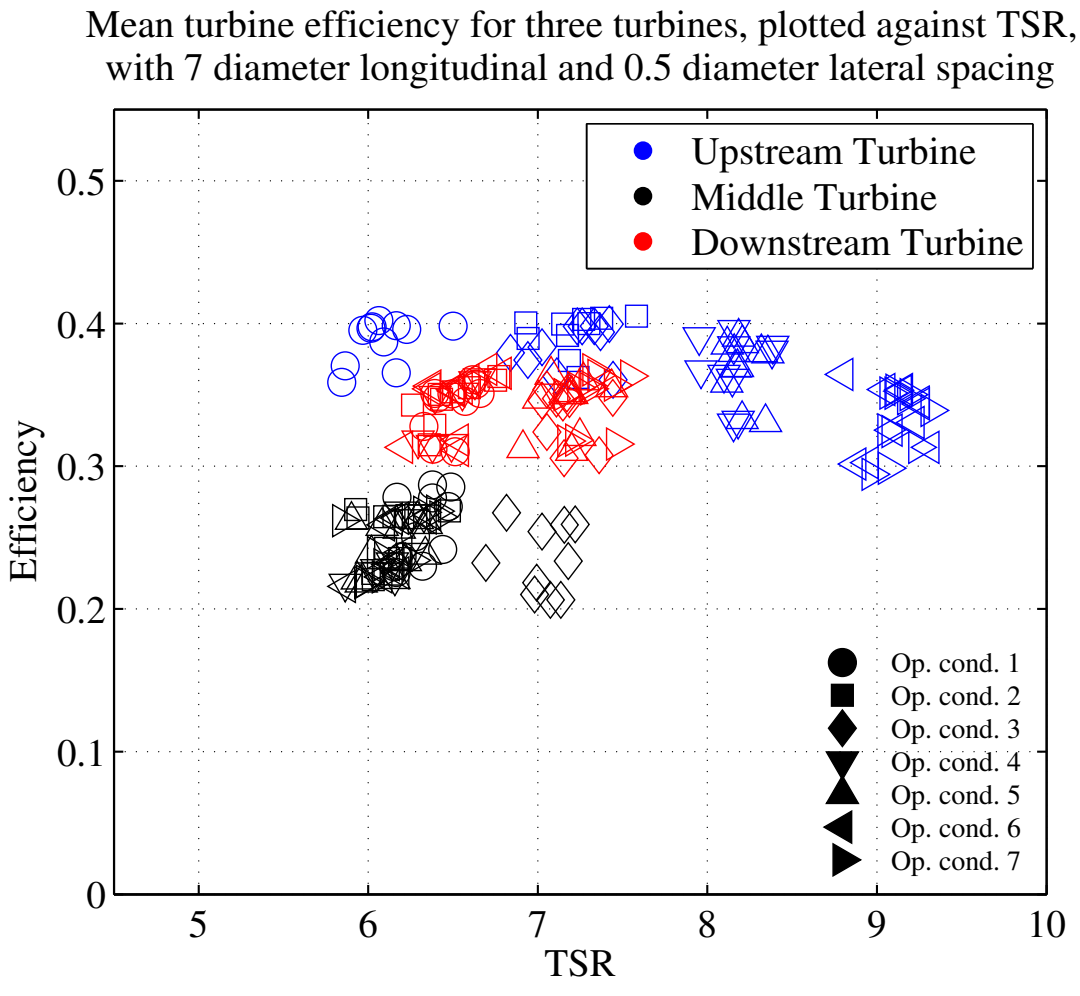
Alberto Aliseda, Brian Polagye, Anthony Poggioli, Alejandro Fernandez Solana, Rob Cavagnaro, the staff at the Bamfield Marine Science Centre, especially Eric Clelland, Eamon McQuaide, Kevin Soderlund, Bill Kuykendall, Zoë Parsons, Jim Thompson, Teymour Javaherchi, Adam Niblick, James Joslin, Amirhossein Amini, Samantha Adamski, and Danny Sale.
This project was funded by the Department of Energy

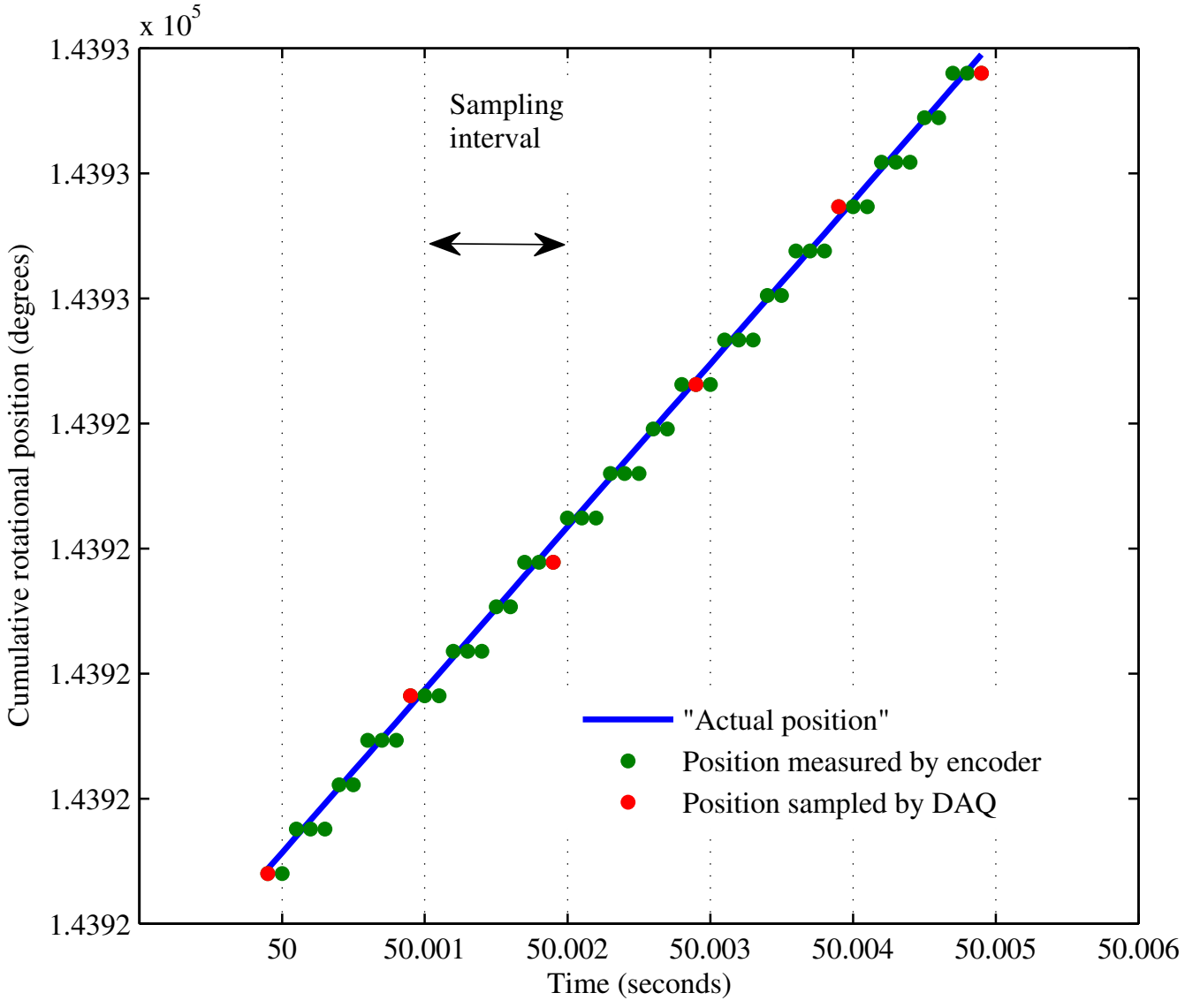

THREE TURBINES SEPARATED BY 5 DIAMETERS WITH LATERAL OFFSET



THREE TURBINES SEPARATED BY 7 DIAMETERS WITH LATERAL OFFSET



ROTATIONAL SPEED FROM UNDER-SAMPLED POSITION



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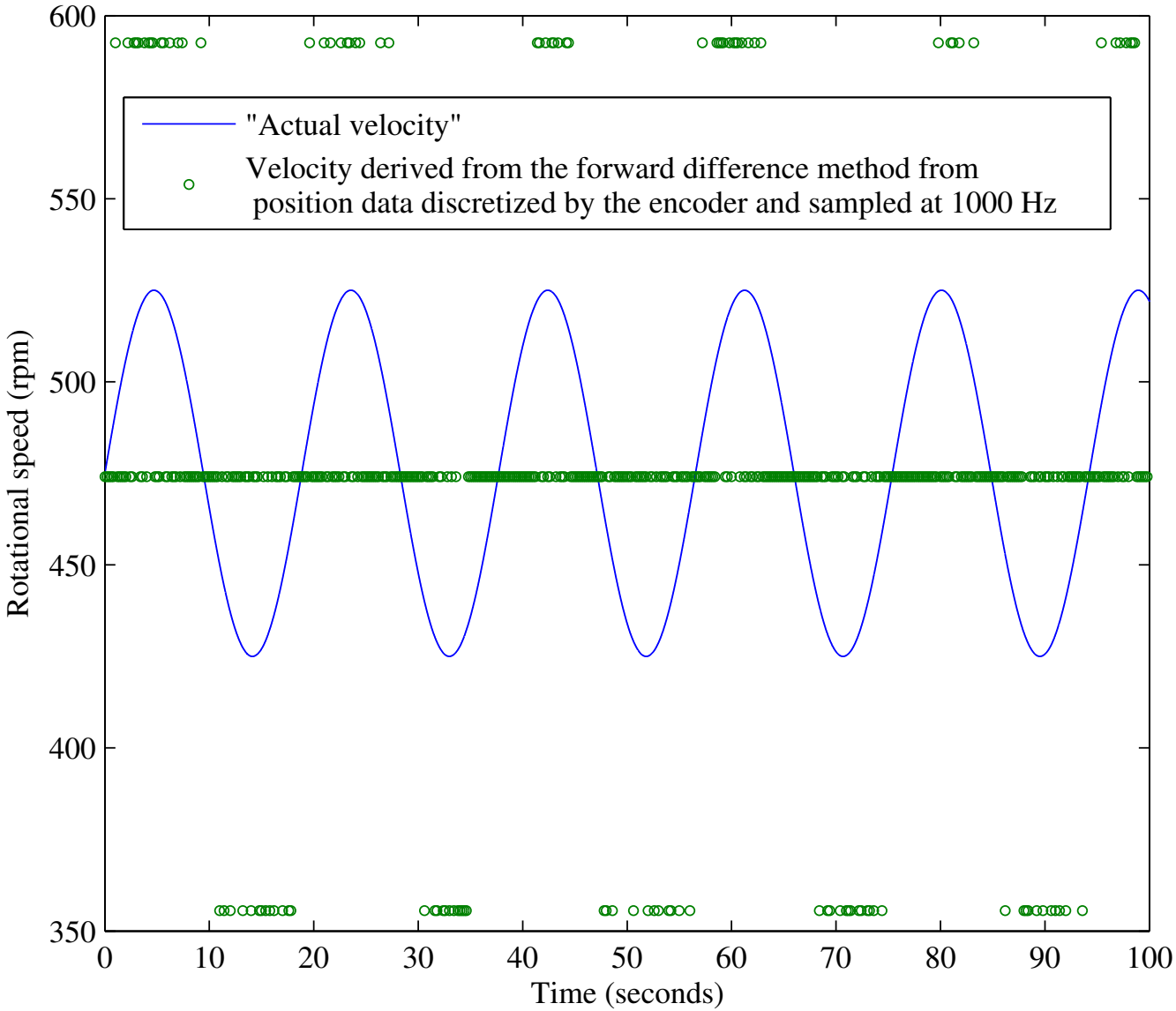

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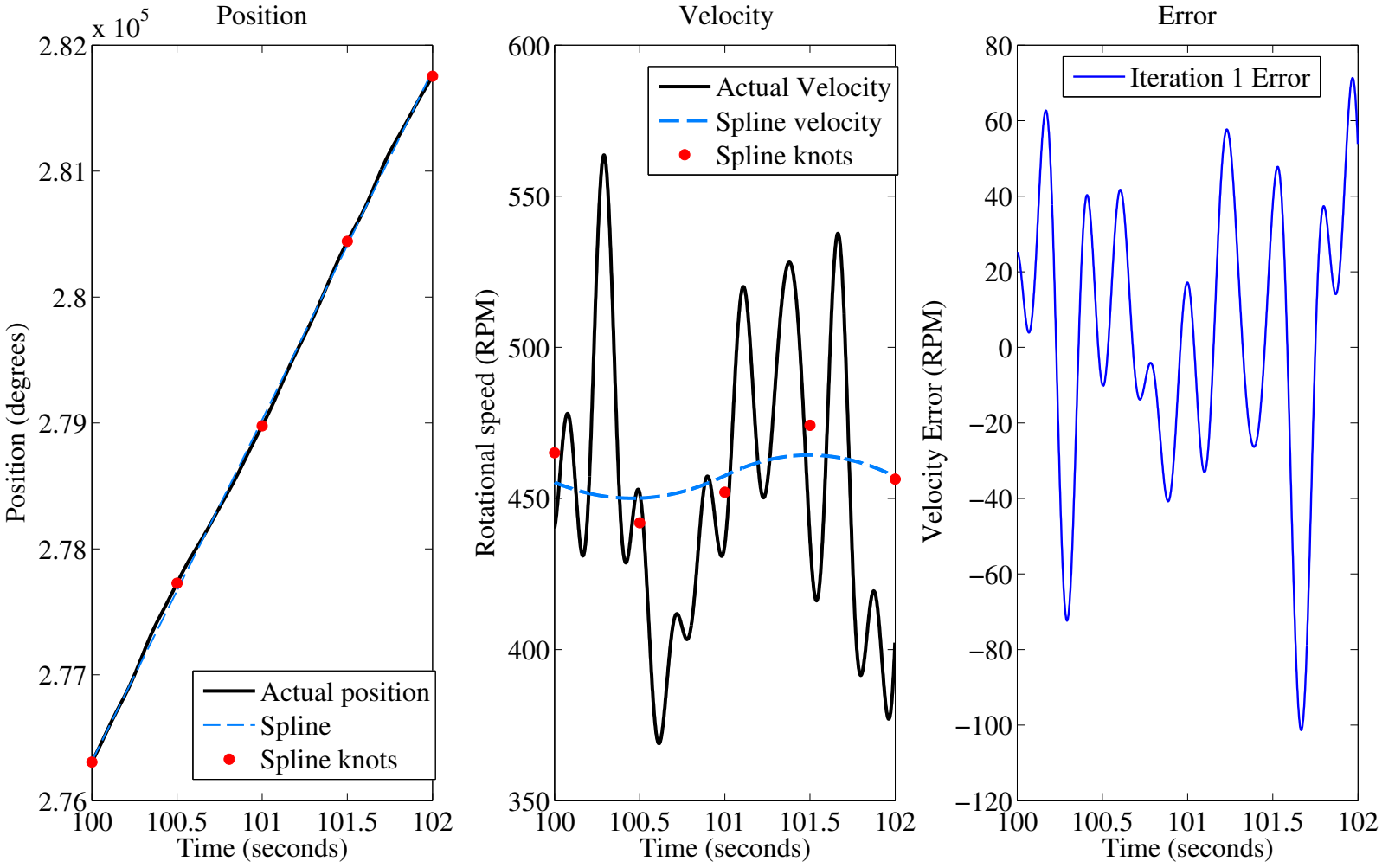

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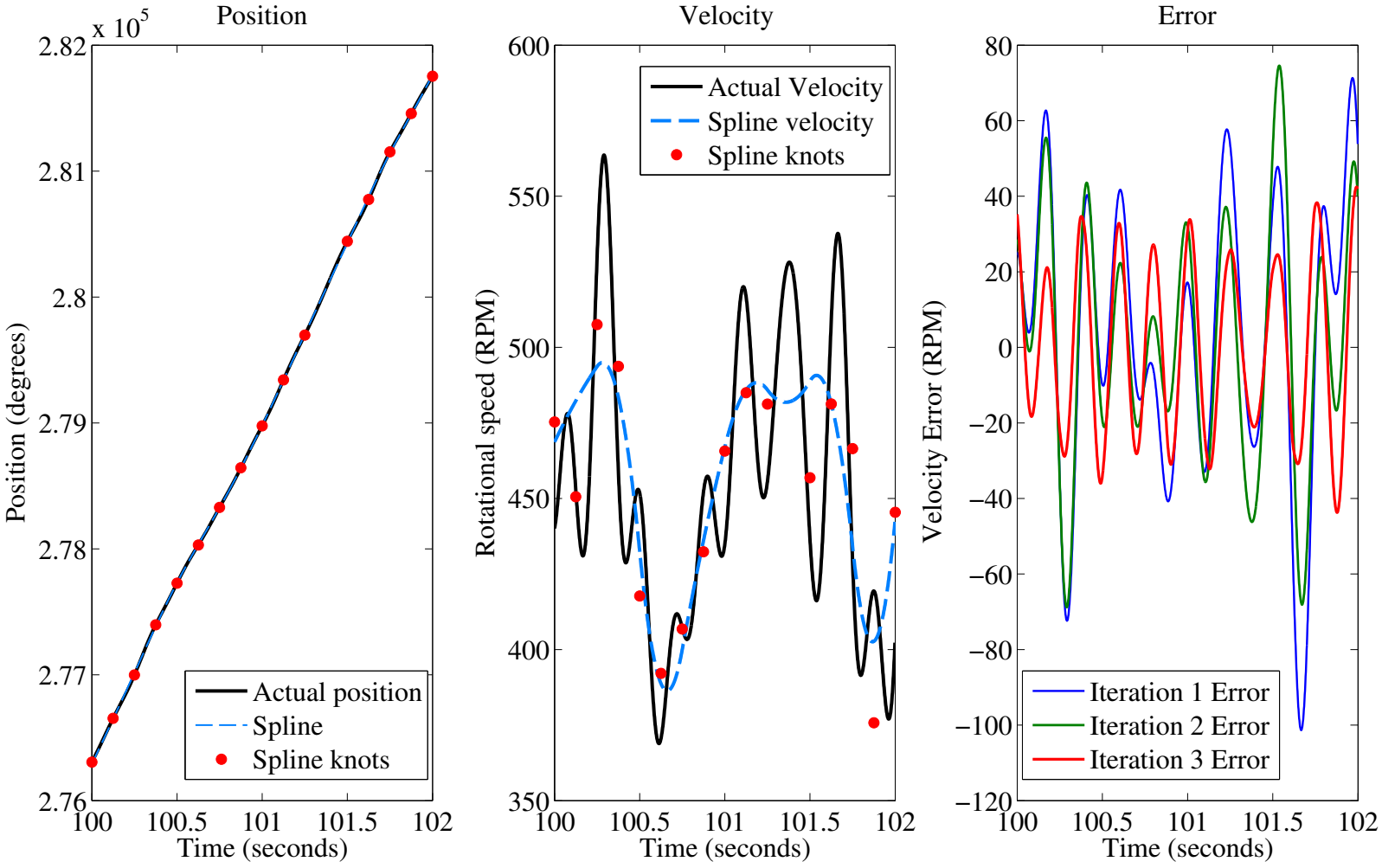

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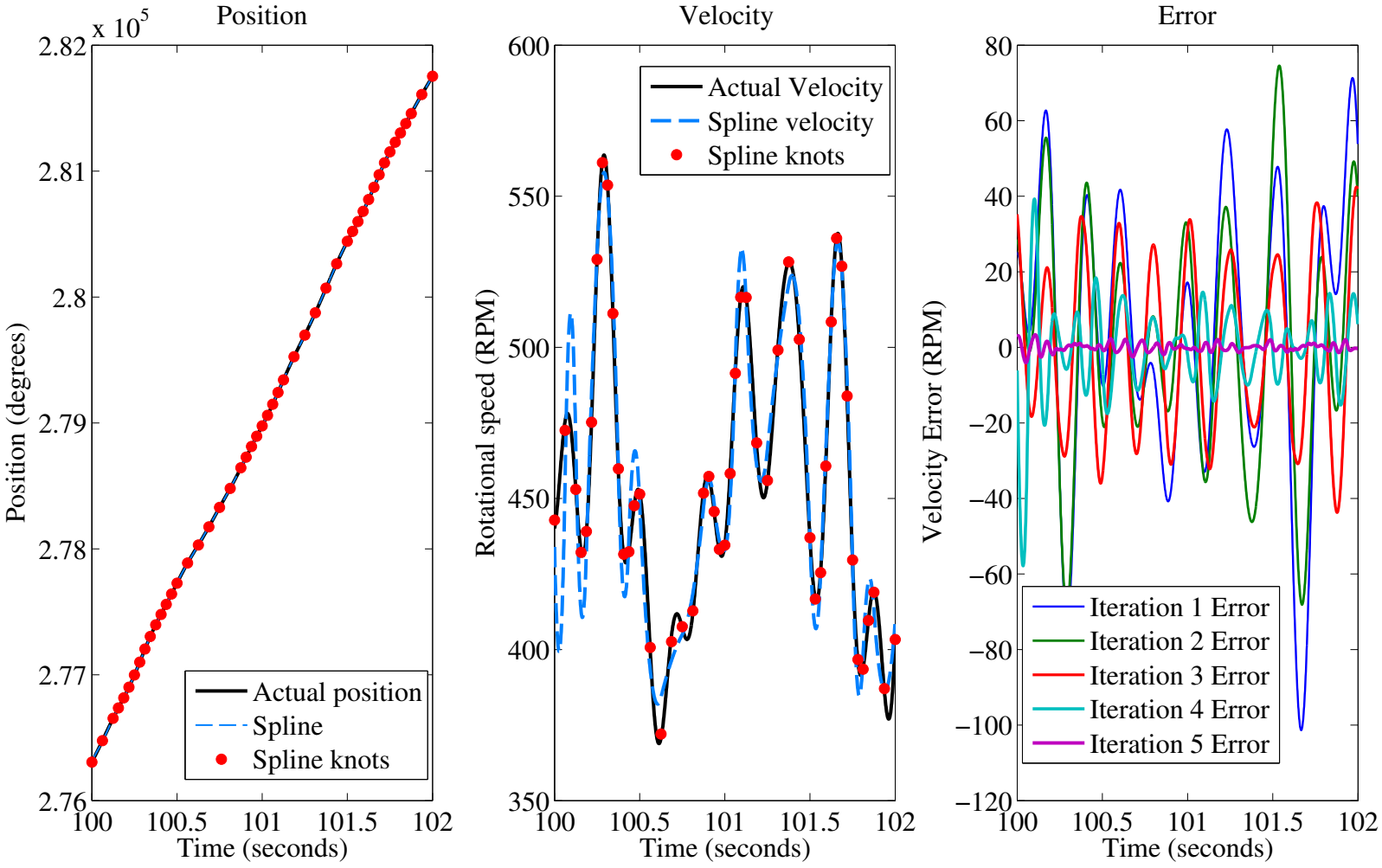
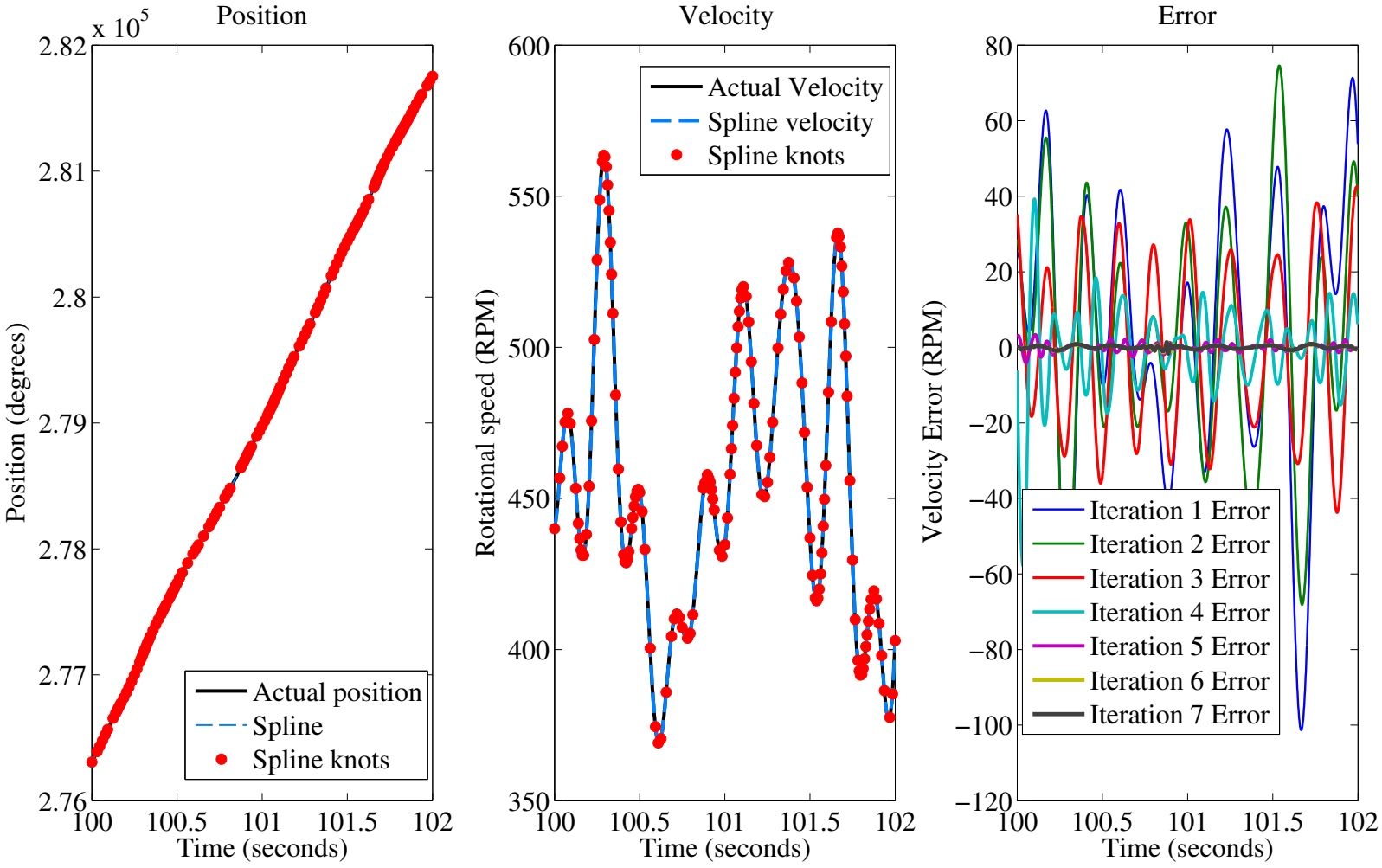
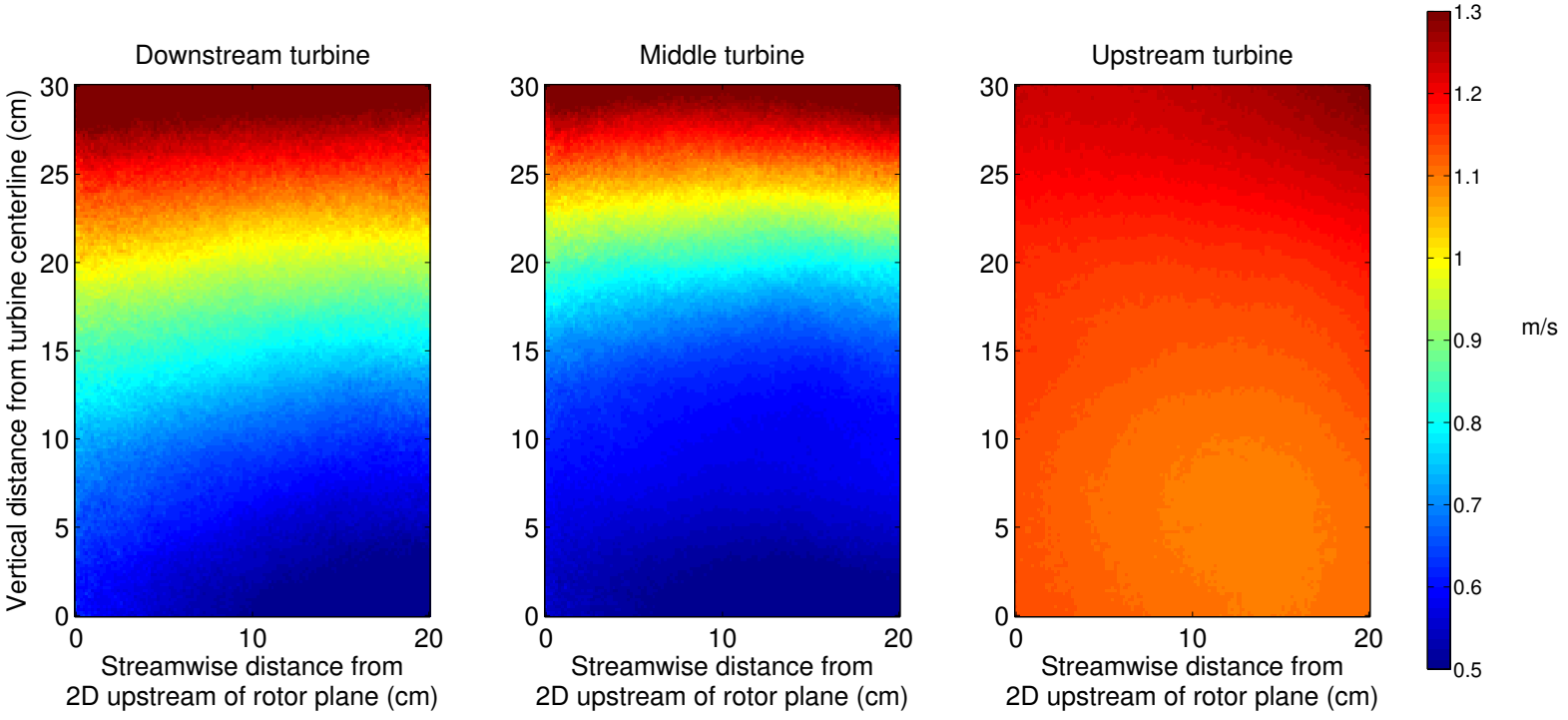


ROTATIONAL SPEED FROM UNDER-SAMPLED POSITION

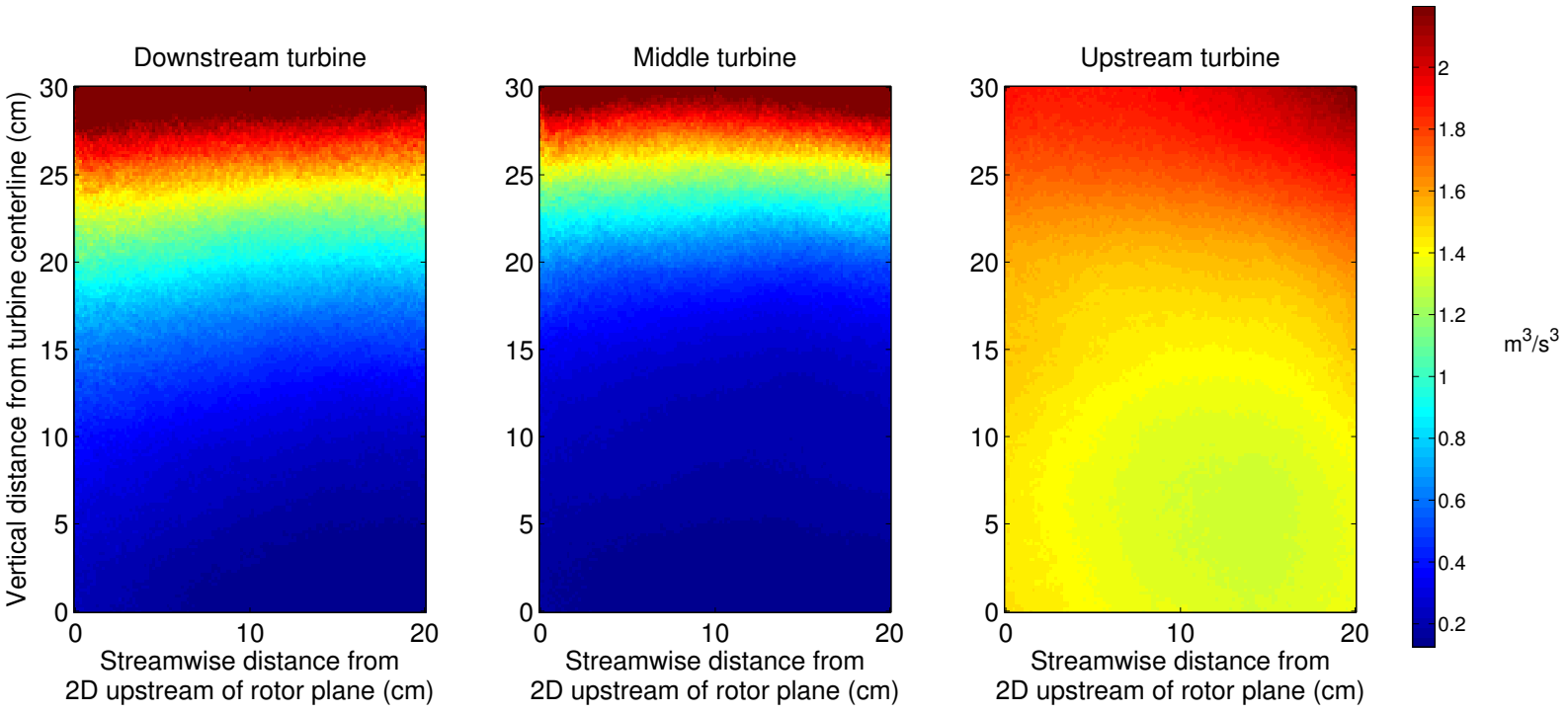


INCIDENT MEAN STREAMWISE VELOCITY ON THREE TURBINES, 5D



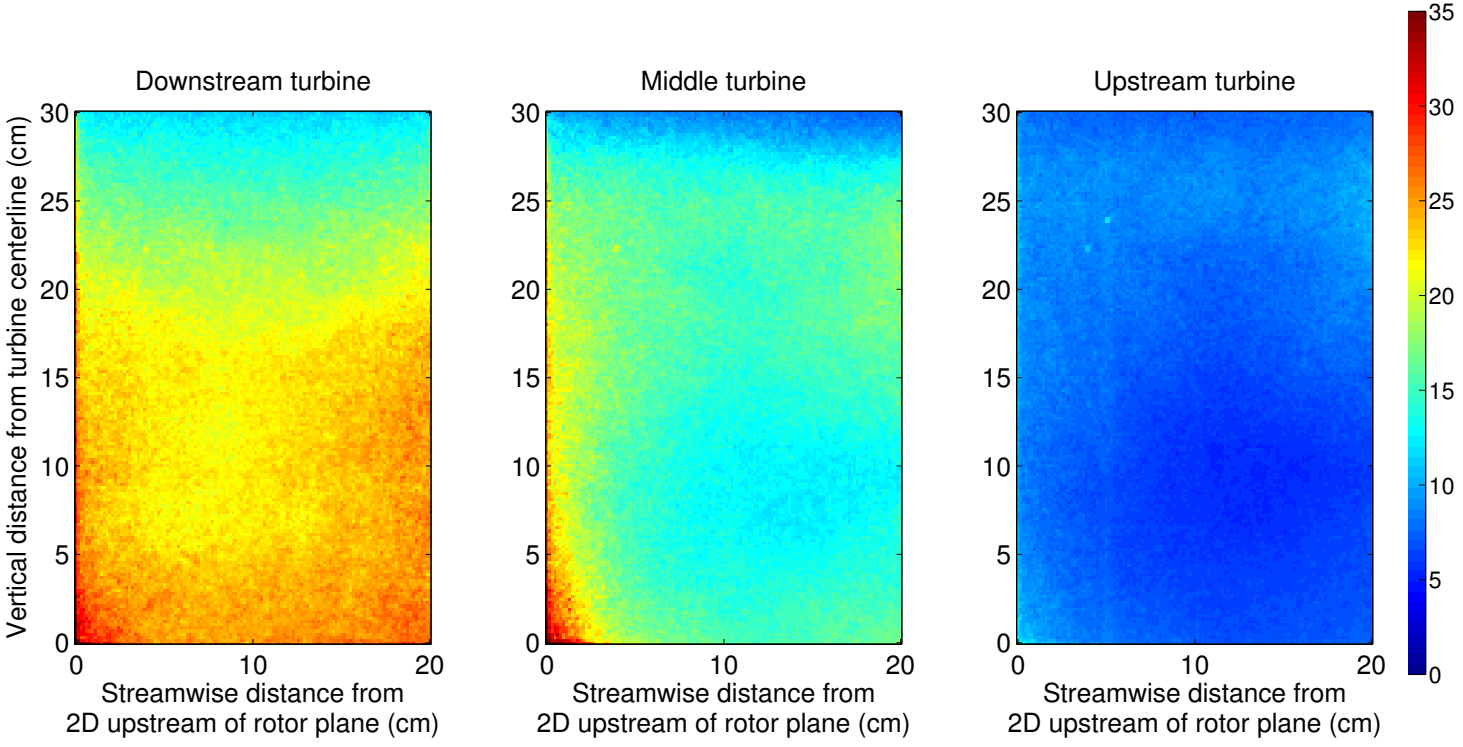
⇐ Direction of flow

INCIDENT POWER ON THREE TURBINES, 5D



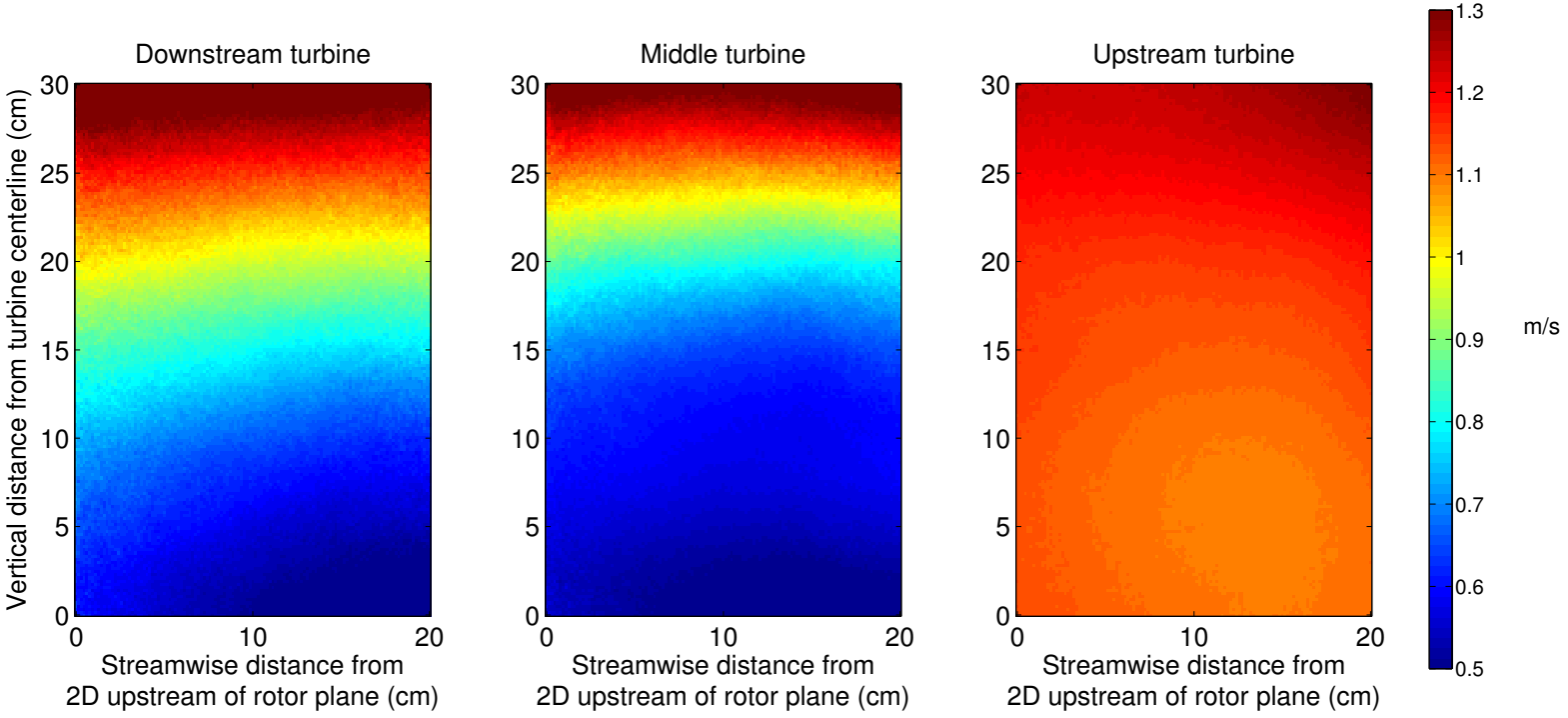
⇐ Direction of flow

INCIDENT TURBULENCE INTENSITY ON THREE TURBINES, 5D



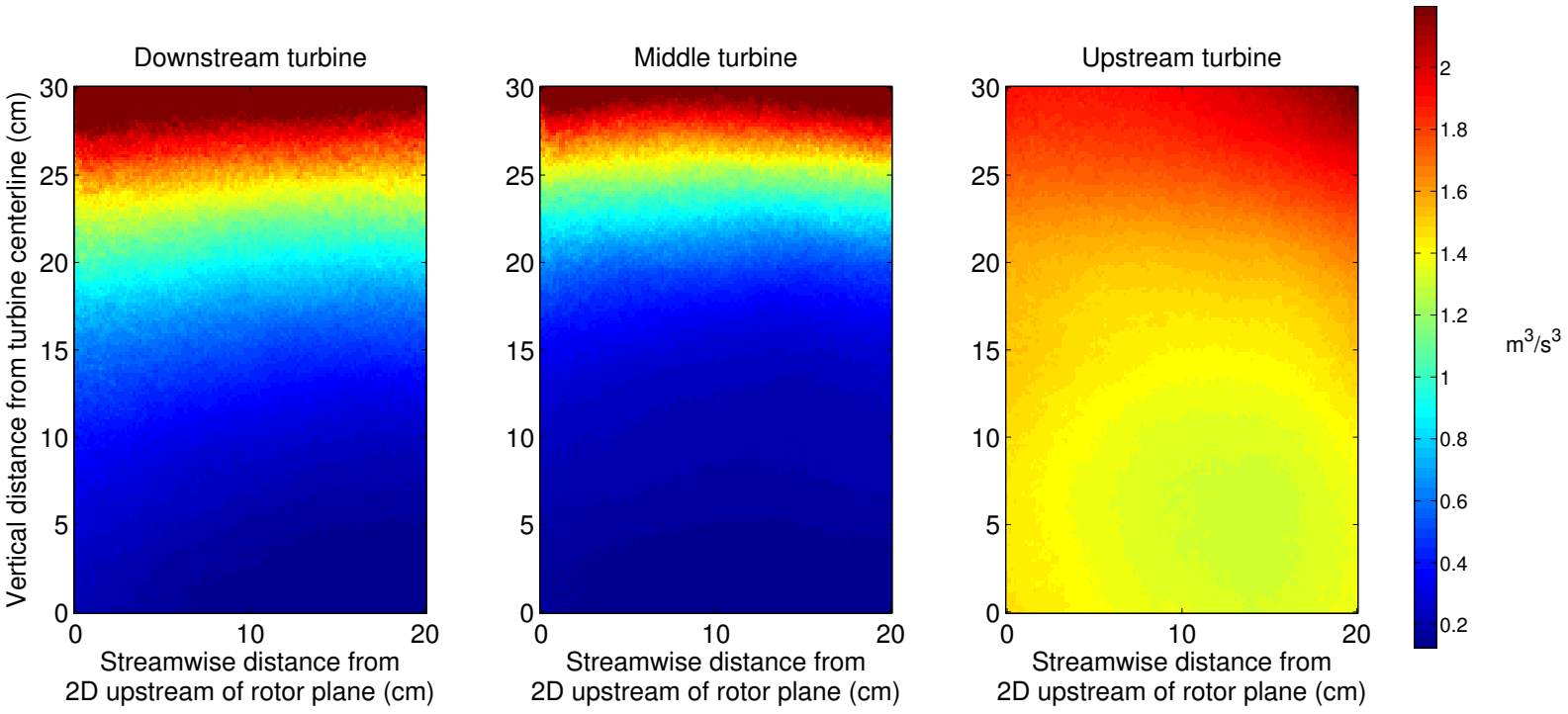
⇐ Direction of flow

INCIDENT MEAN FLOW ON THREE TURBINES, 7D



⇐ Direction of flow

INCIDENT POWER ON THREE TURBINES, 7D



⇐ Direction of flow