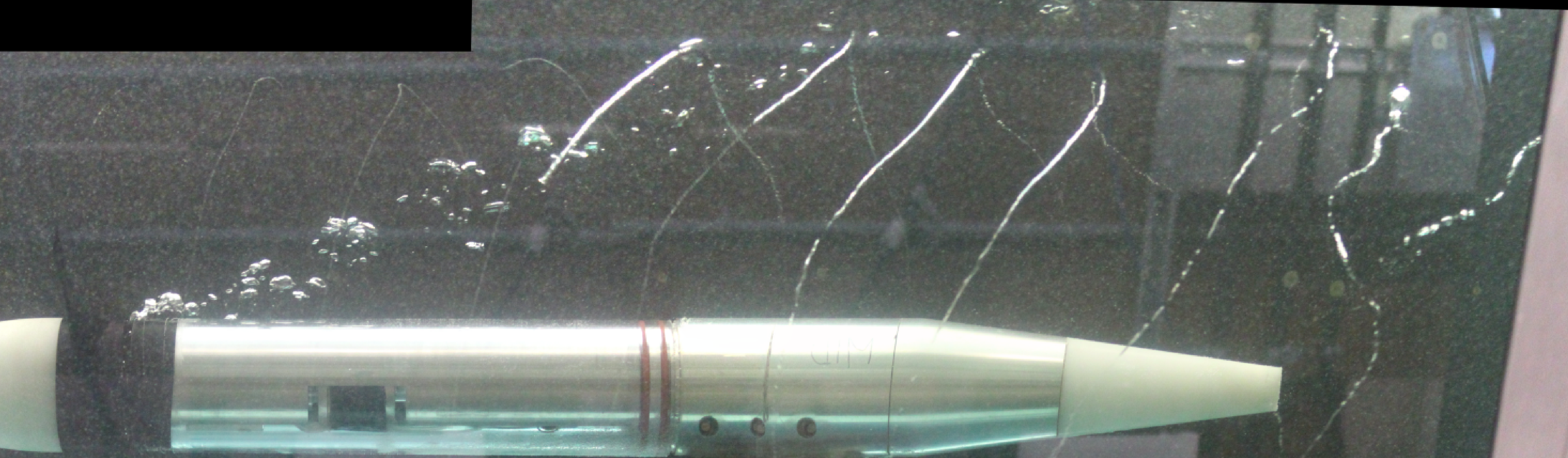

Experimental/Numerical Comparison of Turbine Efficiency and Wake Structure in an Array of 3 Scale-Model Marine HydroKinetic Turbines

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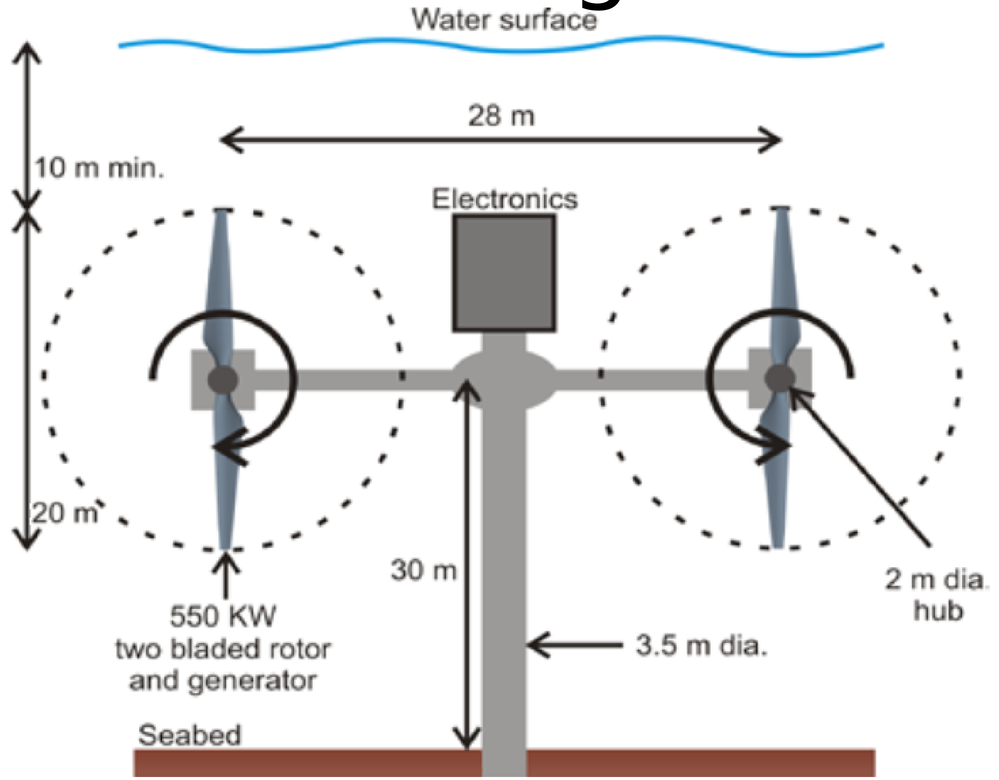
What is this talk about?

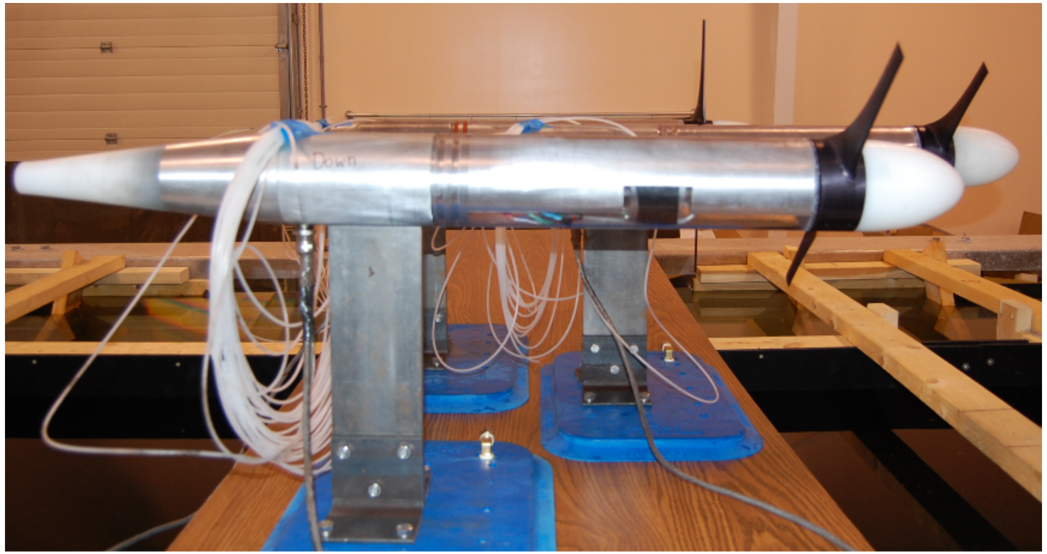
- **Marine Hydrokinetic Turbines:**
  - Flume experiments: measuring power performance, and wakes using PIV (Particle-Image-Velocimetry)
  - CFD simulatations: various RANS and LES model comparisons
- **Case Studies:**
  - Single turbine and 3 turbine arrays at various spacings/layouts

Inflow Speed (m/s)	TSR	Yaw Angle (deg)	Rotor Control
0.9, 1.0, 1.2	6 to 13	0, 20	open & closed loop

- **Questions:**
  - How can lab scale experiments inform the design of utility scale tidal power plants?

Turbine Design

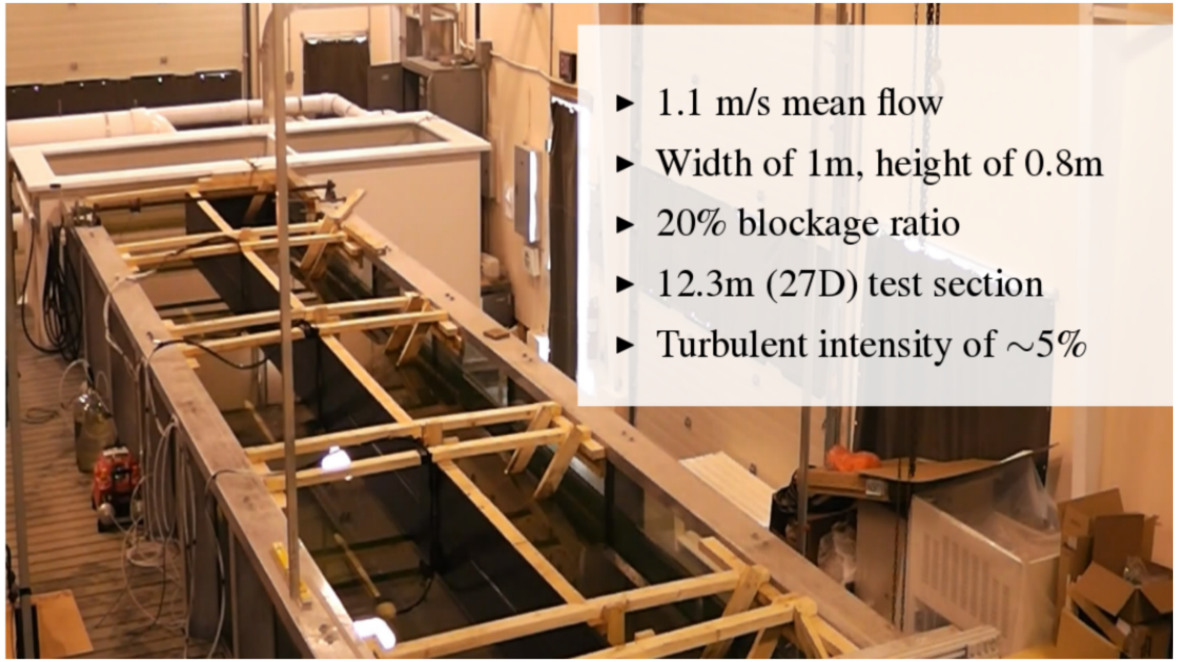


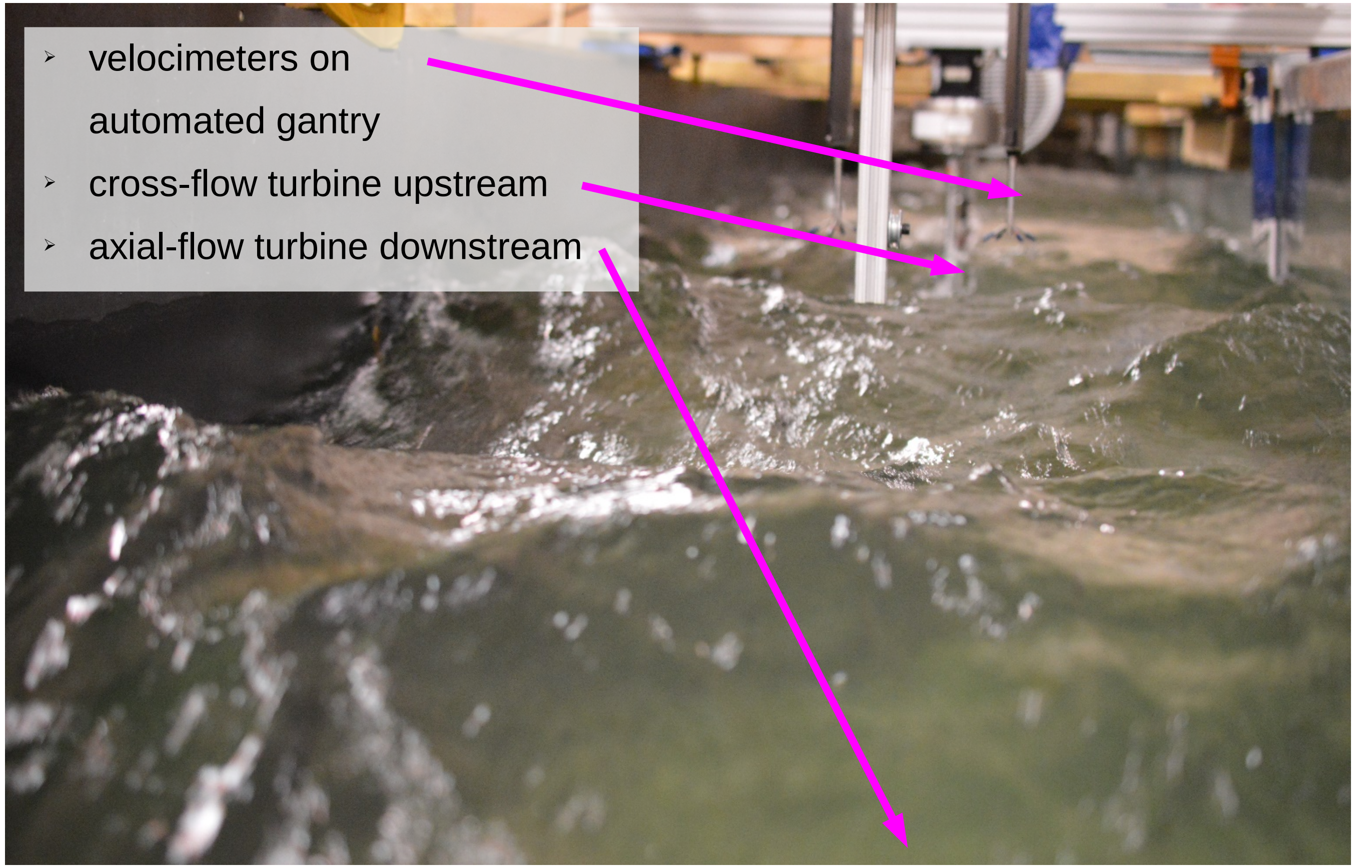


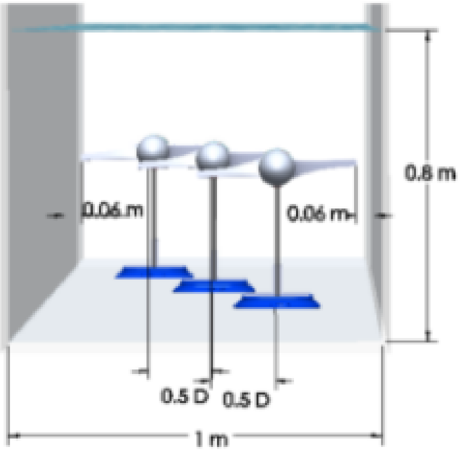
- Full-scale 1.2 MW, dual-rotors, diameter 20m
- Created by US Dept. of Energy to standardize experimental and numerical studies
- Lab-scale turbine 45:1 scaling, diameter 45 cm
- Attempt to match power extraction and wake characteristics of full-scale turbine
- Lab-scale blades were re-designed to minimize Reynolds scaling effects

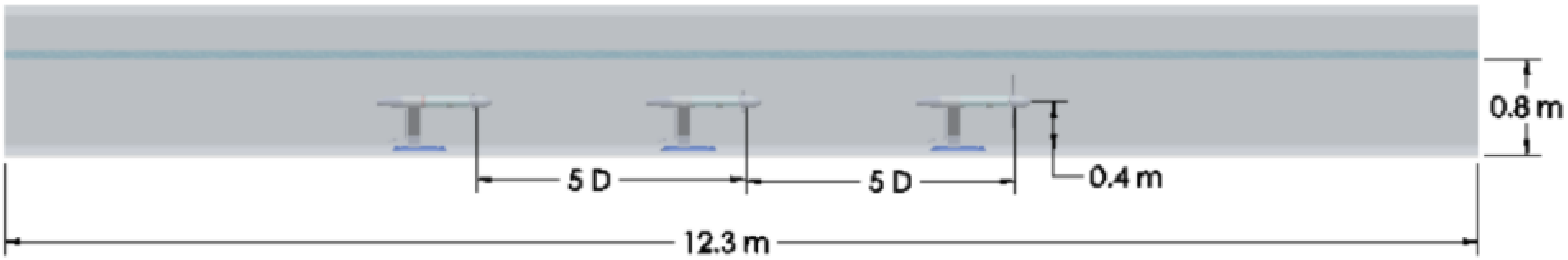
	Full-Scale	**Lab-Scale**
$\text{Reynolds}_{\textbf{chord}}$	2 to 9 million	70,000 to 150,000
$\text{Reynolds}_{\textbf{diameter\_rotor}}$	10 to 60 million	315,000 to 540,000
$\text{Reynolds}_{\textbf{diameter\_nacelle}}$	1 to 6 million	71,000 to 120,000

Flume characteristics



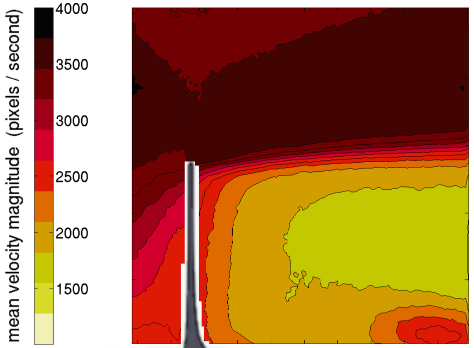






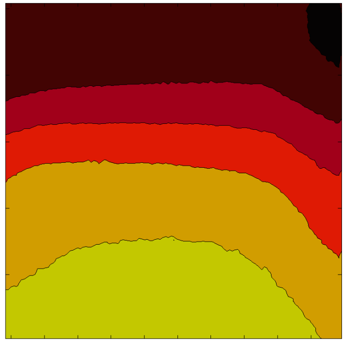
mean of velocity & vorticity, magnitudes (TSR 7, inflow 0.9 m/s)

0D



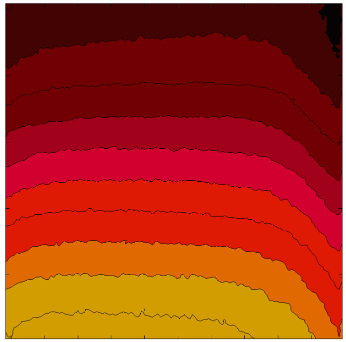
- Flow separation off nacelle.
- interaction of hub vortex with nacelle boundary layer causes a flow ejection

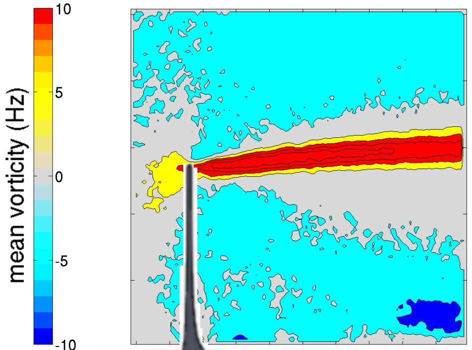
2D



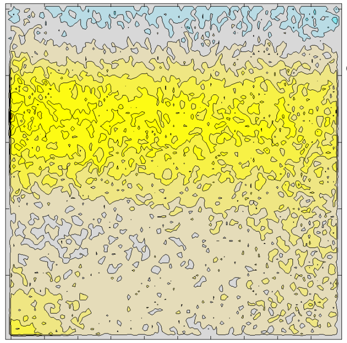
- More flow separation off rear of nacelle, further diffusing the wake
- Wake expansion, and then contraction/diffusion seen by 4D downstream

4D

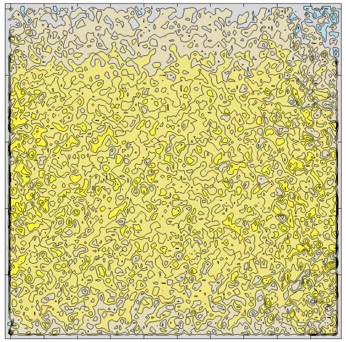




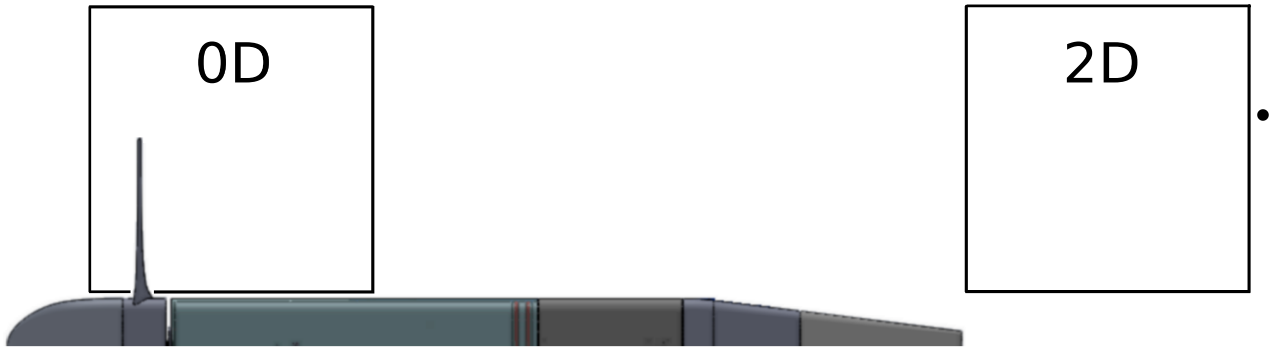
- Tip vortex is clearly visible, identifying the edges of wake and free stream



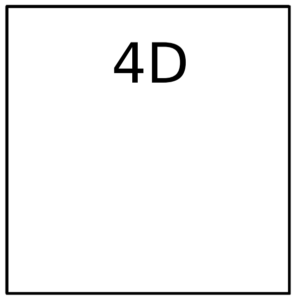
- By 4D downstream, diffusion of vorticity indicates that coherent structures grow in volume, yet also diffuse

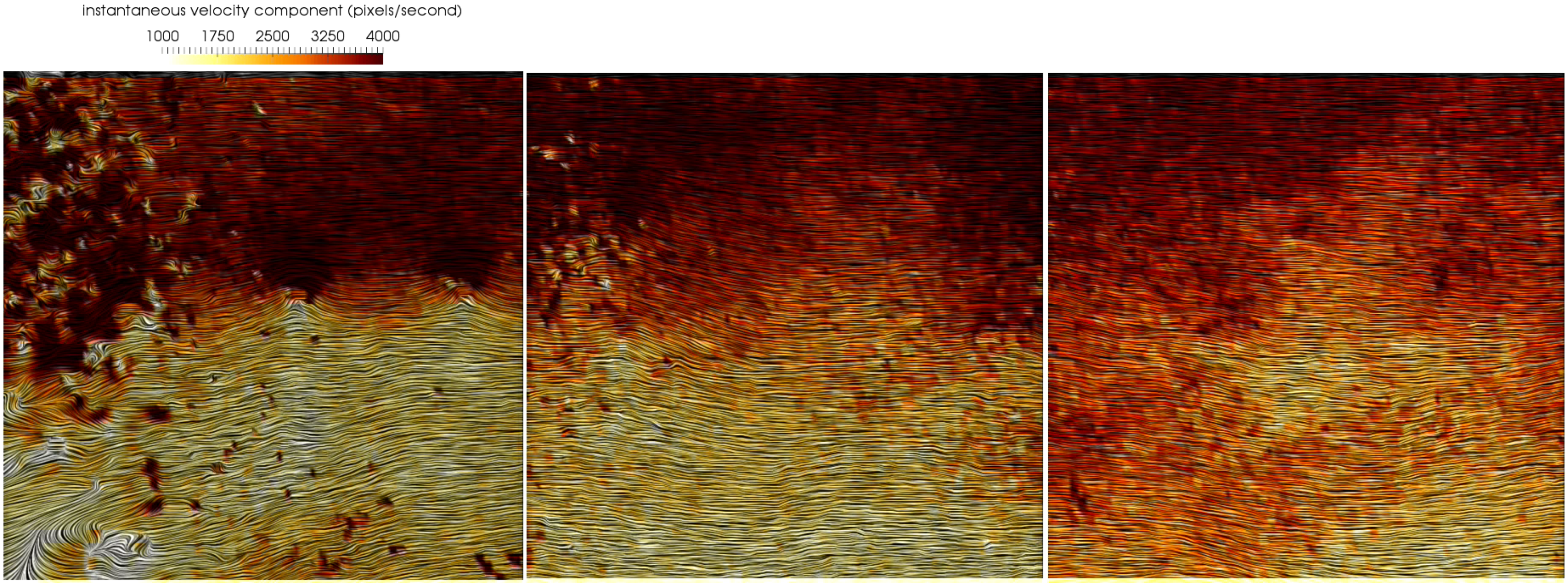


showing LIC of **instantaneous velocity** (TSR 7, inflow 0.9 m/s)

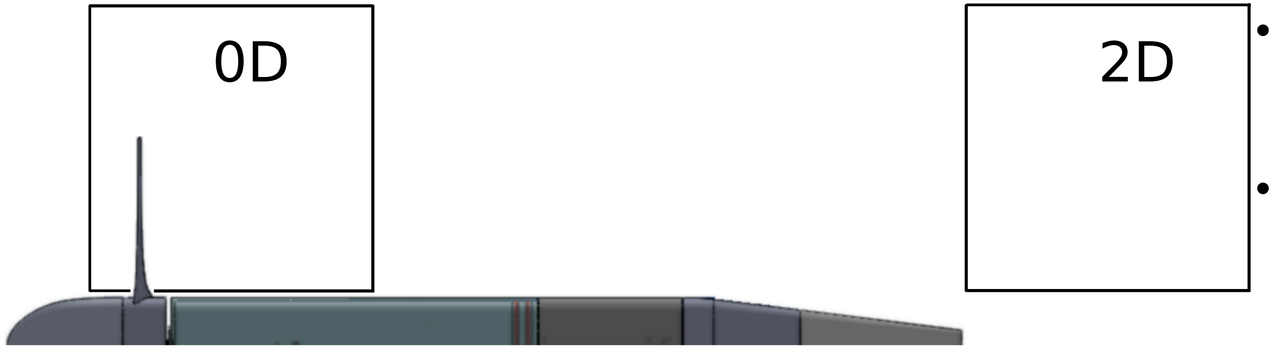


- “Meandering” of wake seen in 2D, and stronger in the 4D window

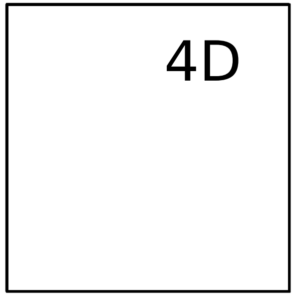


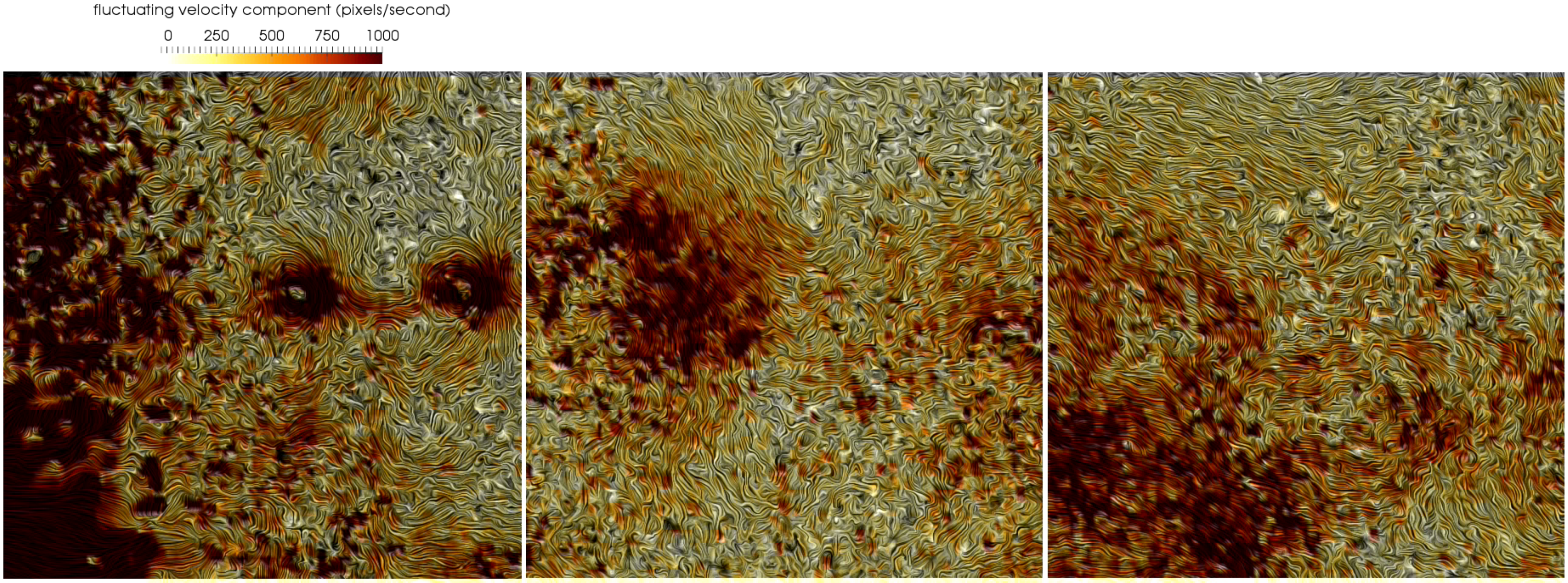


showing LIC of **fluctuating velocity** (TSR 7, inflow 0.9 m/s)

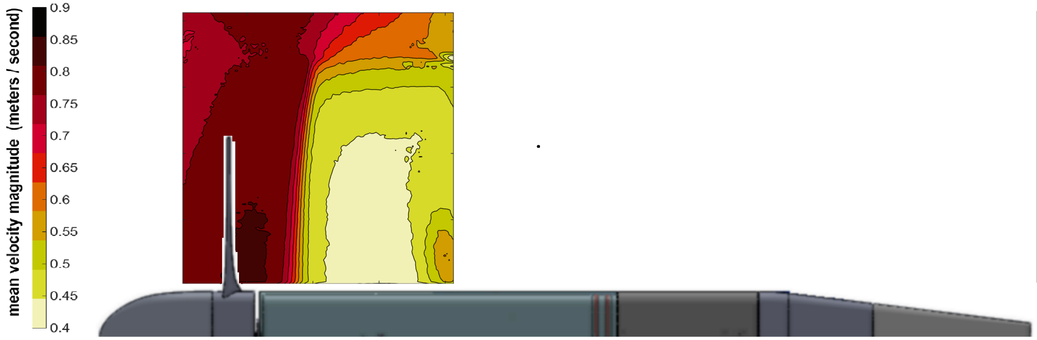


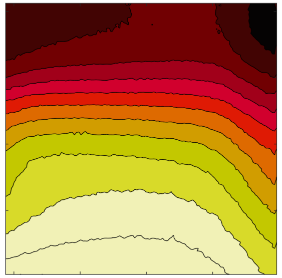
- “wake meandering” also seen in the trajectory of tip vorticies
- Can see that tip vortex moves inboard, and then outboard with the bulk wake expansion



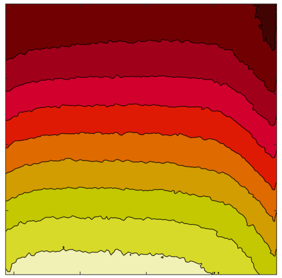


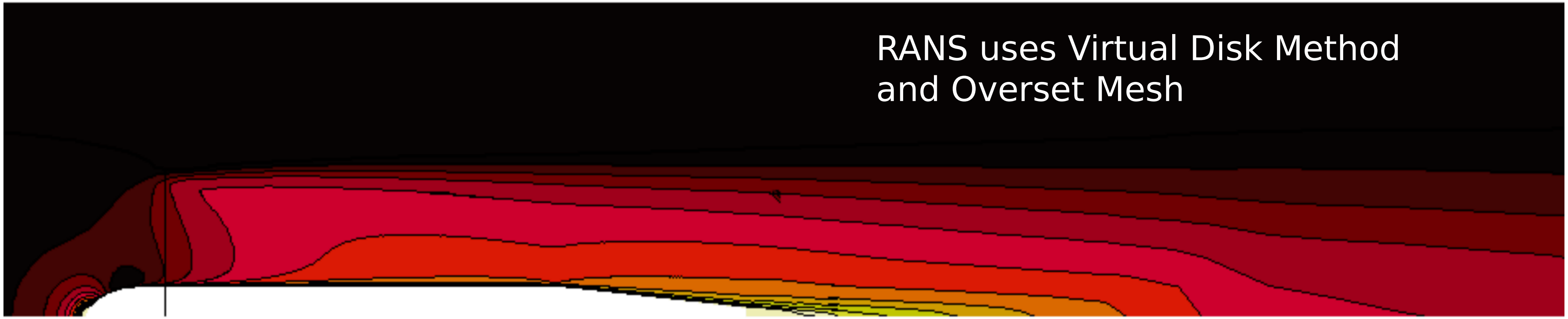
velocity field: compare PIV Experiments to CFD simulations

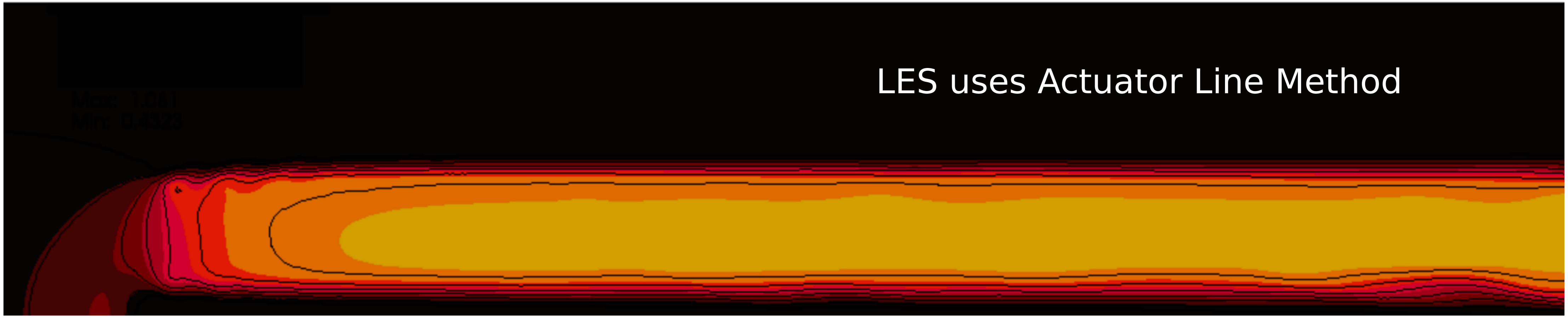




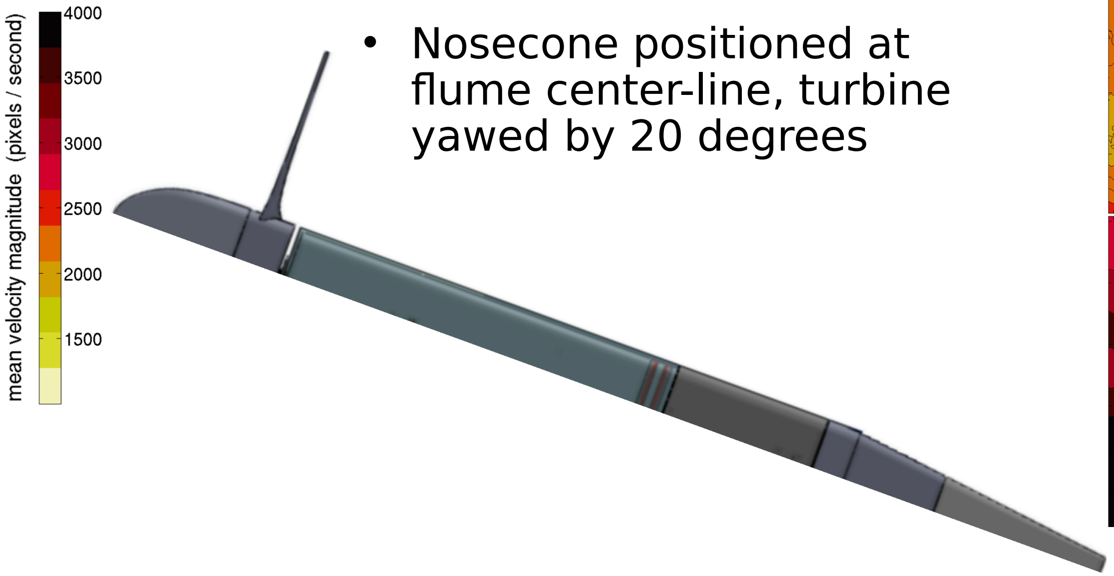
PIV, mean velocity magnitude
TSR 7.0, inflow 1.0 m/s



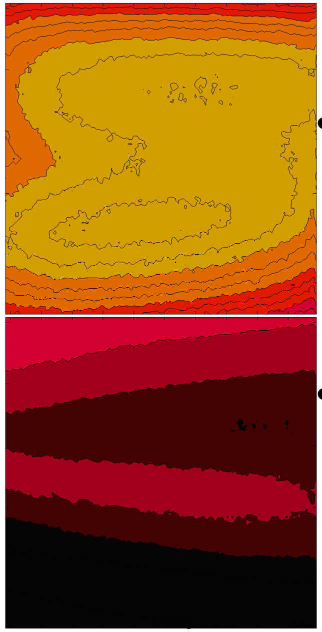


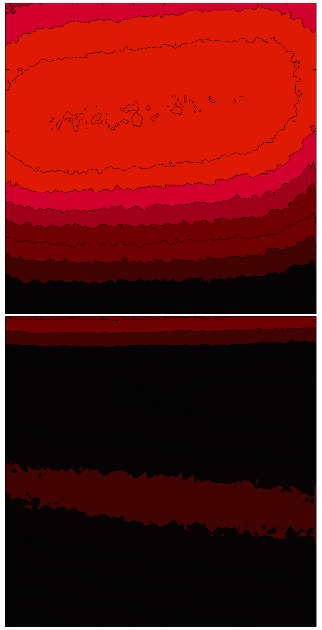


mean of **instantaneous** velocity & vorticity, magnitudes



- Nosecone positioned at flume center-line, turbine yawed by 20 degrees

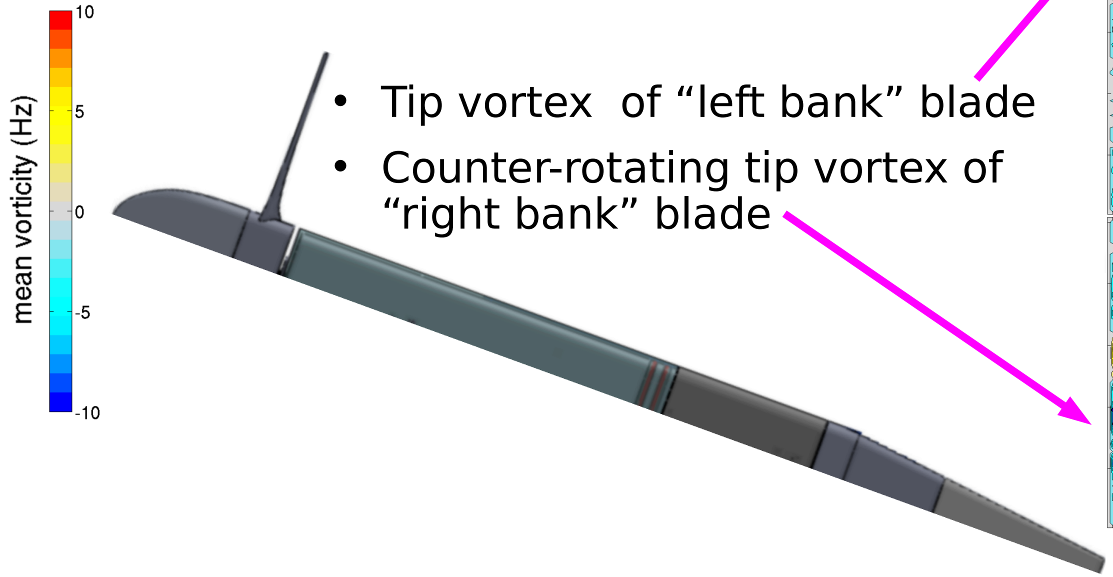




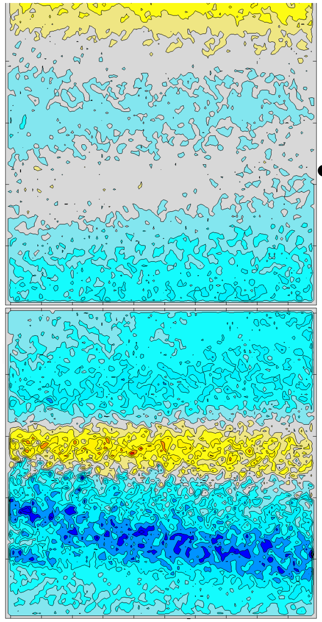
- wake structure has slight deflection (~10 deg.) from the streamwise direction
- Flow speed-up on “right bank” perhaps from tower shadow, or wall blockage

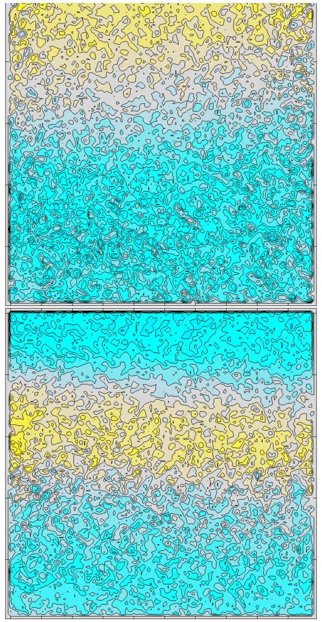
2D

4D

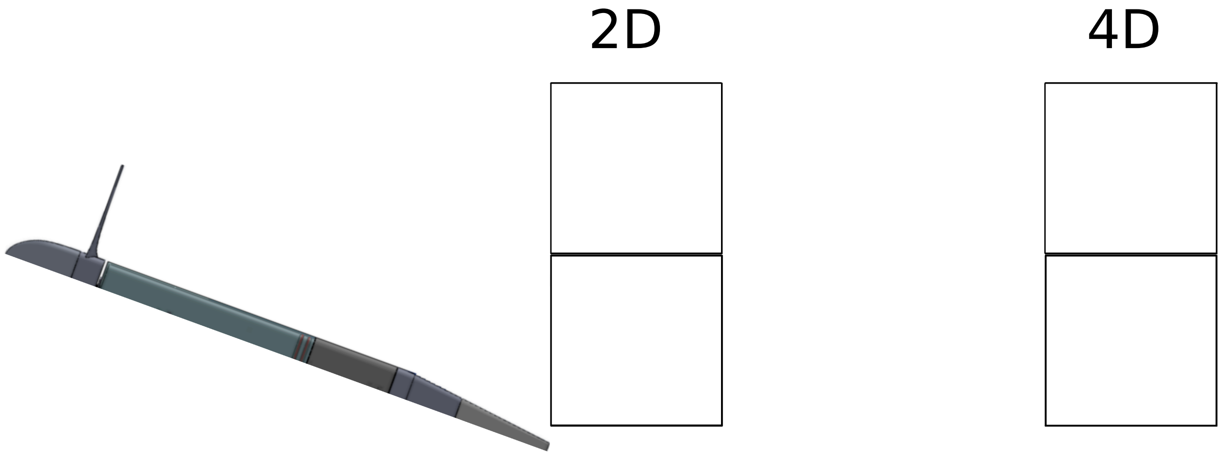


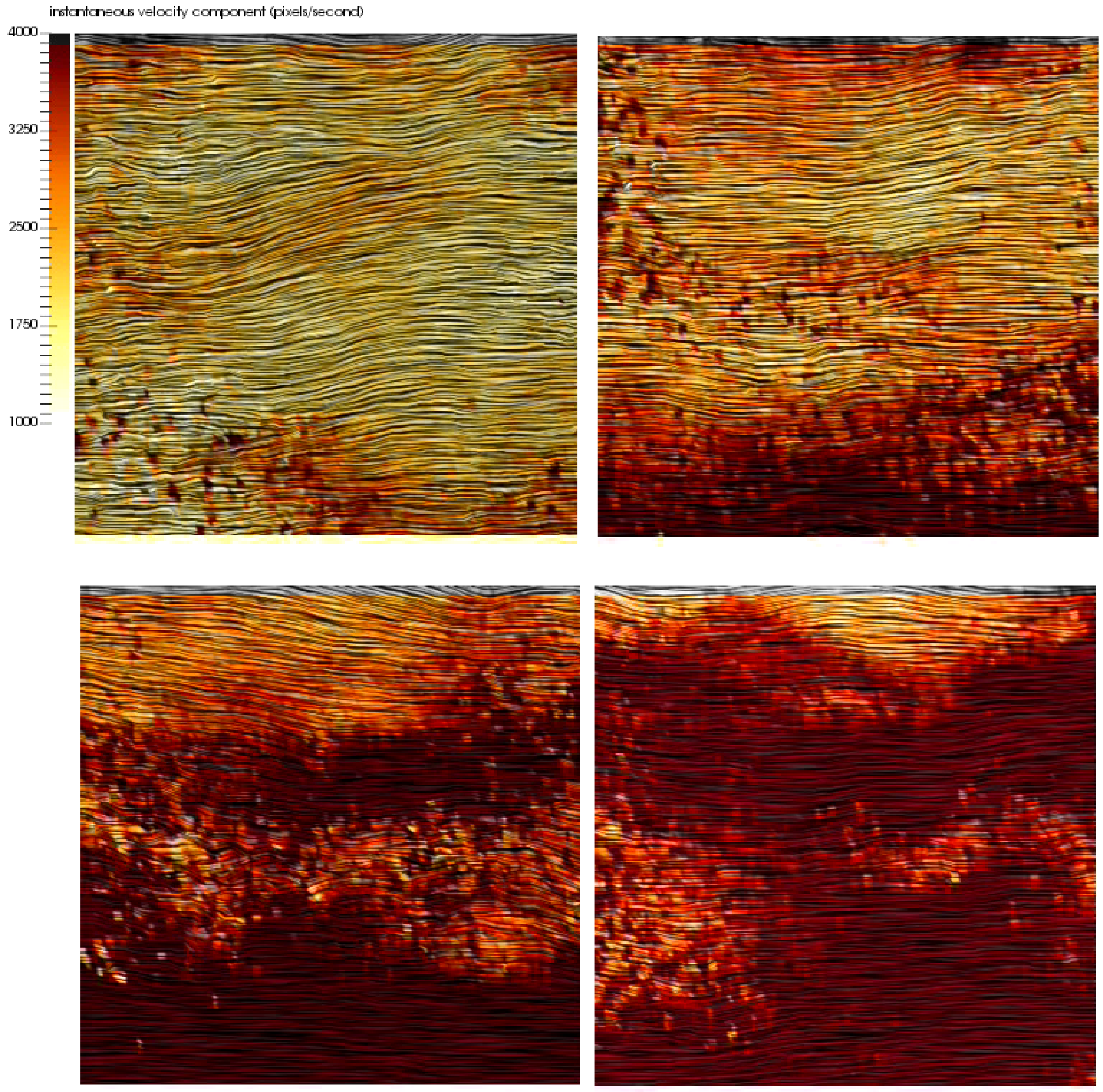
- Tip vortex of “left bank” blade
- Counter-rotating tip vortex of “right bank” blade





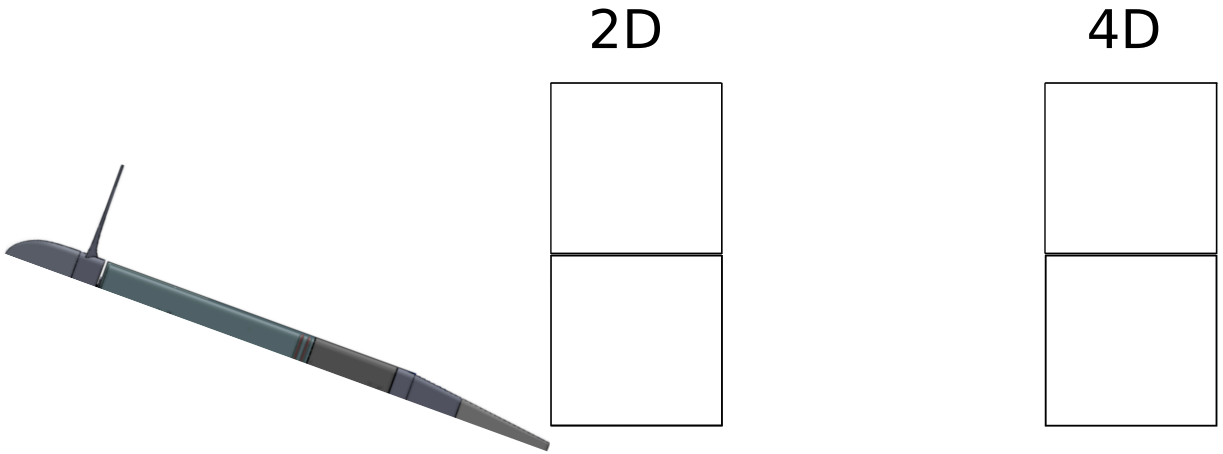
- flow separation off nacelle, counter-rotating to tip vortex showing LIC of **instantaneous velocity** (TSR 7, inflow 1.0 m/s)

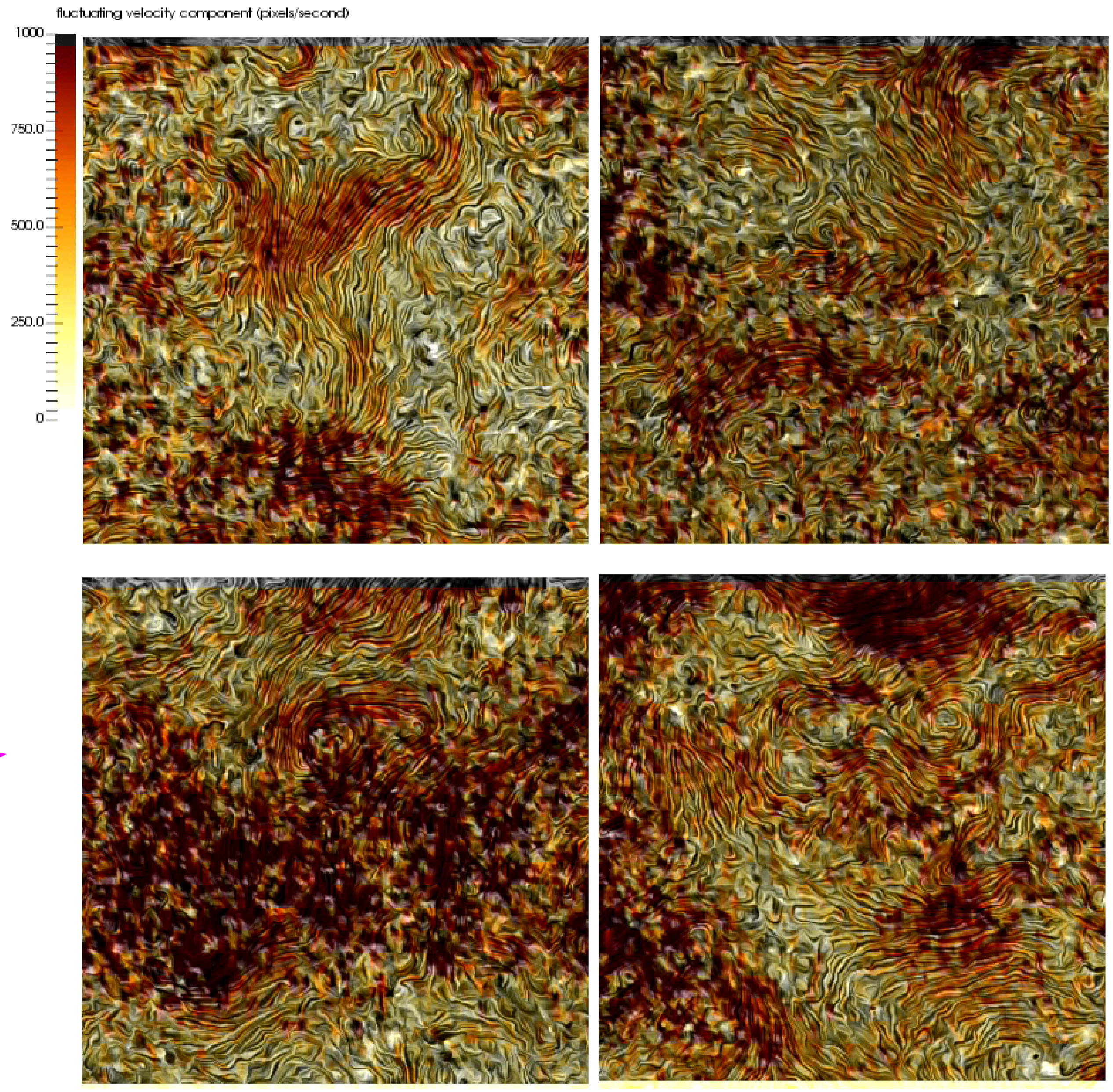




- vortex shedding seen from nacelle, similar to a cylinder in cross-flow, but far from Reynolds independence (*Re* ~120,000)

showing LIC of **fluctuating velocity** (TSR 7, inflow 1.0 m/s)

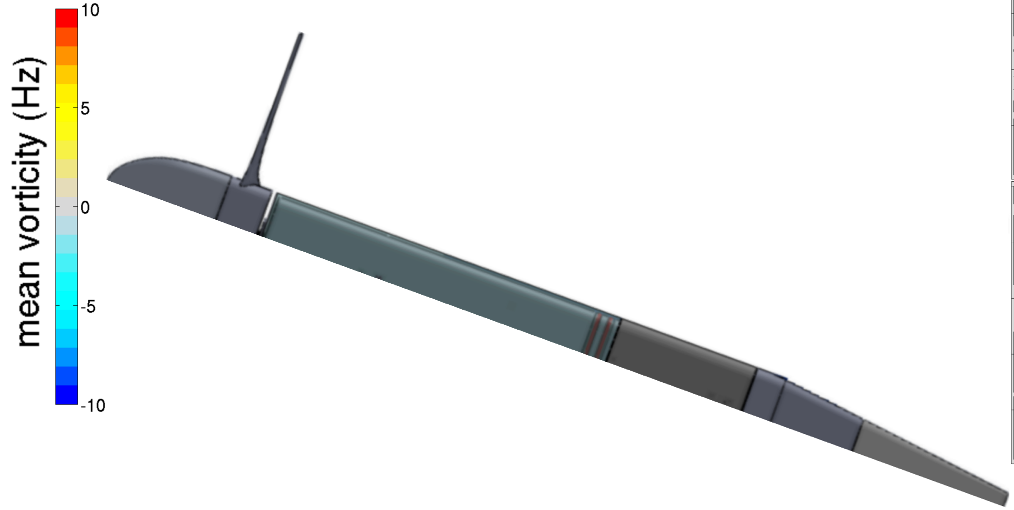


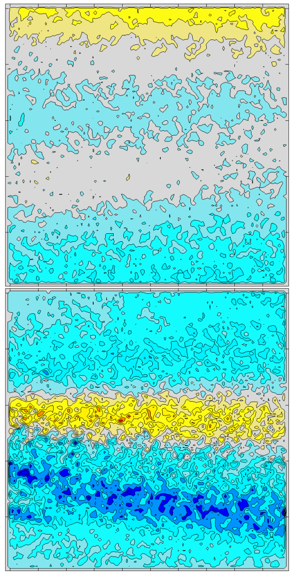


- vortex shedding from nacelle causes additional “meandering” of blade tip vortex

compare different inflow speeds (TSR = 7.0)

mean of **instantaneous vorticity**

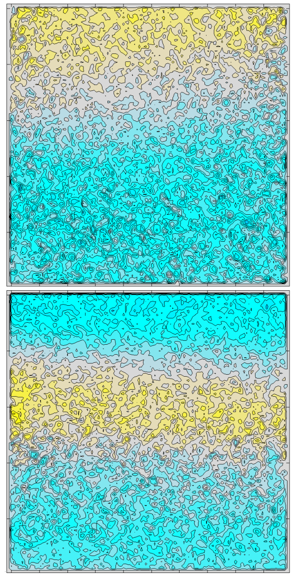




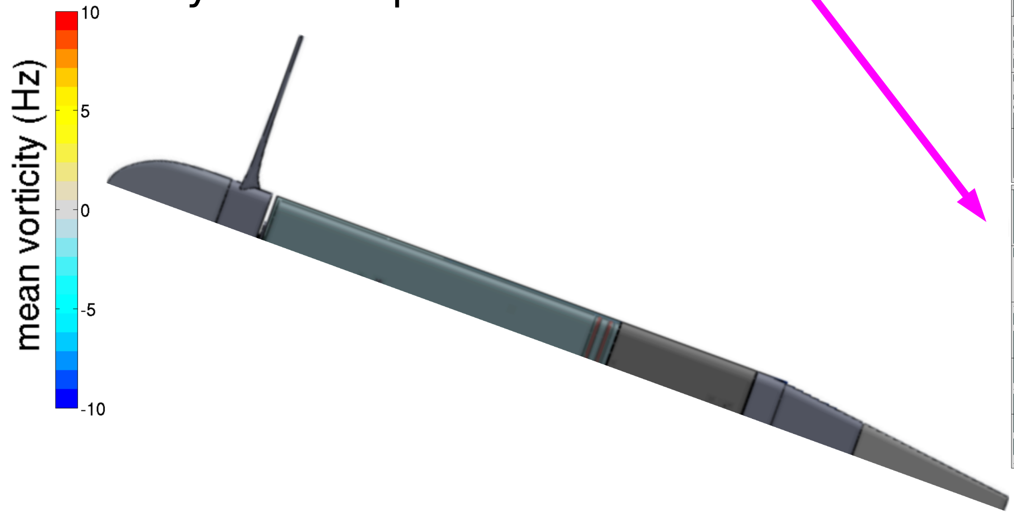
$Re_{\textbf{\textit{diameter\_rotor}}}$

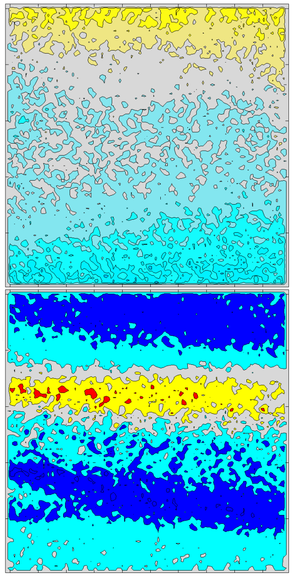
~300,000

inflow 1.0 m/s



- An additional flow structure appears!
  Reynolds dependent flow

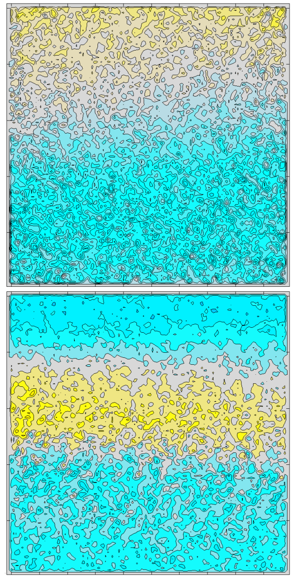




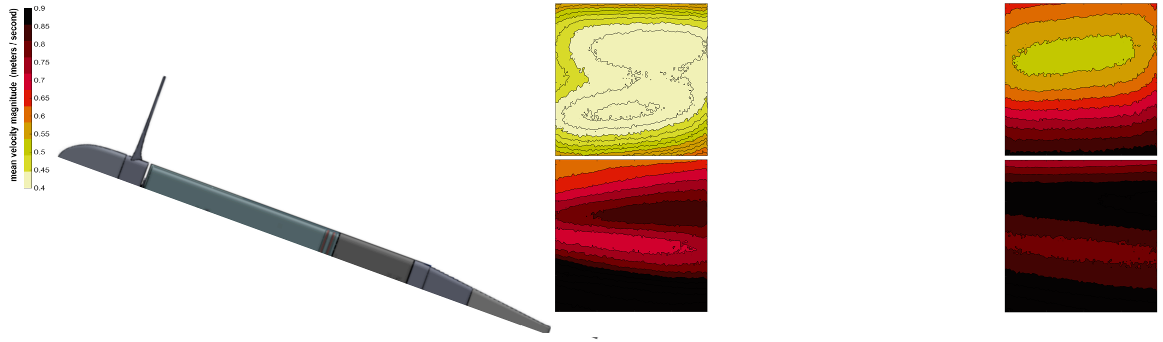
$Re_{\textbf{\textit{diameter\_rotor}}}$

~500,000

inflow 1.2 m/s



velocity field: compare PIV Experiments to CFD Simulations



PIV, mean velocity magnitude
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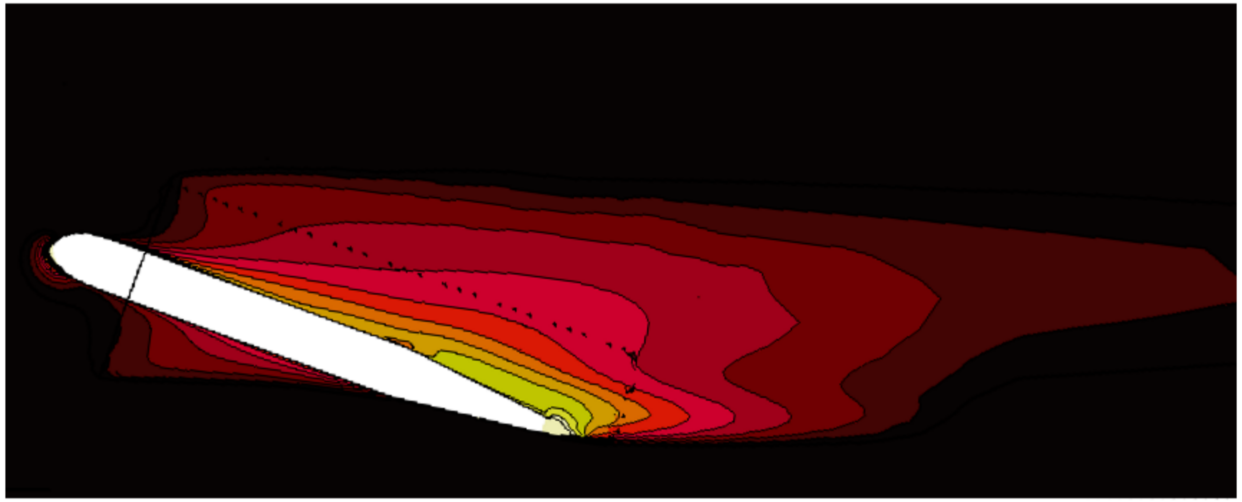
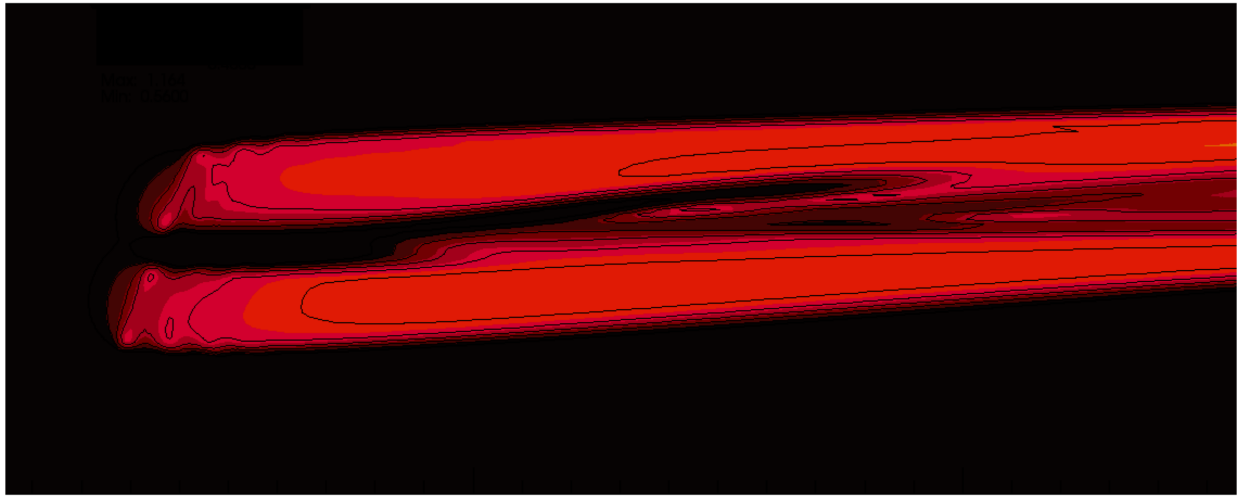
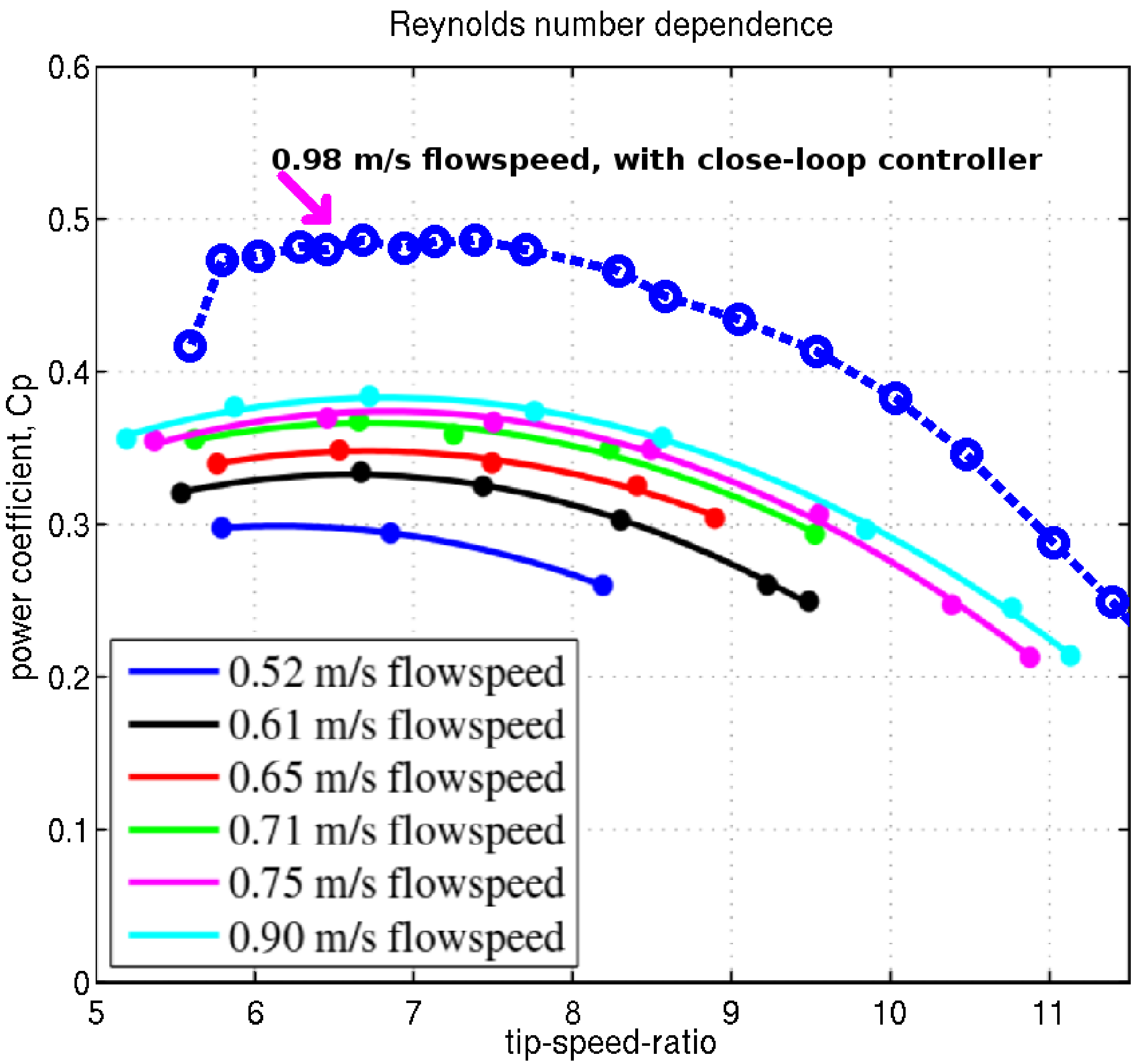


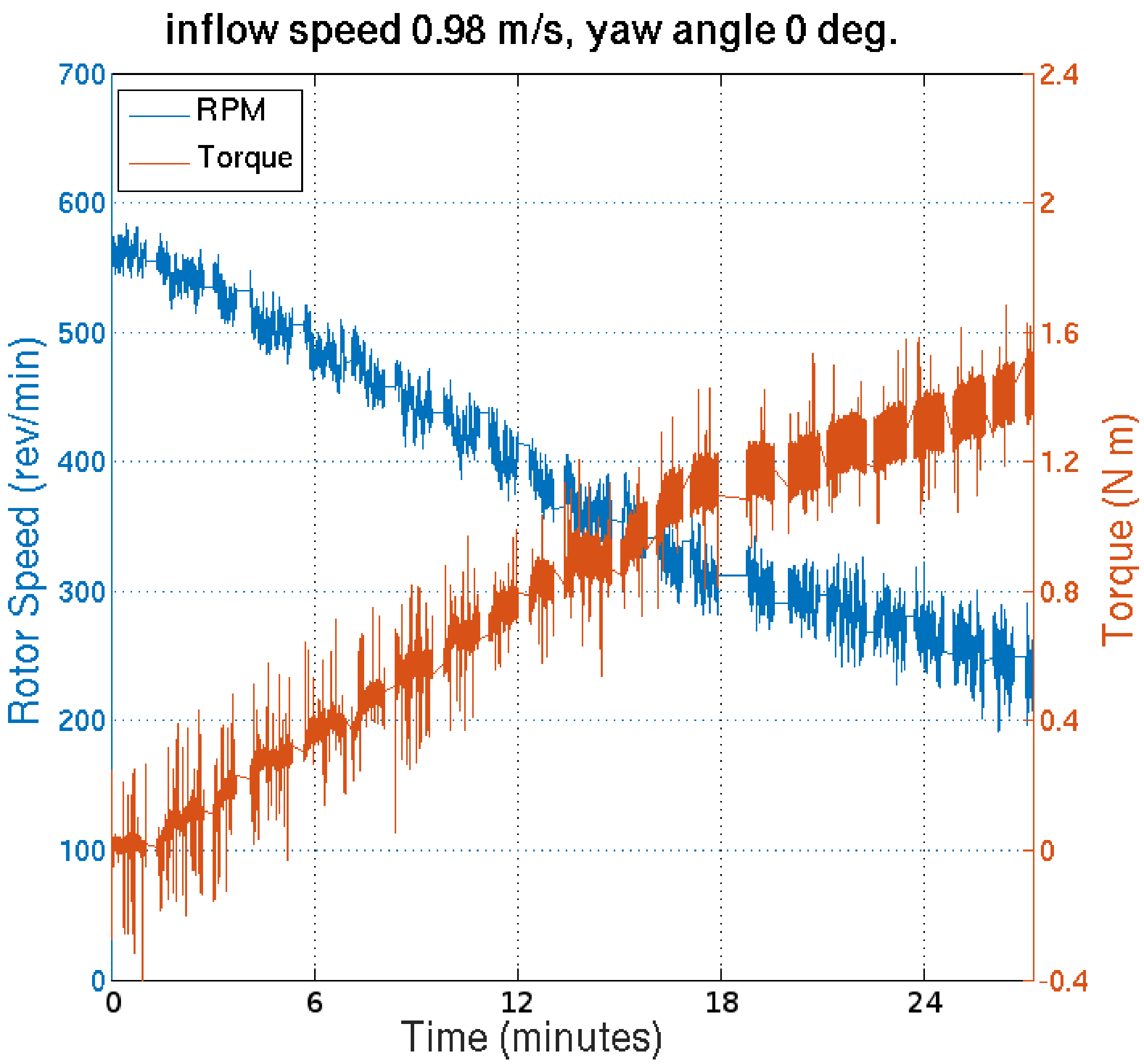
RANS uses Virtual Disk Method



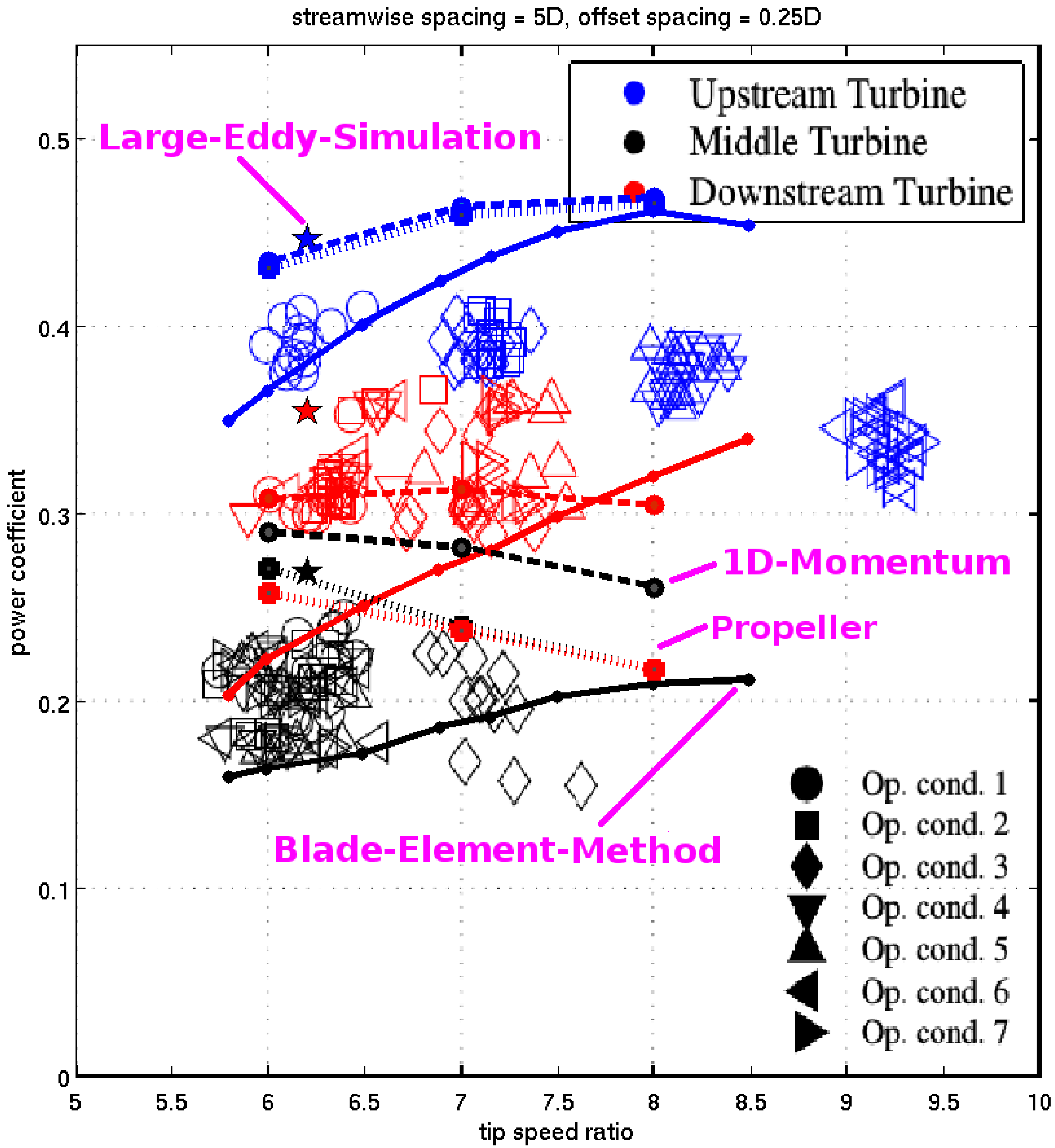
LES uses Actuator Line Method

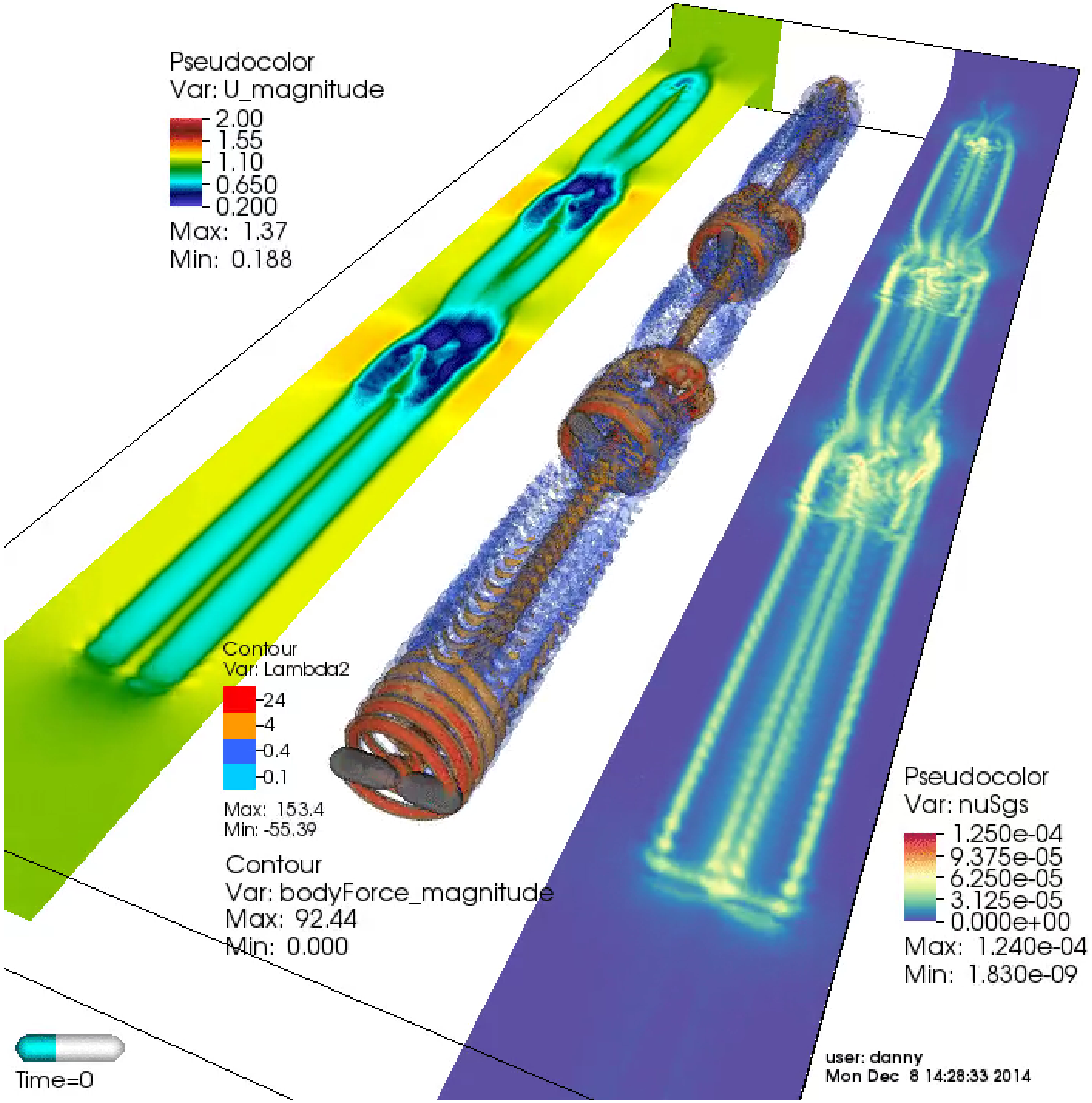
Power Performance: compare Reynolds effect, and new controller





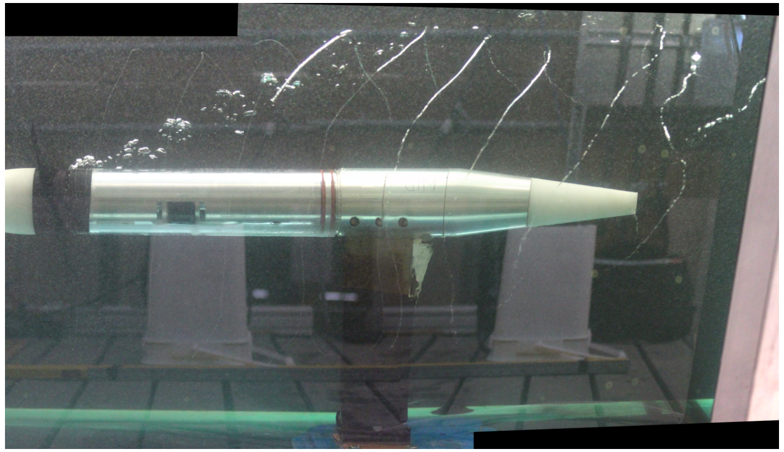
Power Performance: 3 turbines, compare CFD models





OUTRO

- **Conclude:**
  - Achieve realistic turbine efficiency at lab-scale, similar performance curves to full-scale
  - Relate Cp-vs-TSR to wake structure via PIV and CFD models
  - CFD models range from RANS to LES (actuator methods)
  - Investigated subtle effects from nacelle, Reynolds dependence, and TSR controls
  - We like to share our data and CFD case files!! see **https://github.com/nnmrec**



Thank you !! Questions ?? Suggestions ??

Acknowledgments: NNMREC Oregon State University University of Washington, NSF, NAVFAC Naval Facilities Engineering Command