Experimental Measurements and Numerical Simulations in a 3-Turbine Array of 45:1 Scale DOE RM1 Turbines

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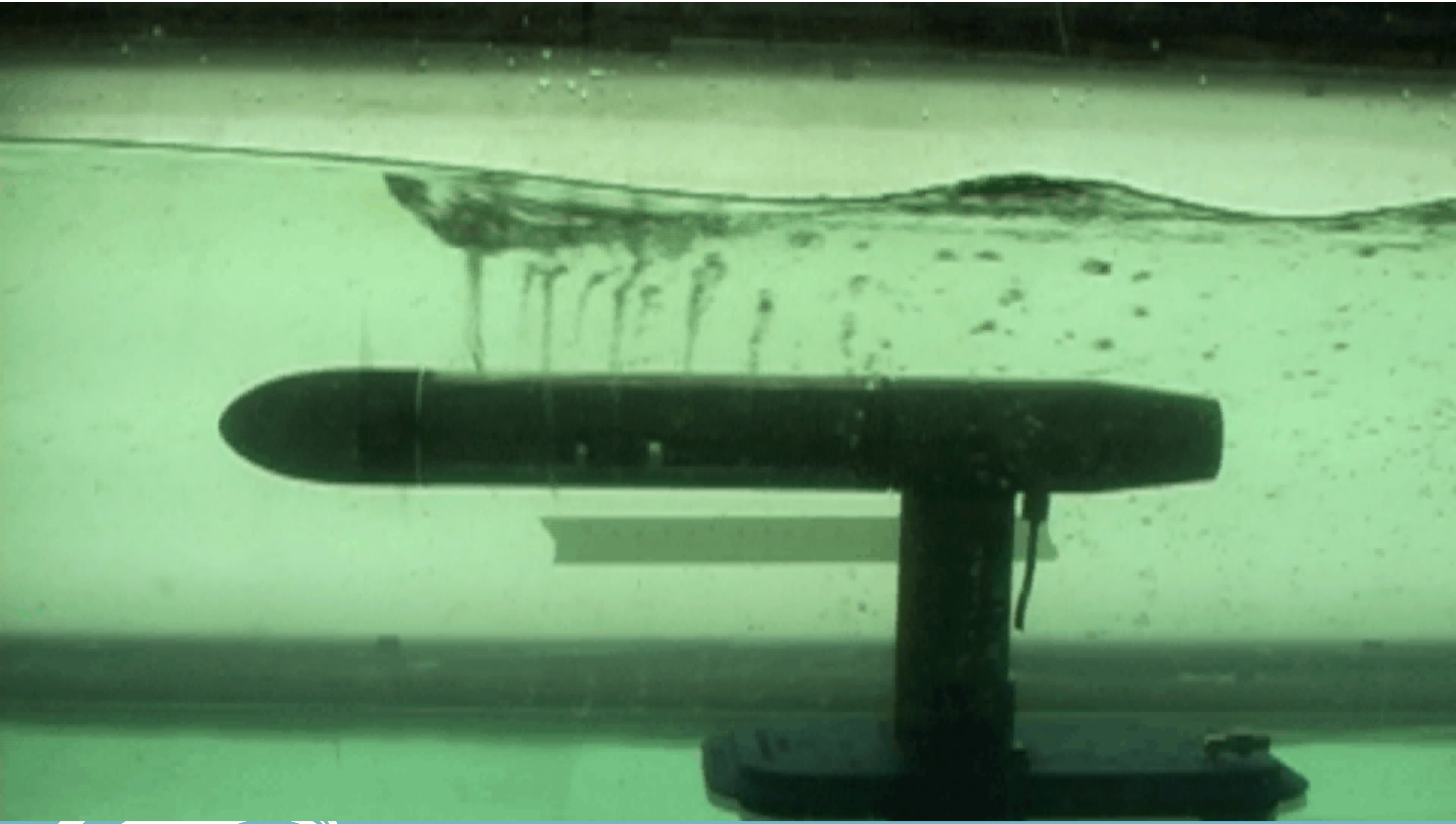

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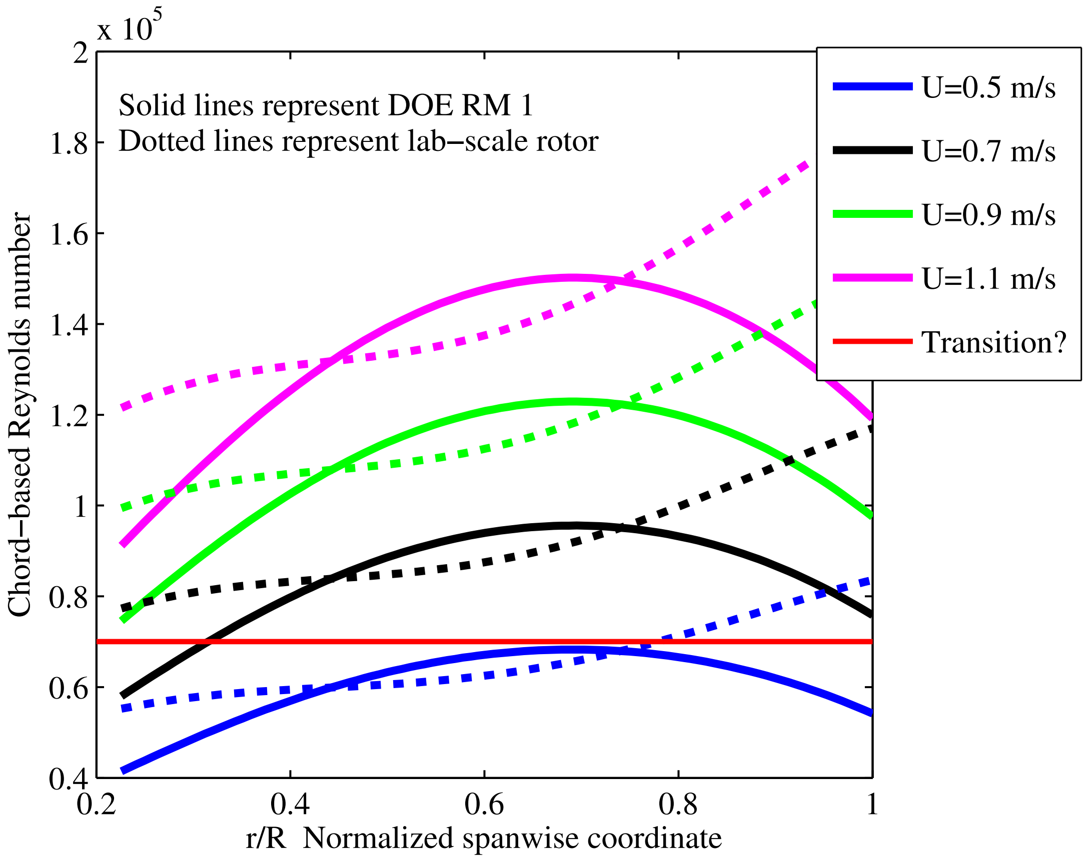
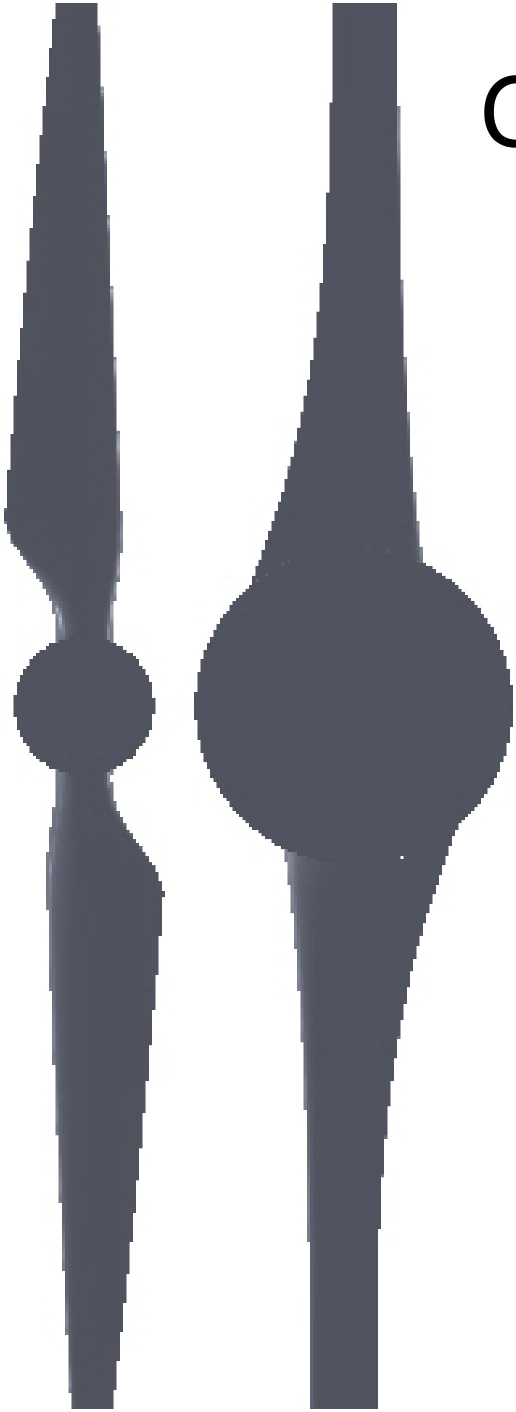
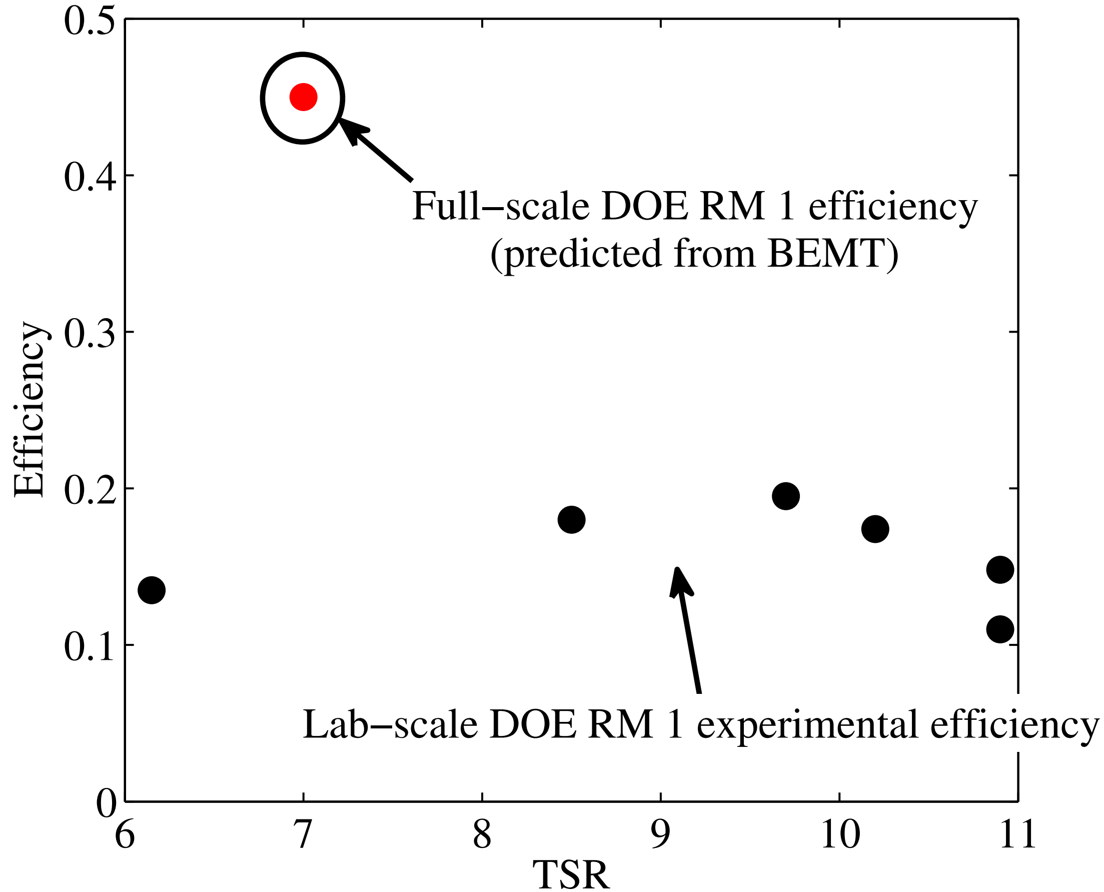
DOE RM 1 Turbine Scaling down process

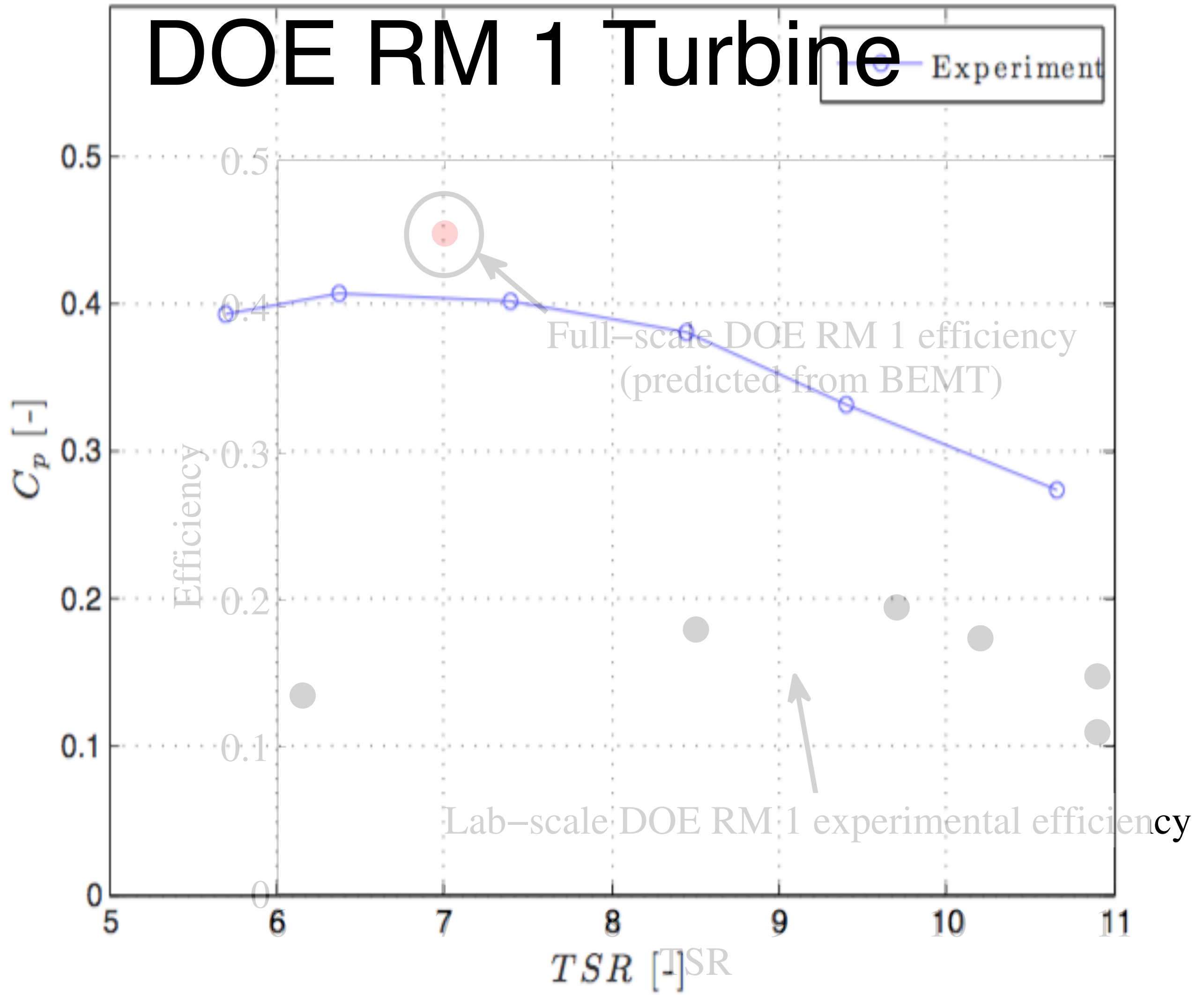


Geometrically-scaled DOE RM 1 Turbine Performance



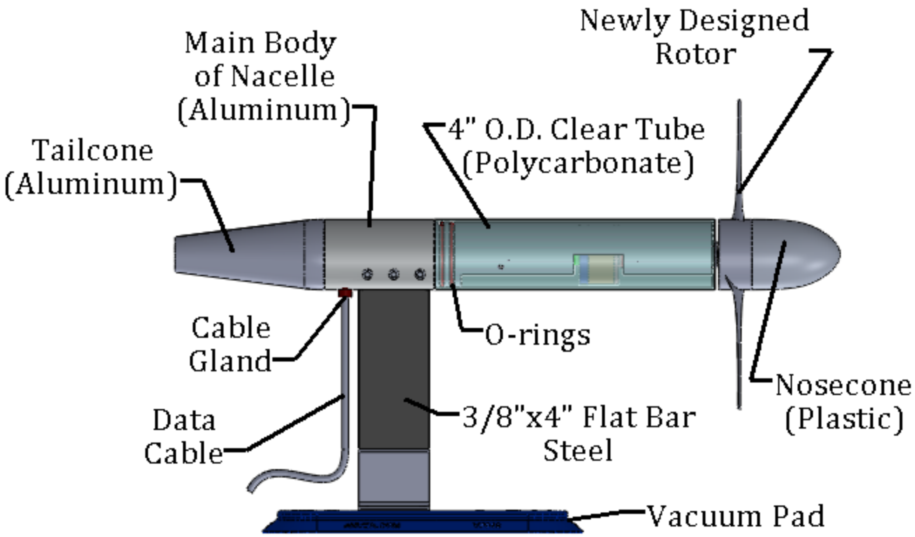


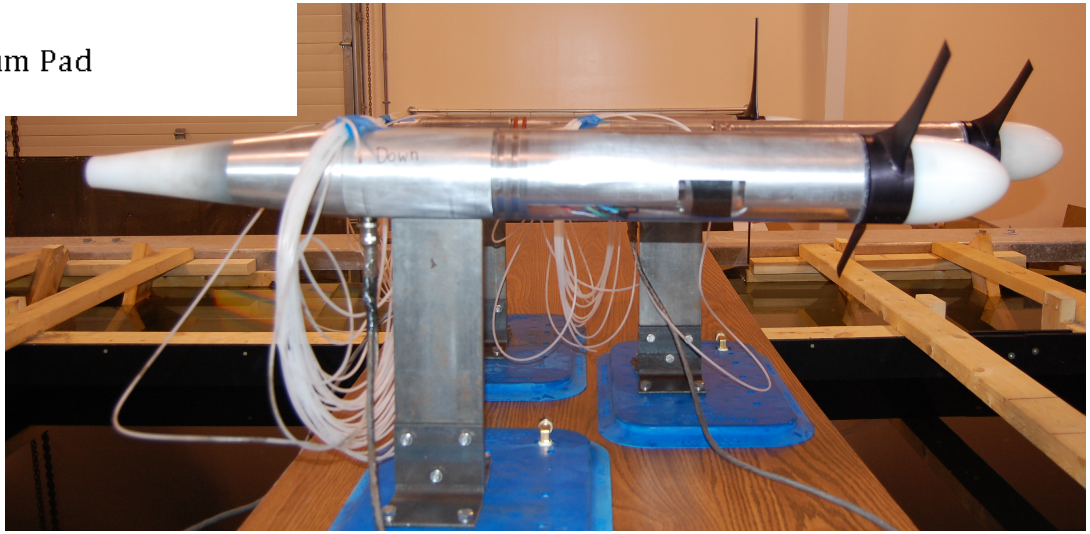
Performance-scaled DOE RM 1 Turbine



DOE RM1 @ 45:1 scale

Similarity based on performance curves



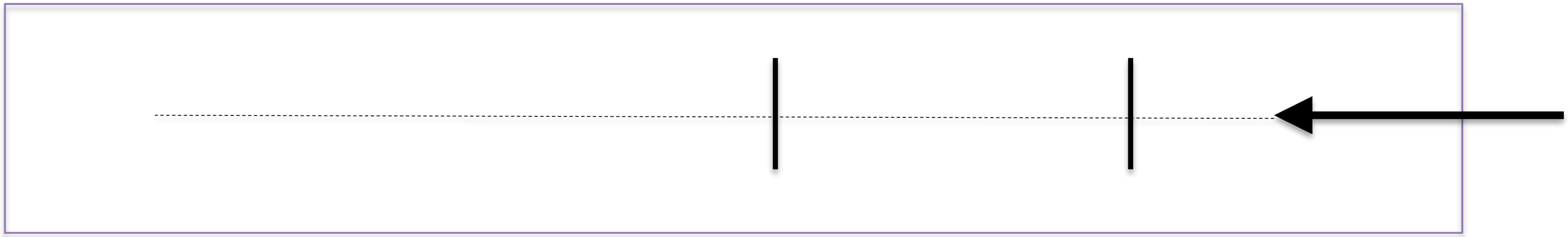


Experimental Conditions

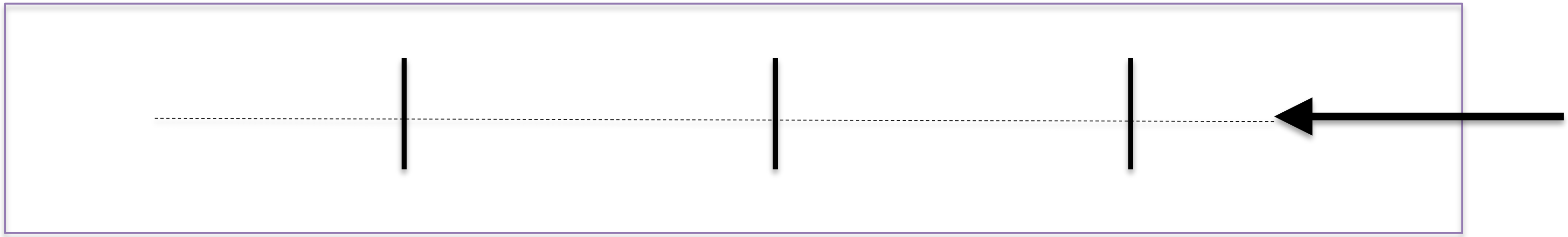
Re_{chord} ~ 10^5 Tip Speed Ratio (TSR) = 4.5-8
Blockage Ratio = 20%

Three Different Array Configurations

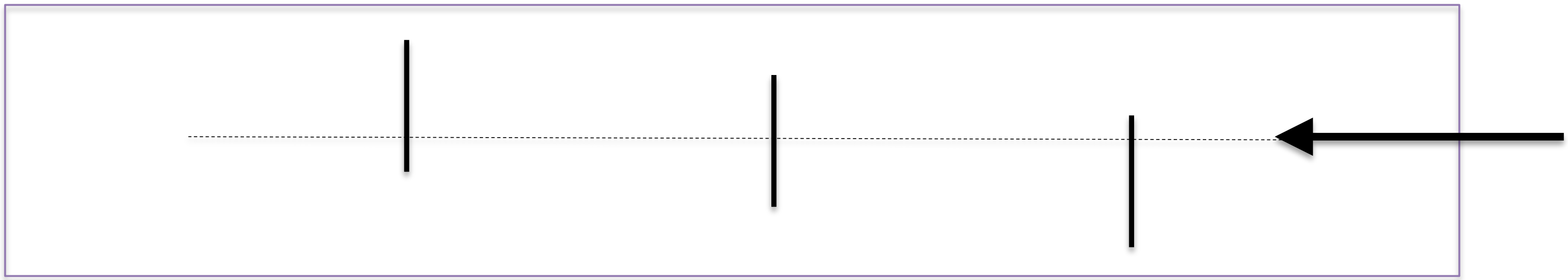
1. Array of two coaxial turbines.



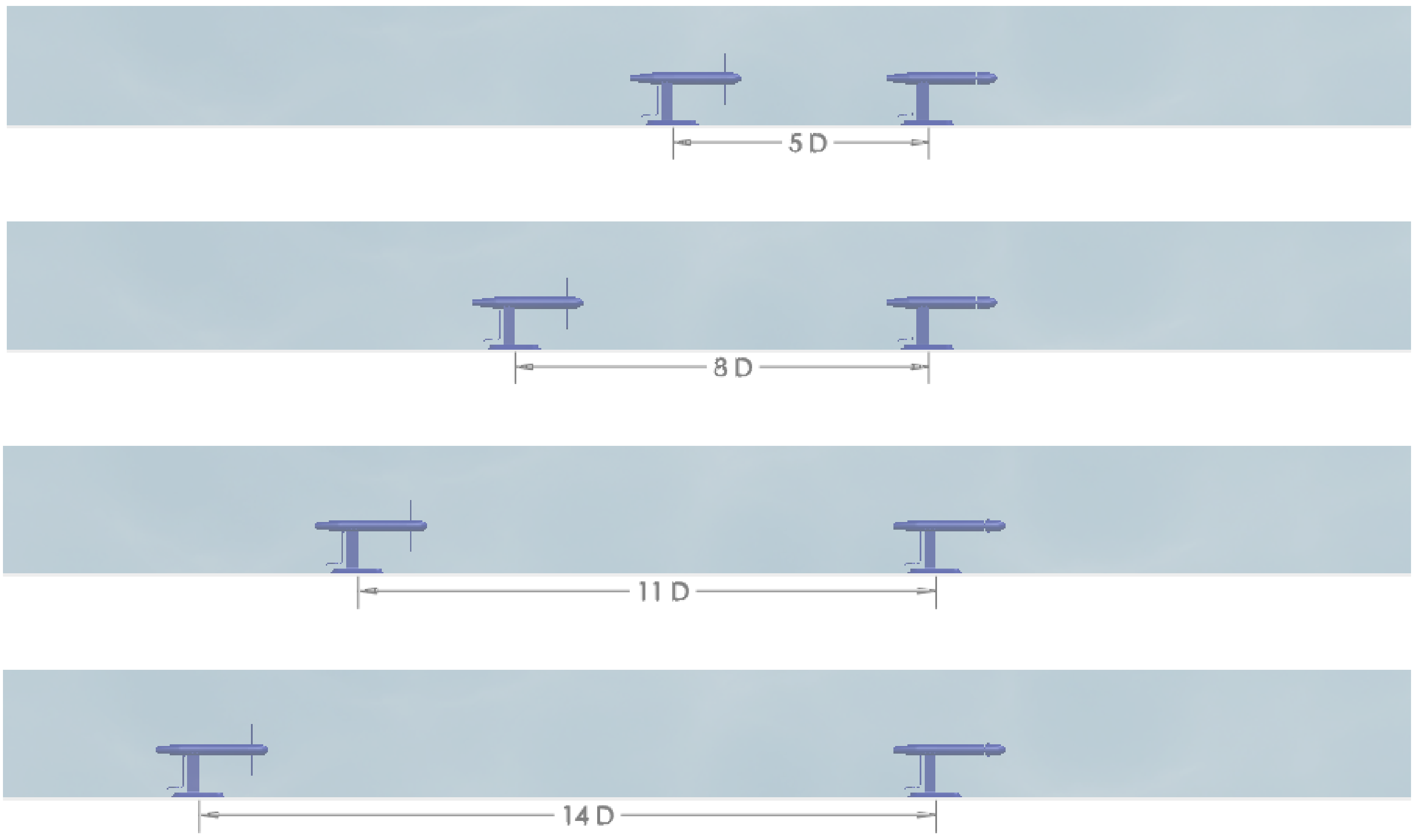
2. Array of three coaxial turbines.



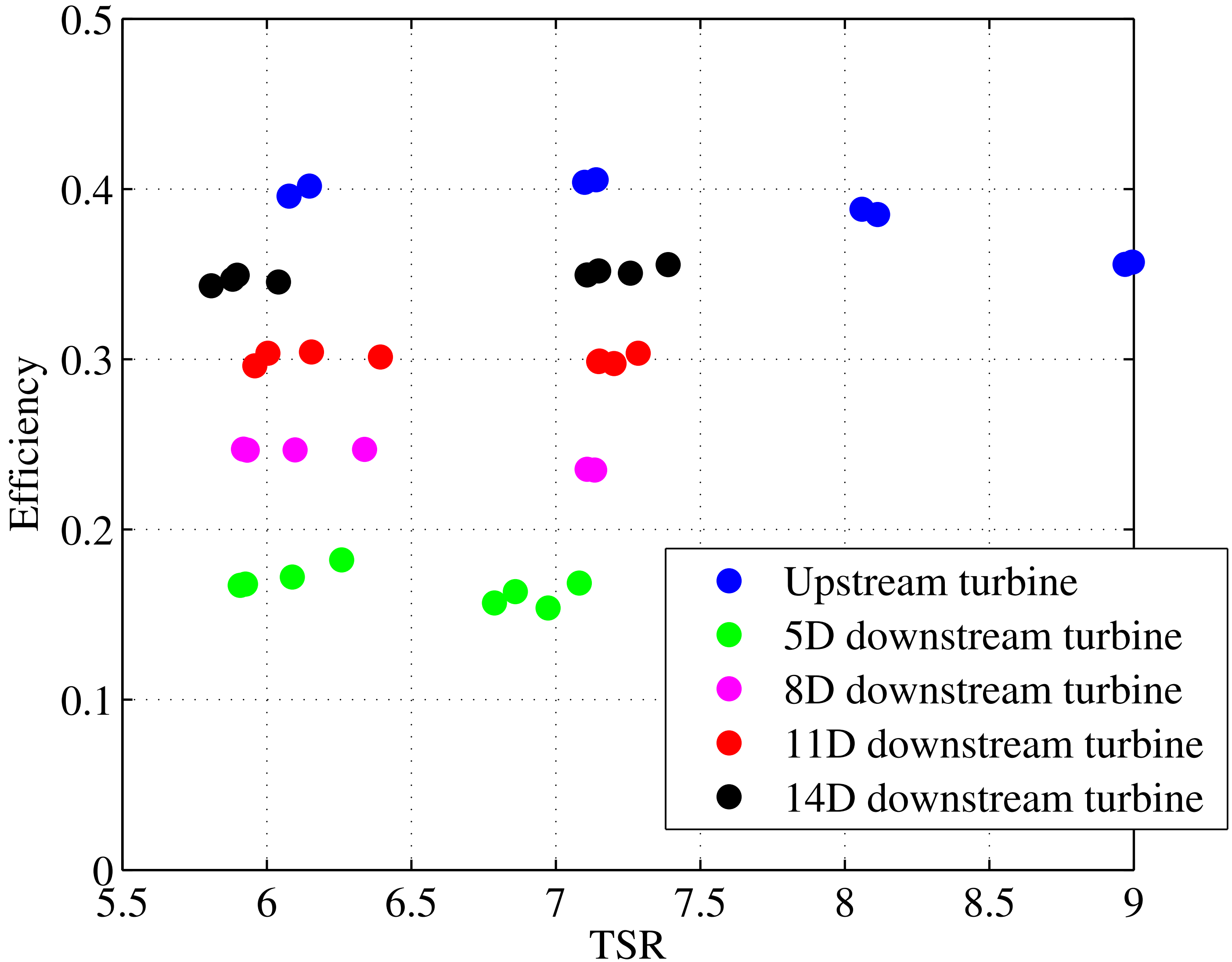
3. Array of three turbines with lateral offset.



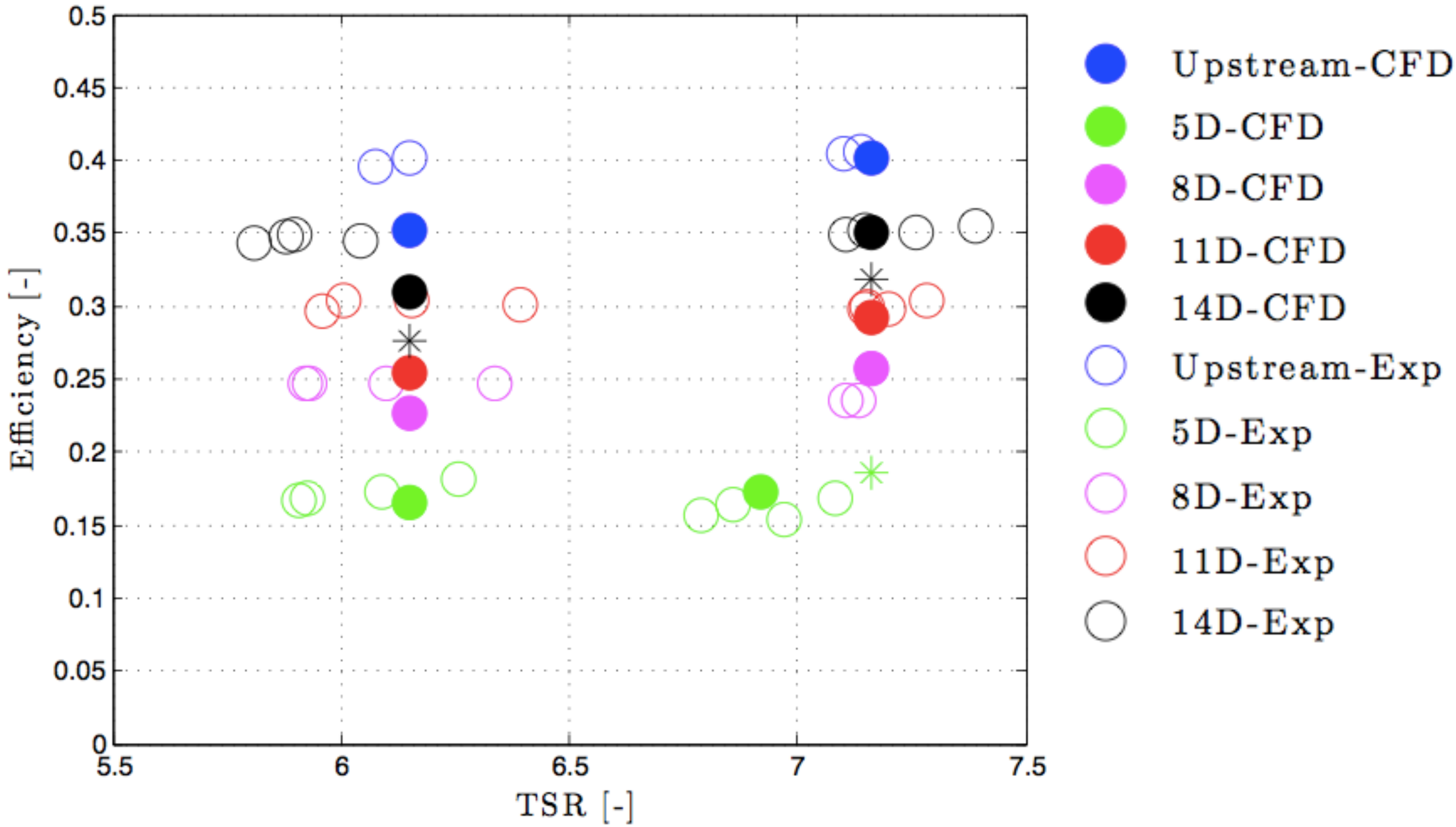
Measurement Locations: Two Turbines Coaxially Mounted



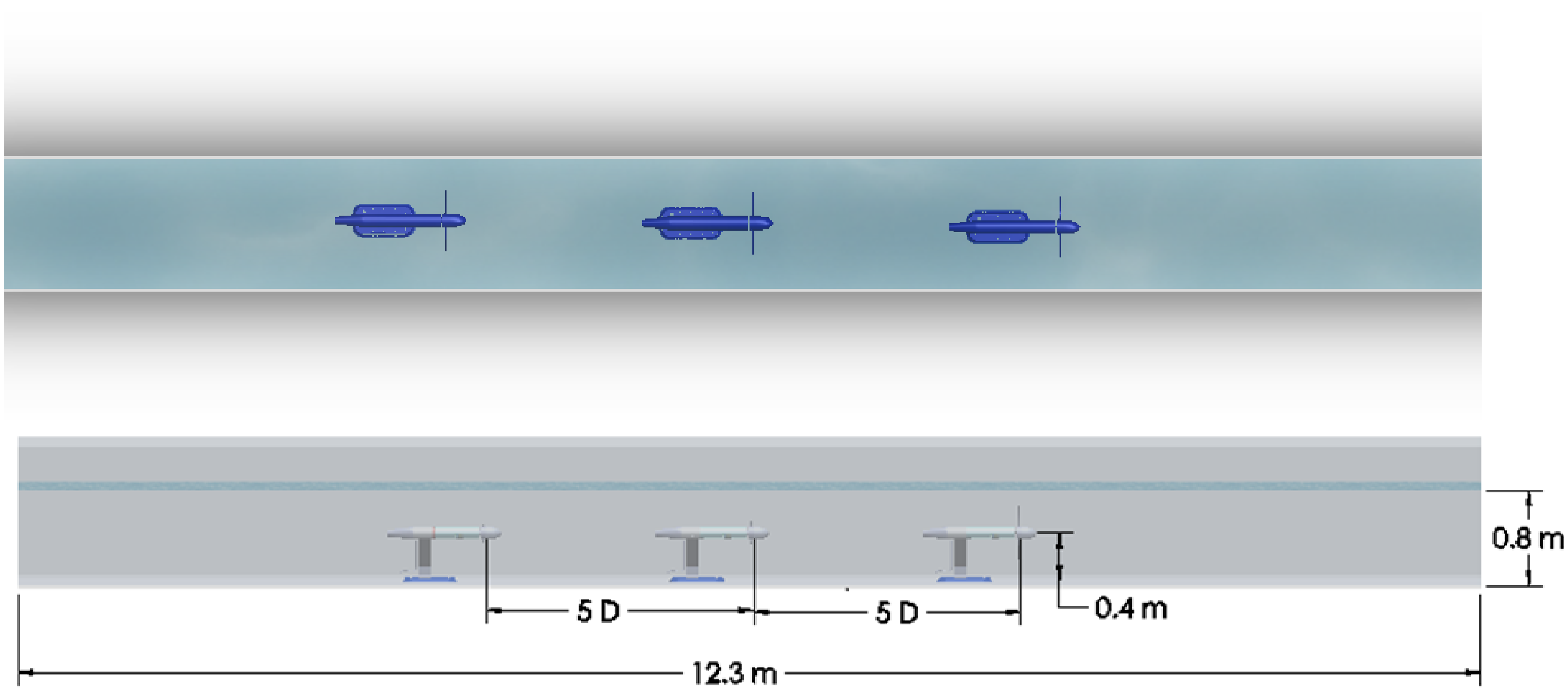
Performance for Two Coaxial Turbines: Experimental Measurements



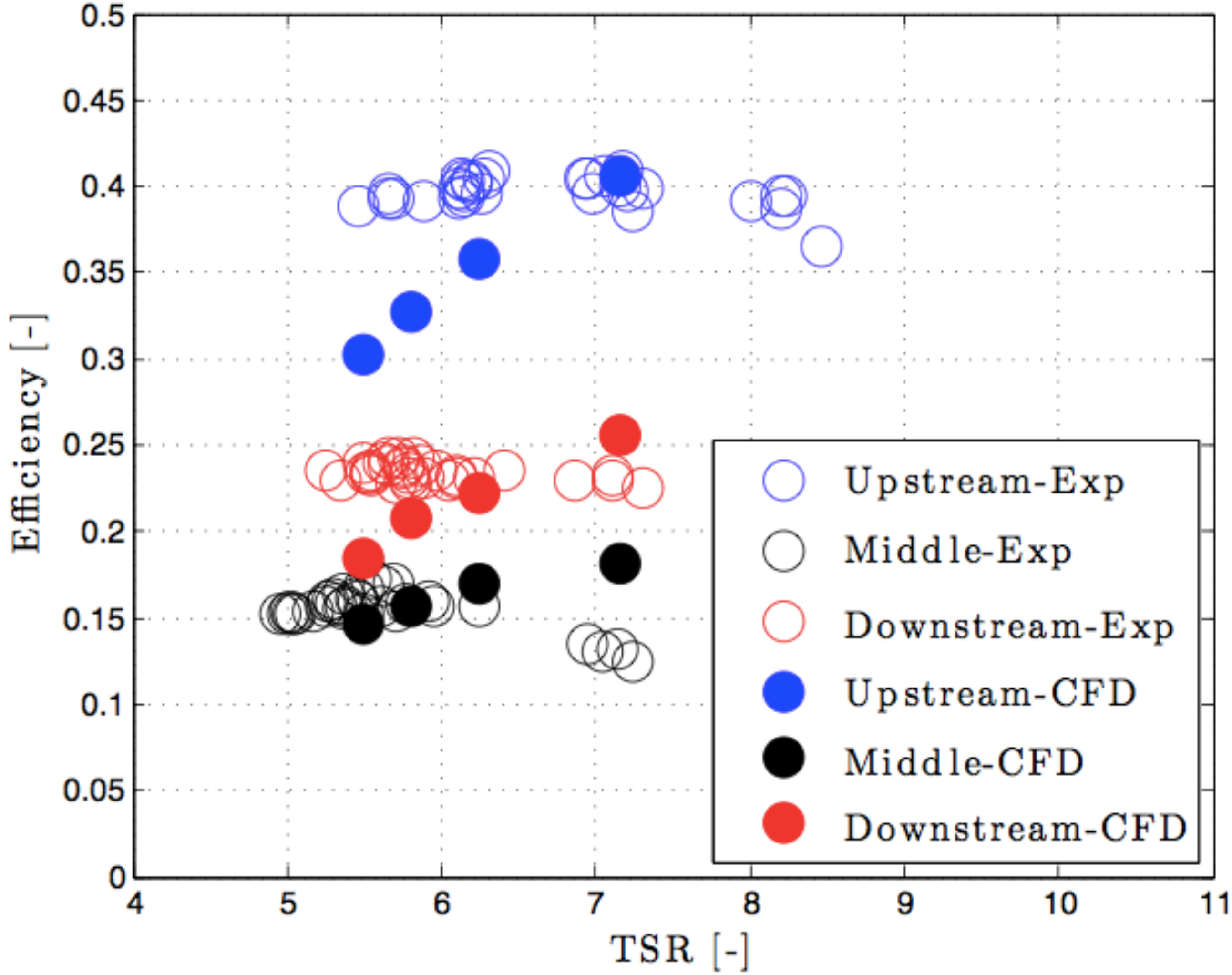
Performance of Two Coaxial Turbines: Comparison of Experiments and Simulations



Measurement Locations: Three Turbines Mounted Coaxially



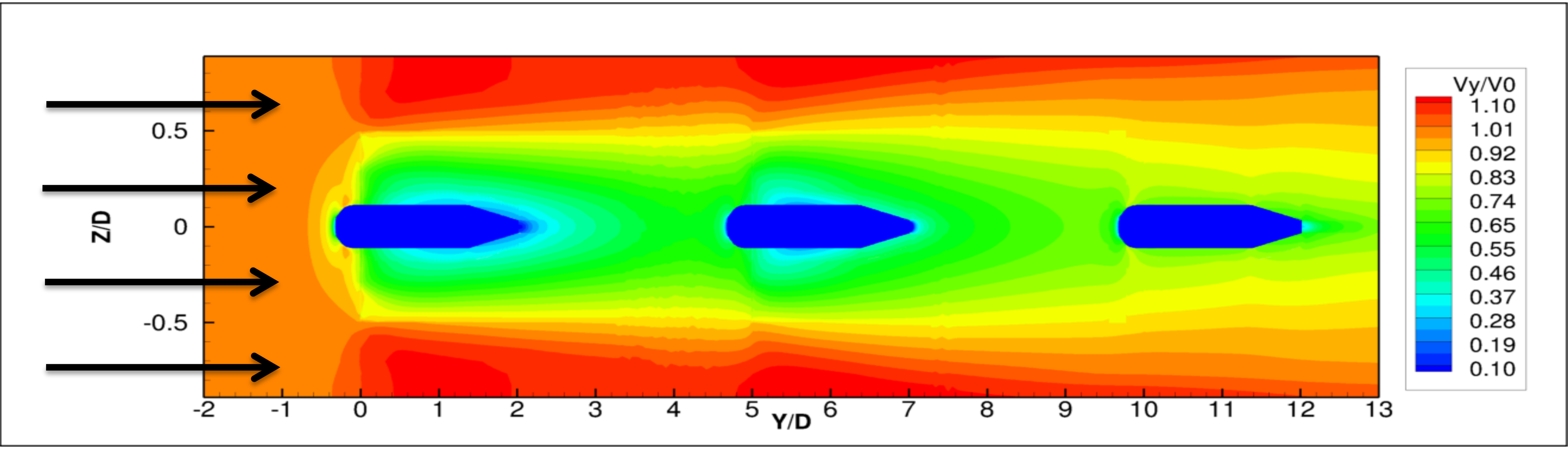
3-Turbine Coaxial Array Performance
Comparison of Experiments and Simulations



Downstream separation 5D

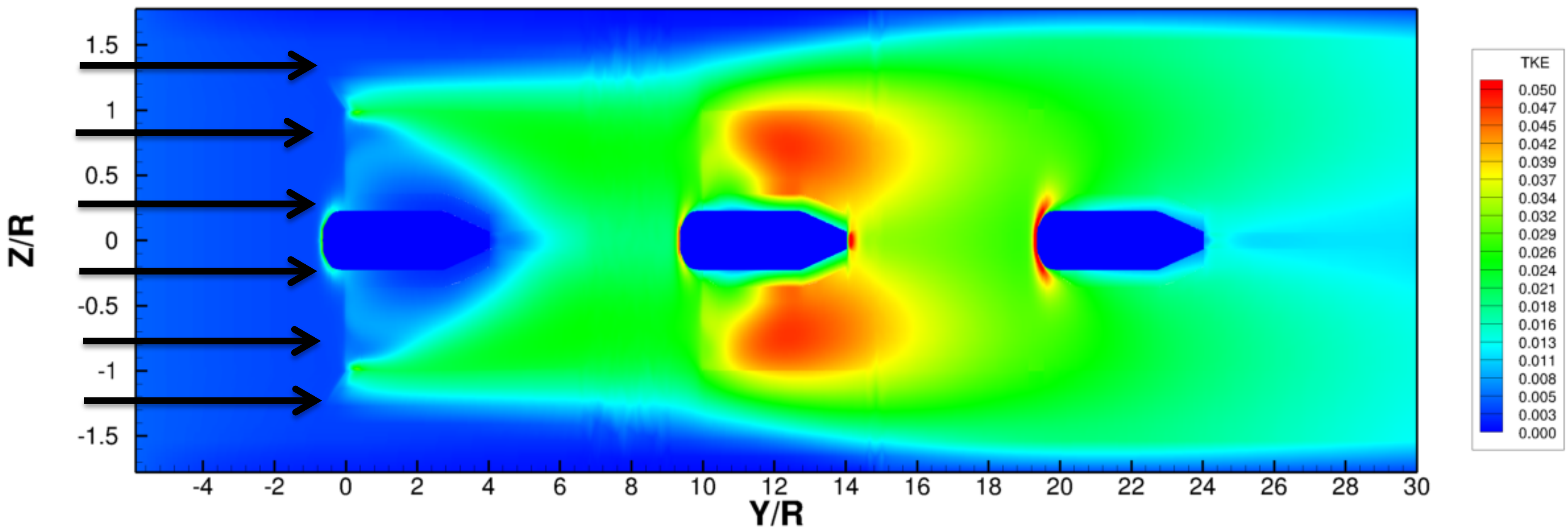
Evolution of the available Kinetic Energy Flux a 3-Turbine Coaxial Array

$$Normalized\ Avail.\ KE\ Flux = \frac{\int \frac{1}{2}\rho < V_{2D}^3 > dA}{\int \frac{1}{2}\rho V_{\infty}^3 dA}$$



Downstream separation 5D

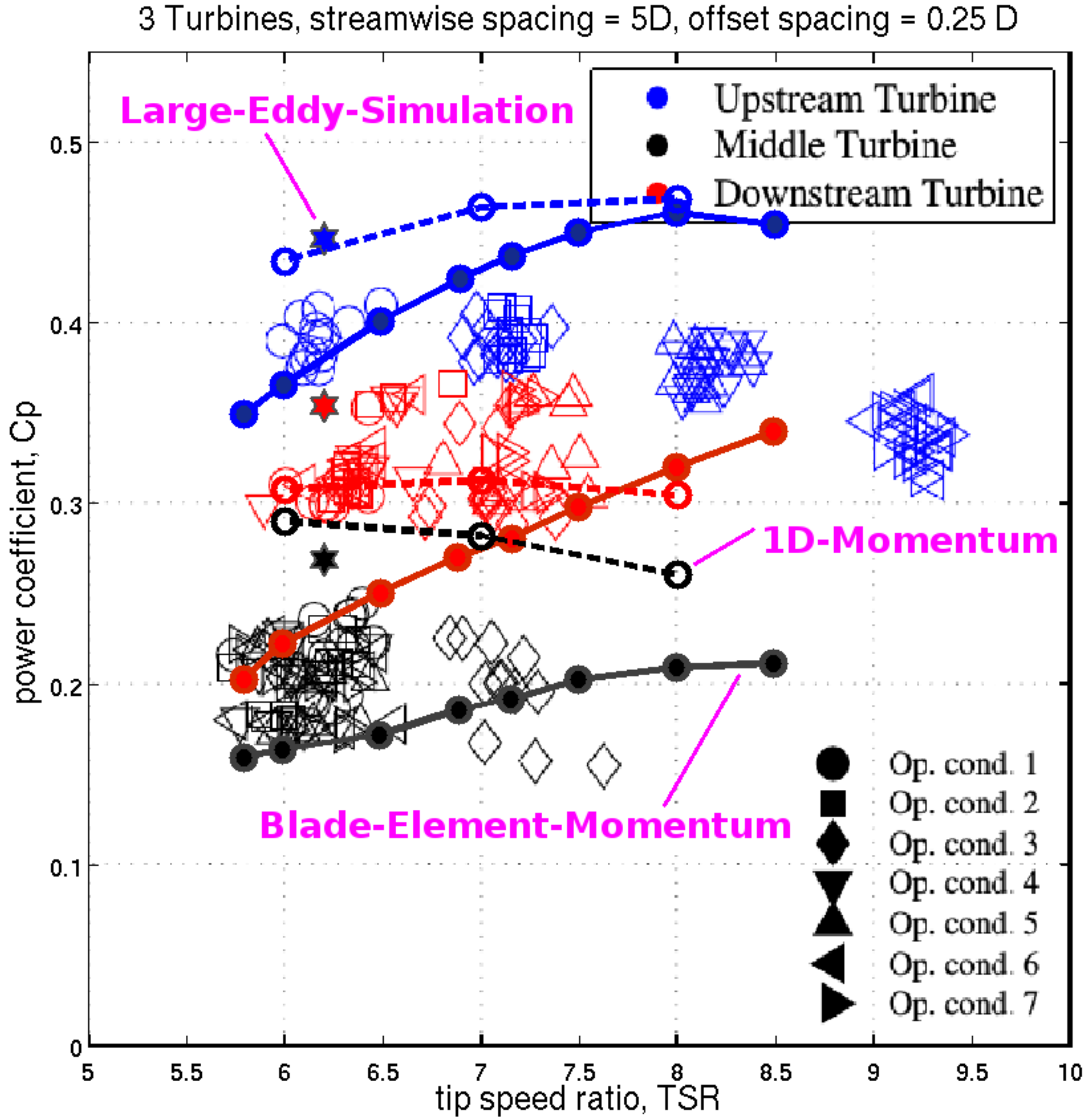
Evolution of TKE contours in a 3-Turbine Coaxial Array



Downstream separation 5D

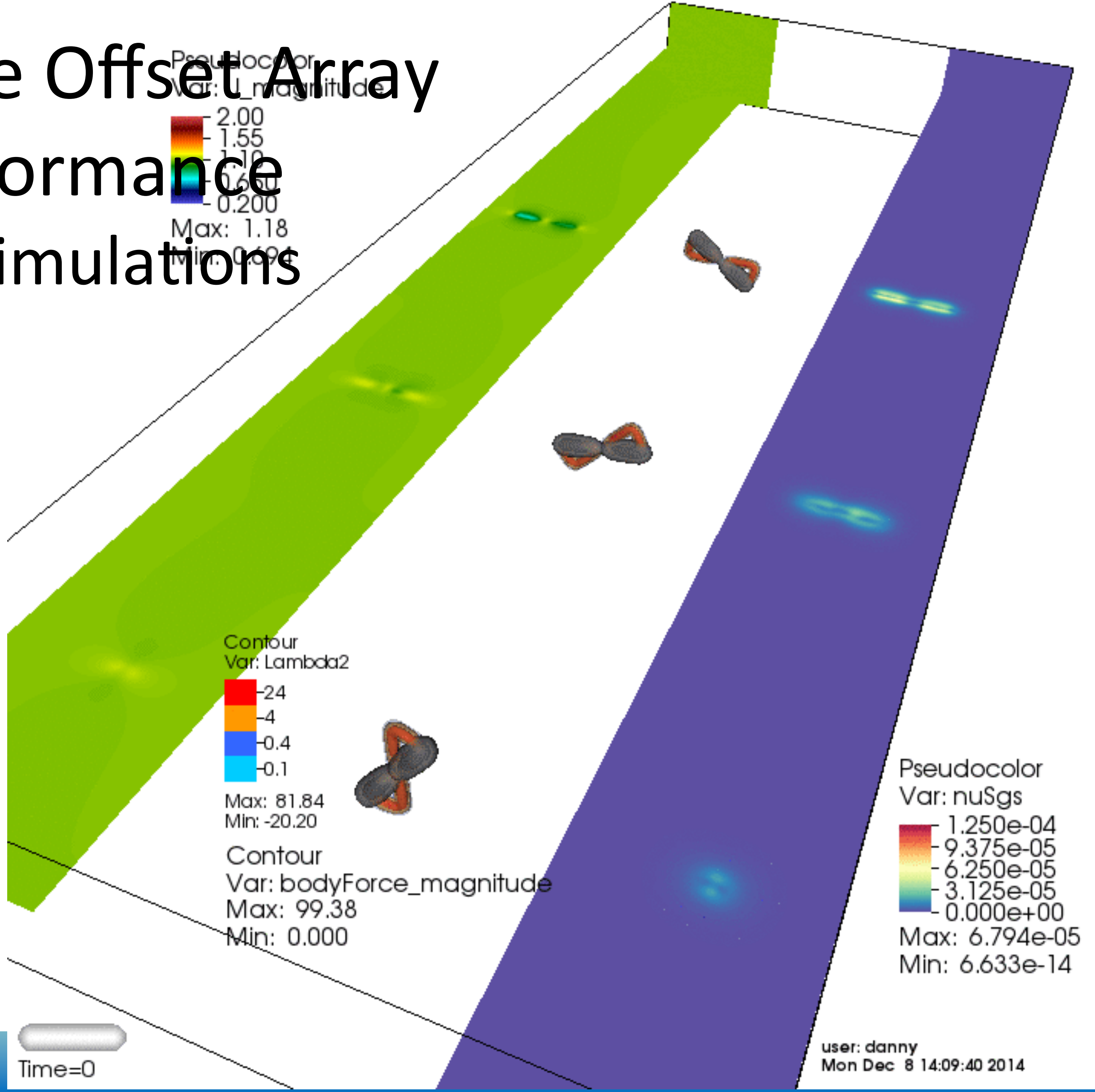
3-Turbine Offset Array Performance

Comparison of Experiments and Simulations

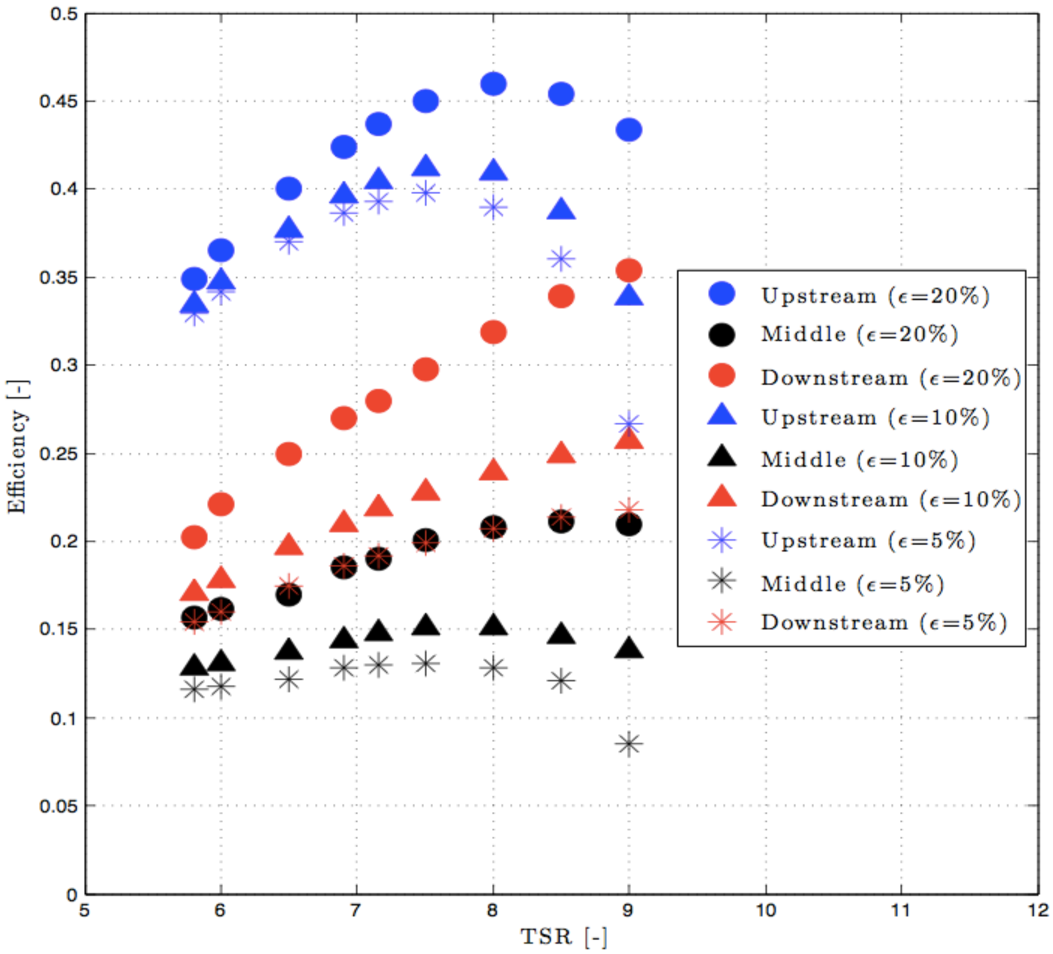


3-Turbine Offset Array Performance

LES Simulations



Investigation of the Flume Blockage Effect



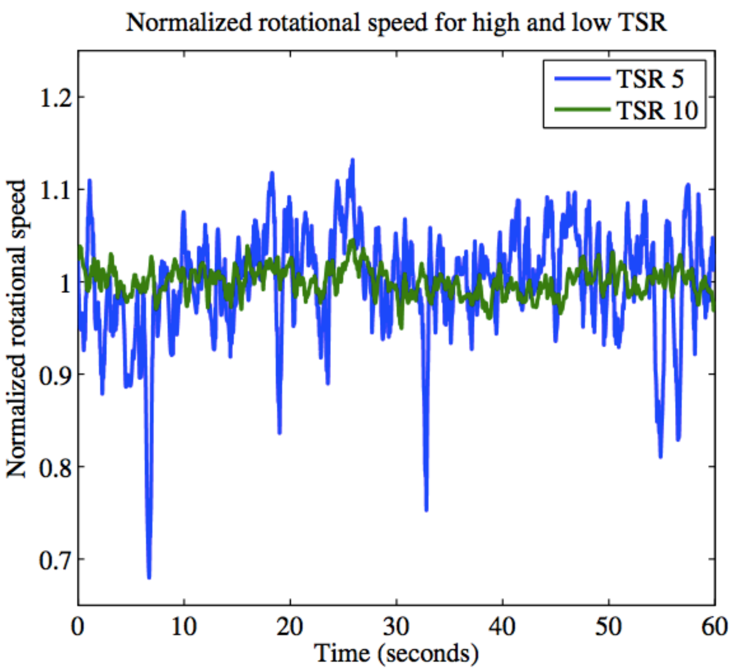
ε = 20 % ●
ε = 10 % ▲
ε = 5 % *

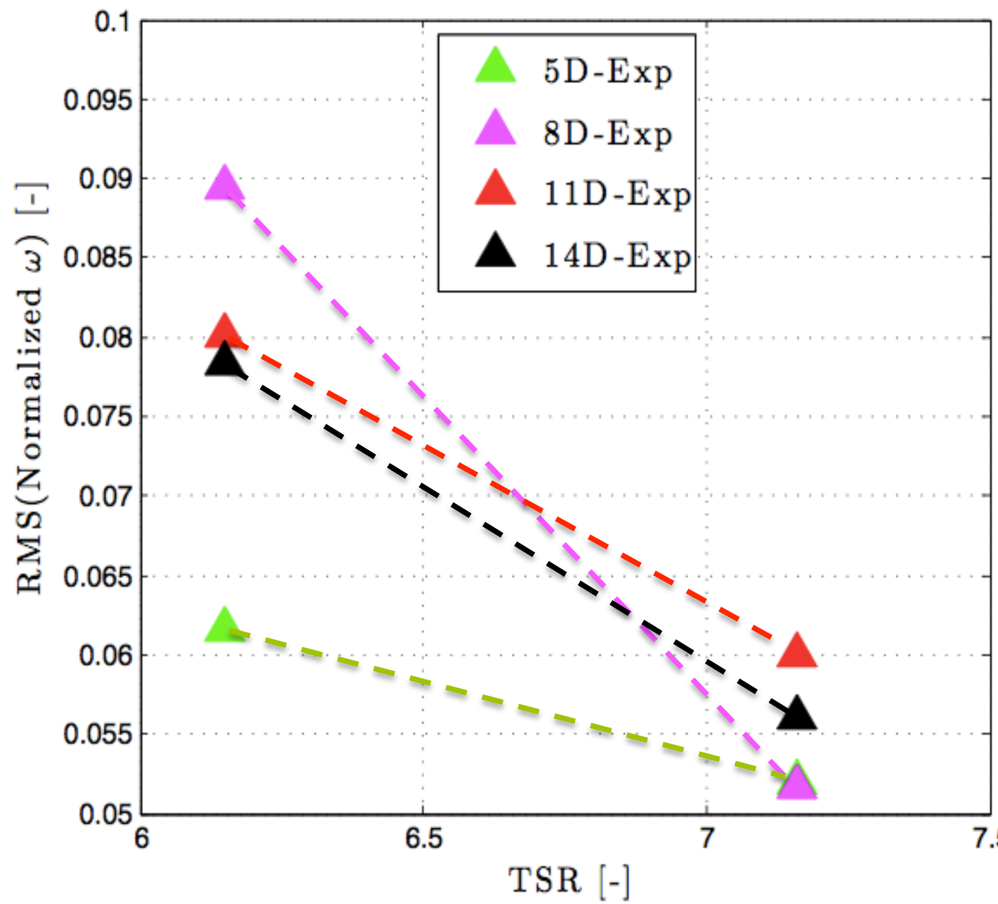
- Increase in blockage leads into increase in efficiency (vertical shift of C_p curve).
- Increase in blockage shifts the peak of efficiency toward higher TSR values (horizontal shift of C_p curve).

Summary and Conclusions

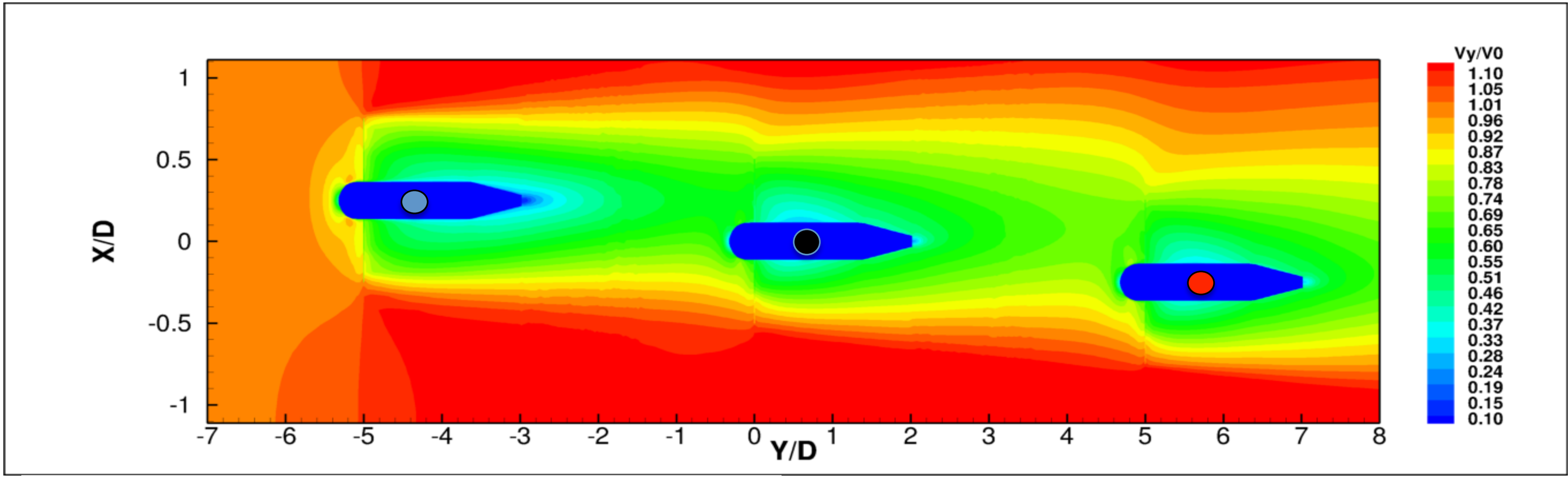
- Three Turbines Array present non-monotonic performance: third turbine has higher efficiency than middle turbine
- Confinement plays a increasingly important role for higher number of turbines and lateral offset in the Array.
- Agreement between experimental and numerical results is best for single turbine and optimum TSR.
- Angular velocity fluctuations in the experiments, and enhanced wake recovery, not captured by simulations, leads to numerical/experimental divergence with lower TSRs, larger arrays and higher confinement.

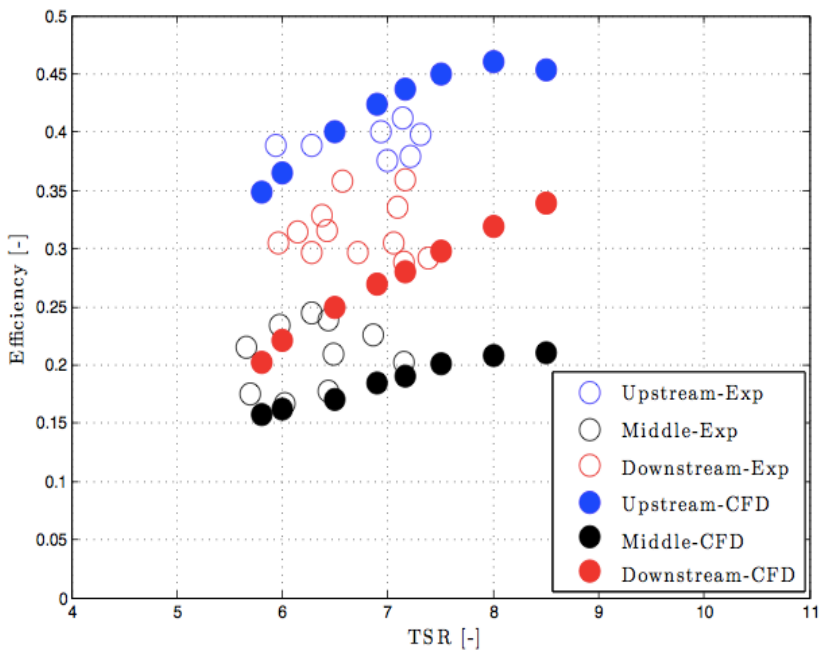
RMS of Normalized Rotational Velocity Temporal Evolution (TSR = 6.15, 7.16)





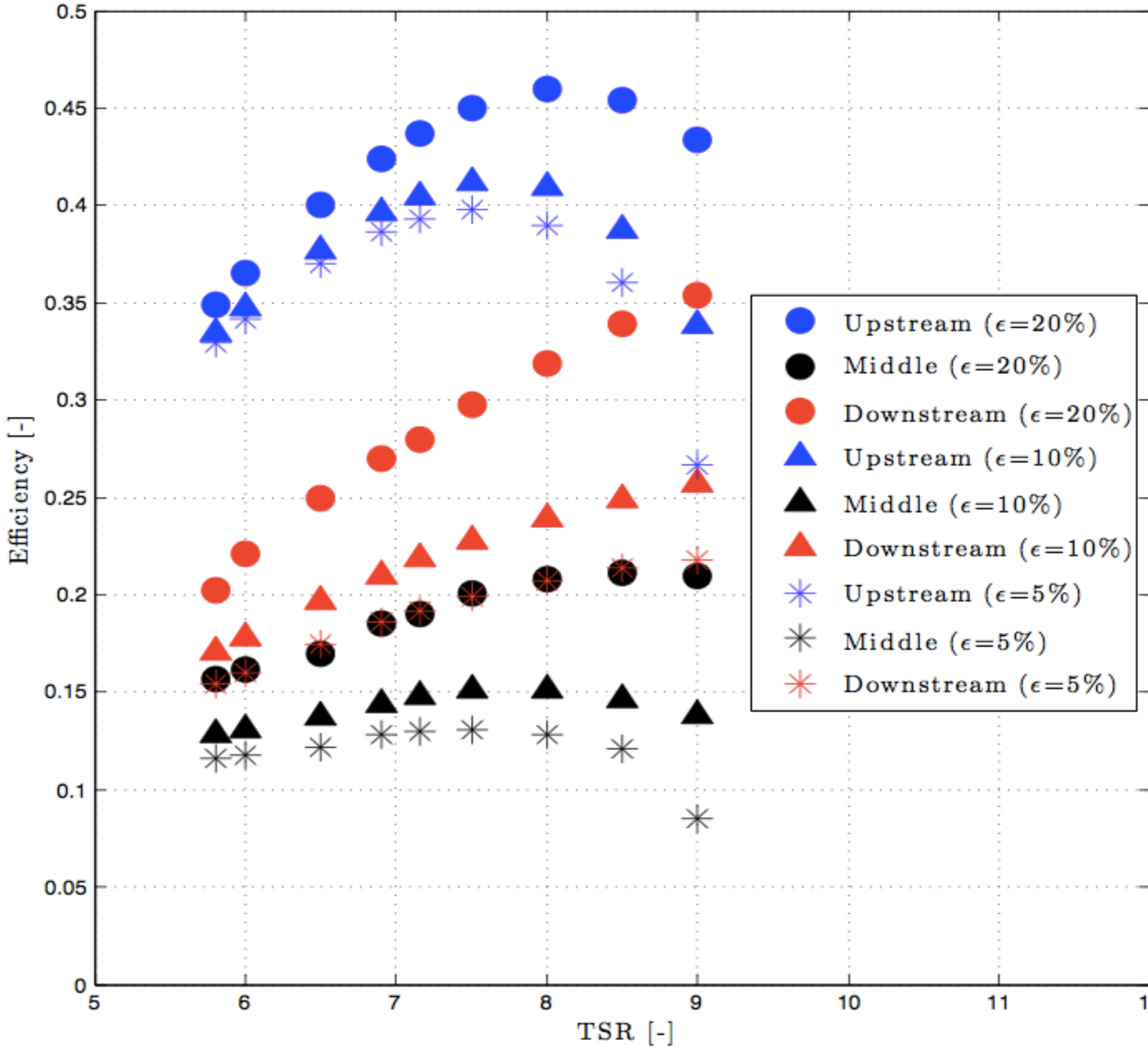
Array of Three Turbines with Lateral Offset



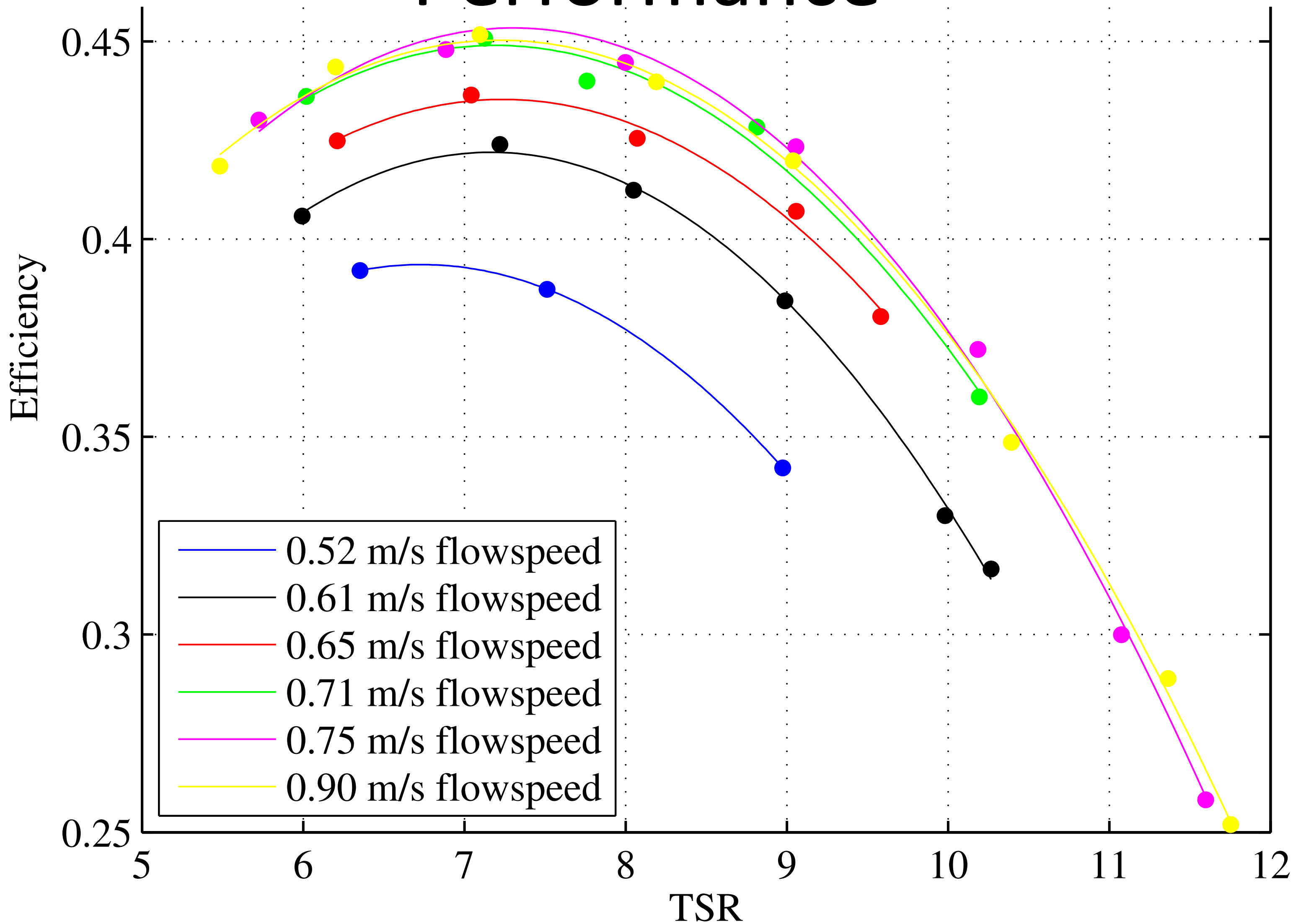


- Observation of similar physics compared to results from array of two & three coaxial turbines.
- Downstream turbines' efficiency increase monotonically with the TSR value.

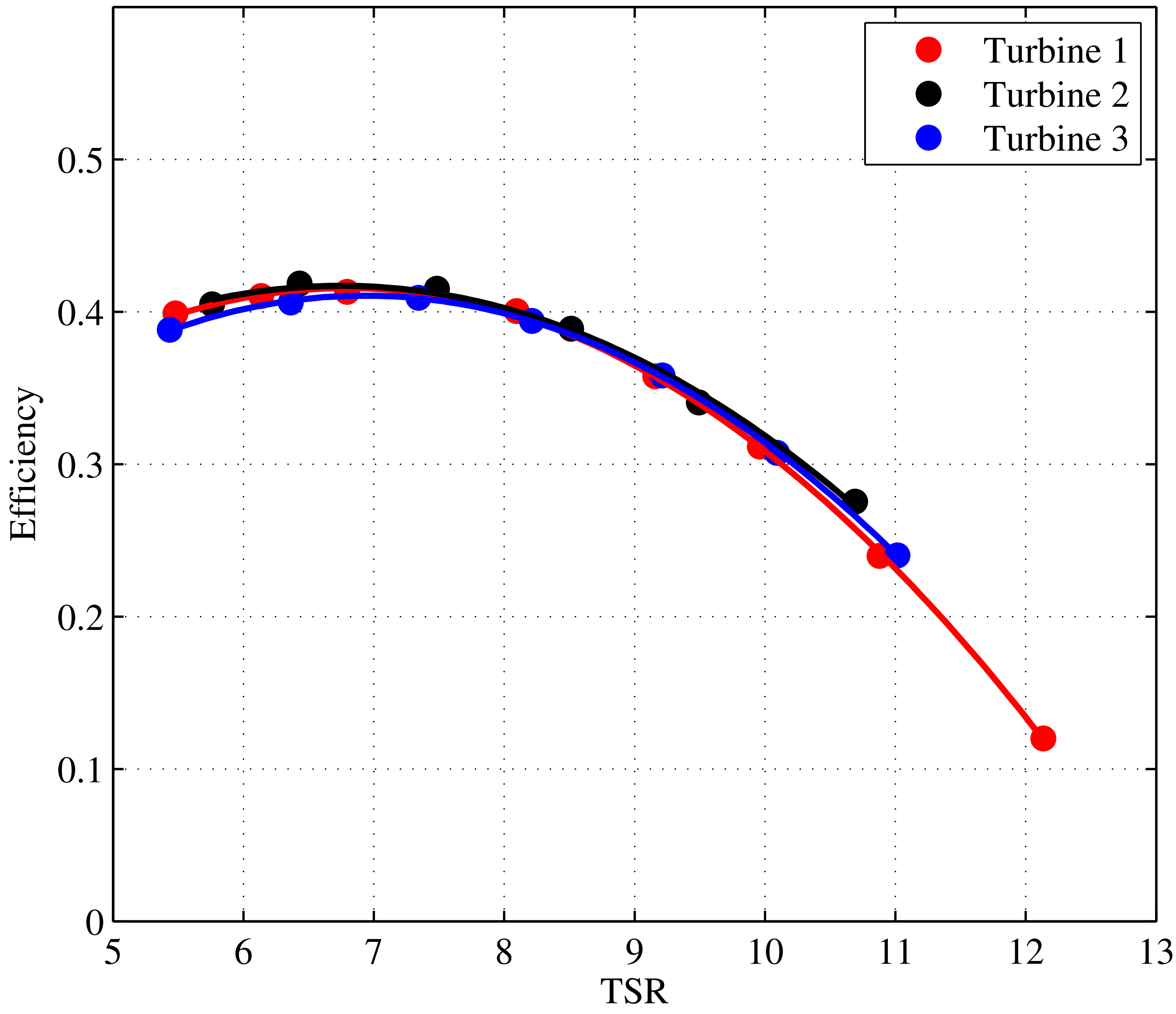
3-Turbine 1/4D Lateral Offset Array Performance



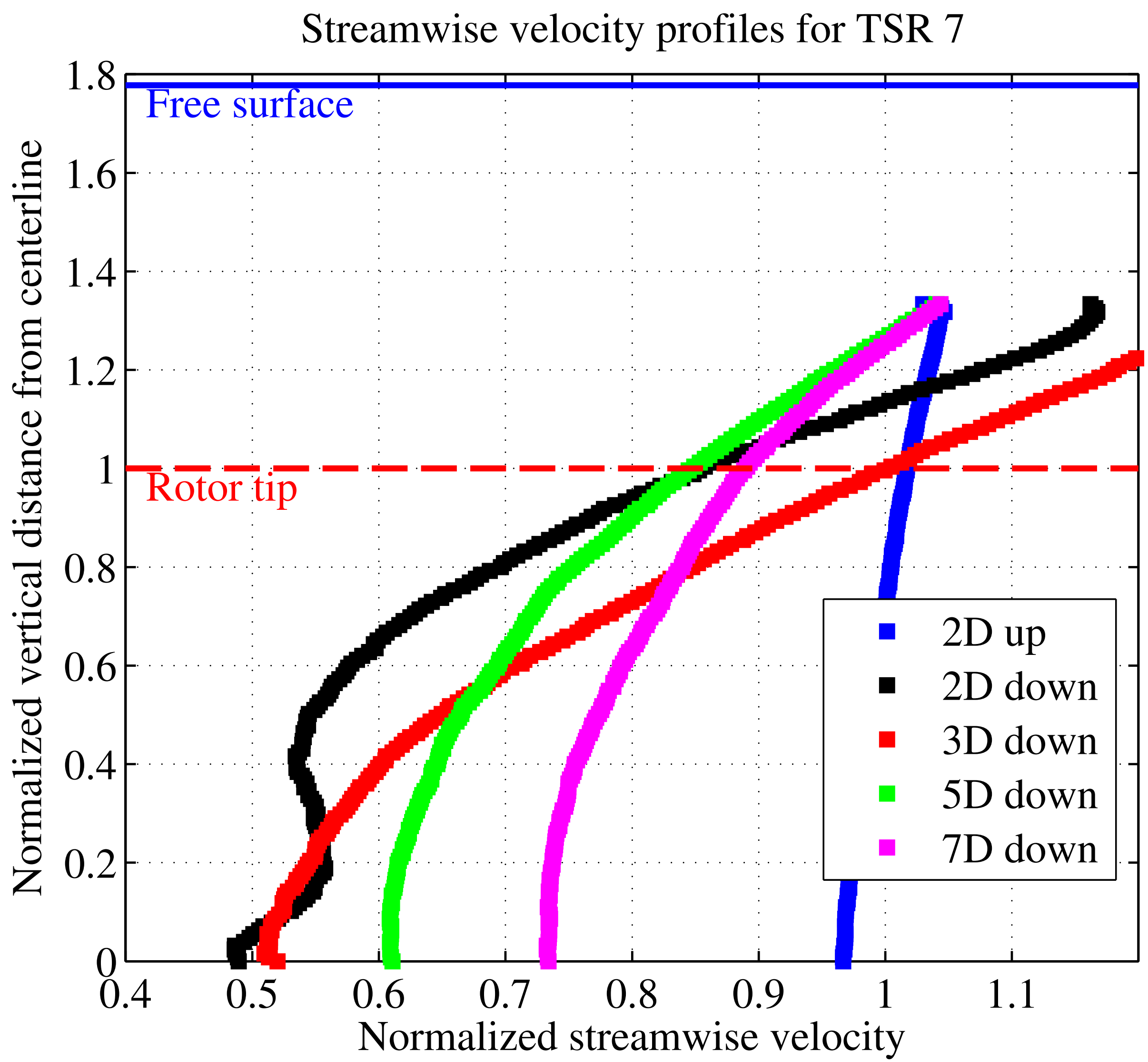
Reynolds-number Dependent Performance



Turbine Comparison for Performance

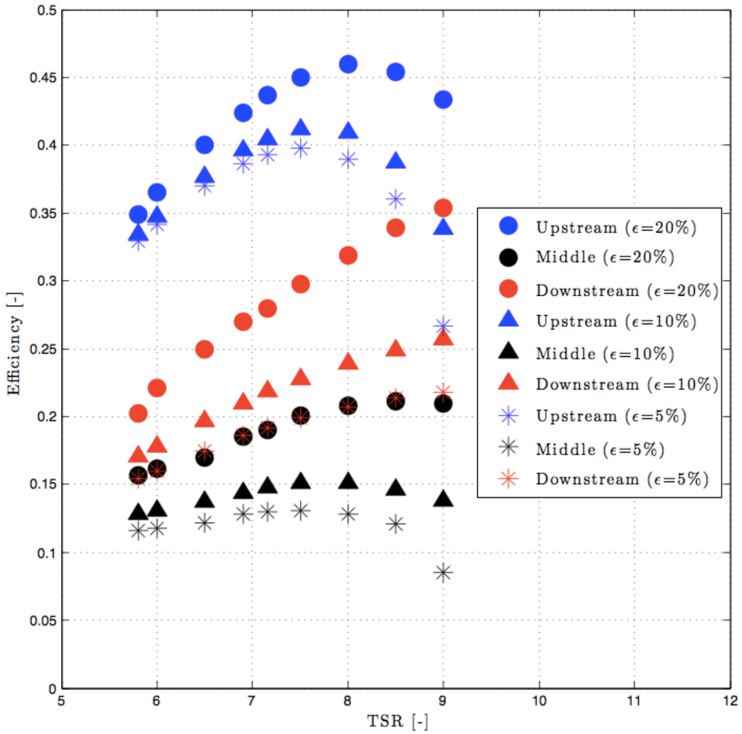


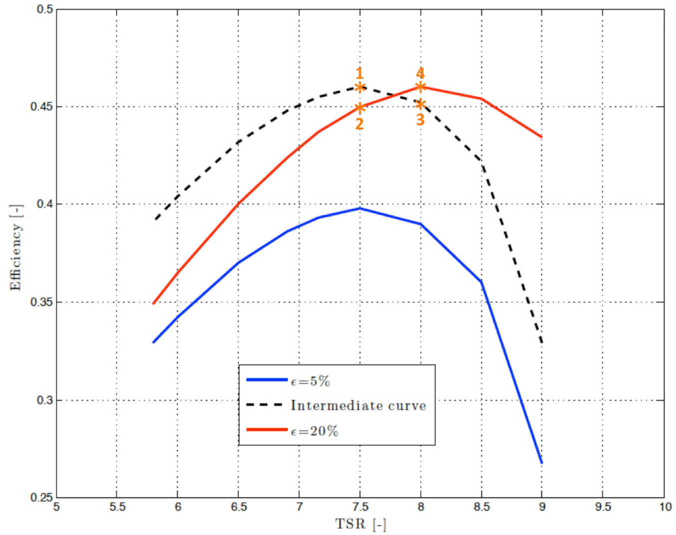
PIV Velocity Profiles in the Wake



Results of BEM study (3/3)

Effect of blockage on efficiency

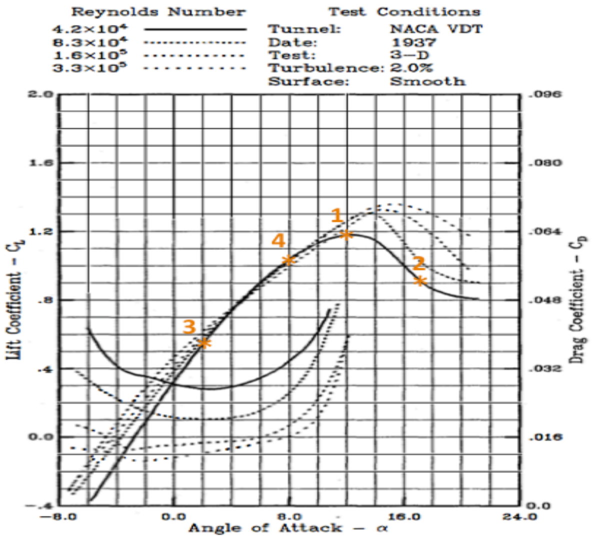




Angle of attack :

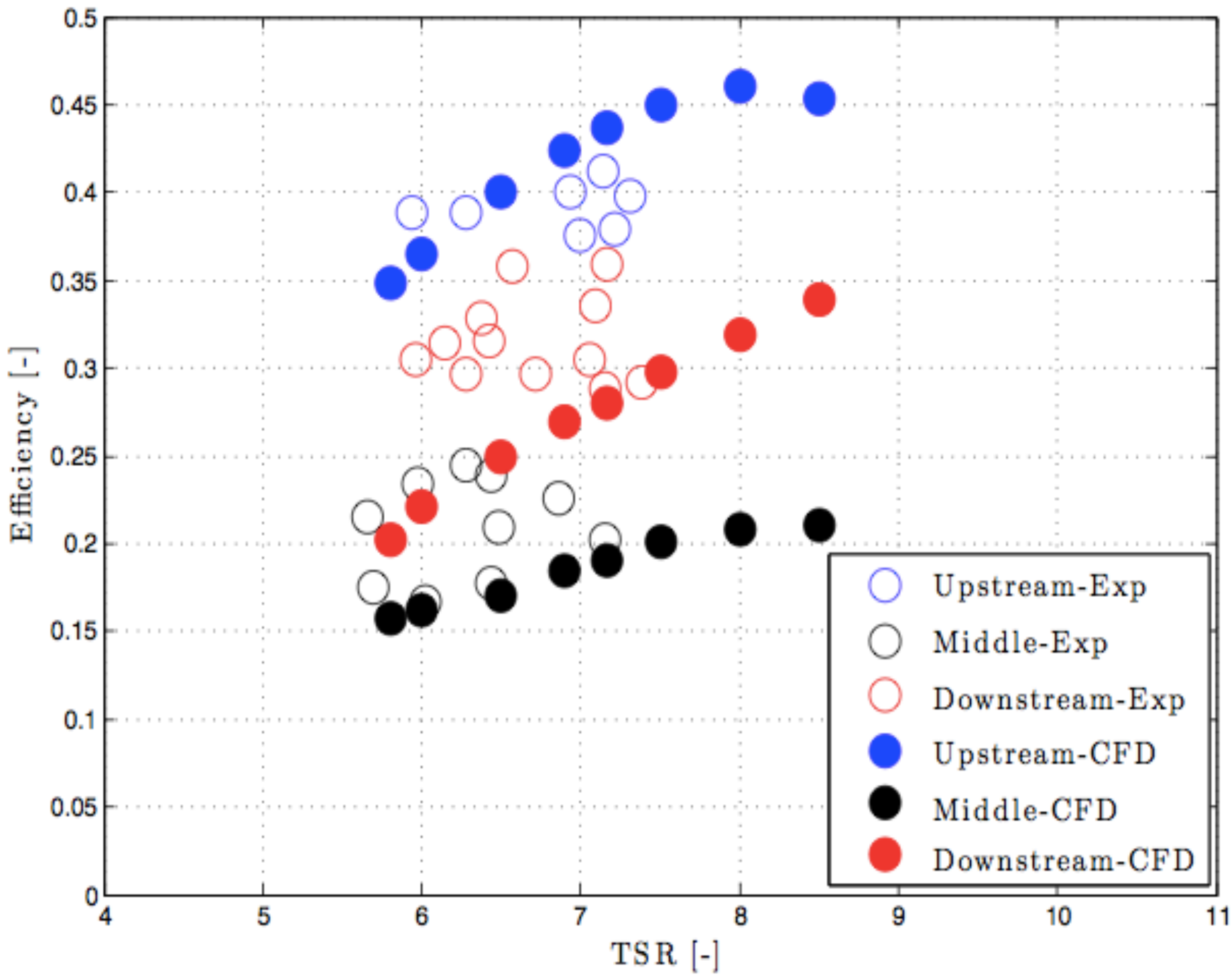
$$\alpha(r) = \arctan\frac{V_{inc}(r)}{r\omega} + \beta(r)$$

- Blockage increases the efficiency.
- Blockage shifts the peak of efficiency to the right.
- Blockage delays the peak of efficiency of the two downstream turbines.



Source : S. J. Miley's catalog of airfoils

3-Turbine 1/4D Lateral Offset Array Performance



Downstream separation 5D