UCDAVIS
UNIVERSITY OF CALIFORNIA

A Focus on the Flow in the Inboard Part of the Blade

Raymond Chow (rchow@ucdavis.edu)
C.P. van Dam (cpvandam@ucdavis.edu)

Outline

- Motivation
- Methodology
- NREL 5-MW
- Grid Independence Study
- Ring Fence
- Conclusions

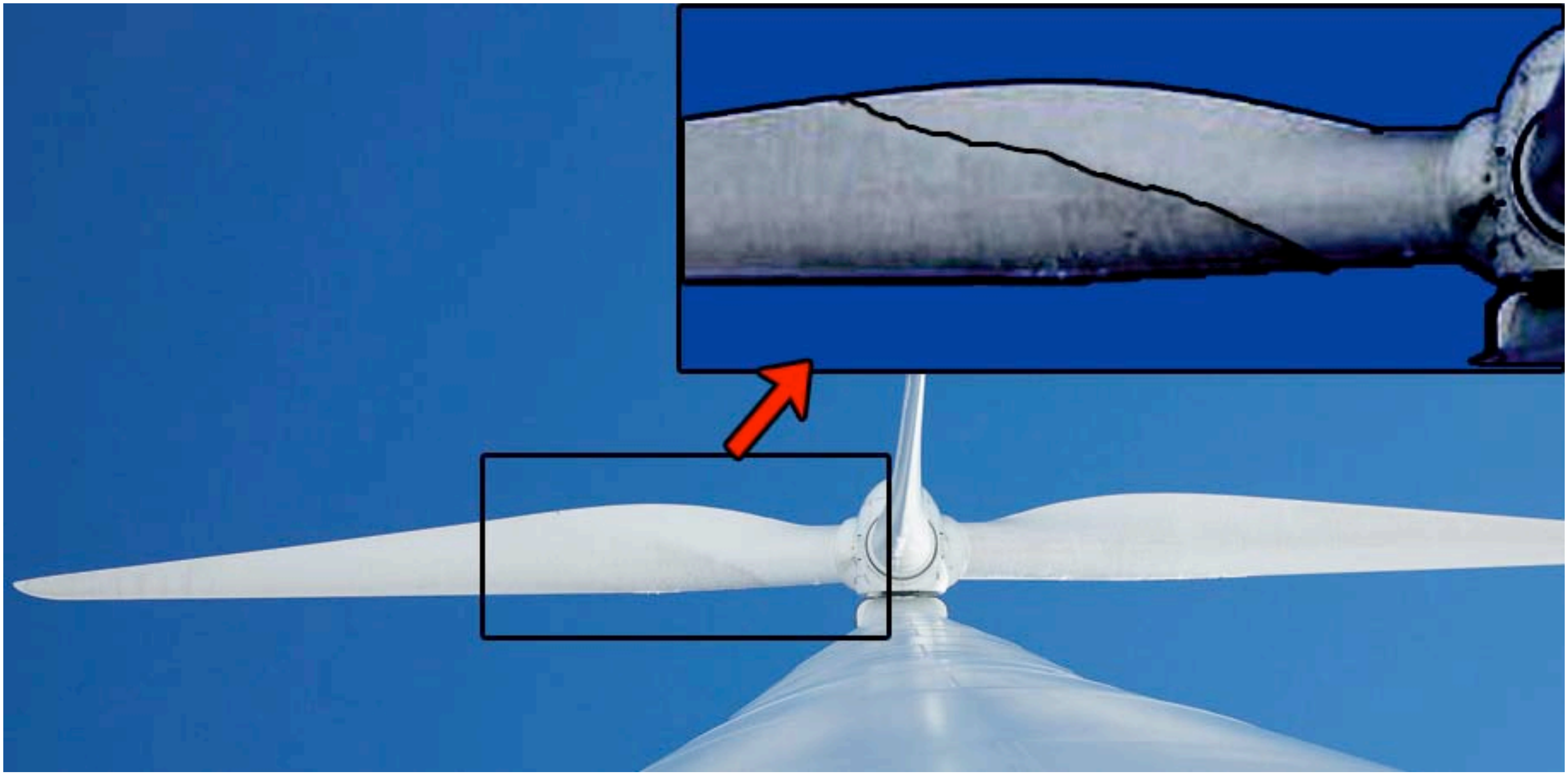
Blade Element Momentum (BEM)

- Idealized 2-D aerodynamic flow
  - Post-stall often based on empirical models
- Actual 3-D flow behavior missed
  - No spanwise interaction
  - No rotational effects
  - Ad hoc "correction models" used
    - Prandtl tip loss
    - Glauert induction correction
    - Hub loss models
    - Etc.
- Current industry aerodynamic design tool

Current Industry Status

- Larger rotors structurally require thick inboard sectional shapes inherently more prone to flow separation
- BEM does not properly model inboard flow development of rotors
- This may lead to overly optimistic blade designs / performance predictions

Power Loss: Inboard Flow Separation



from May 2007 issue of *Win[d]* trade magazine by Vestas

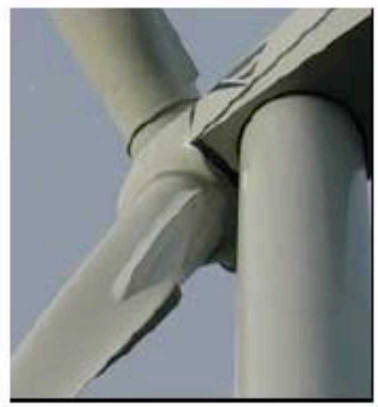
Industry Ad Hoc Solutions

The evolution package increases power curve.

REpower Systems

MM82/MM92 Evolution

Stall Barriers → **Spoilers** →



- After an extensive phase of testing the prototypes as well as the controller changes, REpower Systems AG offers this evolutionary development which increases the already high economic efficiency of the MM Series.

Source: REpower Systems AG

Suction Side Rakes/Fences

40m REpower blades by LM

Pressure Side Spoilers

40m REpower blades by LM

Study Objective

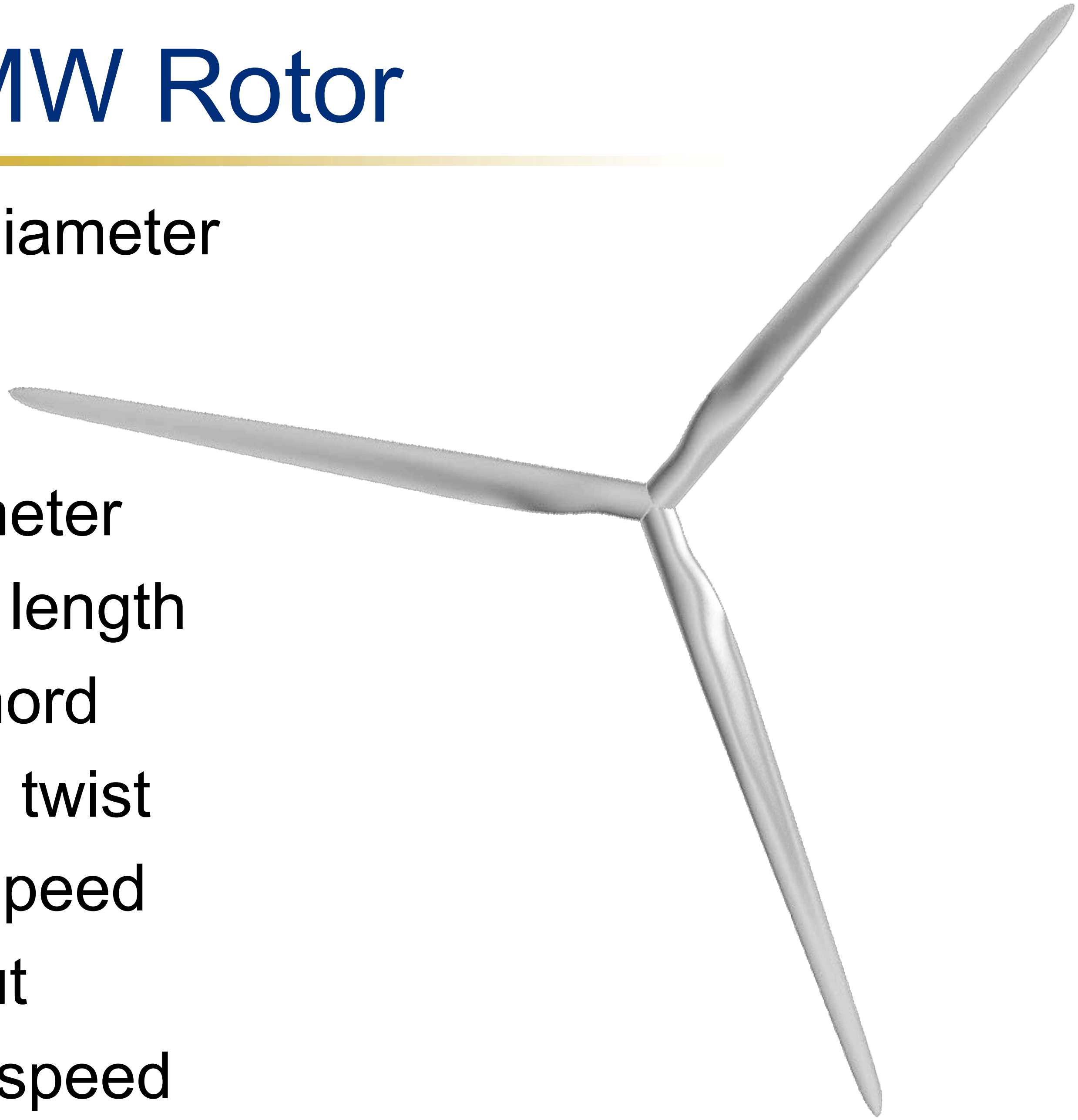
1. Using 3-D CFD examine inboard flow behavior of the NREL 5-MW rotor
2. Find evidence of inboard flow separation and examine effect on power capture and blade loading
3. Explore design solutions to mitigate flow problem in inboard part of blade

NREL 5-MW Rotor

- Geometry based on 6MW DOWEC rotor
  - Conceptual off-shore turbine design
  - ECN (Energy Research Centre of the Netherlands)
- Rotor diameter truncated and hub diameter reduced

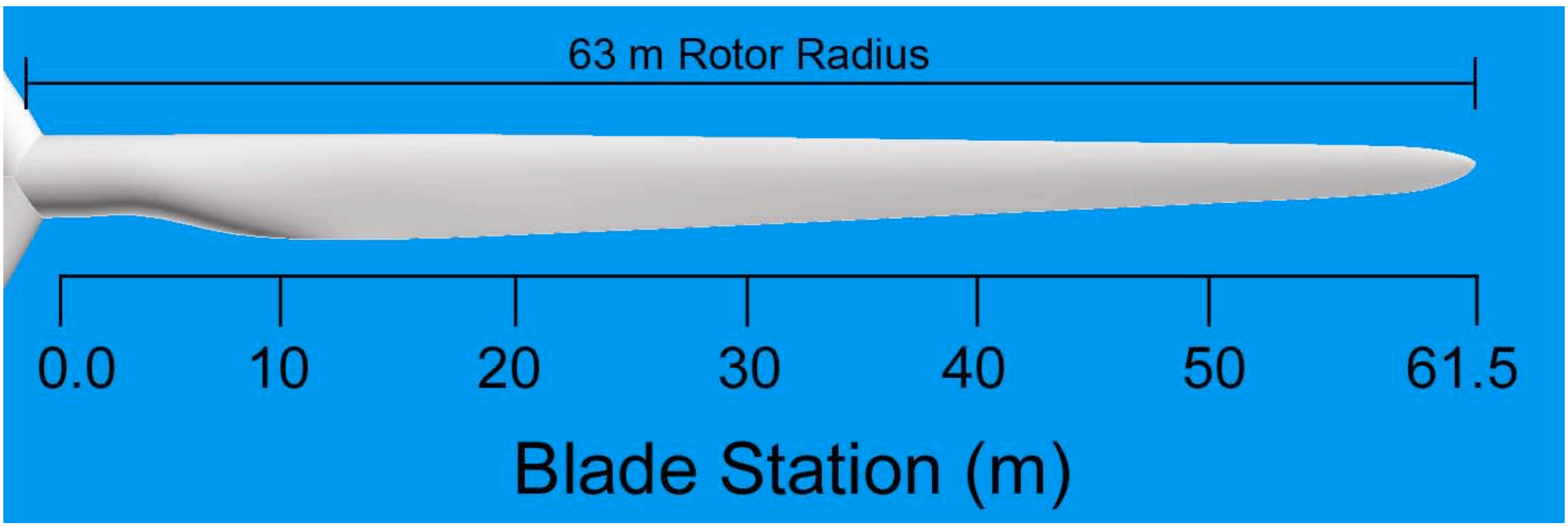
NREL 5-MW Rotor

- 126 m rotor diameter
- 12.1 RPM
- $TSR_{Design} = 8$
- 3 m hub diameter
- 61.5 m blade length
- 4.7 m max chord
- 13.3° inboard twist
- 3 m/s cut-in speed
- 25 m/s cut-out
- 12 m/s rated speed

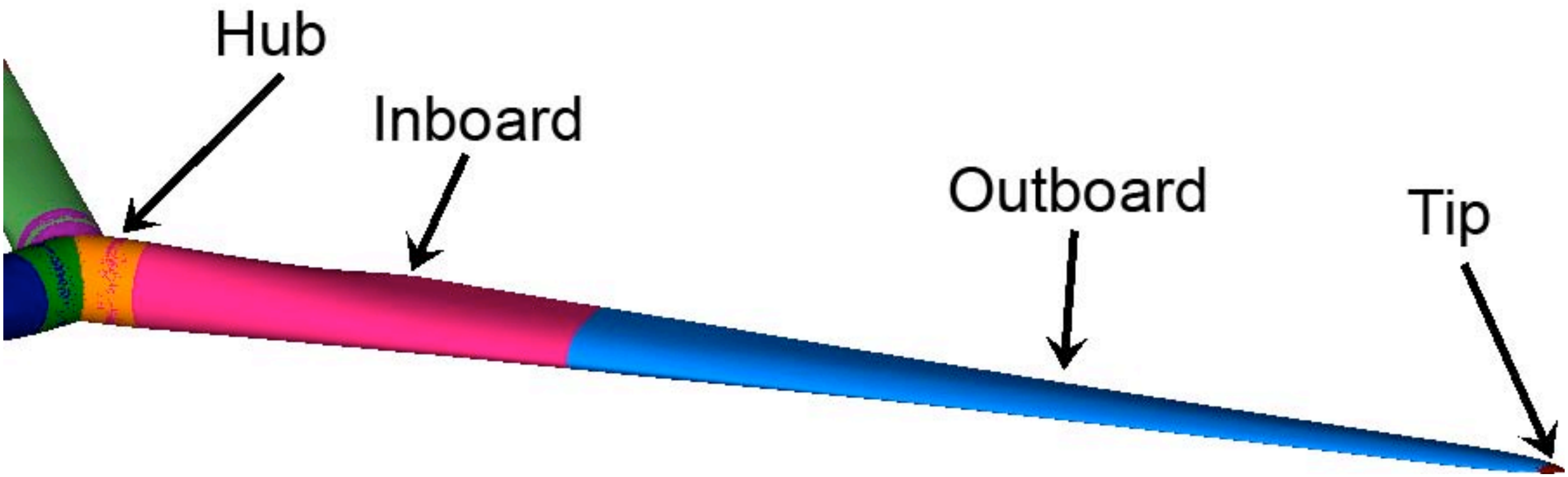


NREL 5-MW Blade

- Inner 58.5m as defined by Lindenburg (ECN) and Jonkman (NREL)
- Using a 3.0m tip region defined by Risø DTU



NREL 5-MW – Grid Topology



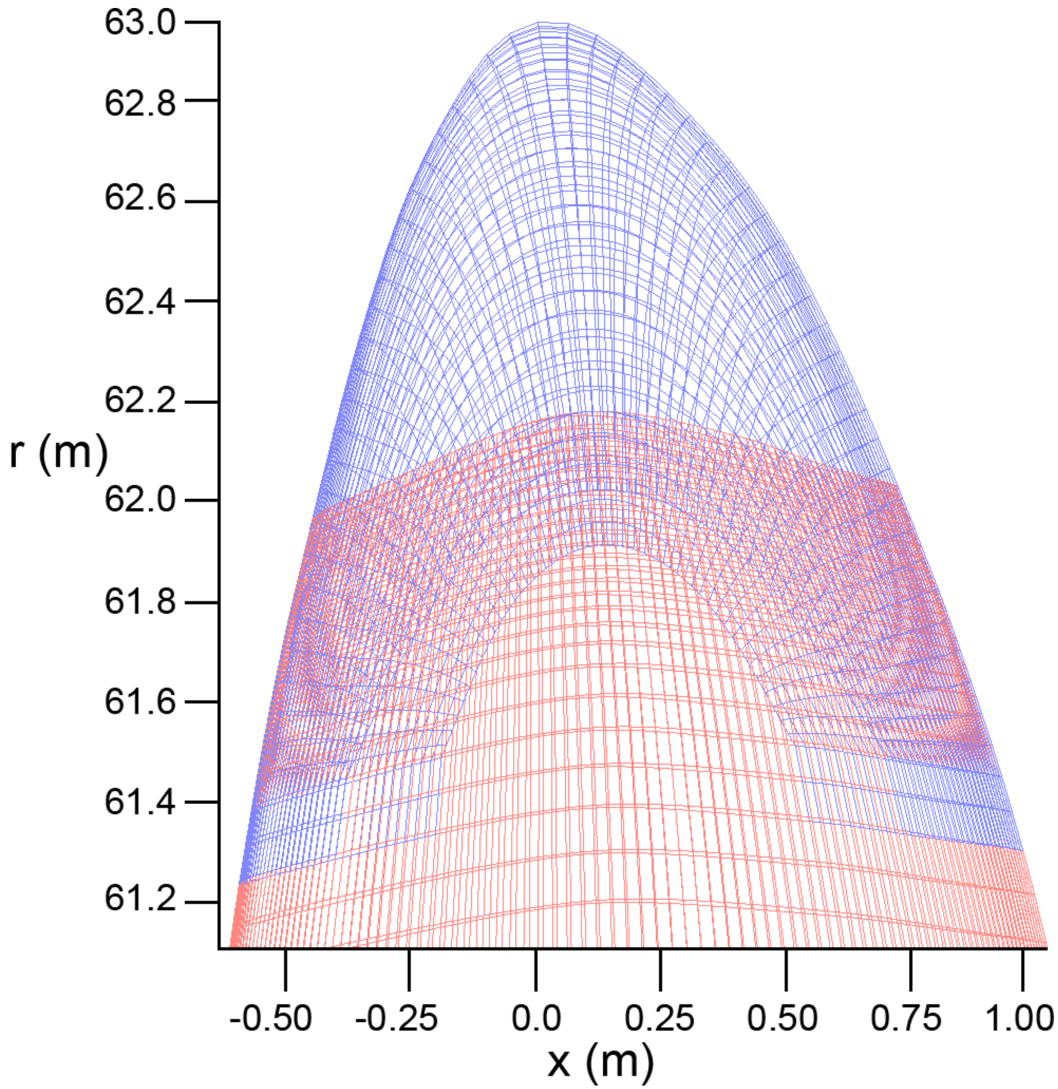
- Grid system designed to take advantage of overset/Chimera topology
- Modifications limited to inboard region

NREL 5-MW – Grid Topology

- Inboard (r < 20 m) blade grid can be modified and replaced
- Surface and volume grids of the outboard and tip regions can be reused
- Geometric modifications can be kept consistent and isolated to inboard region
- Hub geometry can also be examined without affecting remaining grid system

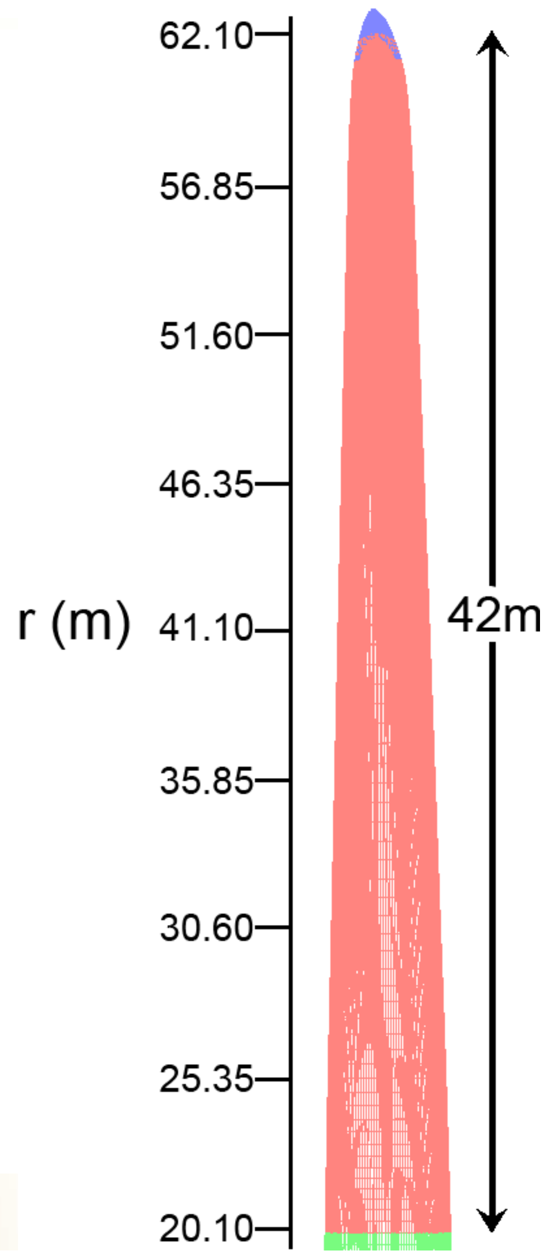
NREL 5-MW – "Baseline" Grid

- Baseline grid
  - Near-body ~10M
- Tip grid: 61×61×81



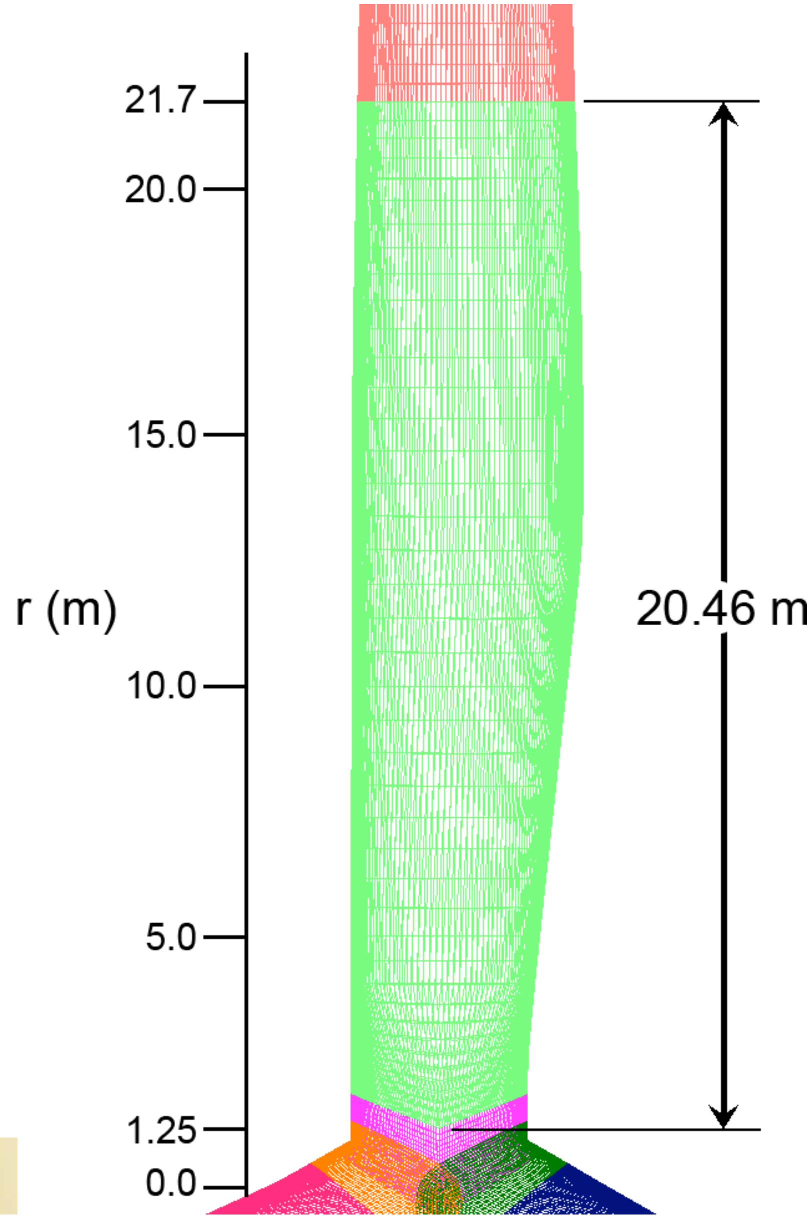
NREL 5-MW – "Baseline" Grid

- Baseline grid
  - Near-body ~10M
- Tip grid: 61×61×81
- Outboard: 201×116×81



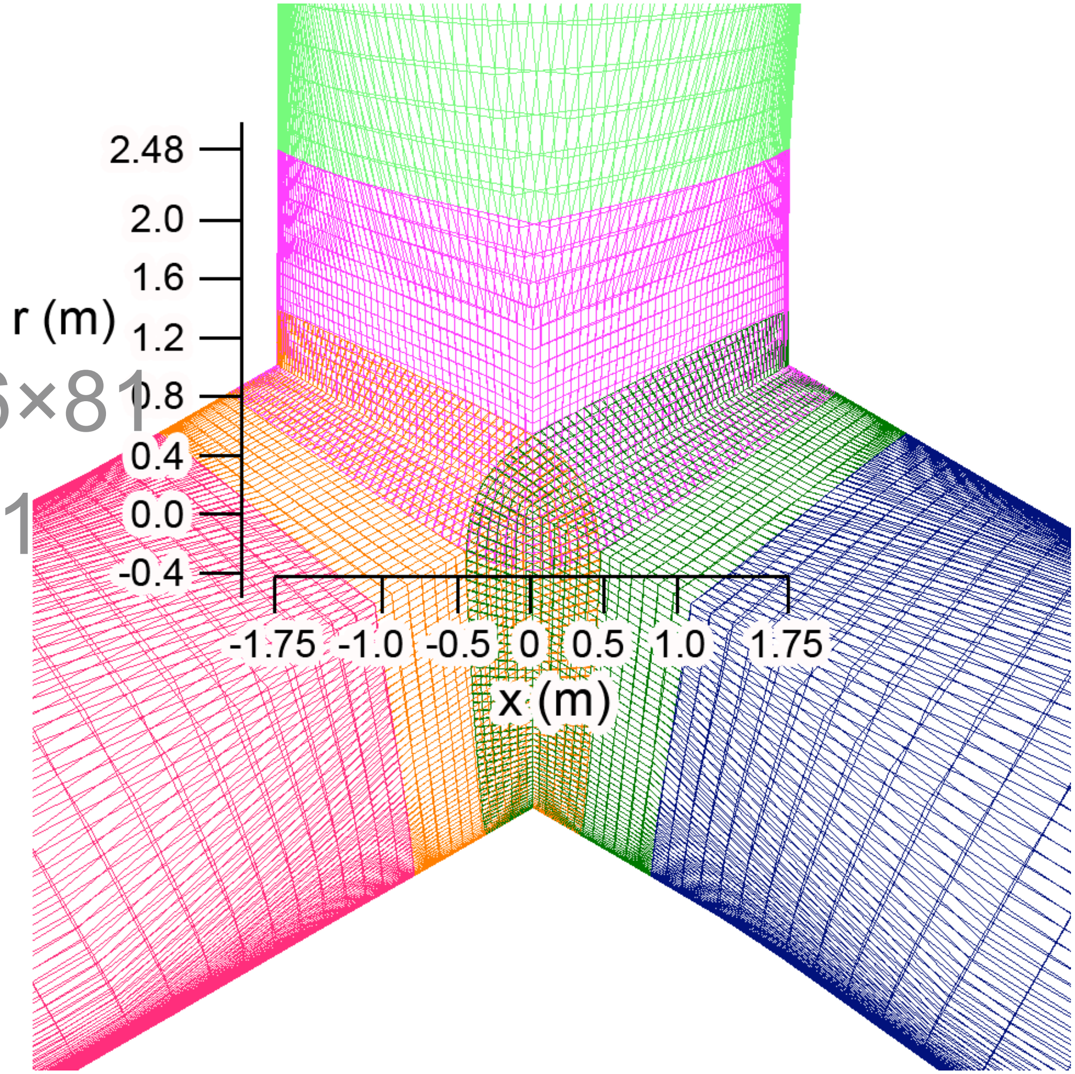
NREL 5-MW – "Baseline" Grid

- Baseline grid
  - Near-body ~10M
- Tip grid: 61×61×81
- Outboard: 201×116×81
- Inboard: 201×43×81



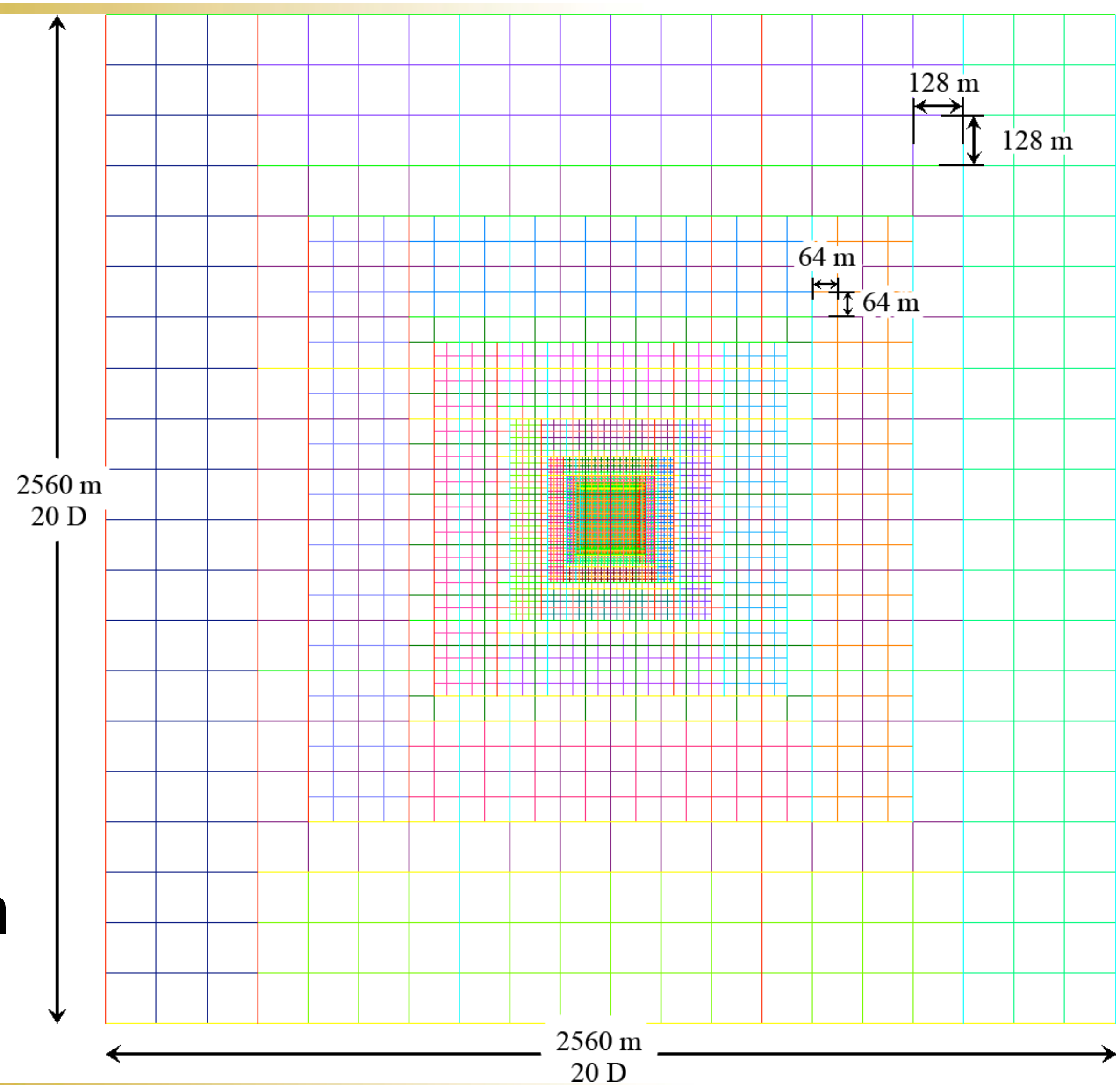
NREL 5-MW – "Baseline" Grid

- Baseline grid
  - Near-body ~10M
- Tip grid: 61×61×81
- Outboard: 201×116×81
- Inboard: 201×43×81
- Hub: 201×26×81



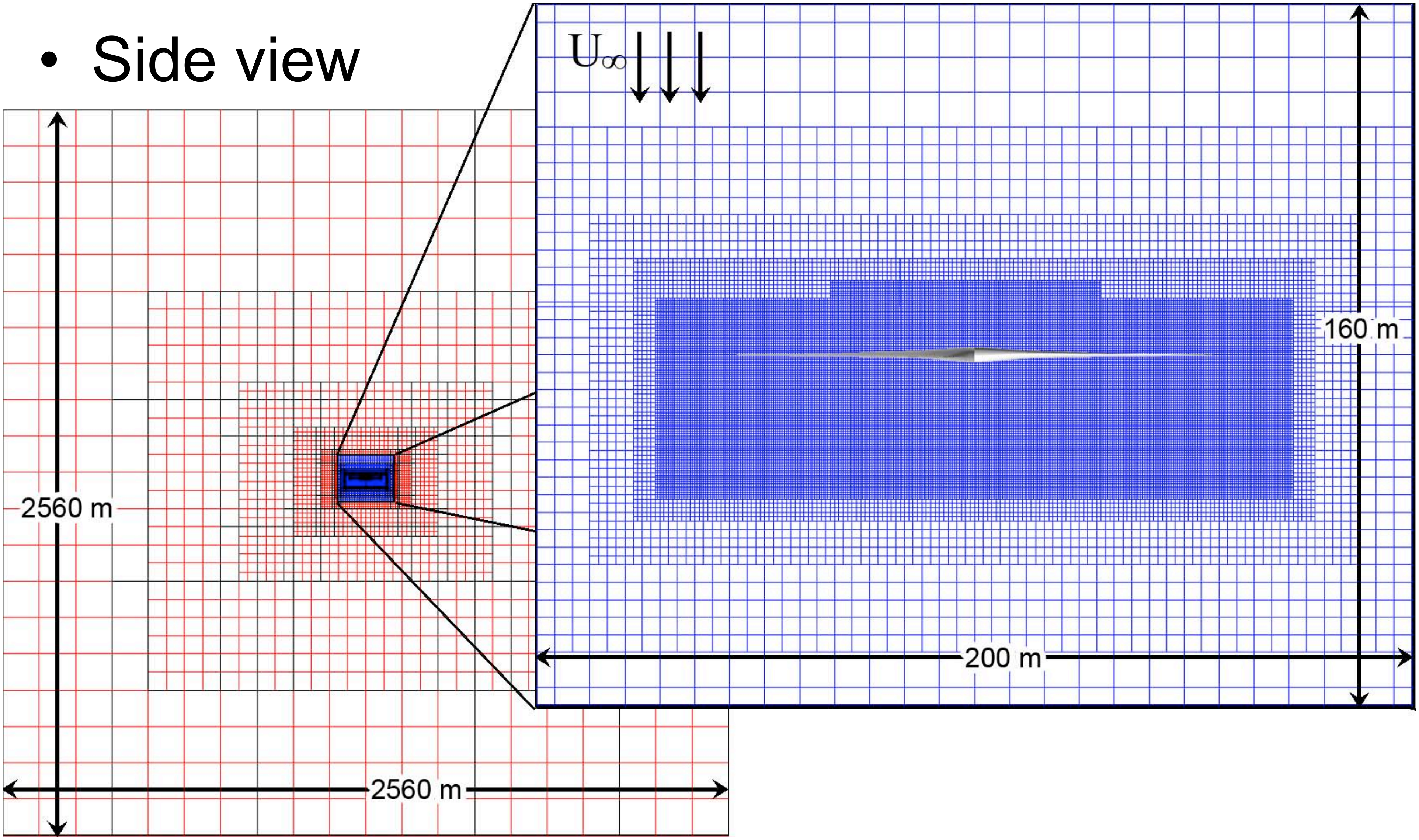
NREL 5-MW – Baseline Grid Domain

- Top view of domain
- 9 layers of BRICKS
- Each layer doubles cell dimension, ie:
  - DS_{inner} = 0.5 m
  - DS_{outer} = 128 m



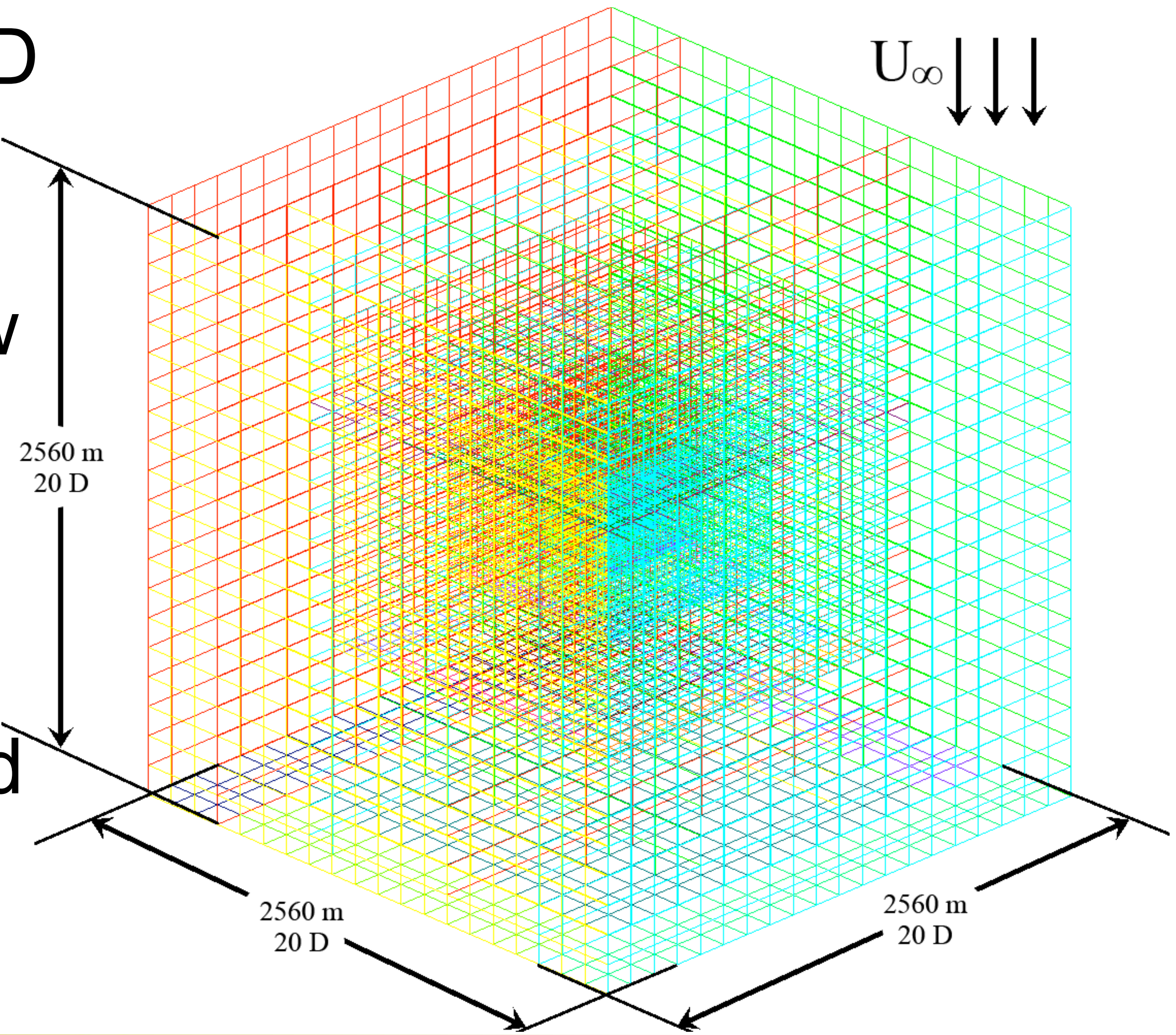
NREL 5-MW – Initial Off-Body Grid

- Side view

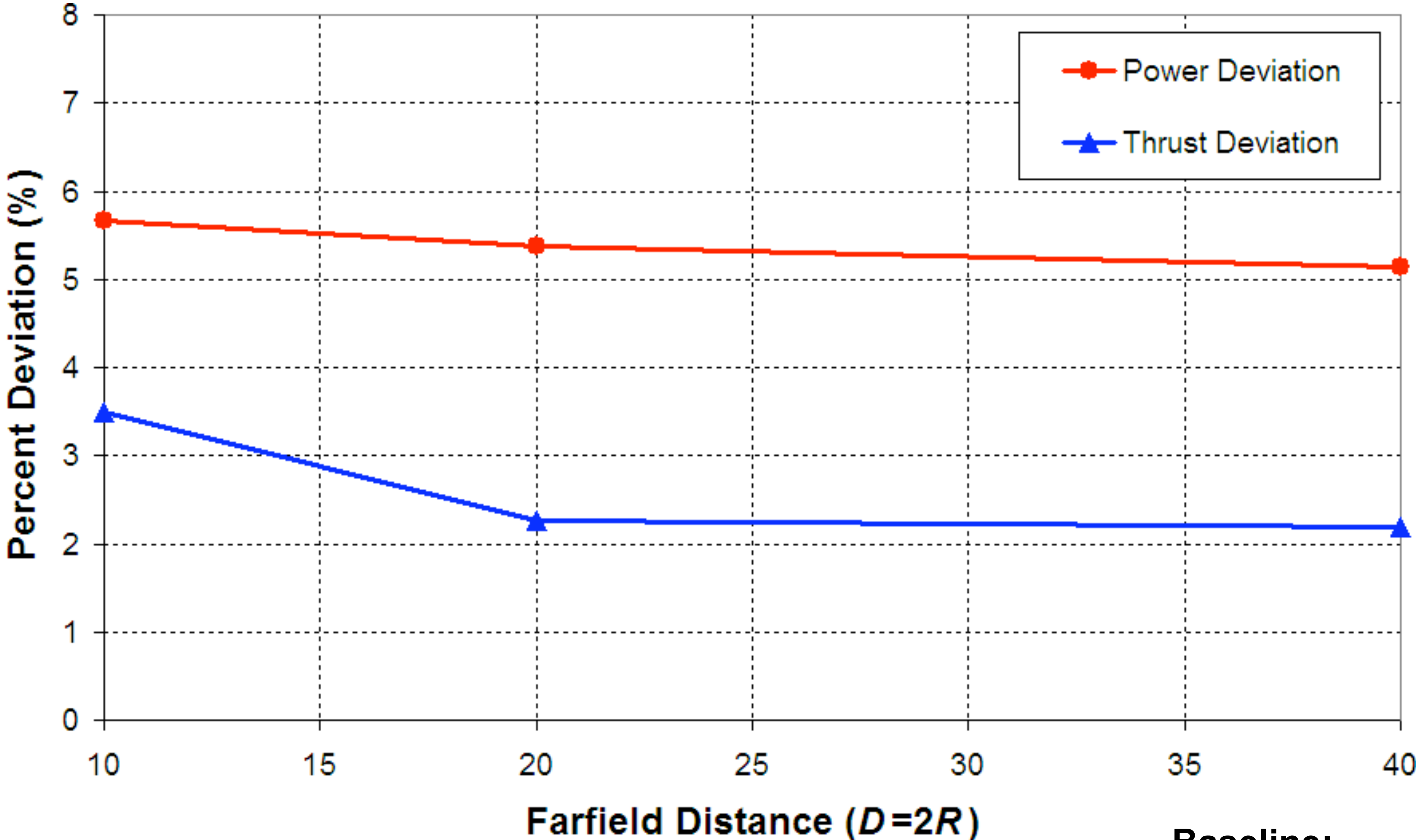


NREL 5-MW – Grid Topology

- Baseline ~10D far-field distance
- BRICKS allow for rapid and efficient domain construction
- Improved load balancing

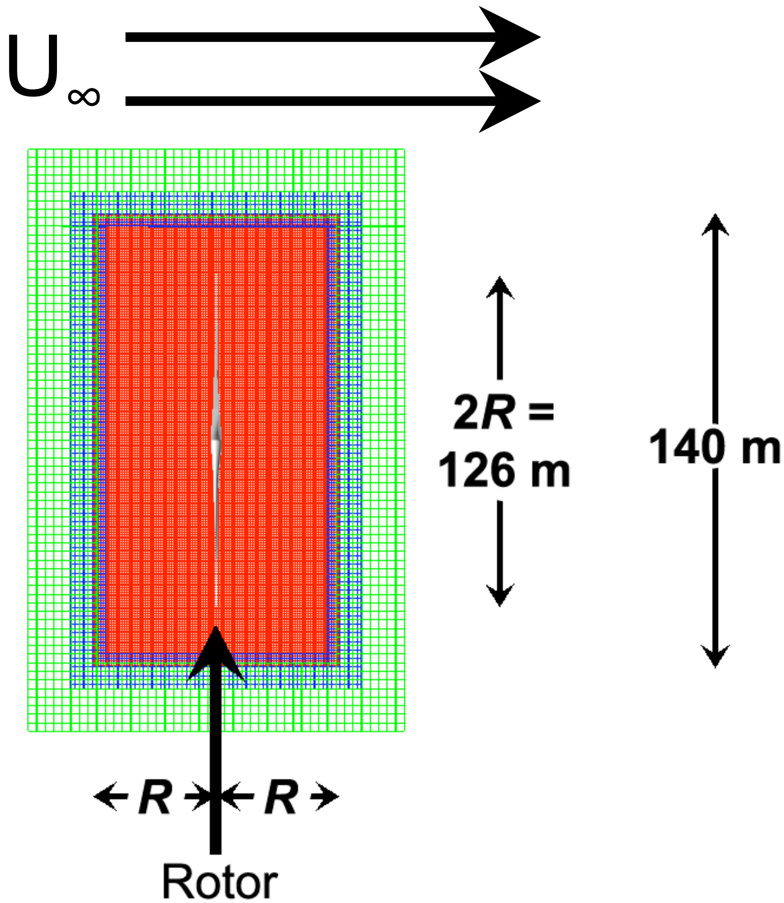


NREL 5-MW – Domain Size



Baseline:
DS = 0.5 m, L = 8R

NREL 5-MW – Near-Wake Size

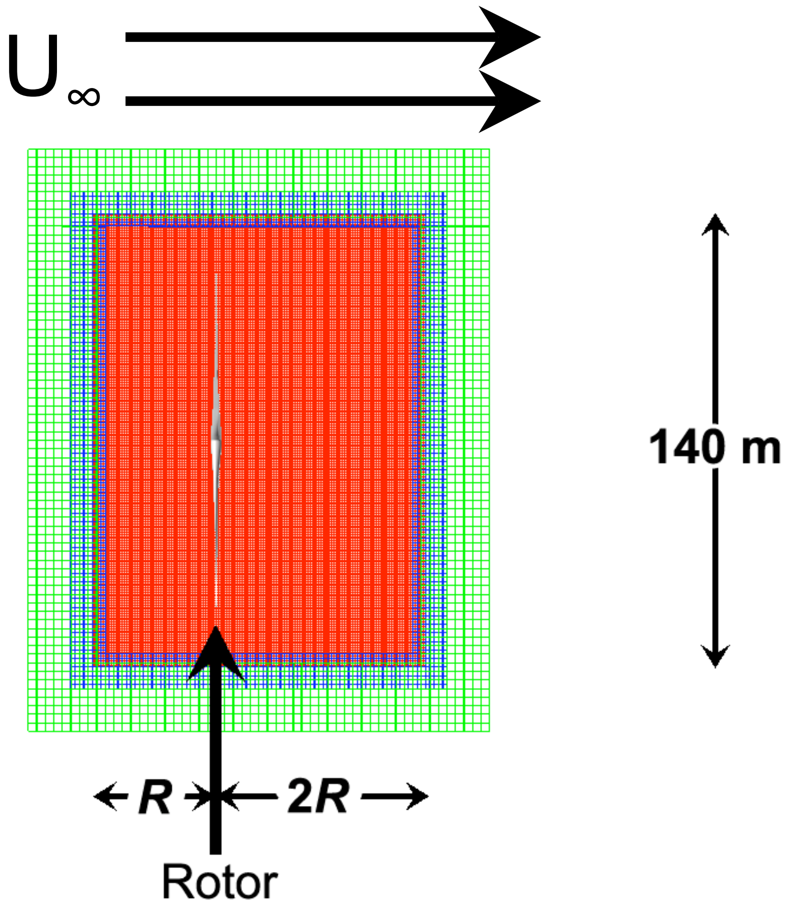


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

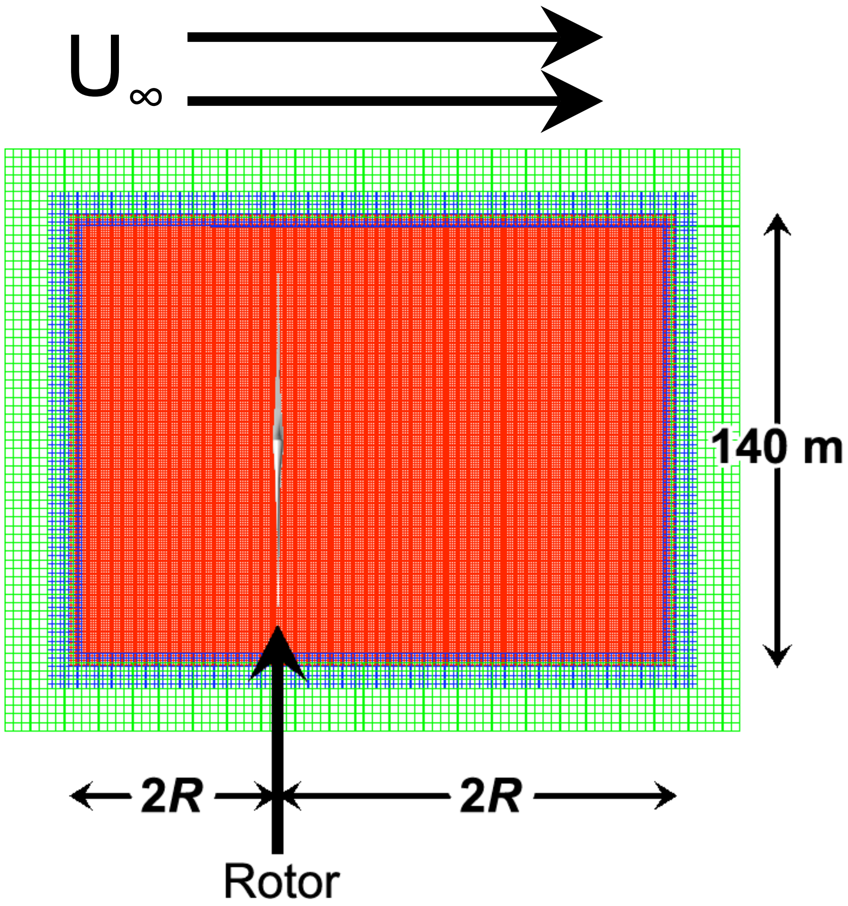


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

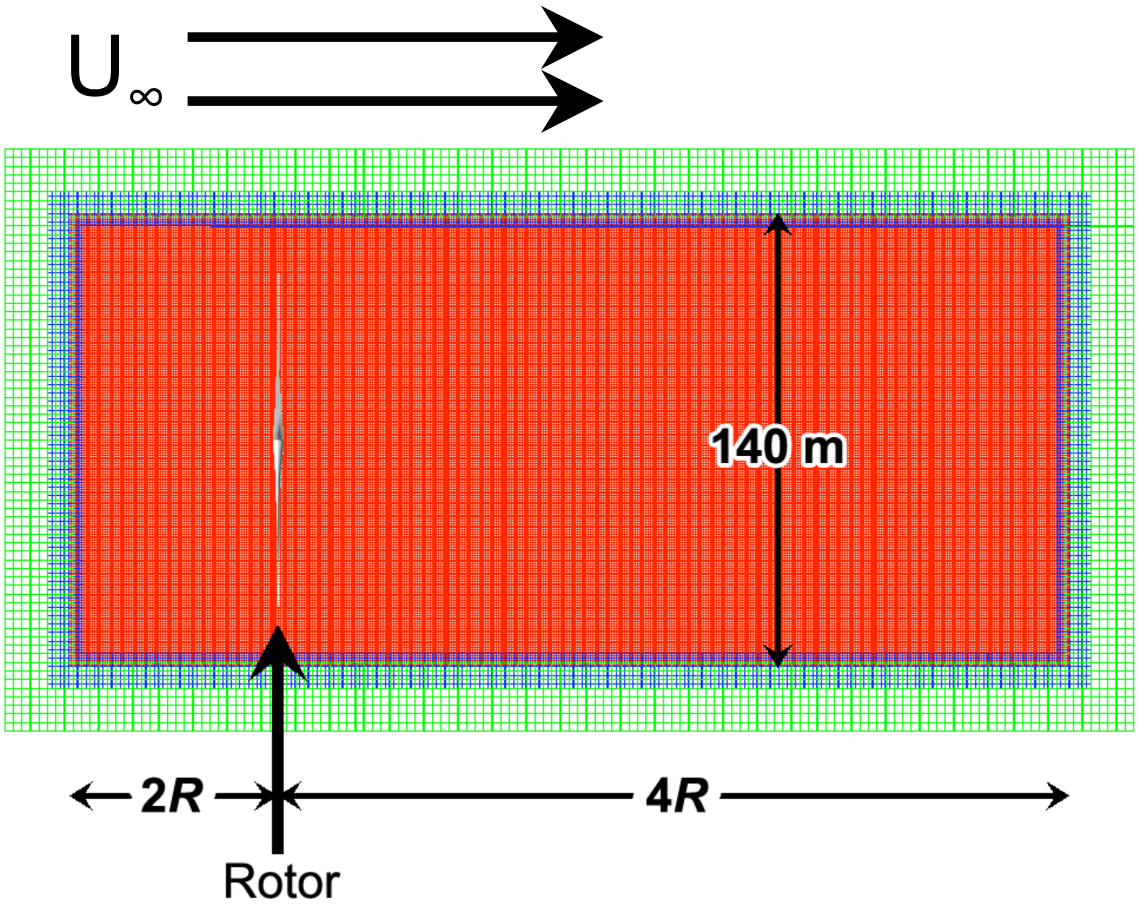


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

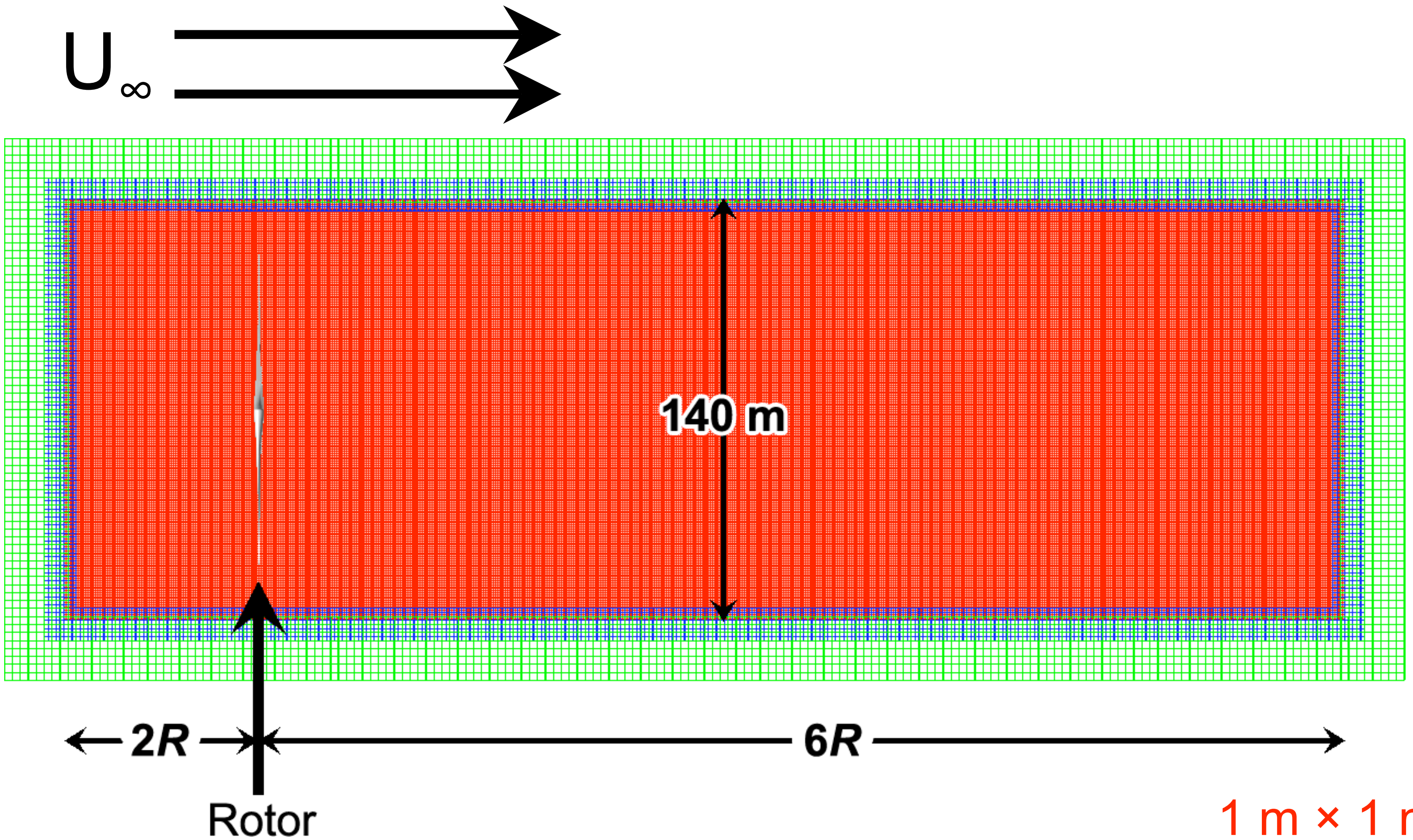


1 m × 1 m × 1 m cells

2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

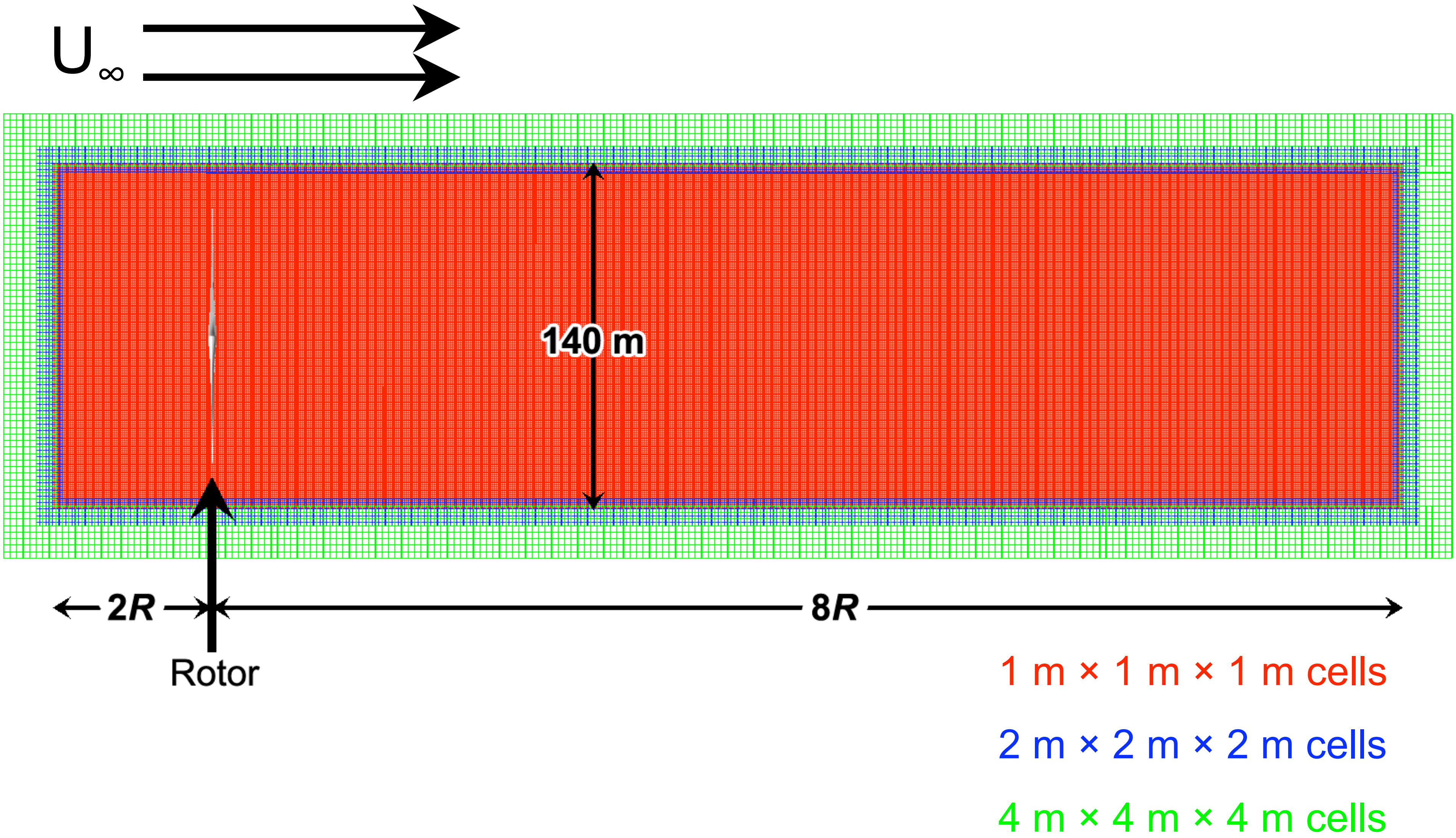


1 m × 1 m × 1 m cells

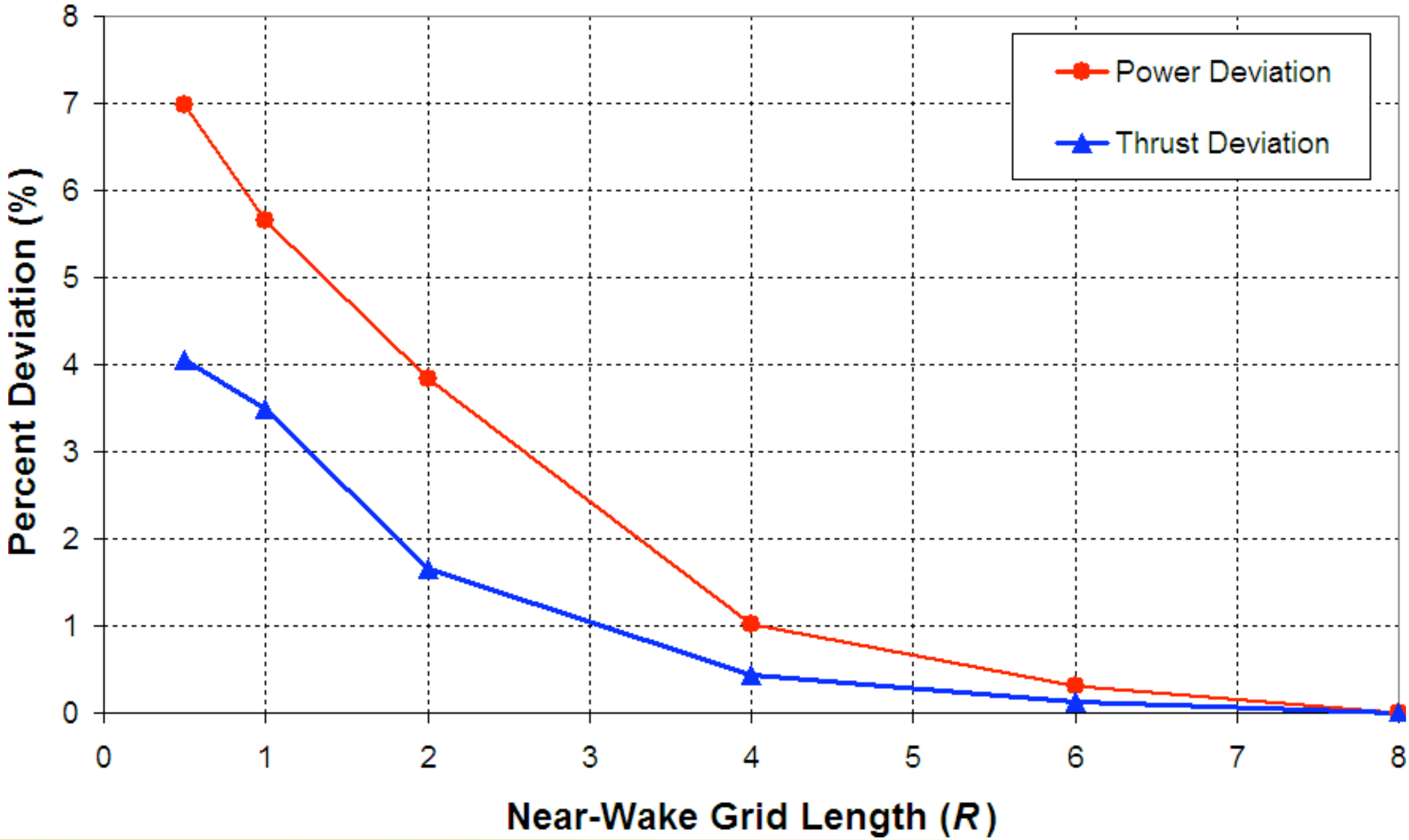
2 m × 2 m × 2 m cells

4 m × 4 m × 4 m cells

NREL 5-MW – Near-Wake Size

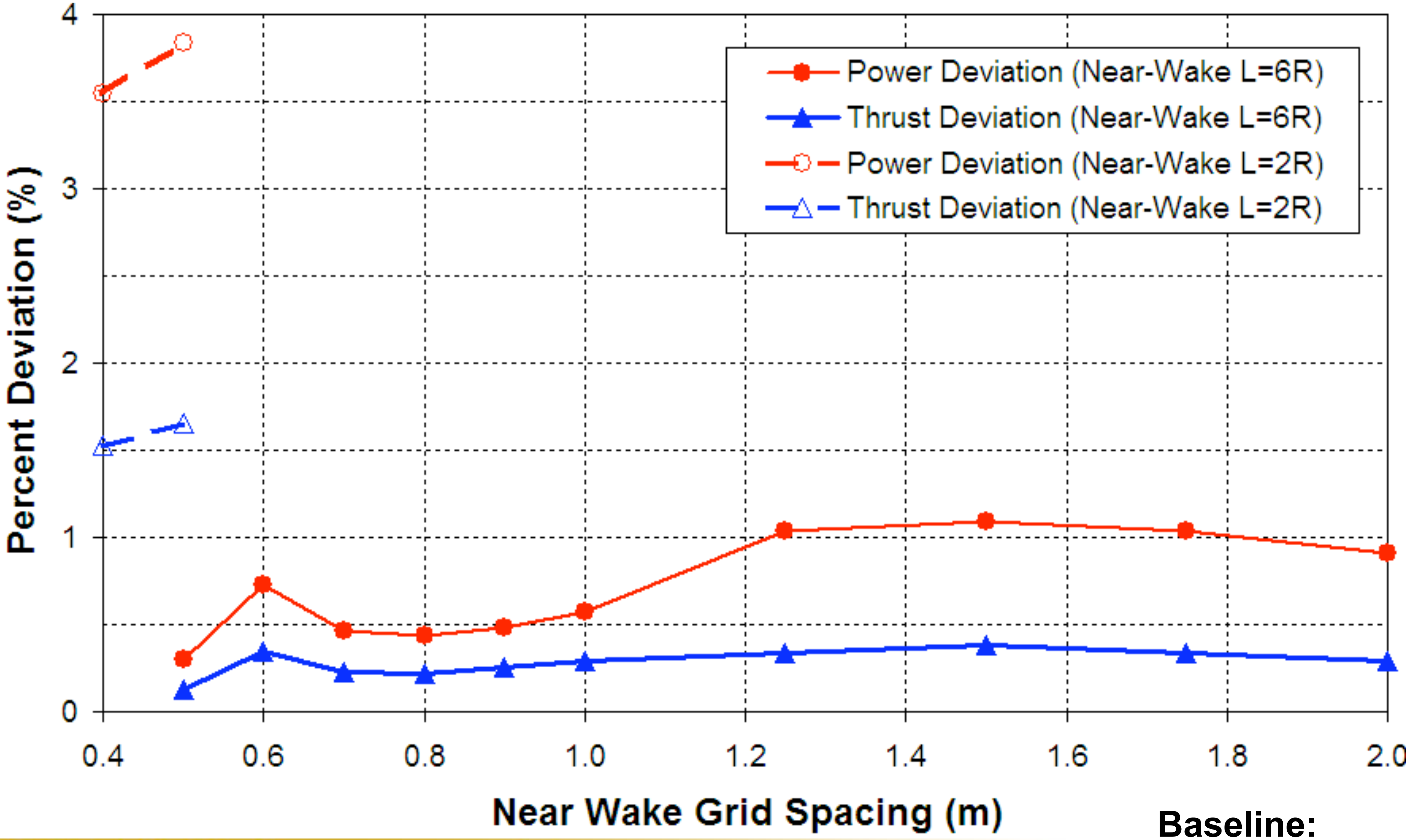


NREL 5-MW – Near-Wake Size



DS = 0.5 m

NREL 5-MW – Near-Wake Cell Size



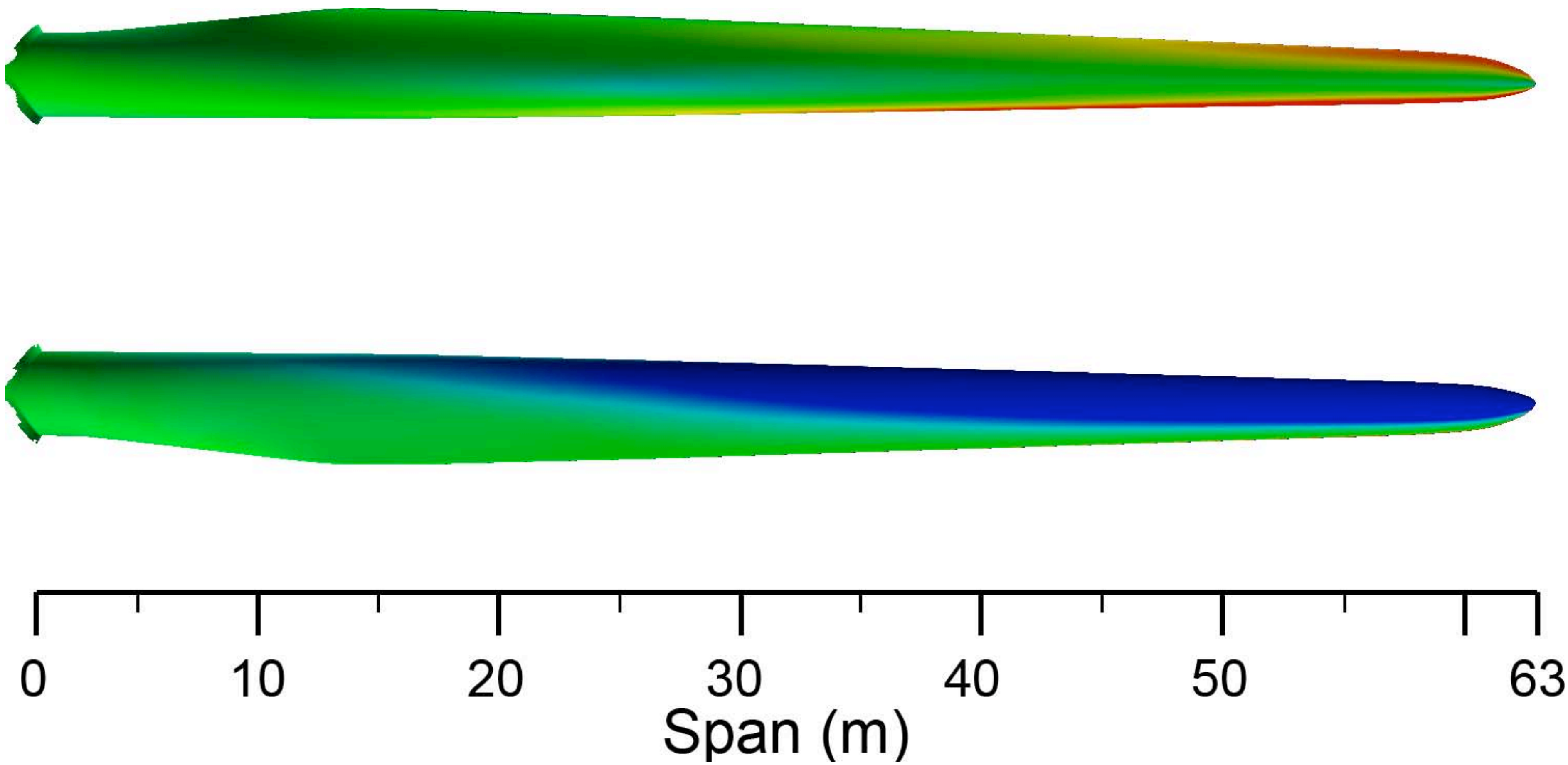
Baseline:
DS = 0.5 m, L = 8R

NREL 5-MW – Final Grid Size

- Near-wake
  - Length = 6*R* = 3*D* = 378 m
  - Width = 140 × 140 m
  - Spacing DS = 1 m
- Far-field
  - 40*D* to inlet, N,S,E,W boundaries
    - Characteristic freestream boundary conditions
  - 80*D* downstream exit boundary
    - 1st order inflow/outflow
- 4th order, inviscid, central difference scheme
- With viscous body-fitted grids ~28 million points

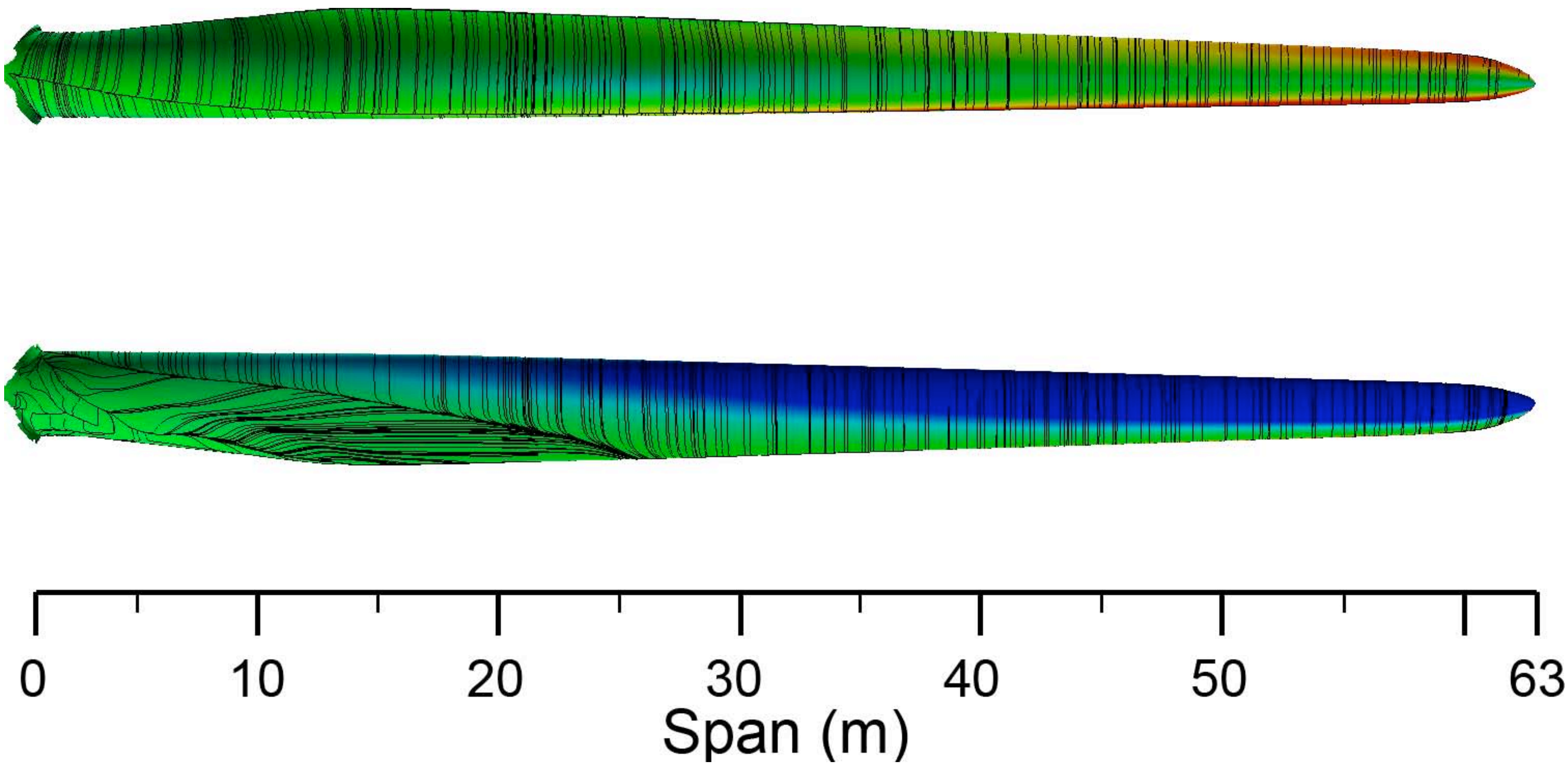
Baseline Results

NREL 5-MW – U_∞ = 11m/s



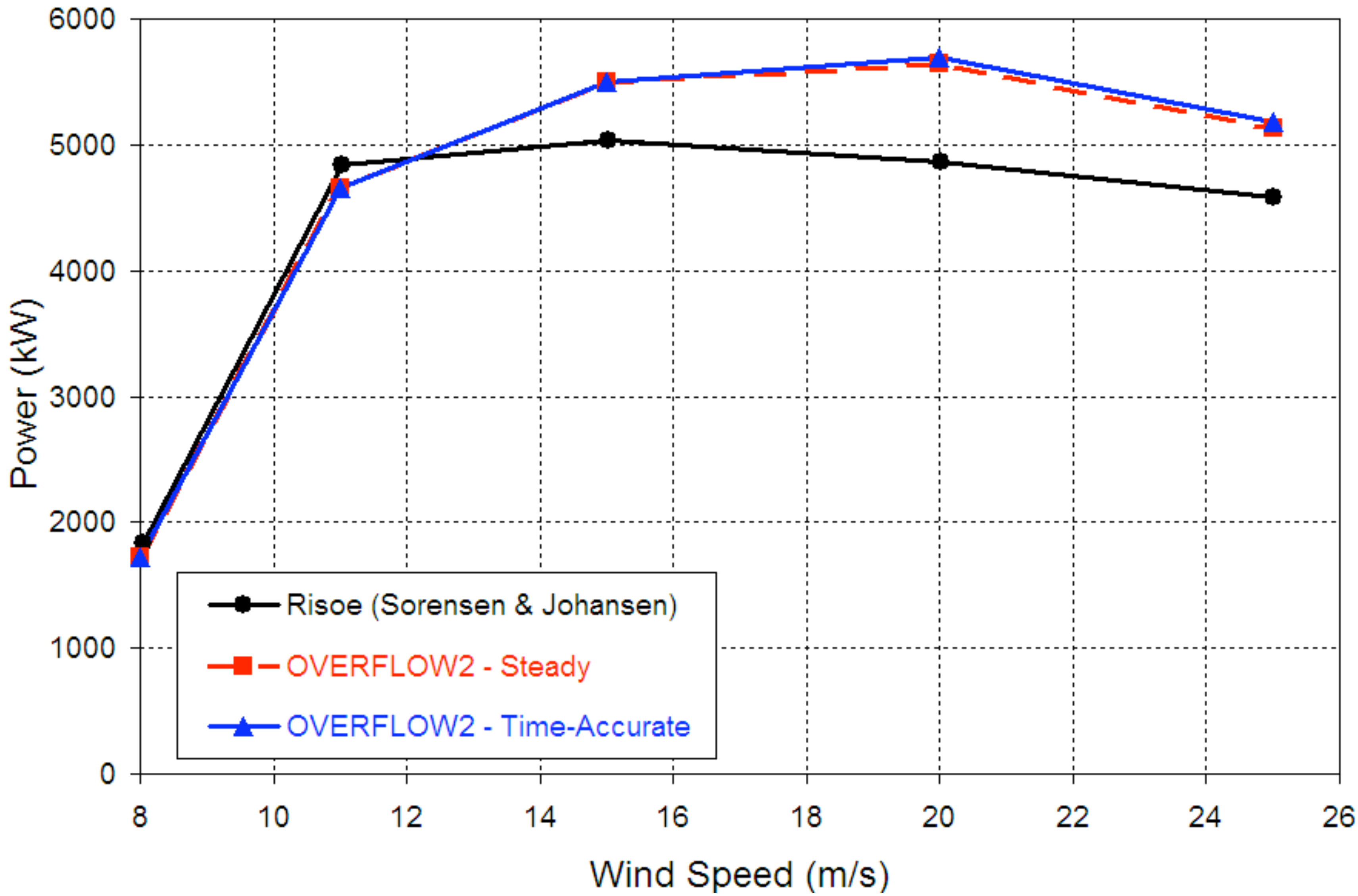
- Surface pressure

NREL 5-MW – U_∞ = 11m/s

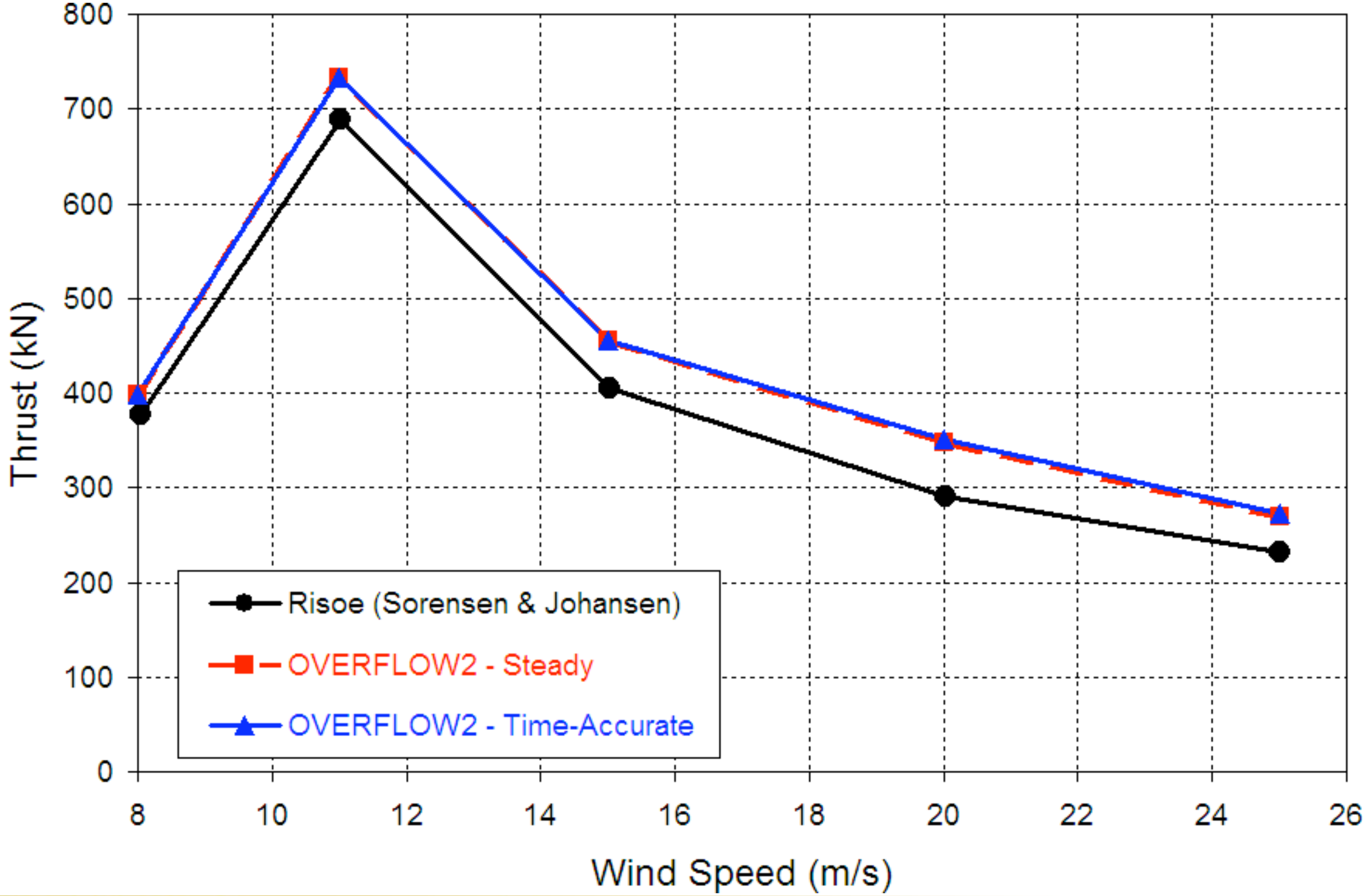


- Surface pressure with streaklines

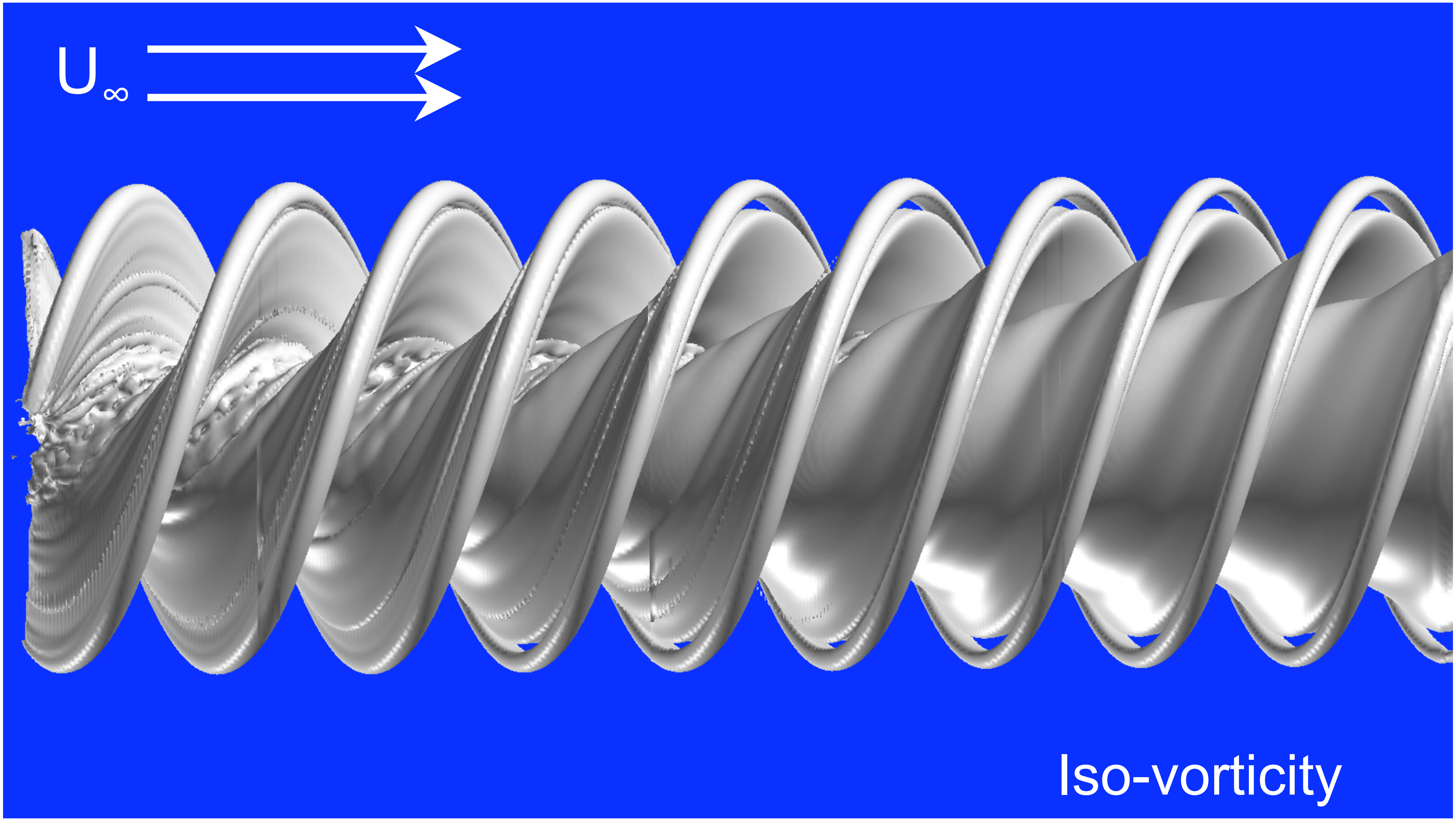
NREL 5-MW – Power



NREL 5-MW – Thrust

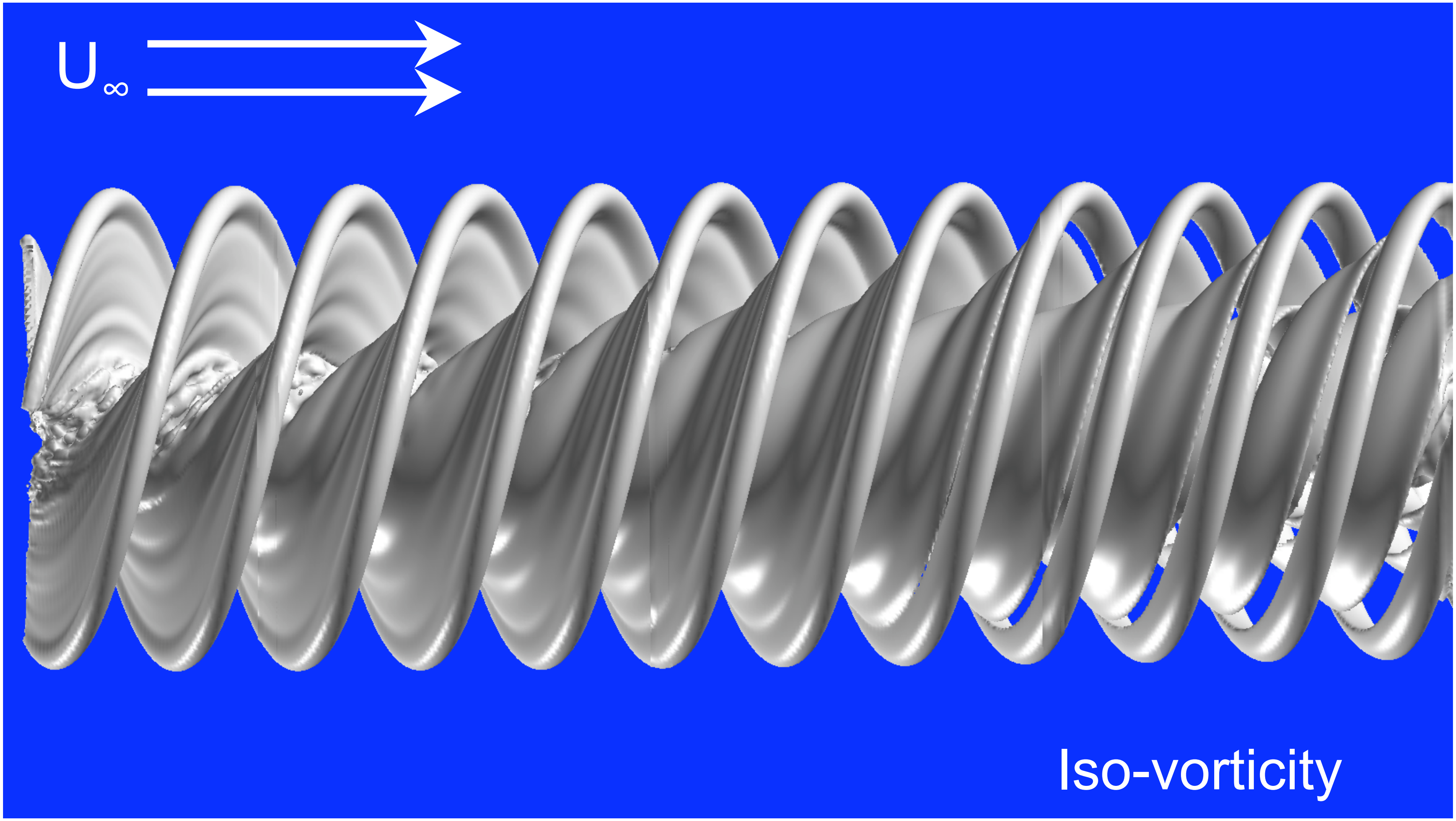


NREL 5-MW – U_∞ = 25 m/s



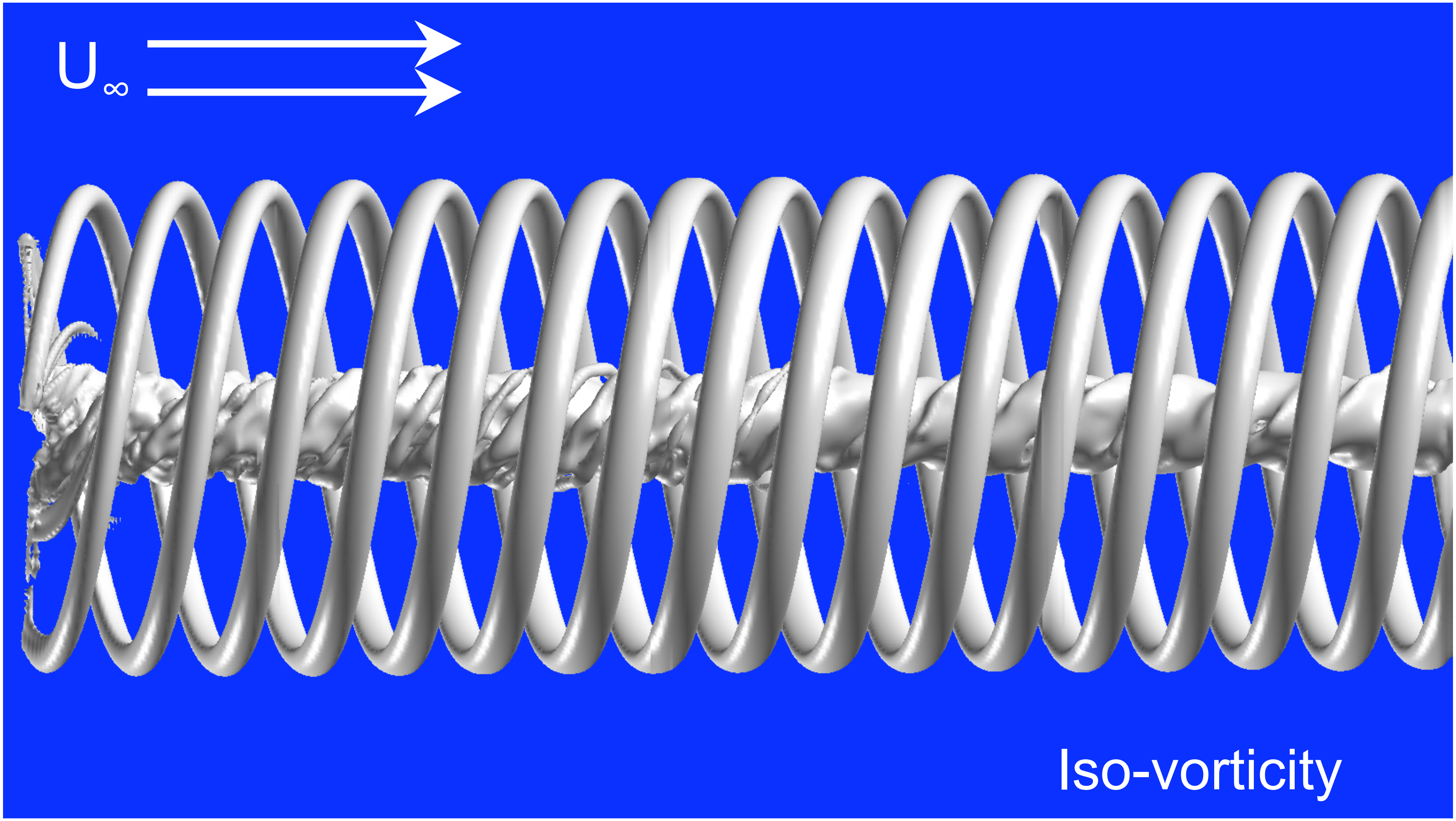
$\omega = 0.00025$

NREL 5-MW – U_∞ = 20 m/s



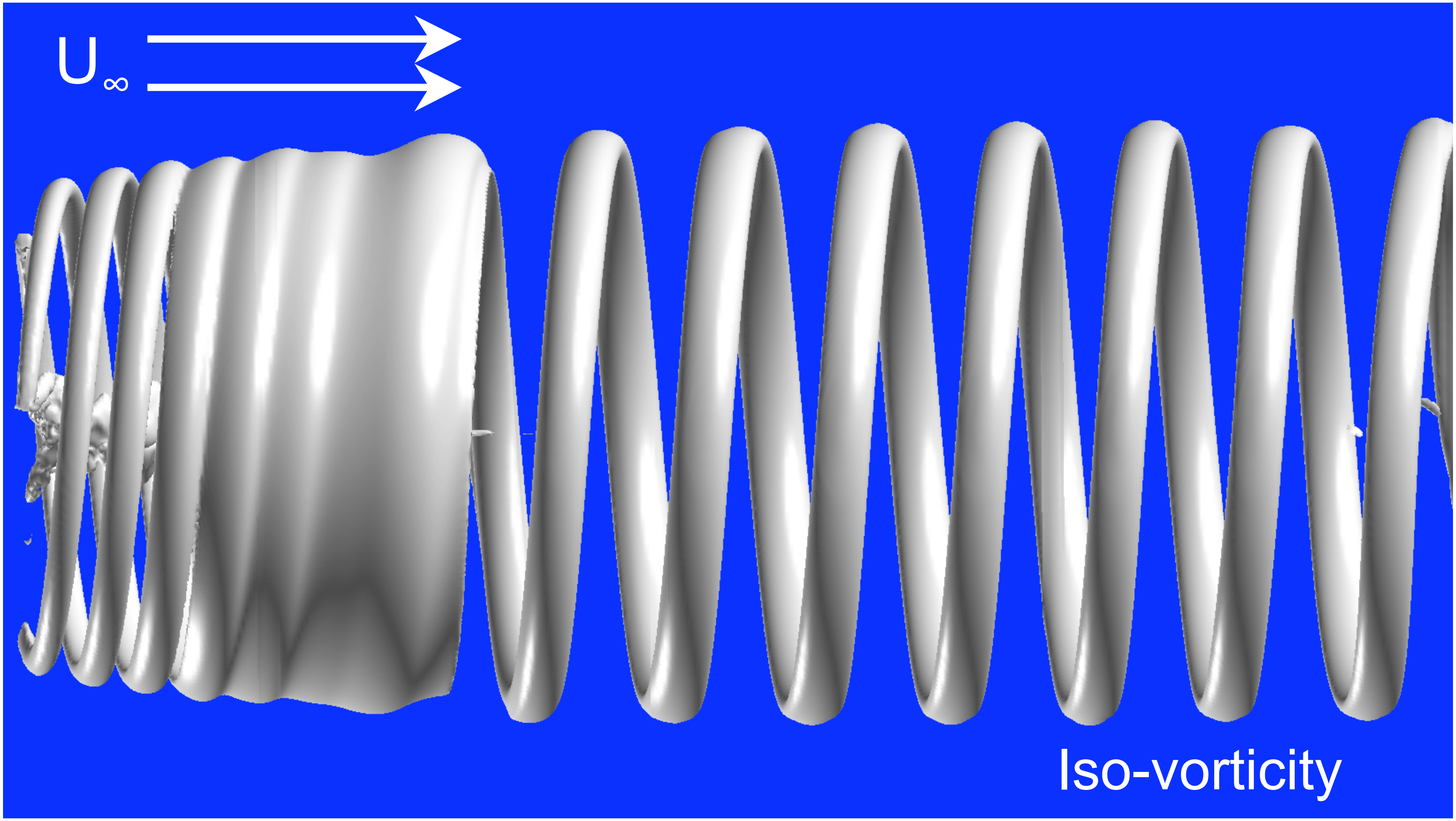
ω = 0.00050

NREL 5-MW – U_∞ = 15 m/s



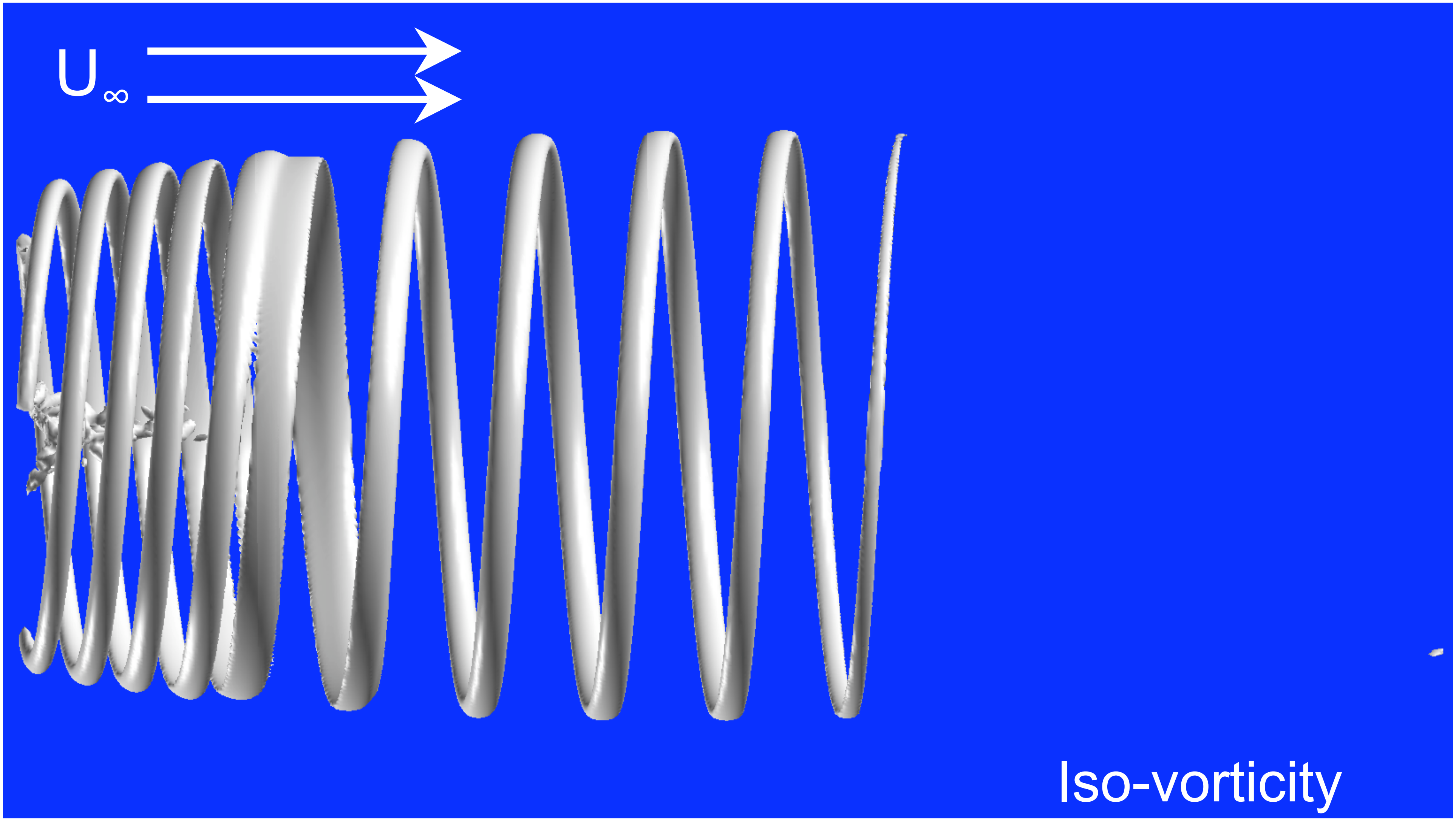
ω = 0.00100

NREL 5-MW – U_∞ = 11 m/s



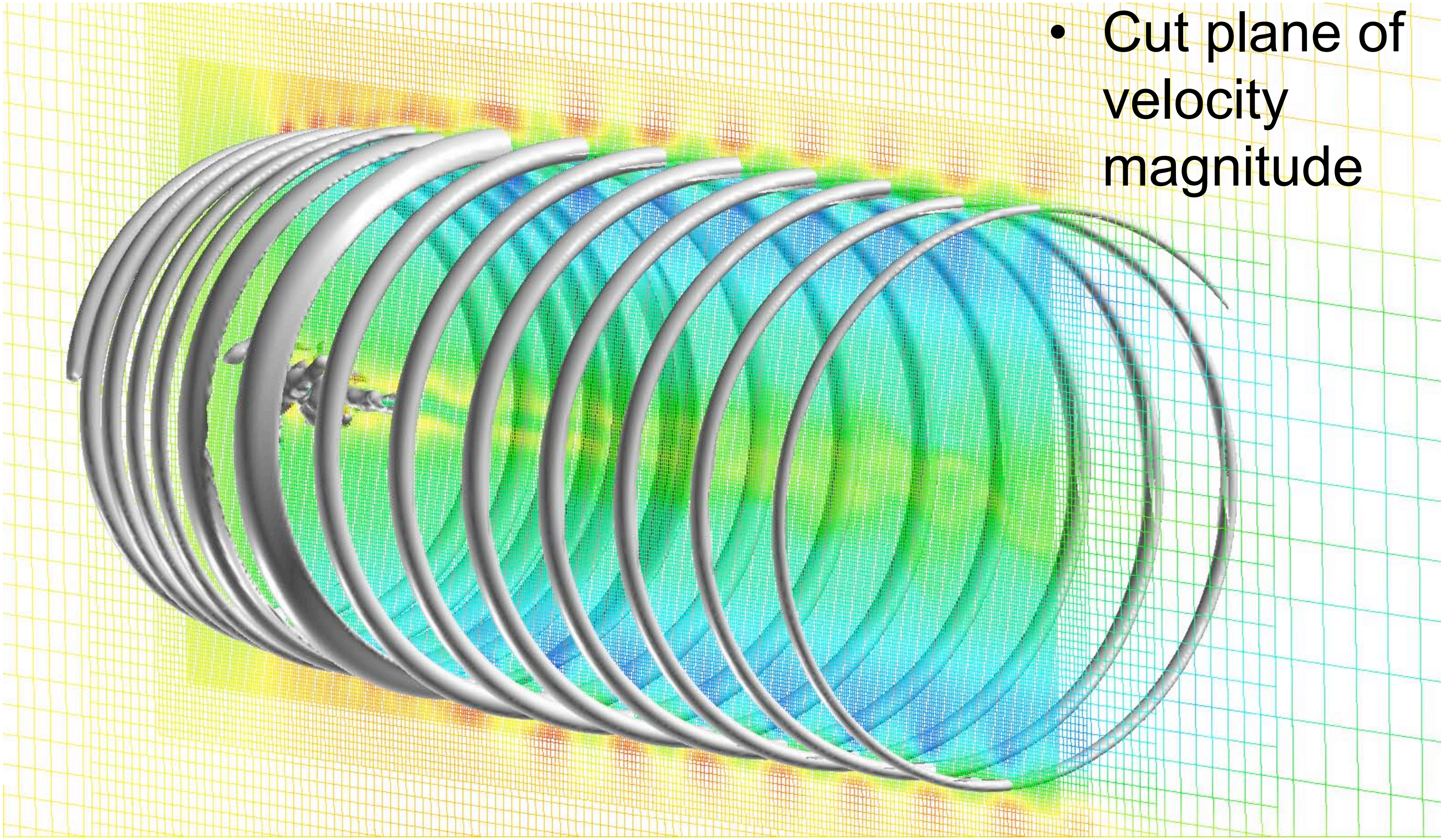
ω = 0.00250

NREL 5-MW – U_∞ = 8 m/s



ω = 0.00300

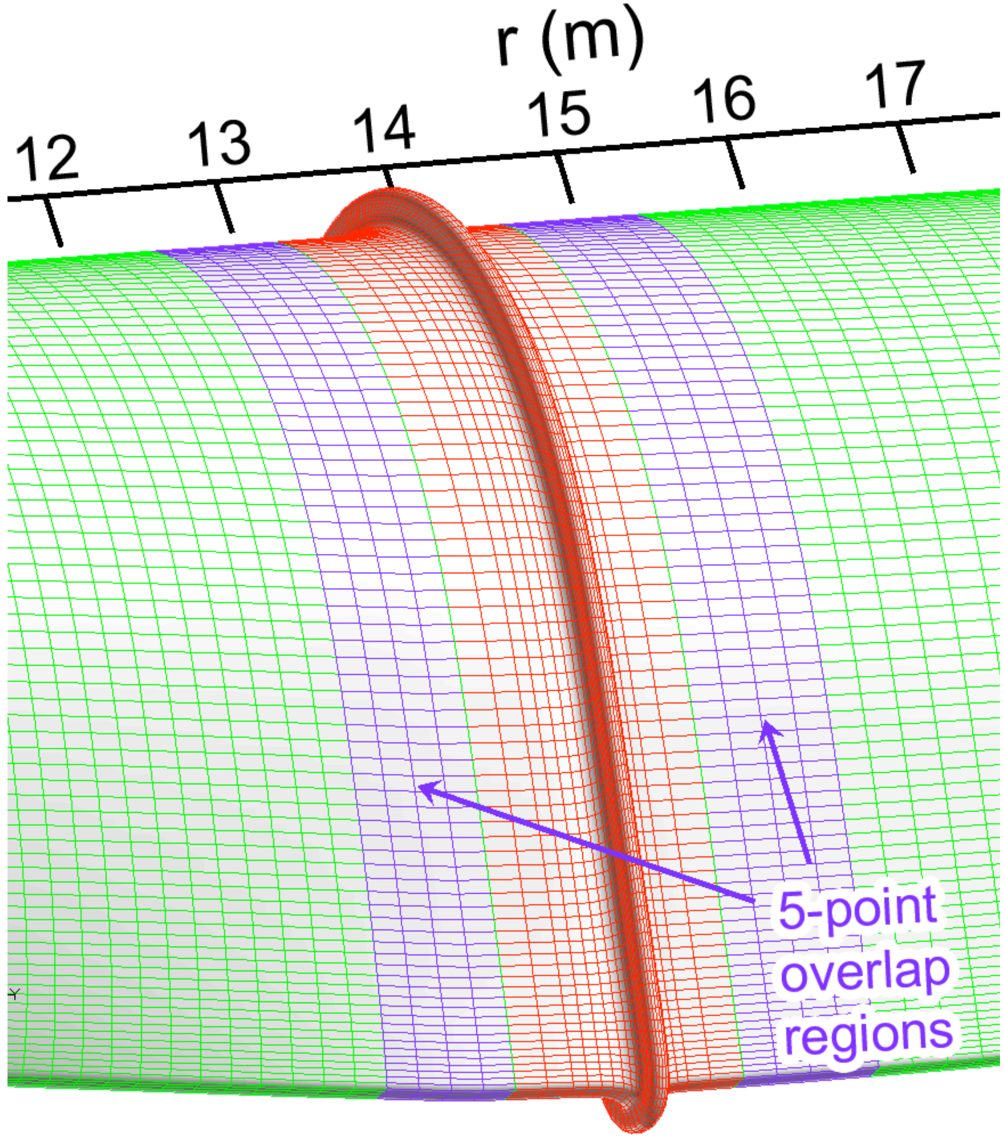
NREL 5-MW – U_∞ = 11m/s



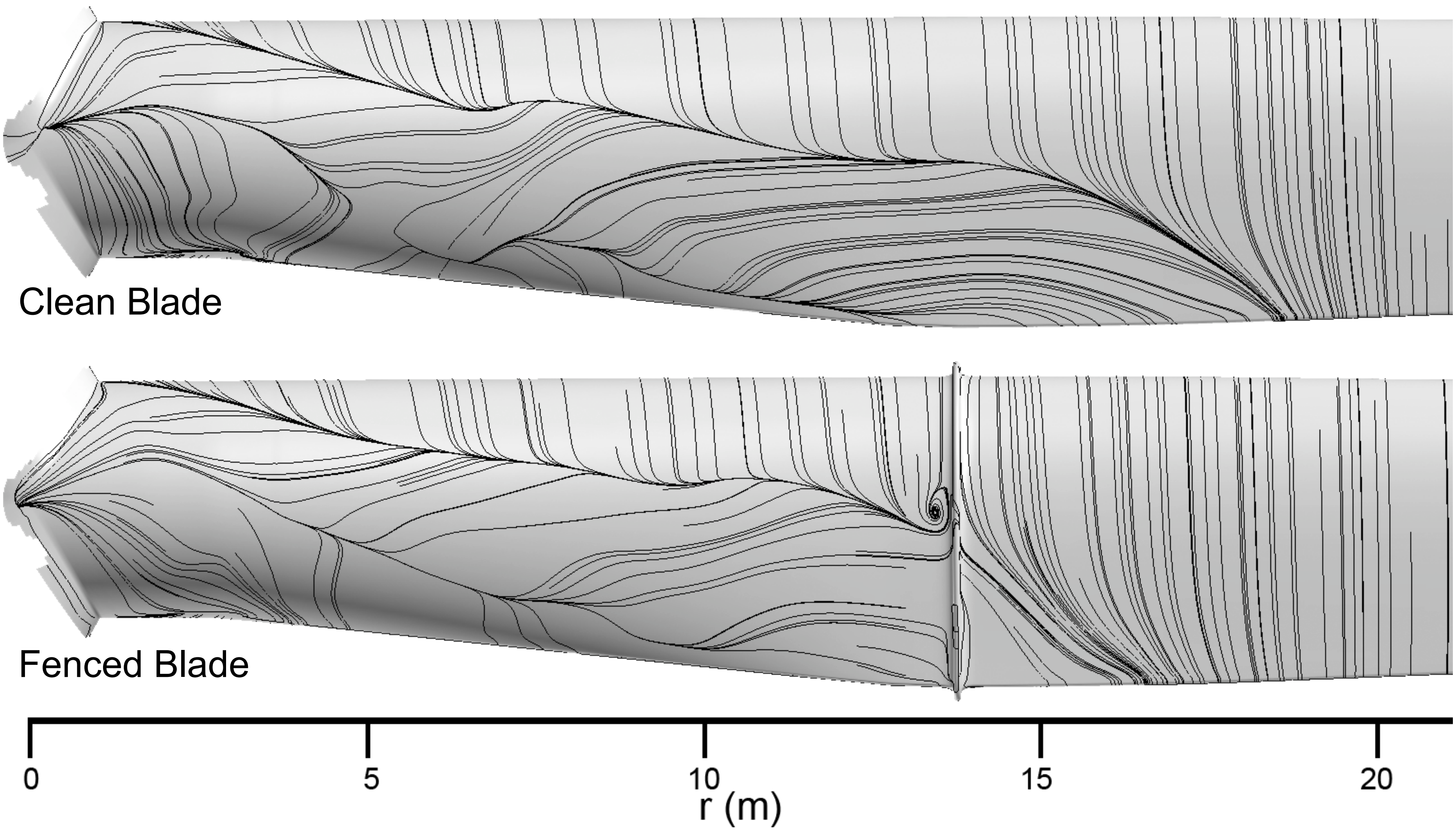
- Cut plane of velocity magnitude

Ring Fence Geometry

- Uniform height
  - $h_{fence} = 0.05c_{max}$
  - $h_{fence} \approx 0.23$ m
- Centered at max chord
  - $r = 13.7$ m
  - $r/R = 21.7\%$
- Overset grid
  - 201×47×81 points
  - ~5M additional points
  - Point-matched overlap on blade surface
  - Existing blade region IBLANKED



Suction Side Streaklines – 8 m/s



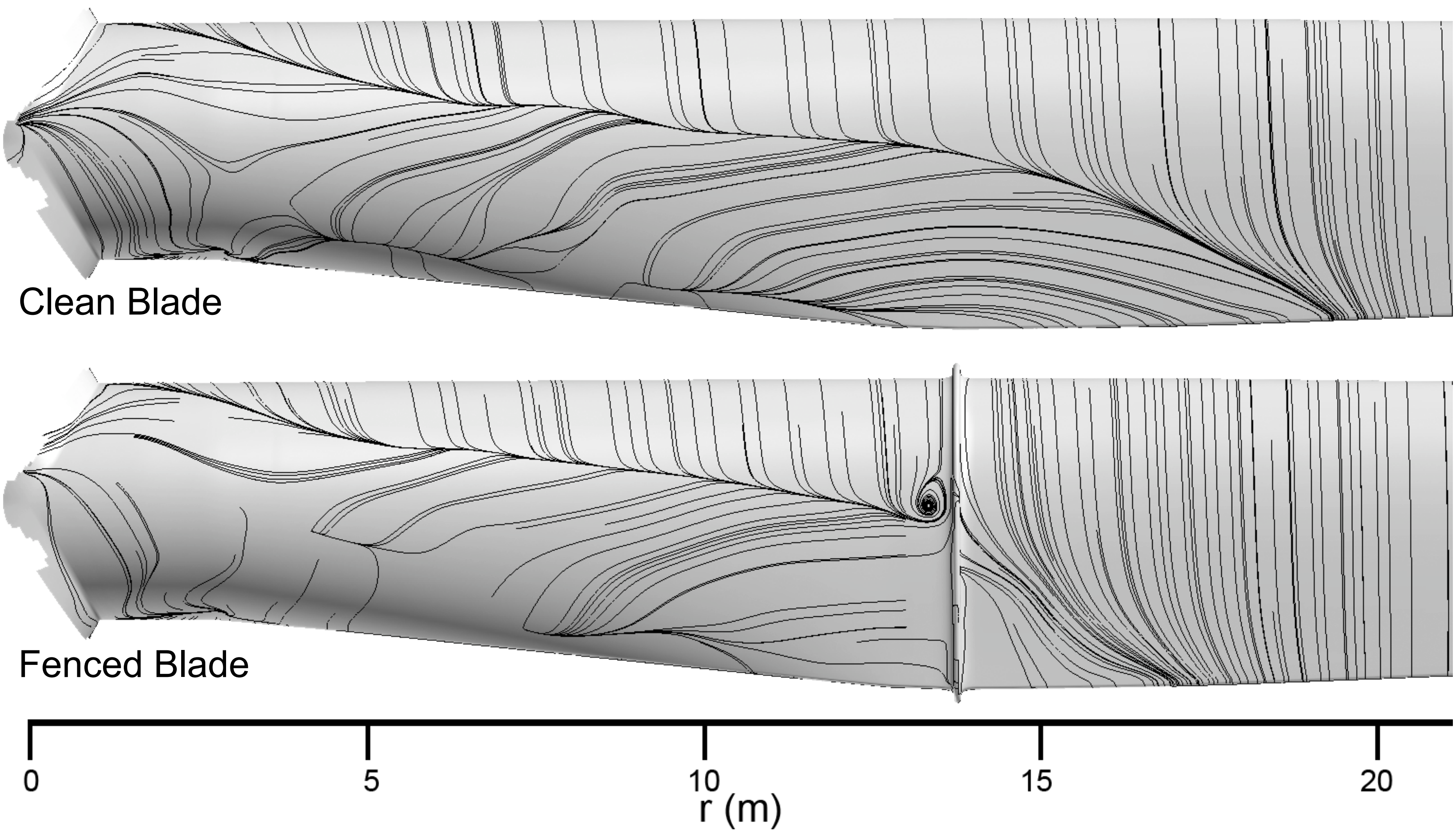
Effect of Ring Fence – 8 m/s

Rotor Power

Solver Mode	U_∞	***RPM***	$P_{baseline}$ (kW)	P_{fenced} (kW)	ΔP (kW)	***% Gain***
Steady	8	9.16	1718	1733	**15.3**	**0.889%**
Time-Acc	8	9.16	1719	1735	**15.3**	**0.888%**

- Consistent change in power between steady-state and time-accurate solutions.
- Both resulting in a power gain of 0.89%

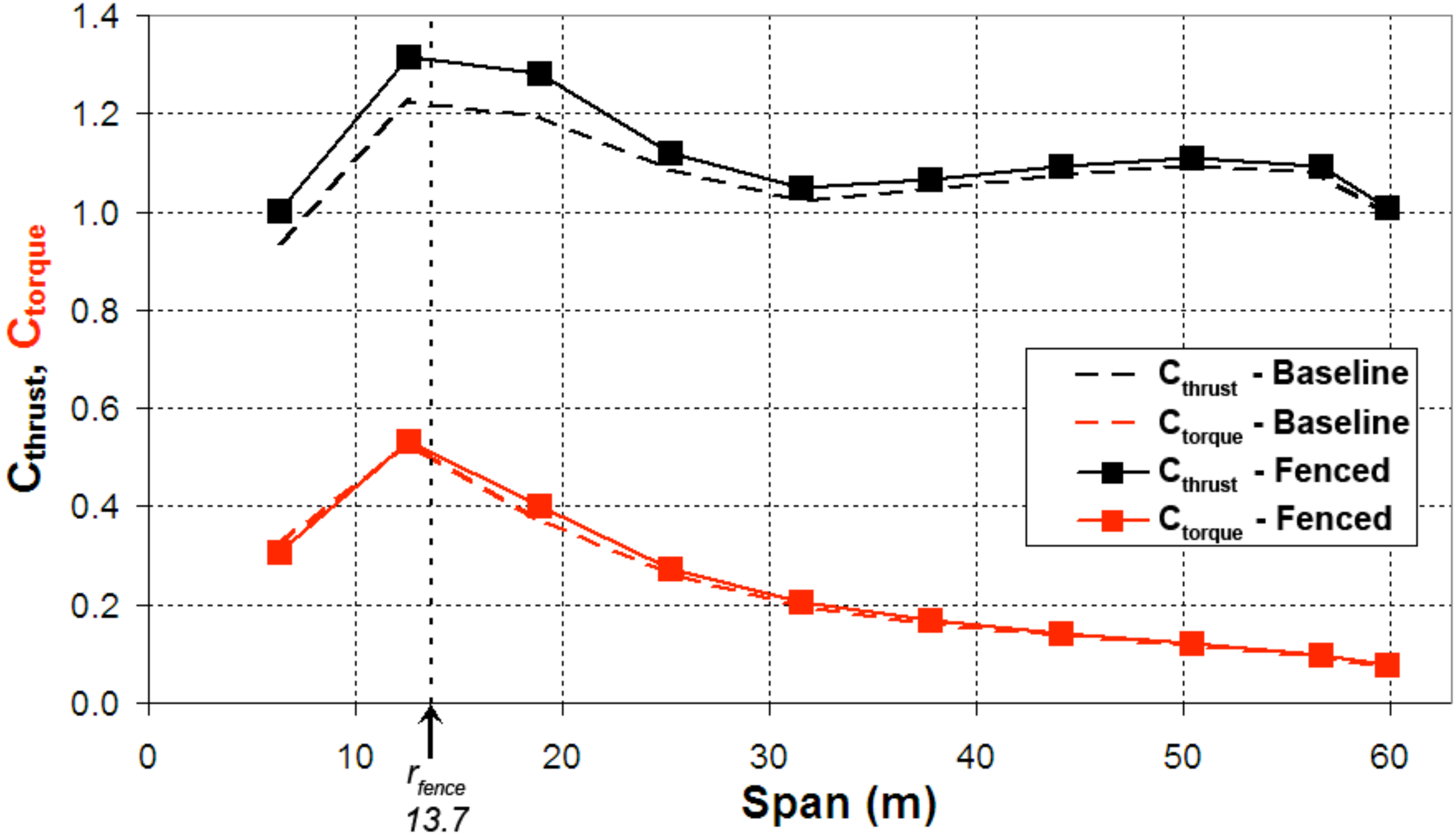
Suction Side Streaklines – 11 m/s



Ring Fence Effect on Rotor Power

Solver Mode	U_∞	***RPM***	$P_{baseline}$ *(kW)*	P_{fenced} (kW)	ΔP (kW)	***% Gain***
Steady	8	9.16	1718	1733	**15.3**	**0.889%**
Time-Acc	8	9.16	1719	1735	**15.3**	**0.888%**
Steady	11	11.89	4650	4679	**28.9**	**0.622%**
Time-Acc	11	11.89	4654	4681	**27.1**	**0.583%**

Ring Fence on Spanwise Loading



UCDAVIS COLLEGE OF ENGINEERING

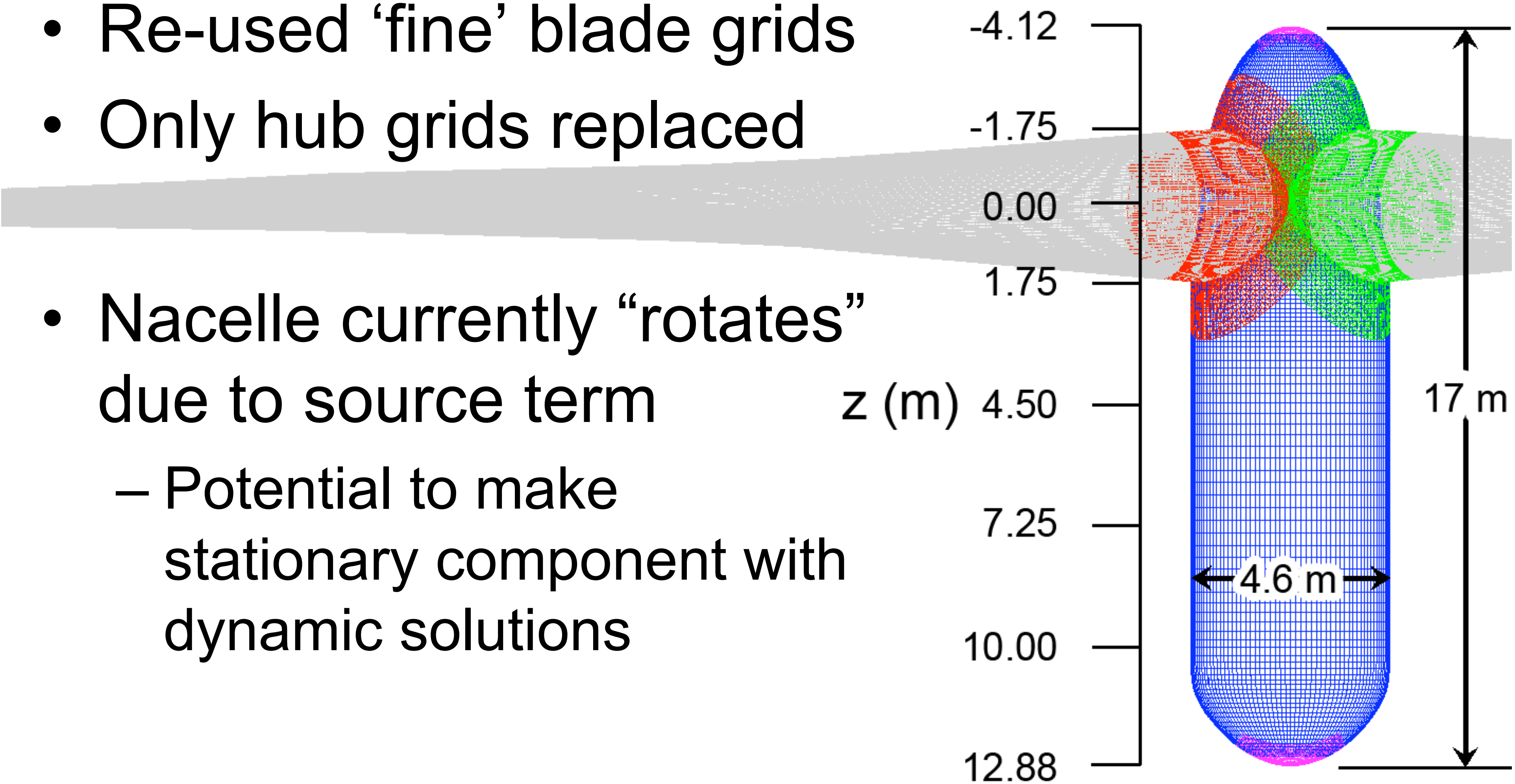
U_∞ = 11 m/s

Conclusions

- Extensive grid independence and external validation were performed to ensure baseline solution accuracy
- Inboard separation was found
- A framework for detailed study of inboard rotor flows has been established
- A simple fence geometry to limit spanwise flow successfully increased power capture by nearly 1% in Region II

NREL 5-MW – Nosecone and Nacelle

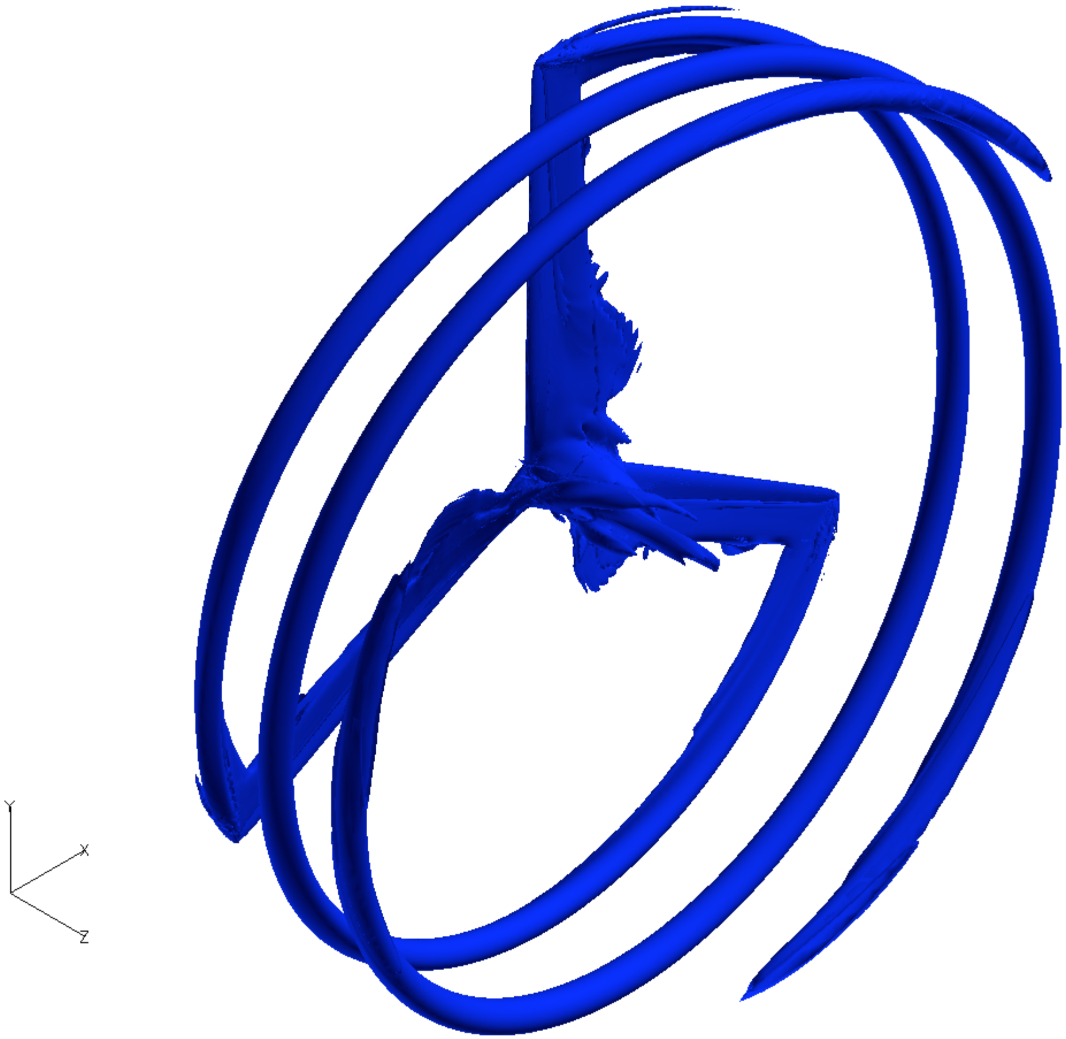
- Re-used ‘fine’ blade grids
- Only hub grids replaced
- Nacelle currently “rotates” due to source term
  – Potential to make stationary component with dynamic solutions



Acknowledgements

- Sandia National Laboratories for supporting this work.

Thank You



NREL 5-MW Iso-vorticity