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KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
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Experimental Details for the VT-NASA CFD Turbulence Model Blind Validation Challenge

Center for Research and Engineering in Aero/Hydrodynamic Technologies

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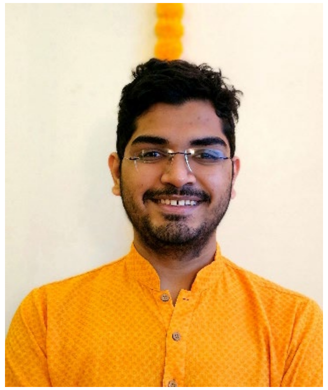
A. Gargiulo
Dept. of Mechanical and Aerospace Engineering, University of Virginia

Team for Validation Challenge

Students:
(Not shown: JoJo Chen and Derek Li)


Advait Borole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Monica Shanmugam

Many thanks to NASA for support under NRA Grant Nos. 80NSSC18M0146 and 80NSSC22M0061, Program Monitors Michael Kegerise and Mujeeb Malik.

Also, thanks to our assessors, Drs. Bill Oberkampf and Mory Mani

Further kind acknowledgements to Daniel MacGregor and Philippe Lavoie at UTIAS.


Aldo Gargiulo


Aurélien Borgoltz


William Devenport


Todd Lowe

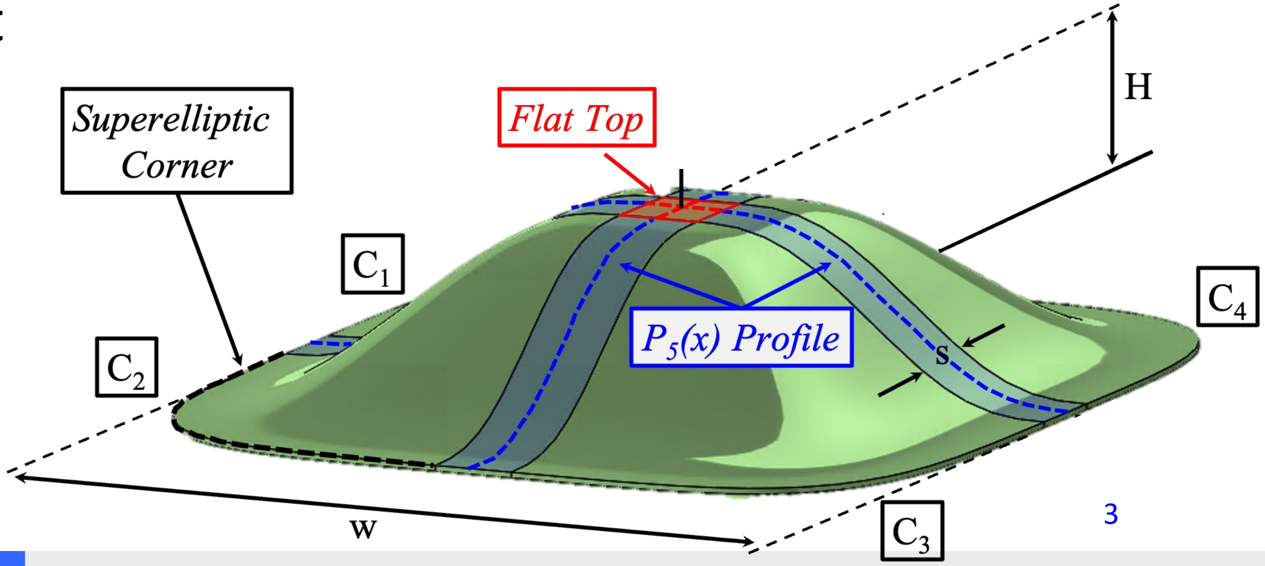

Chris Roy


Máté Szőke

BeVERLI addresses 3D, smooth wall separation

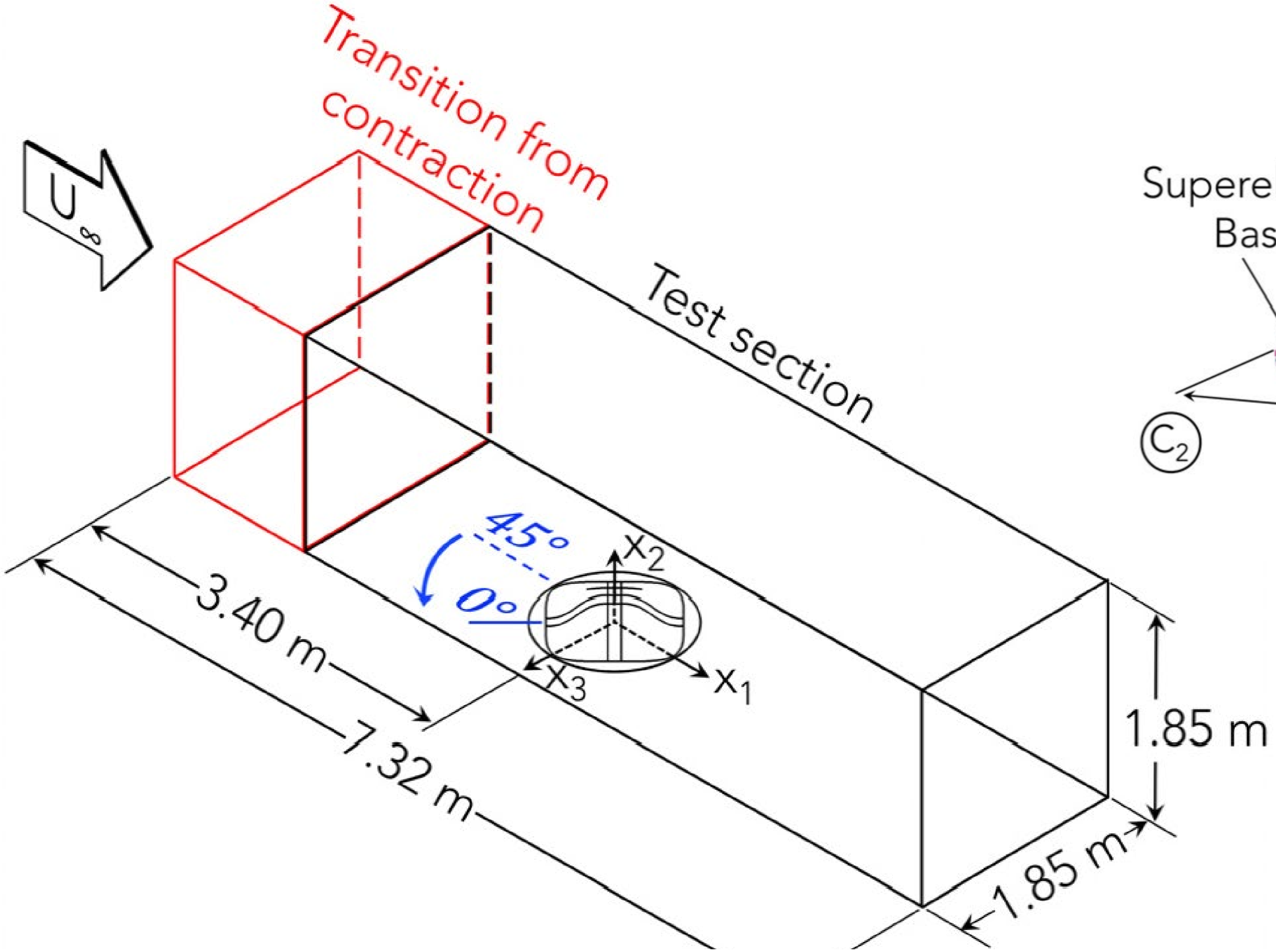
- RANS and turbulence modeling workhorse in CFD
  - DNS and LES still expensive
  - CFD for high-impact decisions
- **Be**nchmark **V**alidation **E**xperiments for **R**ANS/**L**ES **I**nvestigations (BeVERLI) hill case
  - CFD validation experiment at highest levels of completeness
  - Simple hill geometry encapsulating effects of 3D, non-equilibrium TBLs
  - Experiment and simulations

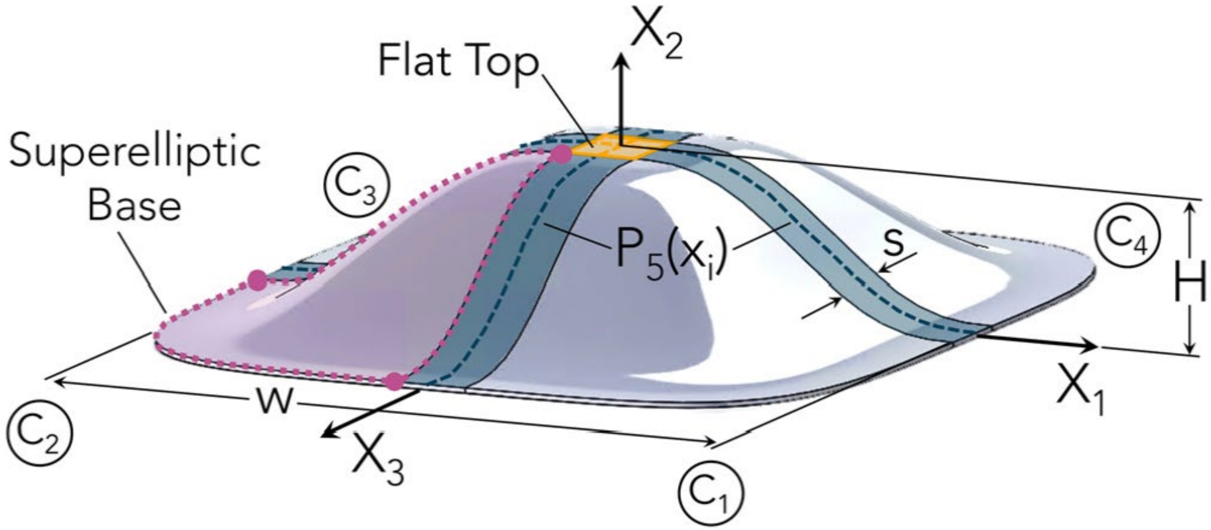
- NATO AVT-349
  - Members from academia, gov. and non-gov. labs, and industry around the globe
  - Advance accuracy and range of prediction models for high Reynolds number non-equilibrium TBLs



The BeVERLI Hill Configuration

***Be*VERLI = *Be*nchmark *V*alidation *E*xperiment for *R*ANS/*L*ES *I*nvestigations**



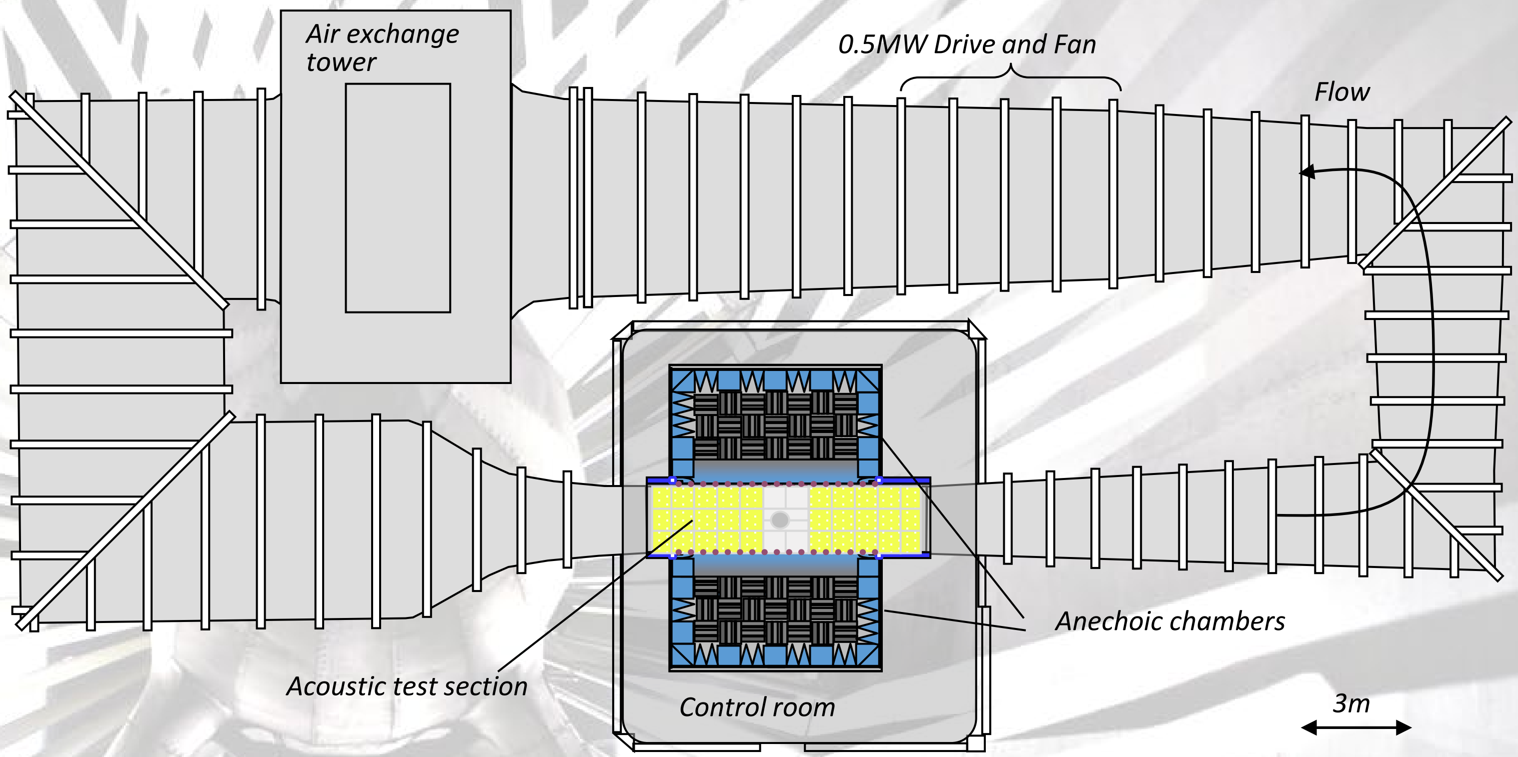


	Condition 1	Condition 2
Re_H	250,000	650,000
Ref. Mach Number	0.06	0.16

Gargiulo, A., Duetsch-Patel, J. E., Borgoltz, A., Devenport, W. J., Roy, C. J., & Lowe, K. T. (2023). Strategies for computational fluid dynamics validation experiments. *Journal of Verification, Validation and Uncertainty Quantification*, *8*(3).

Stability Wind Tunnel

- Test section 1.85×1.85×7.3 m
- Top flow speed 85 m/s, $Re=5x10^6/m$
- Very low turbulence levels
- Interchangeable hard wall and acoustic test sections.
- Modular test section wall structure allows acoustic test section to also be configured as hard wall
- Serves research, education (including undergraduate courses), outreach
- Non-profit cost center



Freestream Velocity U_∞ (m/s)	Turbulence Intensity
12	0.016%
21	0.021%
30	0.024%
48	0.029%
57	0.031%

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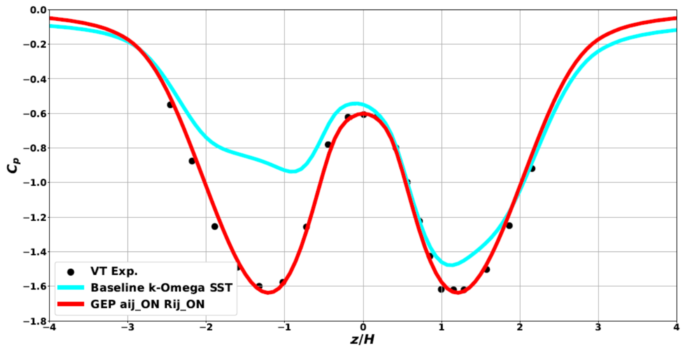
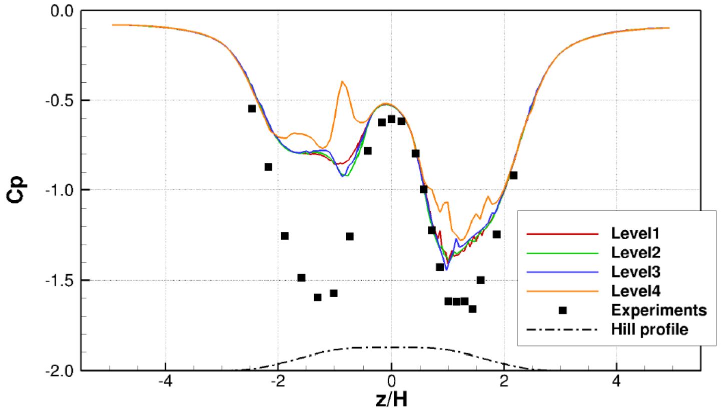
NATO AVT-349 Non-Equilibrium Turbulent Boundary Layers in High Reynolds Number Flow at Incompressible Conditions

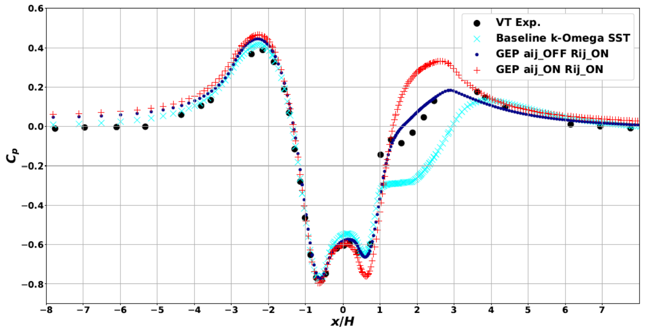
- Success of gene expression programming for improving surface pressure performance
- Mesh sensitivity
- Need for geometrically asymmetric cases
- Non-uniqueness seems fundamental to three-dimensional separation

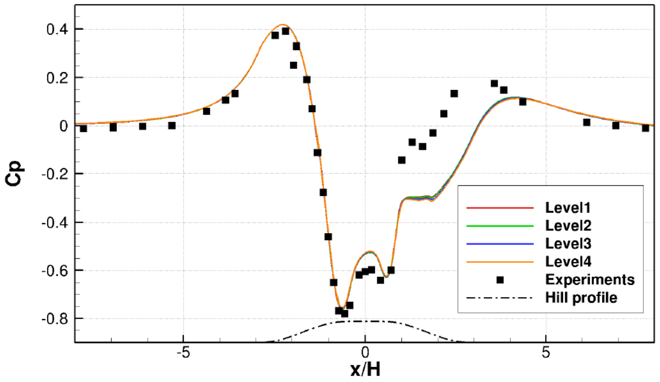




École Centrale de Nantes – CNRS (Michel Visonneau)

University of Melbourne (Richard Sandberg)





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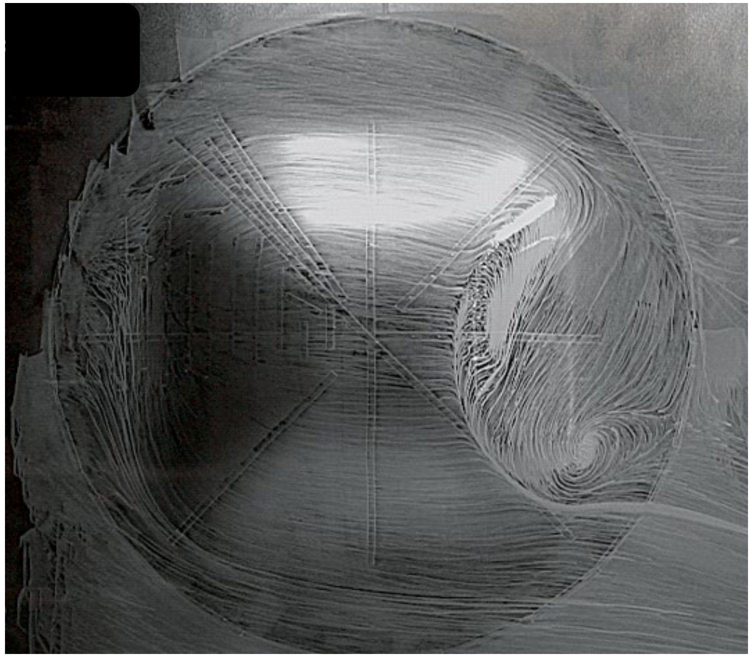
The BeVERLI Hill Geometry Produces a Wide Spectrum of Flow Physics

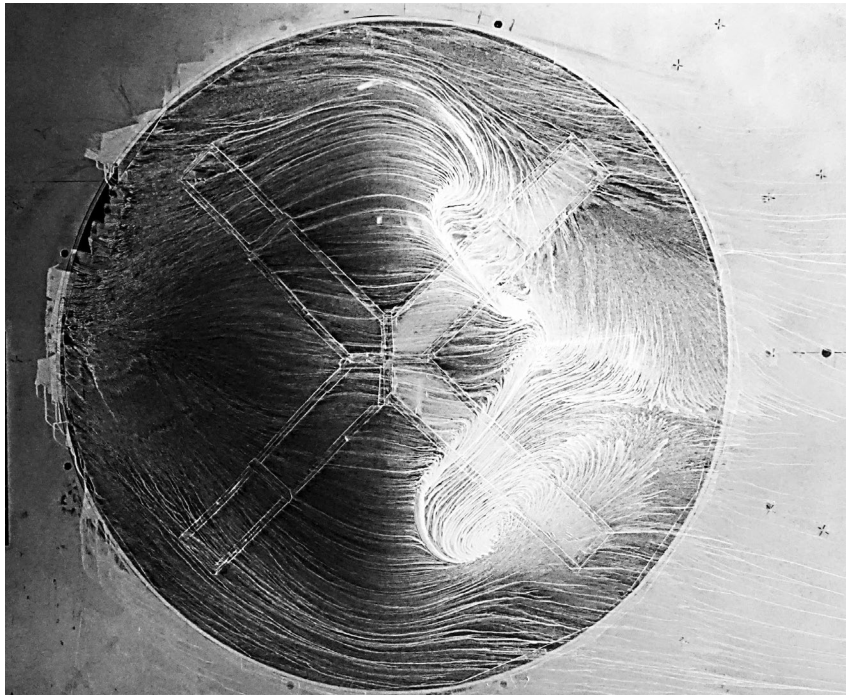
U_∞



0° yaw case (bluff case)

- Asymmetric
- Unsteady/switching asymmetry
- Reduced skew

U_∞



45° yaw case (streamlined case)

- Reynolds number-dependent symmetry
- Steady asymmetry

The blind validation challenge focuses on an asymmetric yaw case, 30° orientation.

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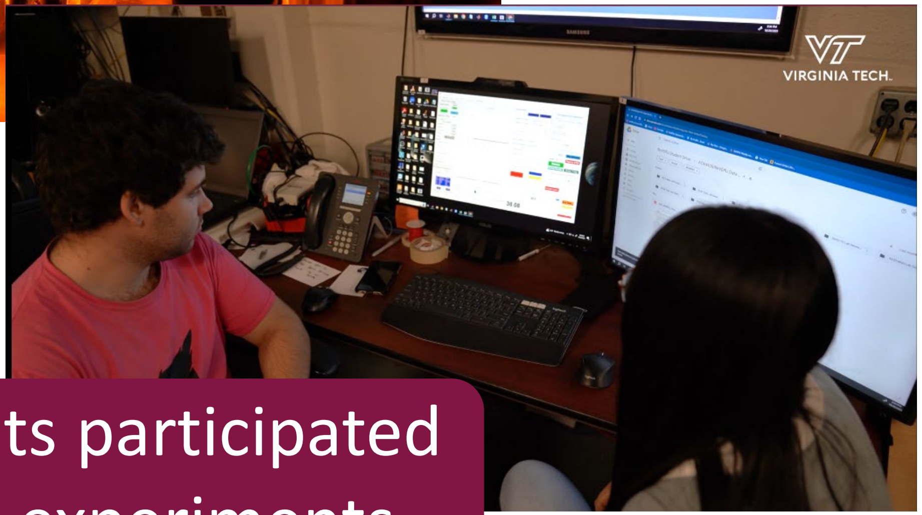
The Experiments Were an Integral Part of Undergraduate Student Labs

RESEARCH

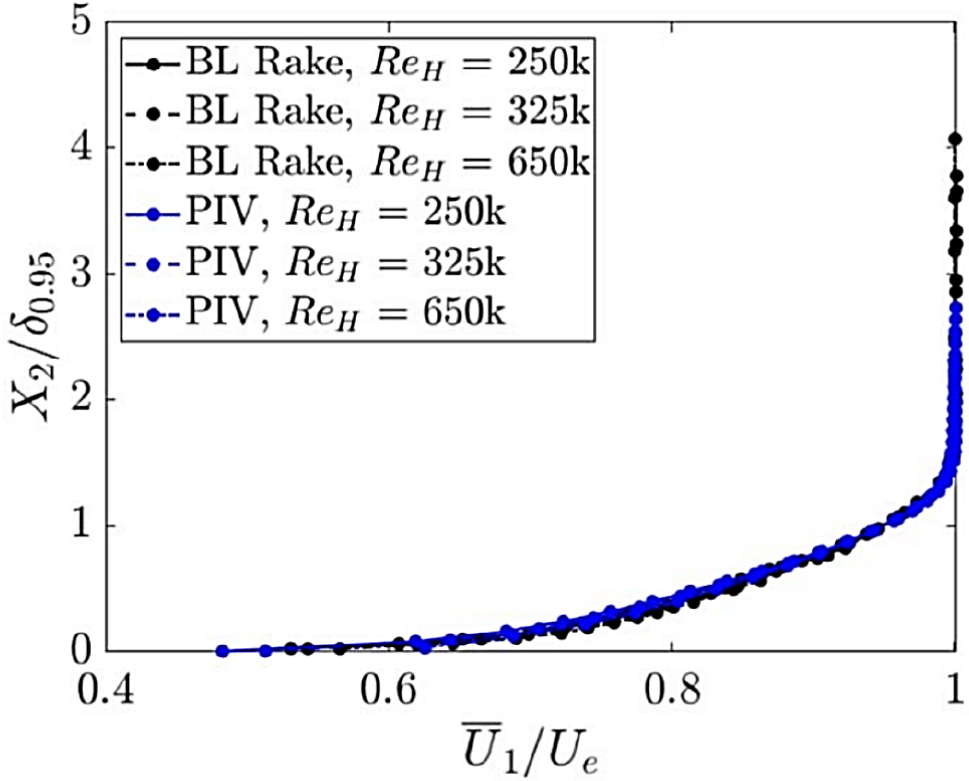
Stability Wind Tunnel project seeks better data for aerodynamic models

Oct 31, 2023



~200 undergraduate students participated in the validation challenge experiments

Boundary and Reference Conditions Measurements

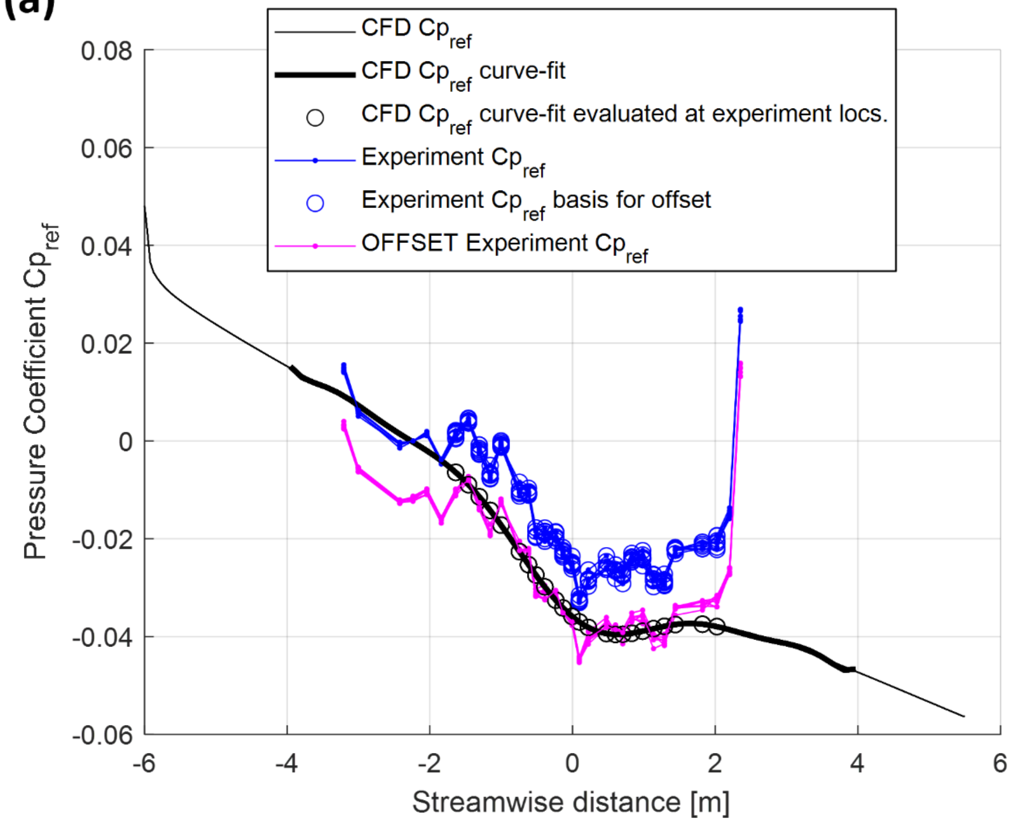


Measured 1.93 m upstream from center of Hill

Re_H	250,000	650,000
$\delta_{0.95}$ (mm)	43.0 ± 1.5	38.5 ± 1.3
δ^* (mm)	8.3 ± 0.2	6.8 ± 0.2
θ (mm)	6.1 ± 0.2	5.2 ± 0.2

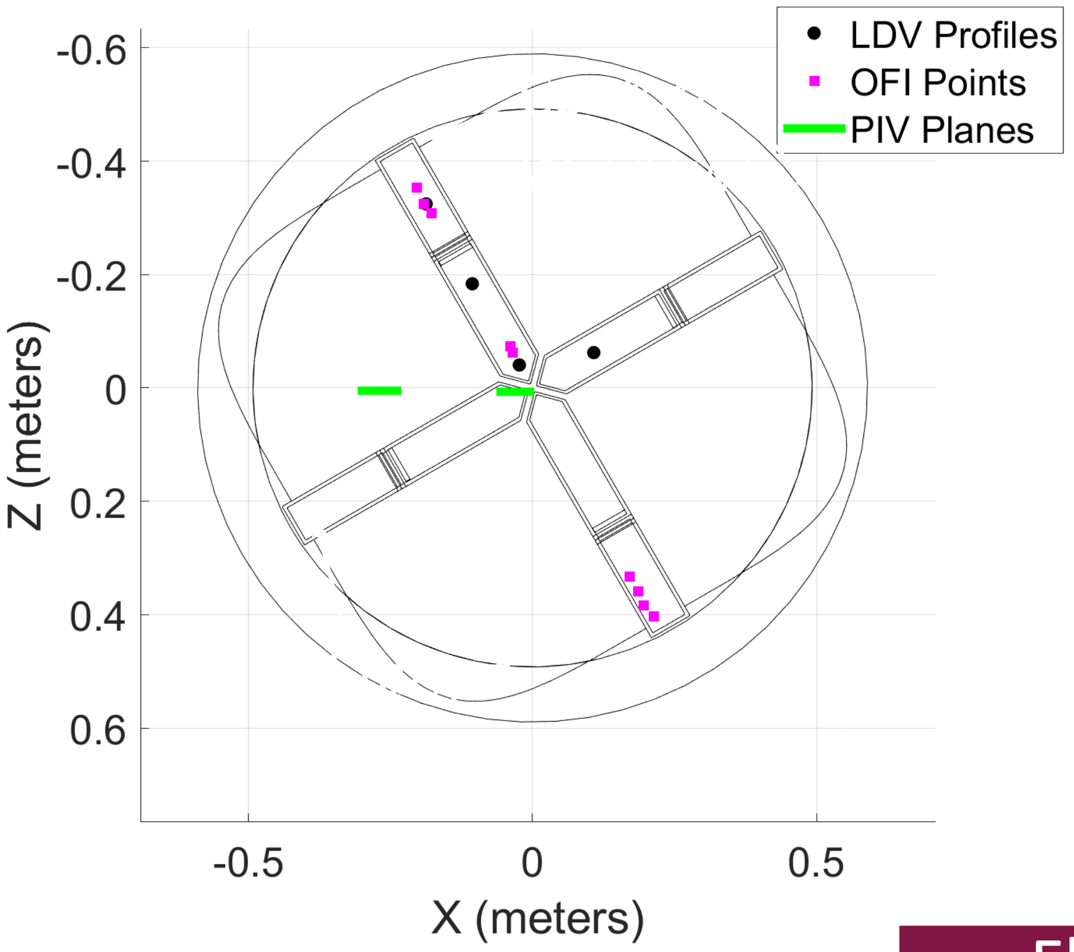
Reference pressures measured 2.2275 m upstream of hill center: test section geometry effects

(a)

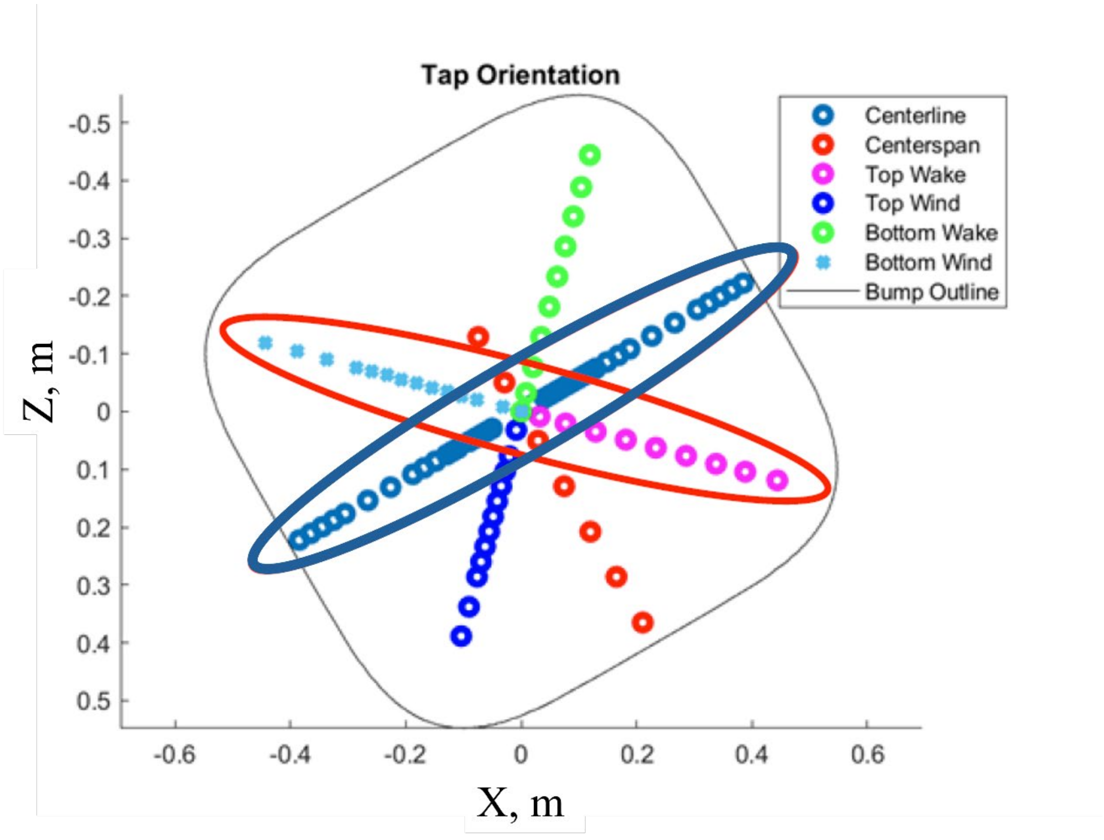


Hill-height-based Reynolds number	250k	650k
Reference Pressure Offset [Pa]	-2.97	-22.48
Mean shift in $c_{P_{ref}}$	-0.0119	-0.0132

Hill Measurements: Overview

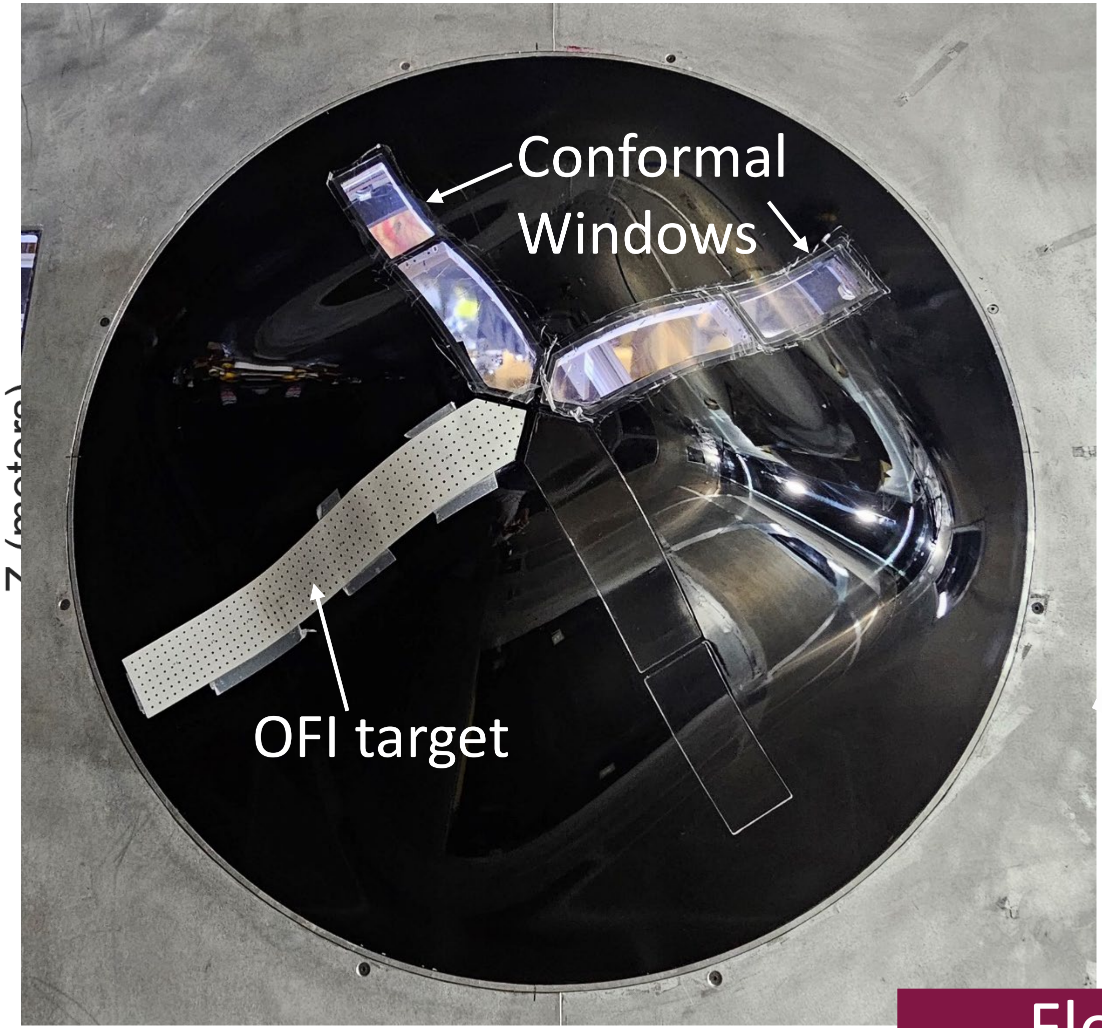


Optical Techniques



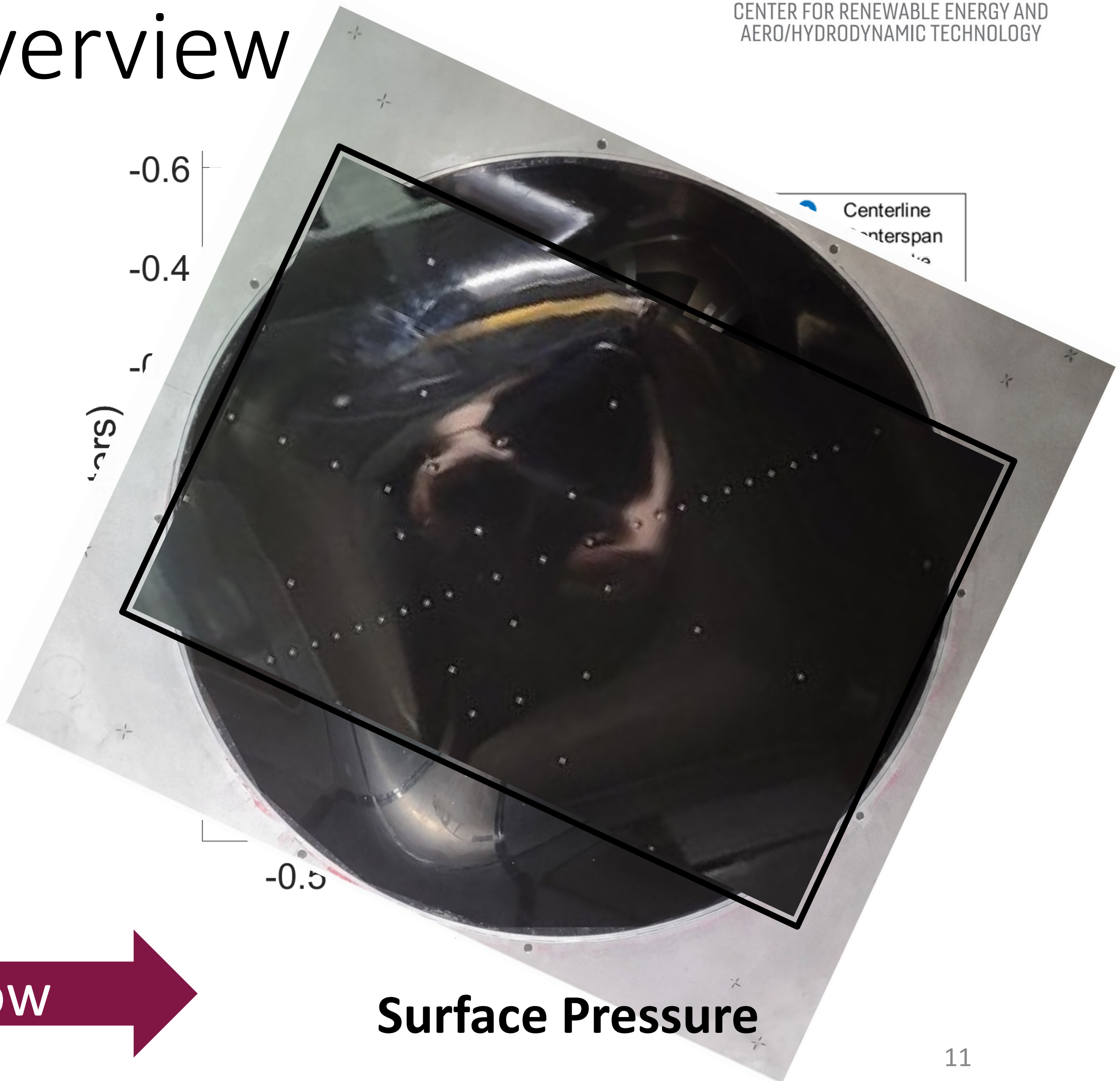
Surface Pressure

Hill Measurements: Overview



Optical Techniques

Flow



Surface Pressure

Pressure and Oil Flow Viz

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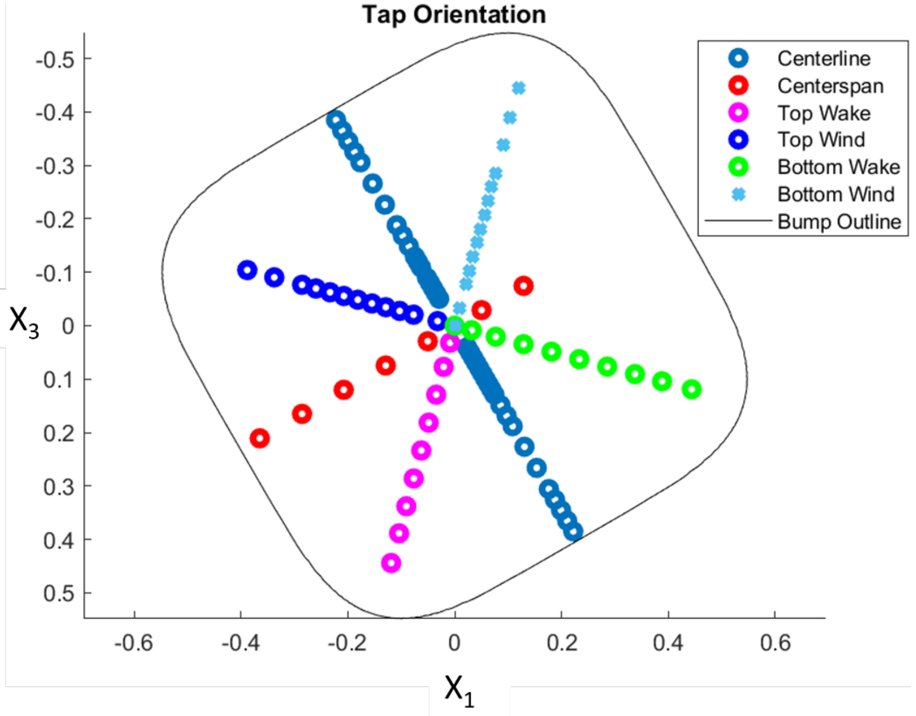
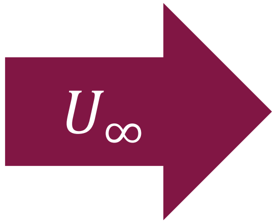
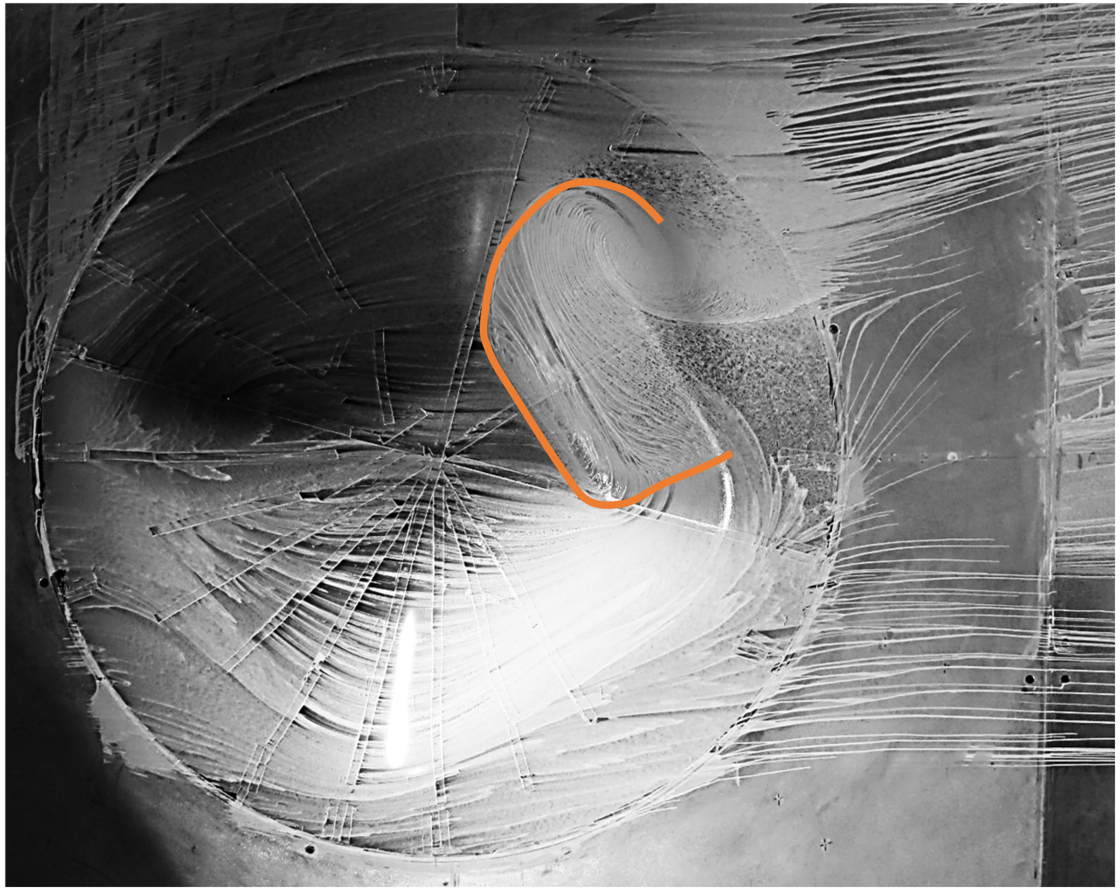
- 135 precision taps on Hill
- Pressure scanners:
  - Esterline 9816/98RK pressure scanners
  - DTC ESP 32HD with unsteady response





Kerosene/titanium oxide/oleic acid mixture



Re_H=650k

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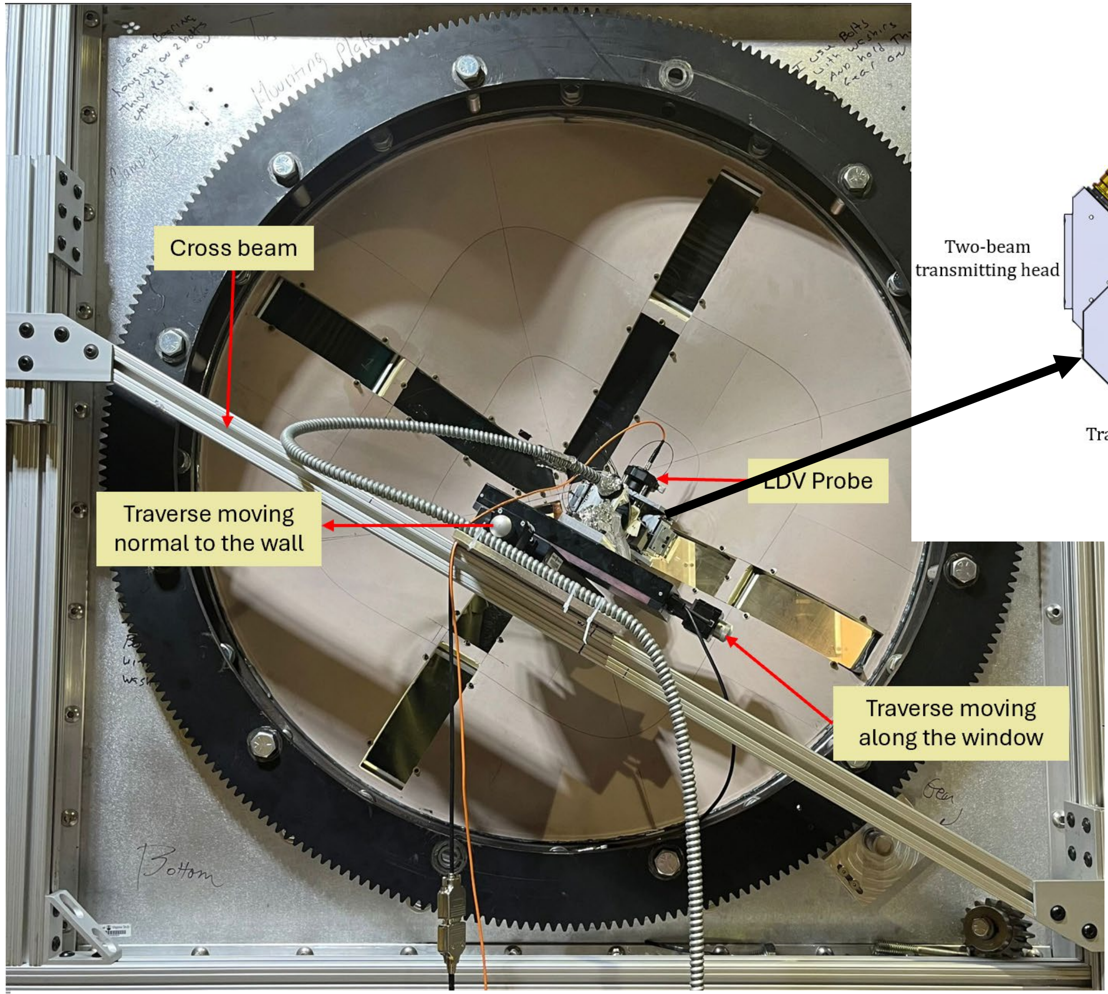
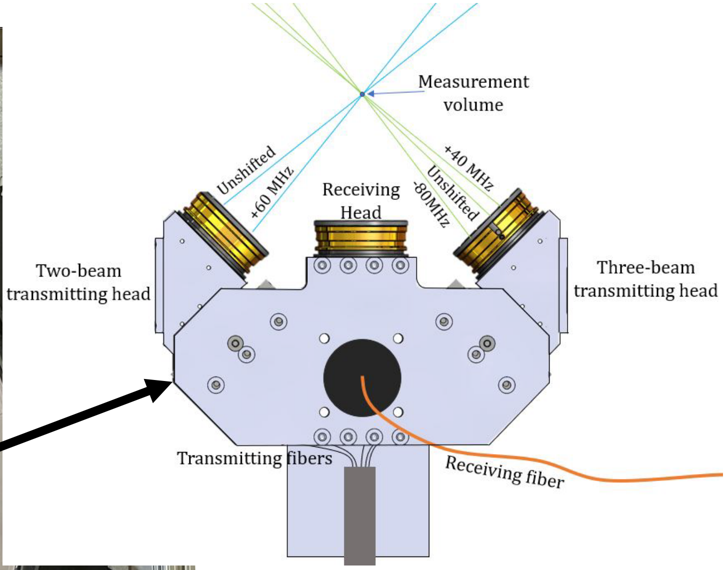
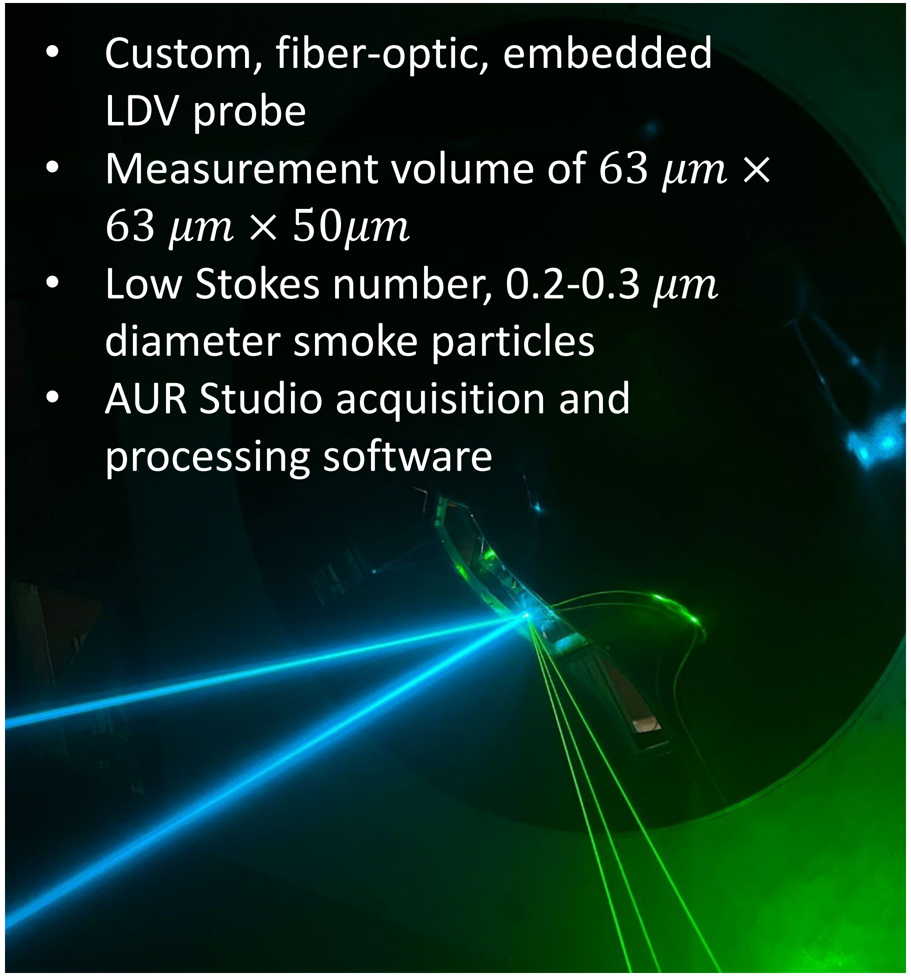
Laser-Doppler Velocimetry





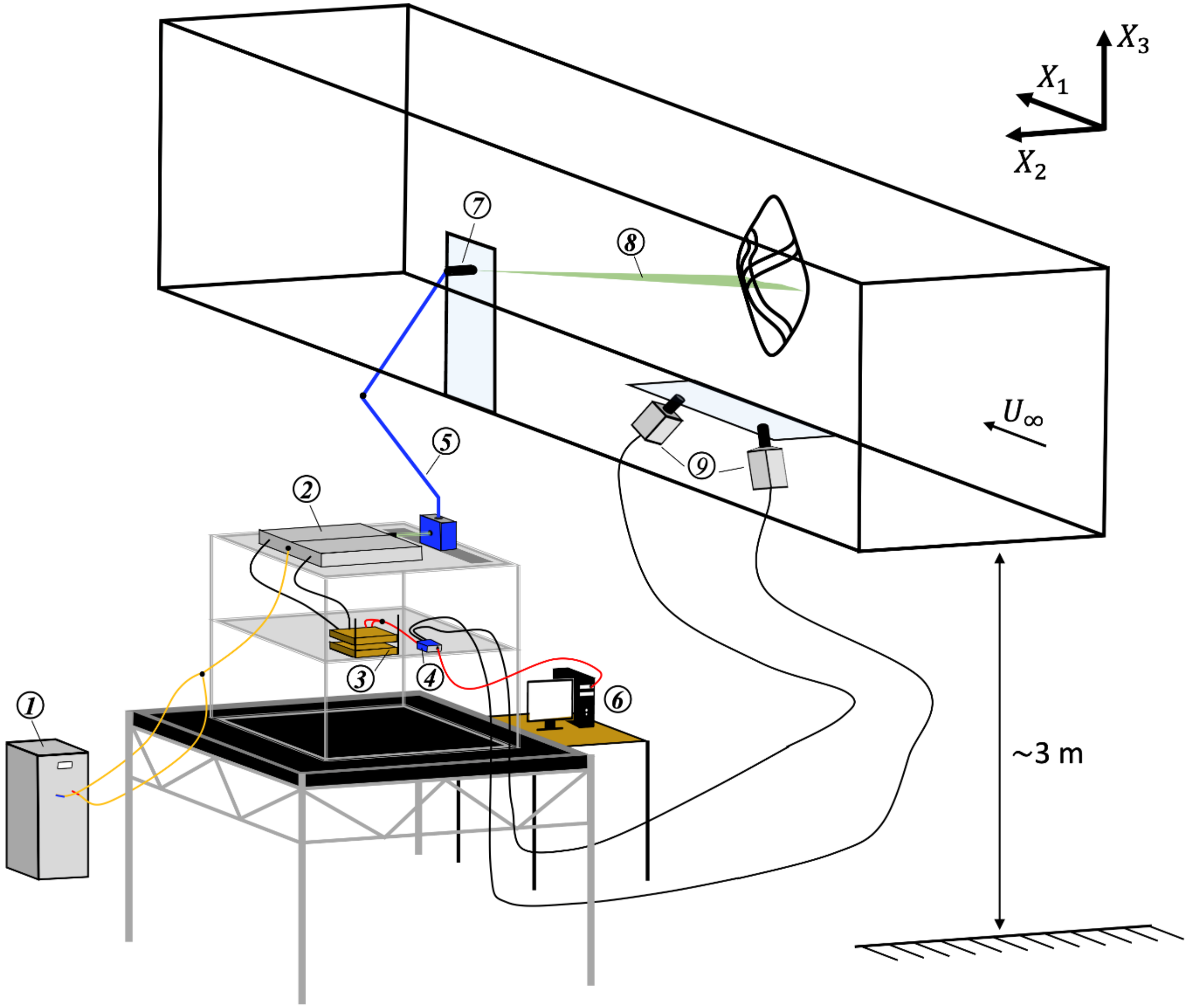
LDV results only at $\mathrm{Re_H}$ =250k

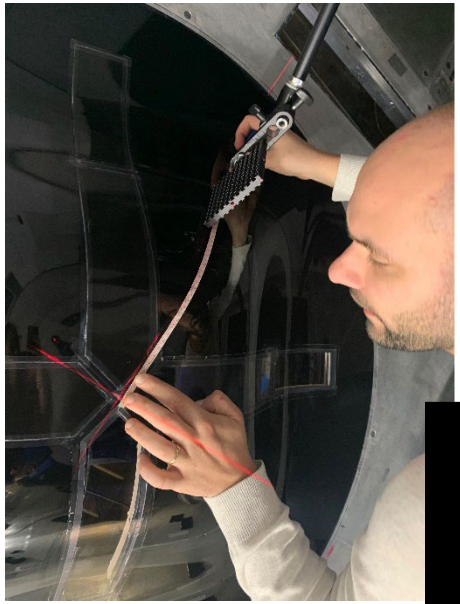


- Custom, fiber-optic, embedded LDV probe
- Measurement volume of 63 $\mu m \times$ 63 $\mu m \times 50\mu m$
- Low Stokes number, 0.2-0.3 μm diameter smoke particles
- AUR Studio acquisition and processing software

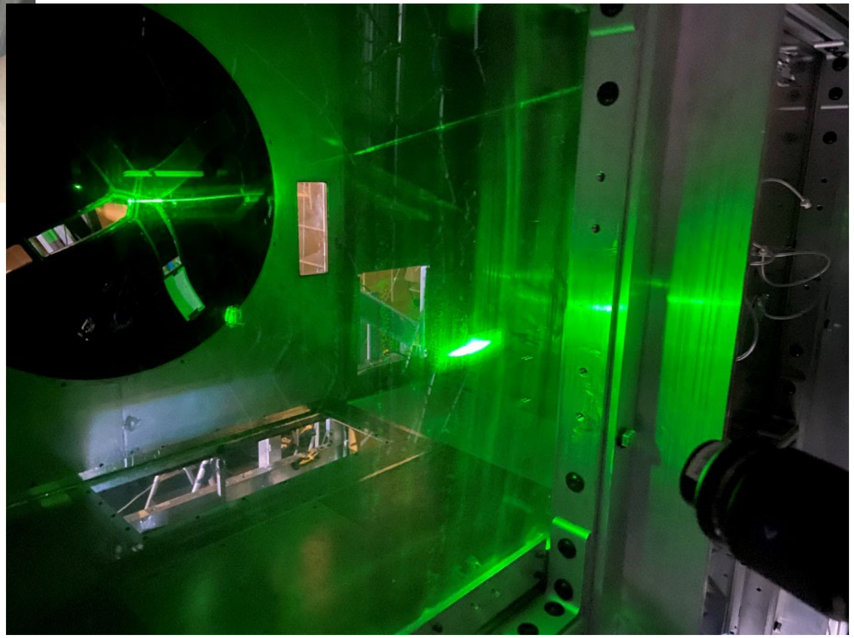
See also: Duetsch-Patel, J. E. (2023). Structure and Turbulence of the Three-Dimensional Boundary Layer Flow over a Hill. Ph.D. Dissertation, Virginia Tech.

Stereoscopic Particle-Image Velocimetry



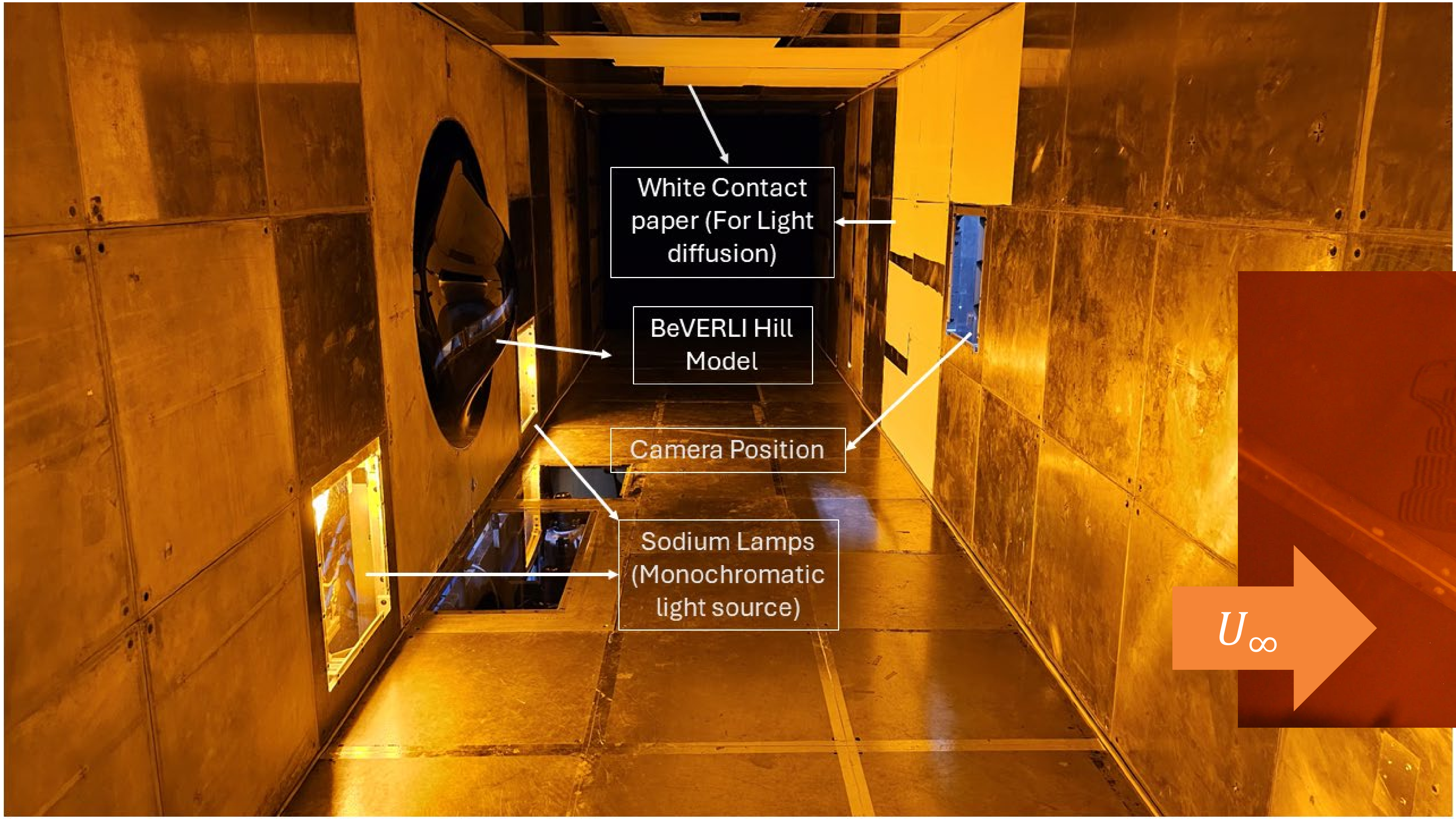


- LaVision, 12.6 kHz high-speed stereoscopic PIV system
- Low Stokes number, 0.2-0.3 μm diameter smoke particles

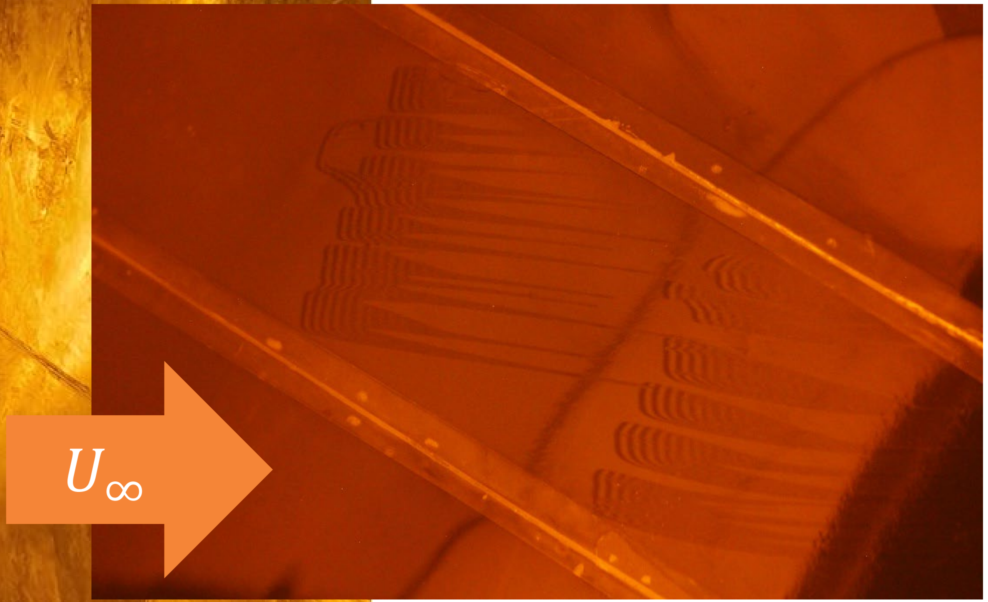


Gargiulo et al. (2023)

Oil Film Interferometry

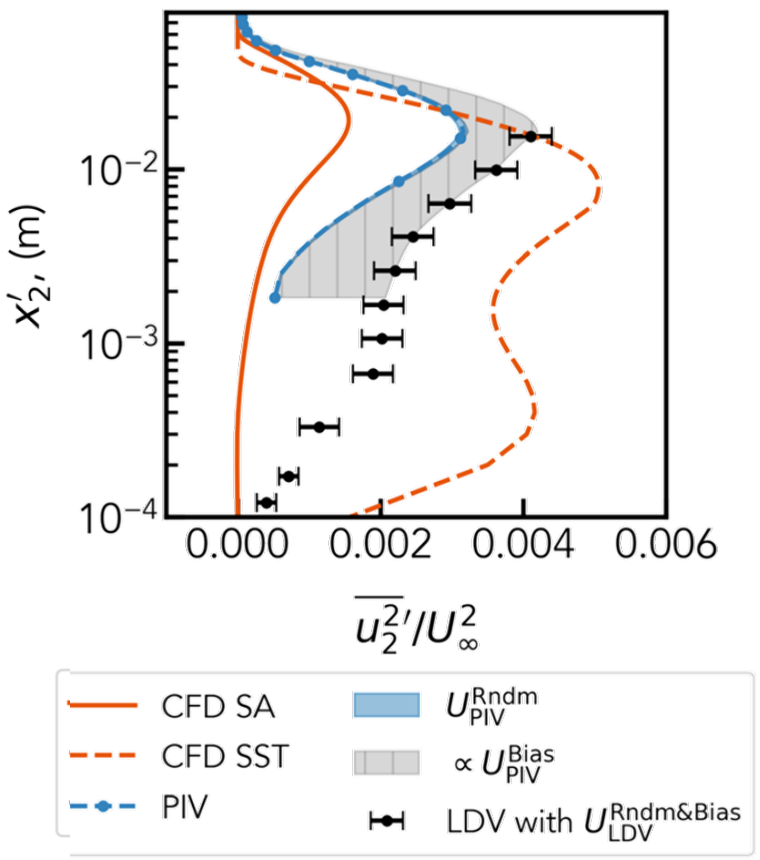


- Silicone oil applied to cylindrical portions of hill
- Fringe processing yields Cf



Uncertainty Quantification Approach

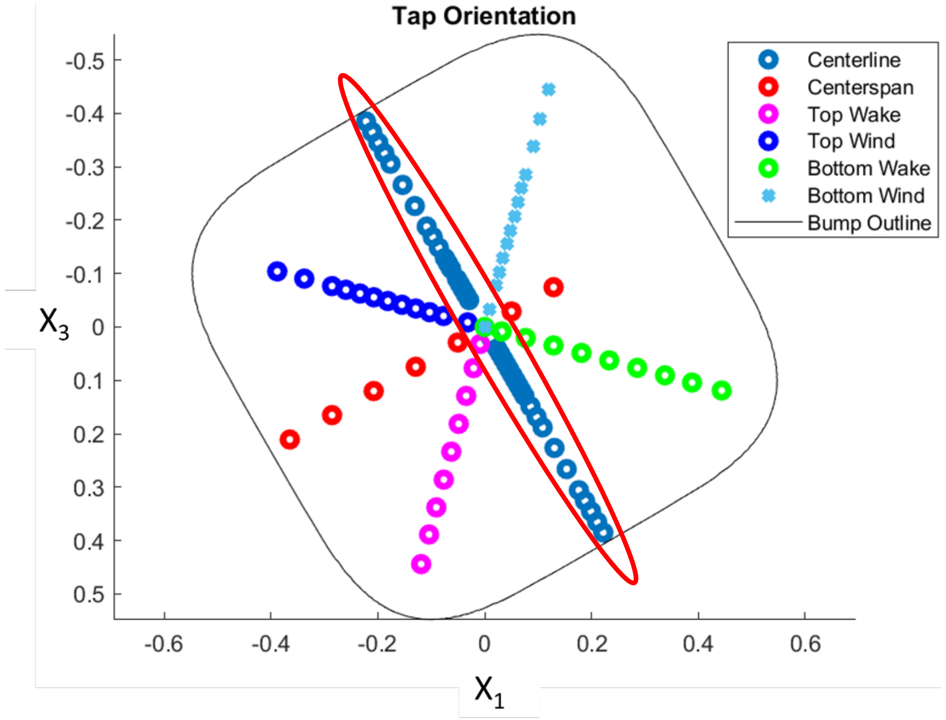
- A priori: How well do your instruments measure what you think you are measuring?
  - Propagation of instrumentation-driven uncertainties
- A posterior: How well did the experiments and measurements reflect the reported/intended boundary conditions?
  - Geometric symmetries
  - Replicate measurements
  - <u>Leveraging multiple diagnostics</u>

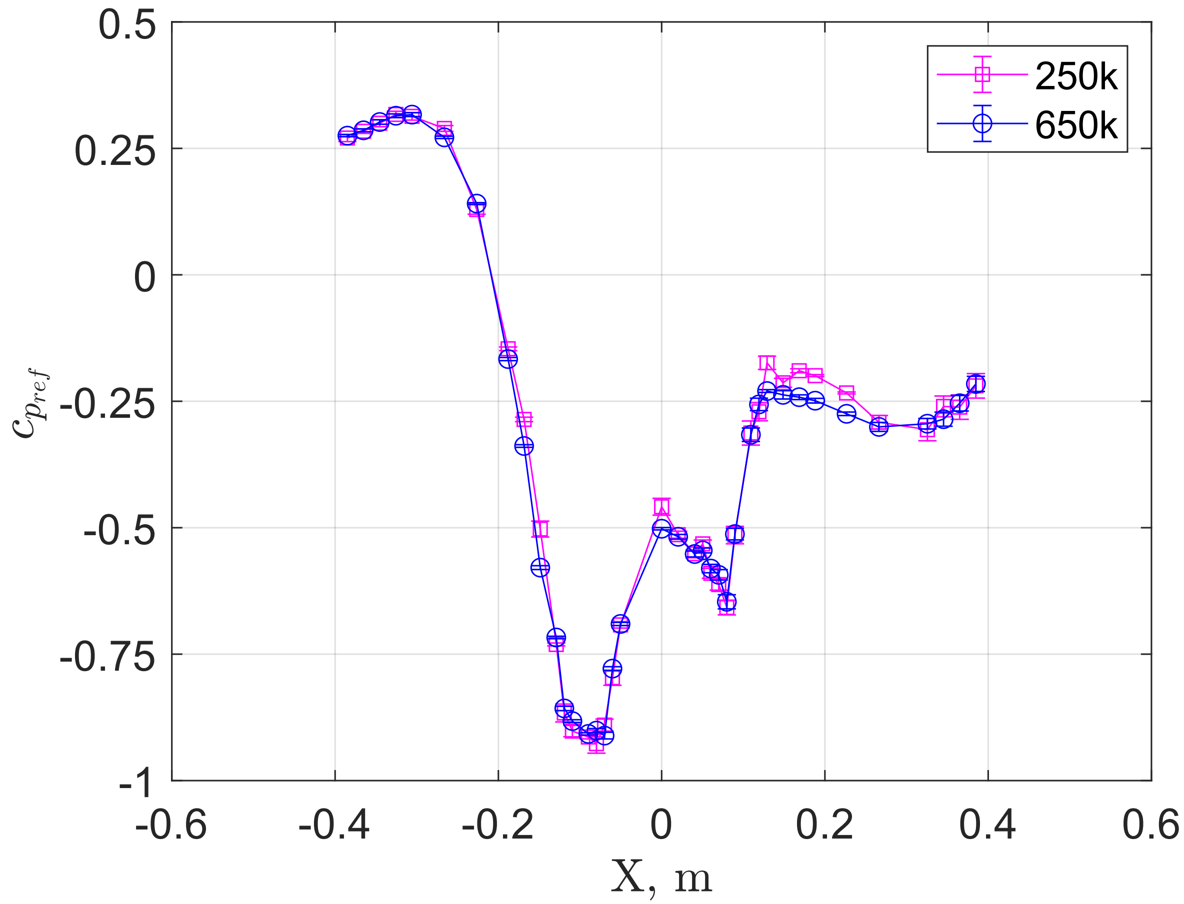


Gargiulo et al. JVVUQ 2023

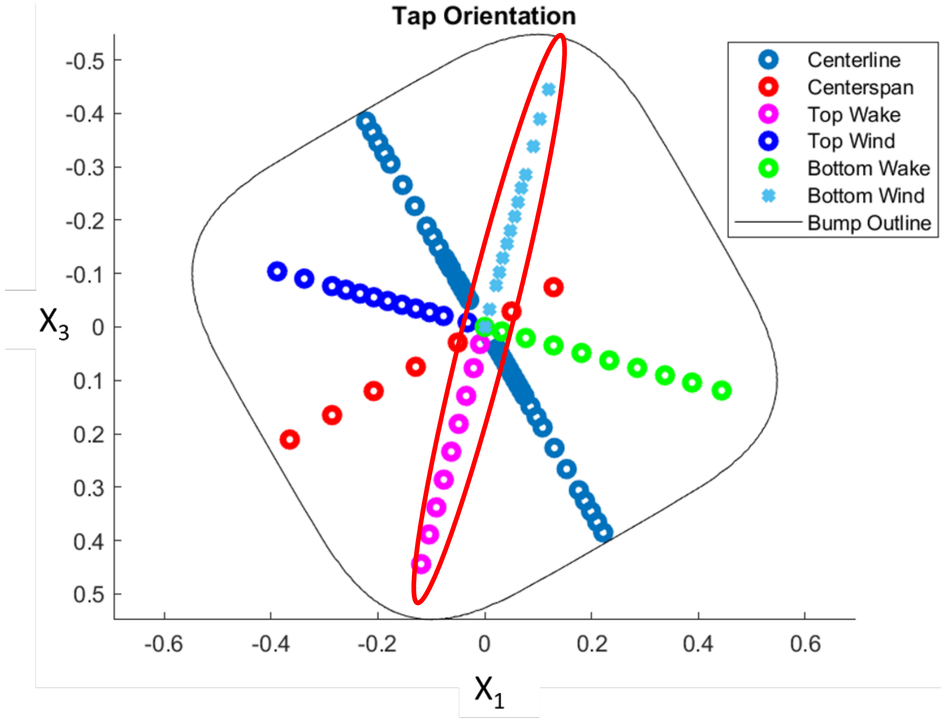
Note: PIV uncertainty is still a work in progress, left off of plots coming up in next talk.

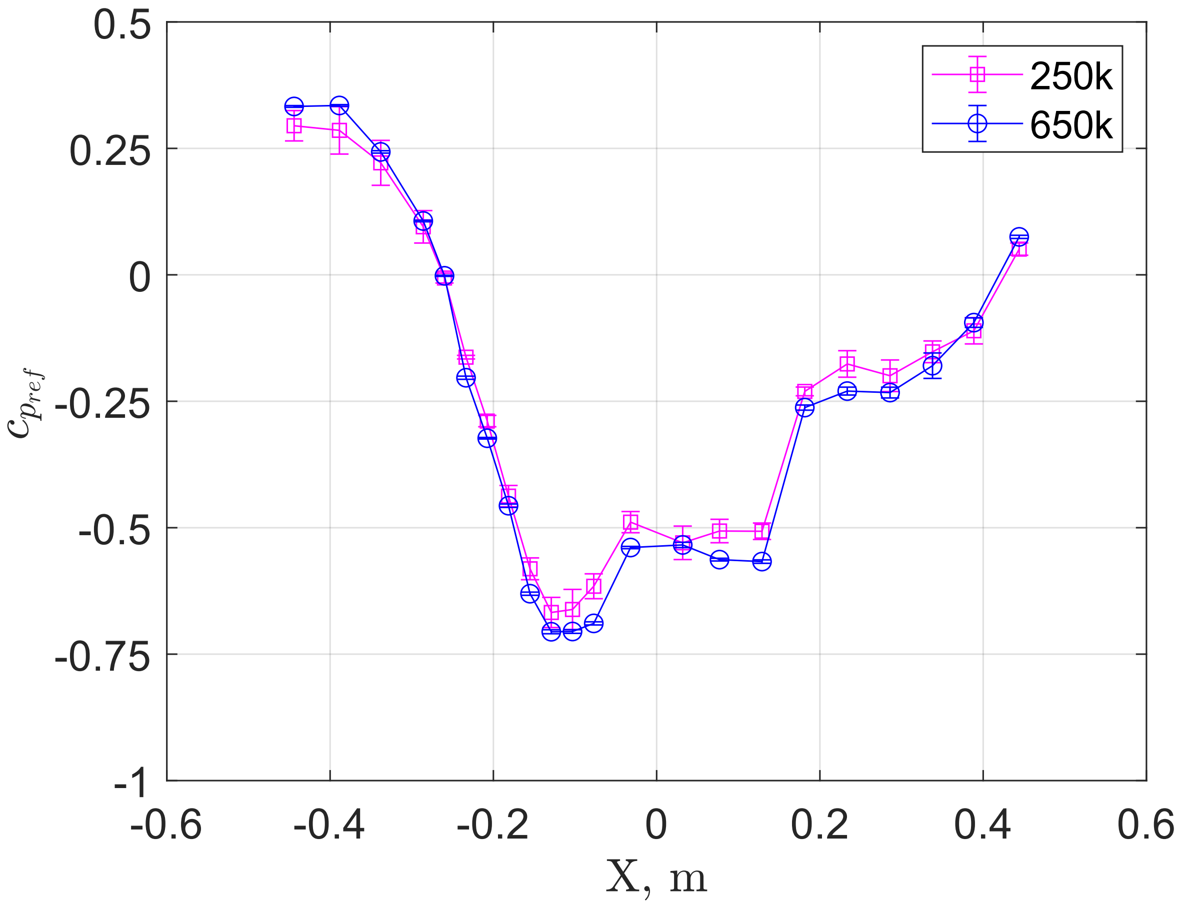
Wall Static Pressure



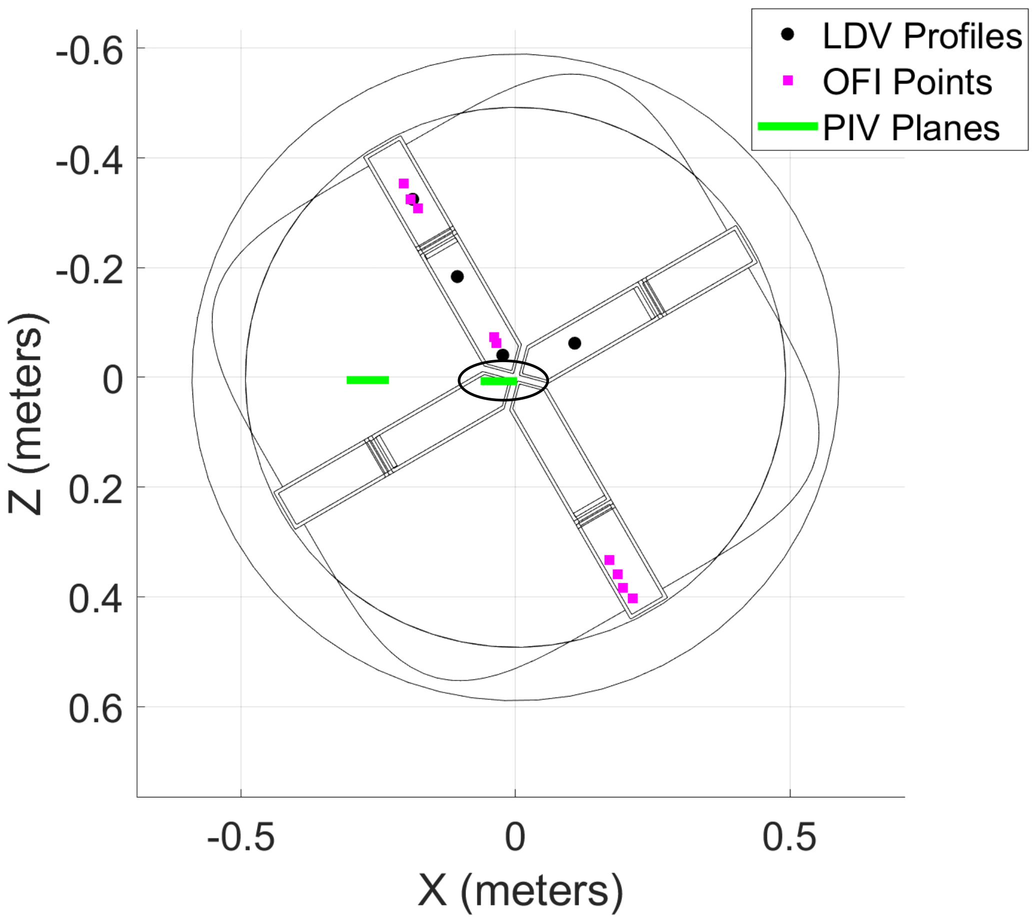


Wall Static Pressure

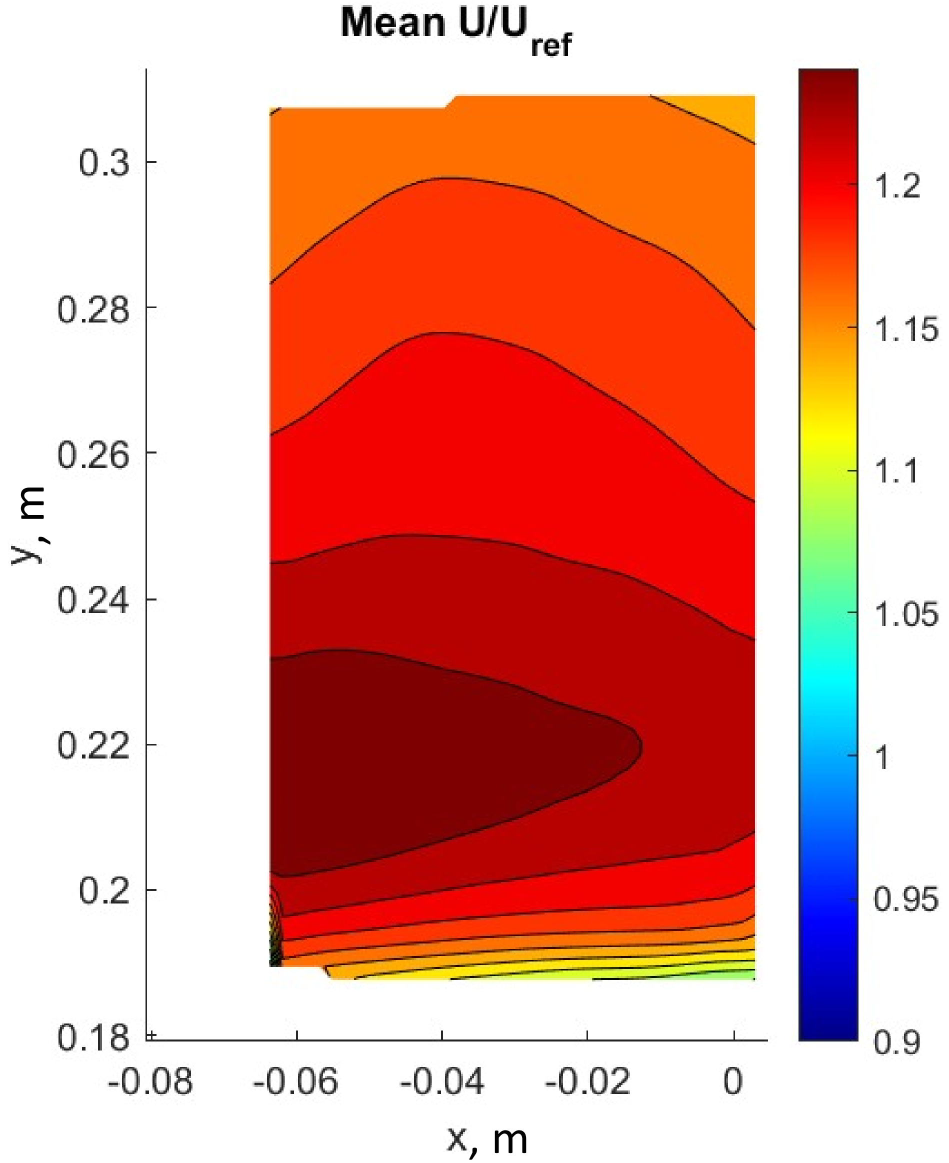




PIV Planar Results



Re_H =250k



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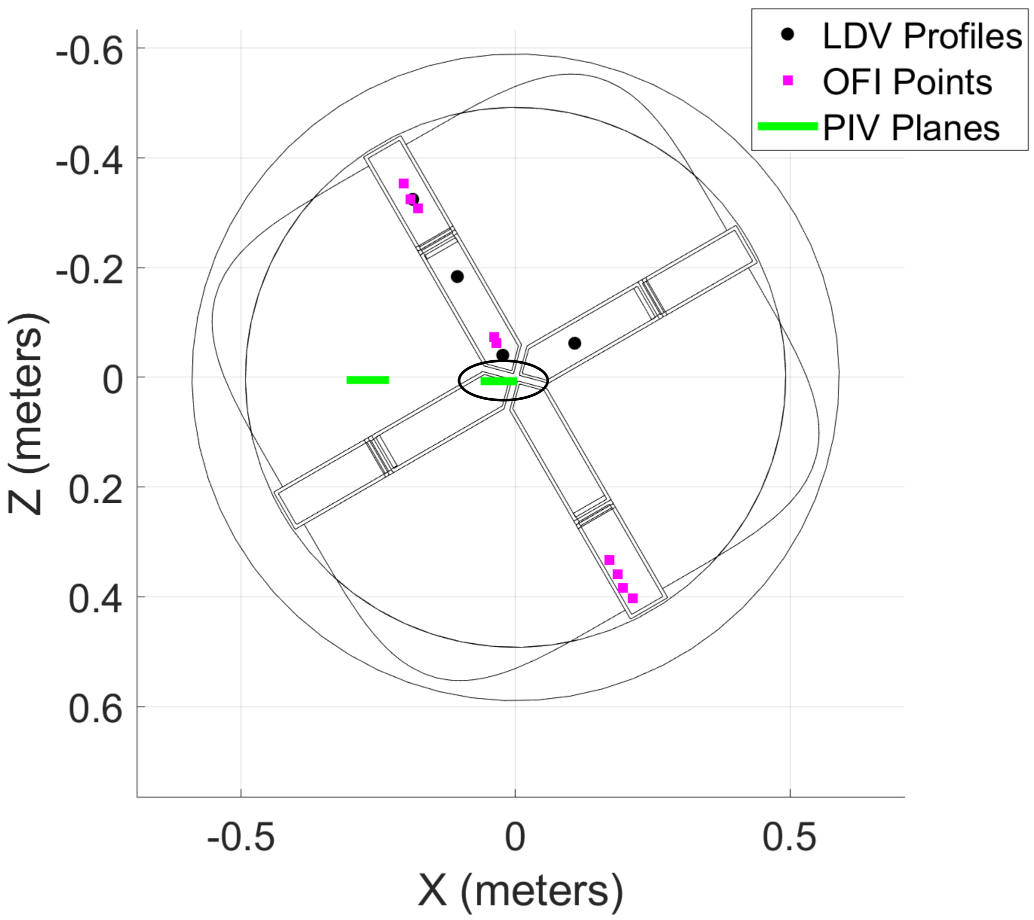
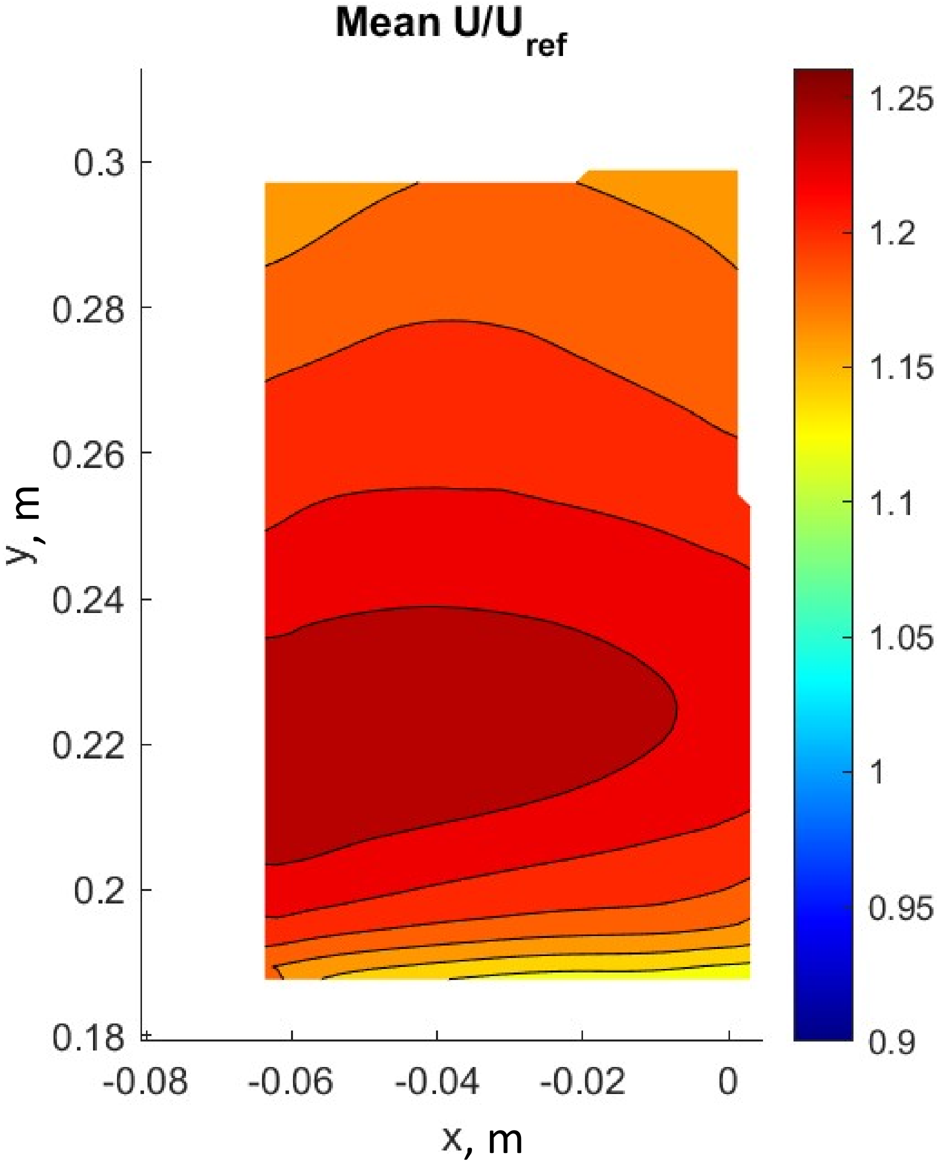


Re_H =650k



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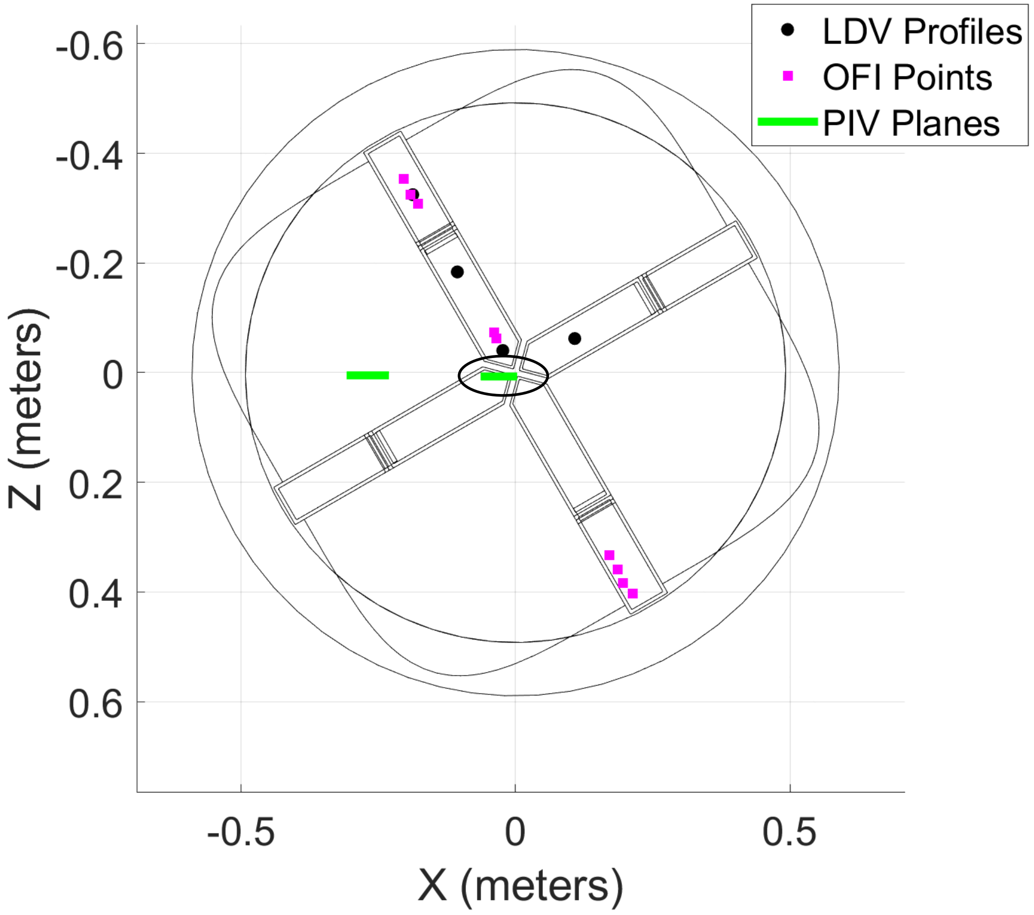

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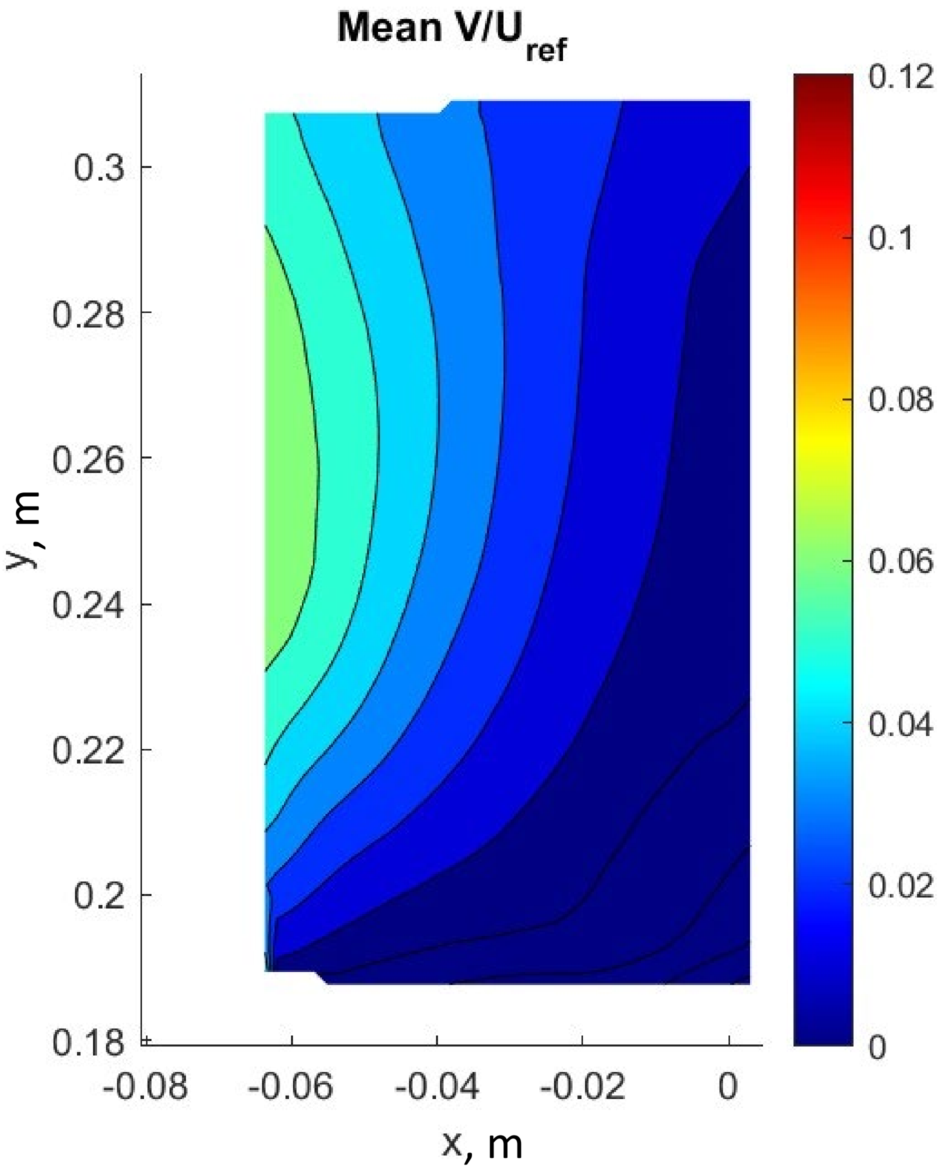

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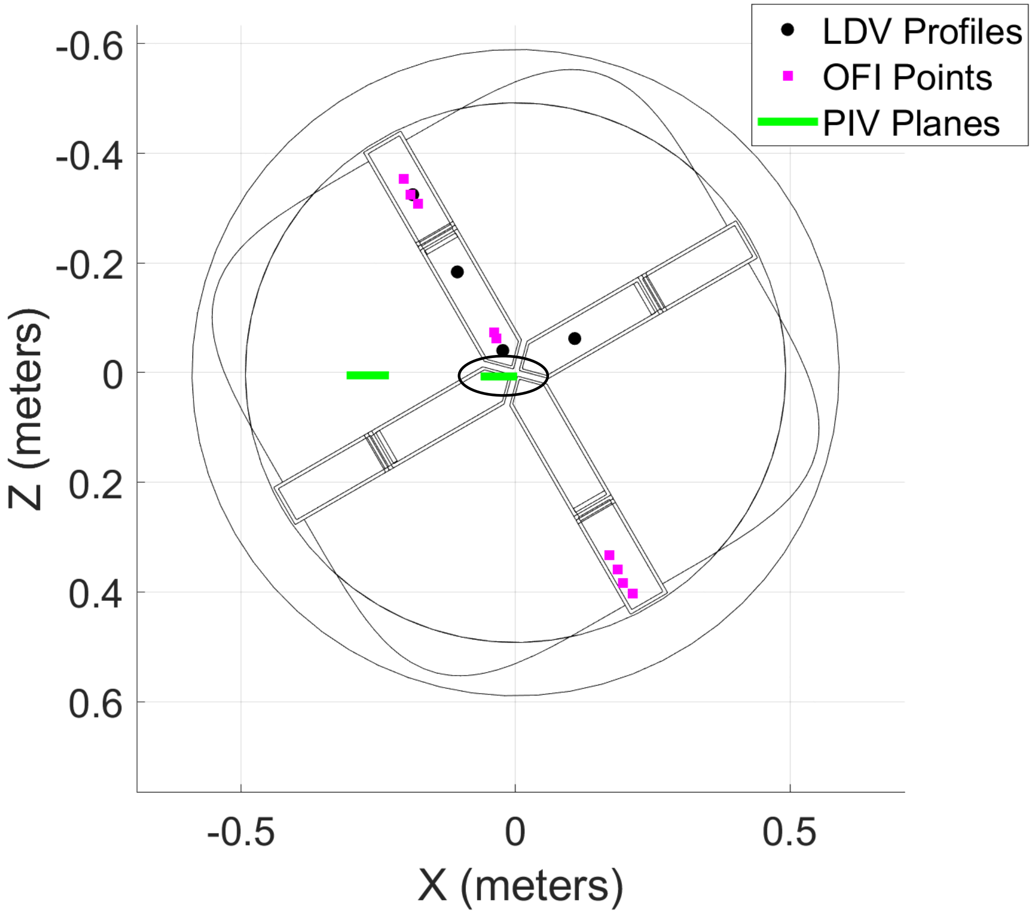

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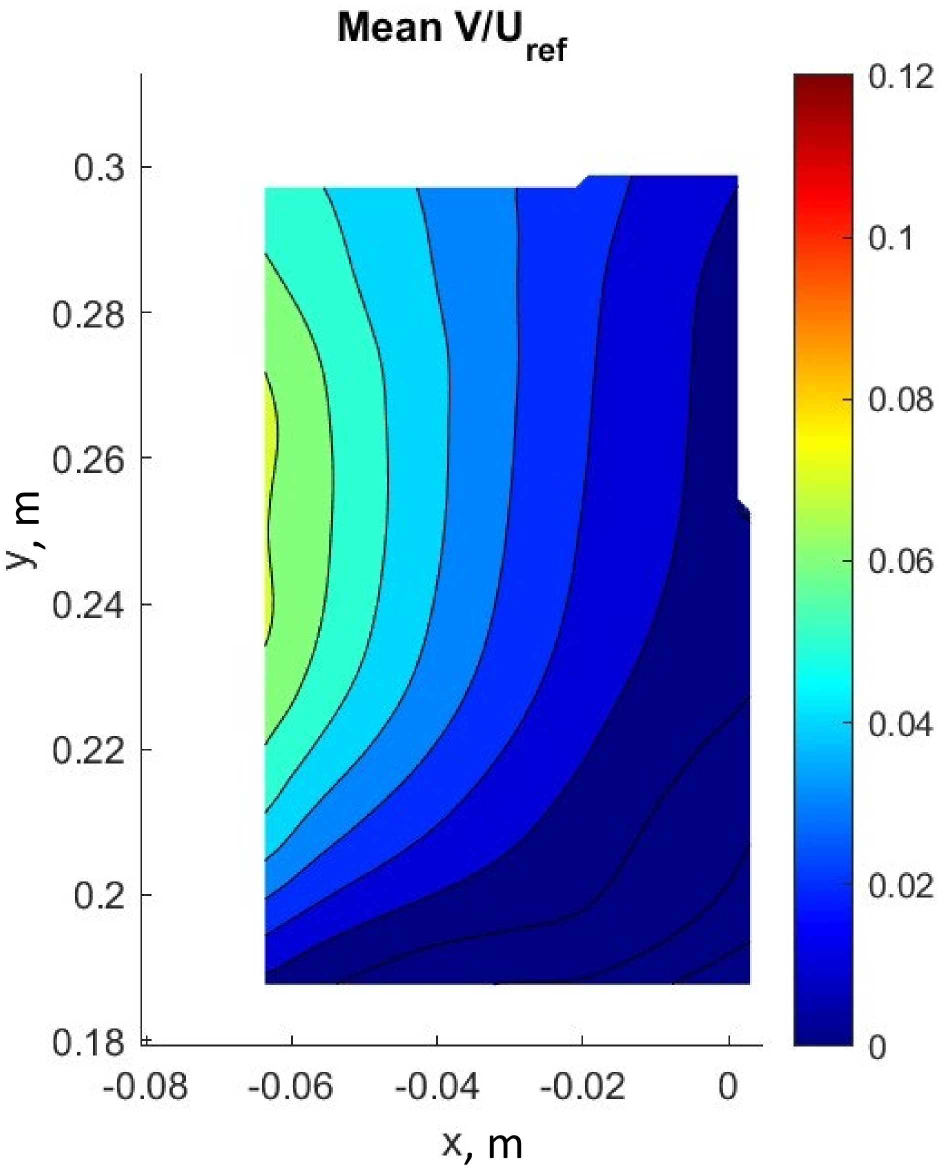

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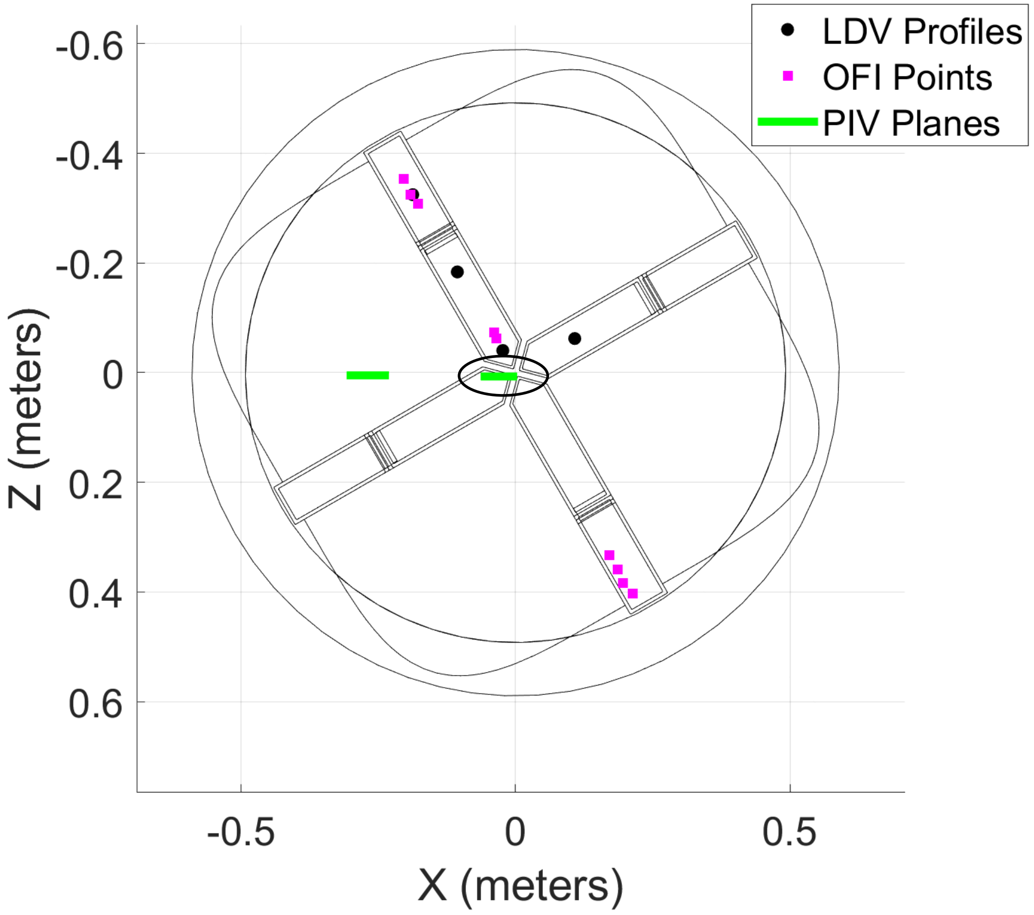

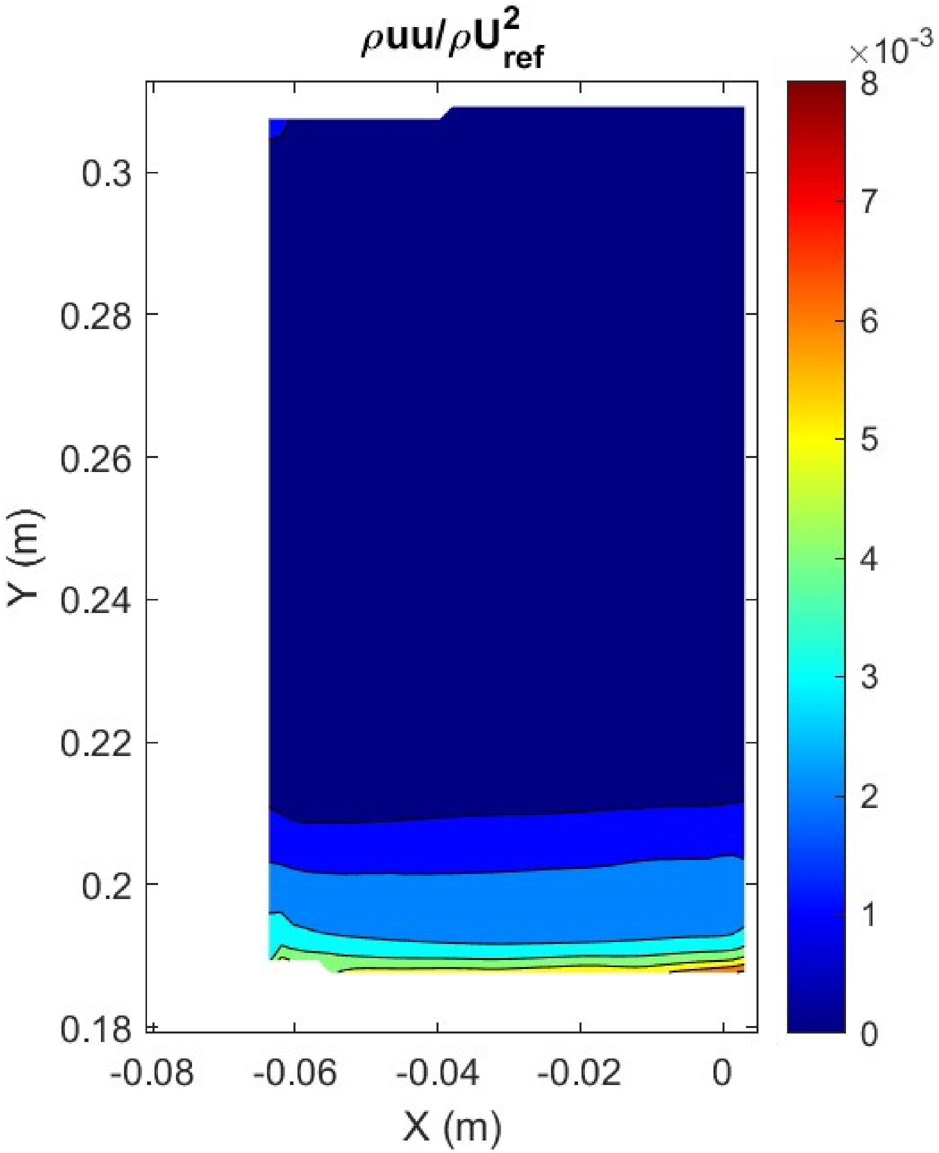

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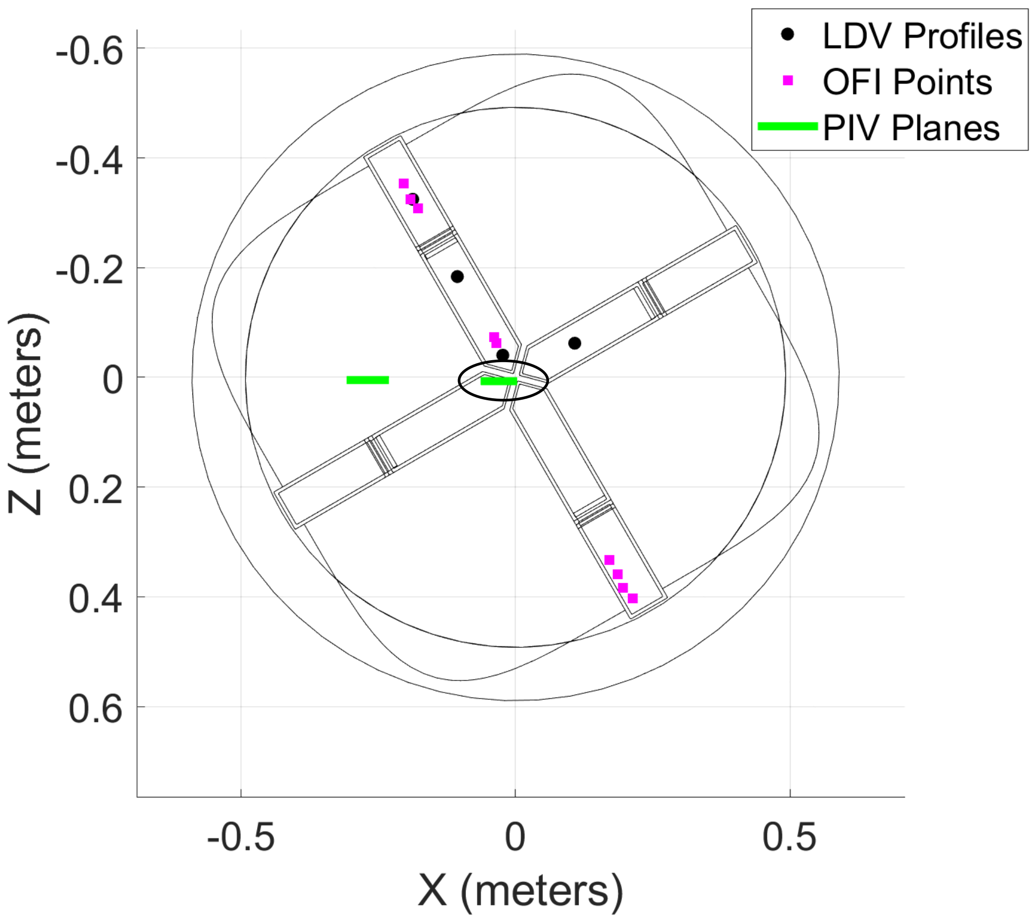

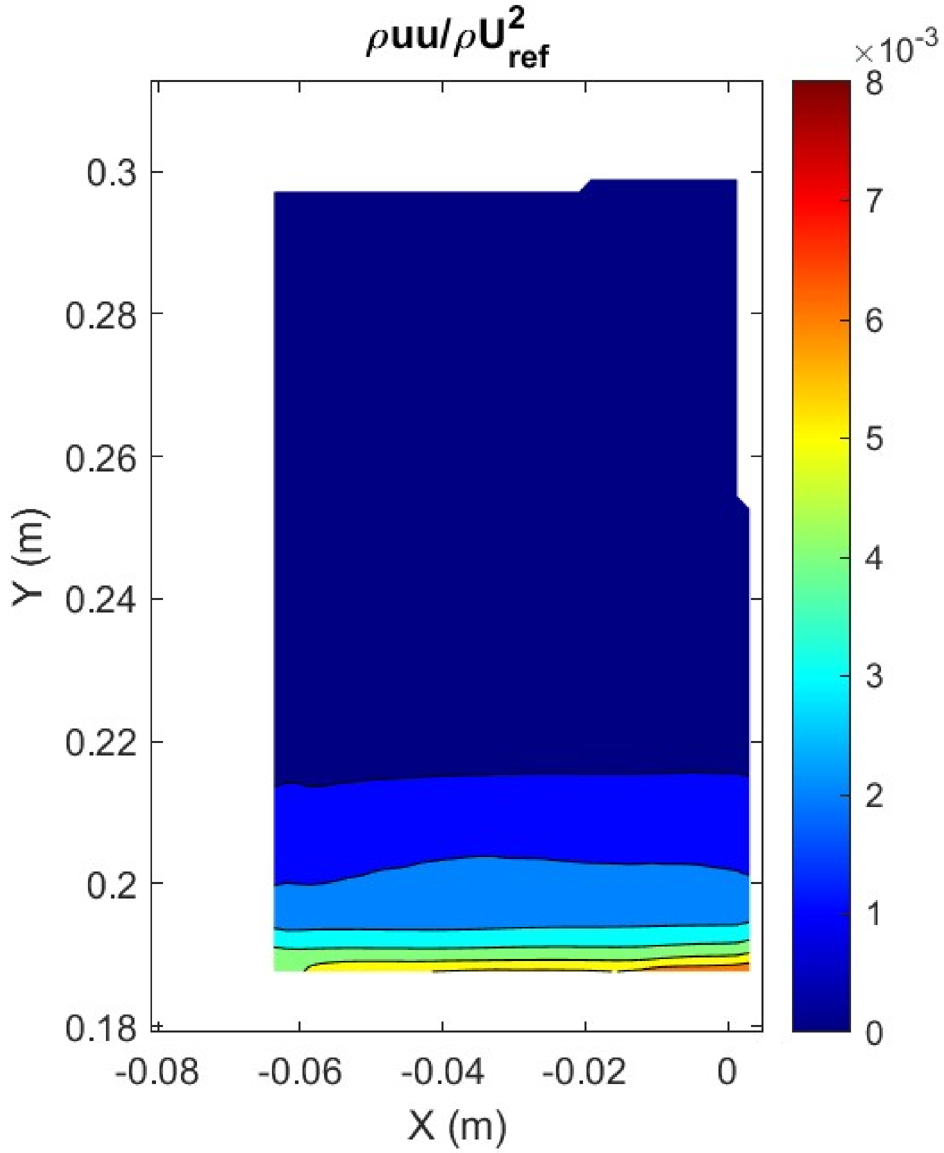

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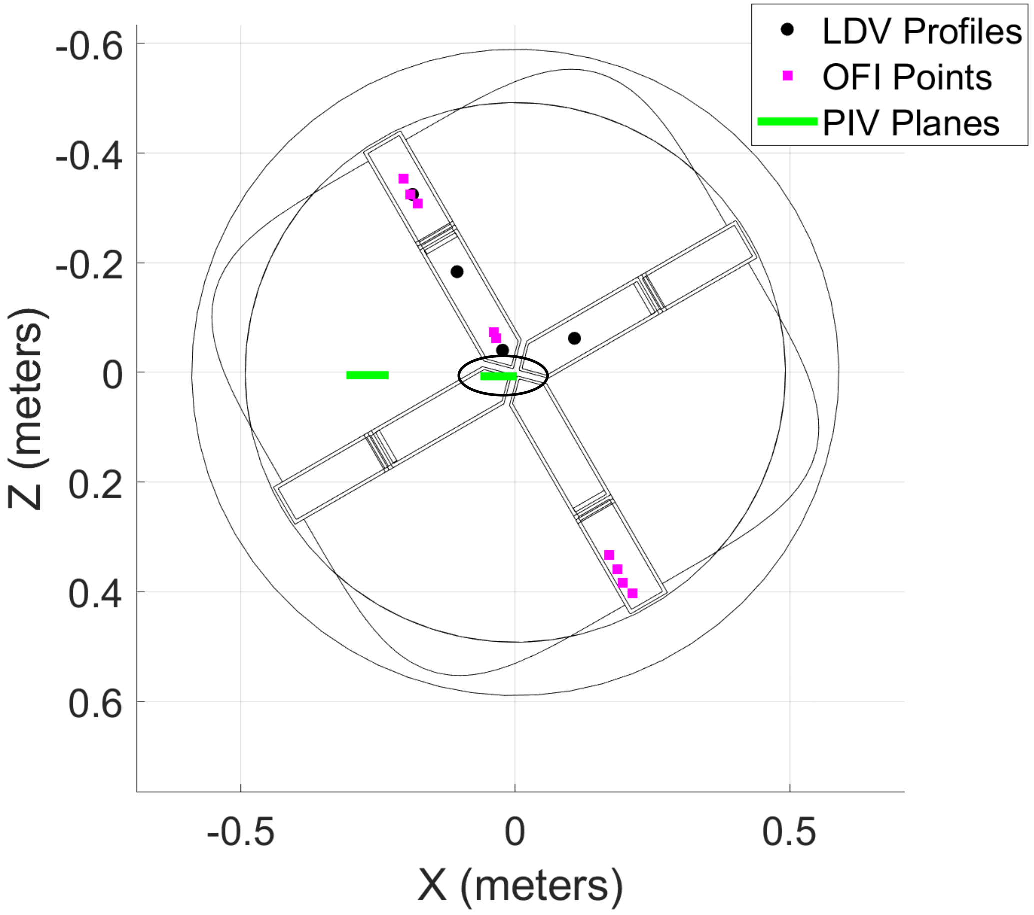

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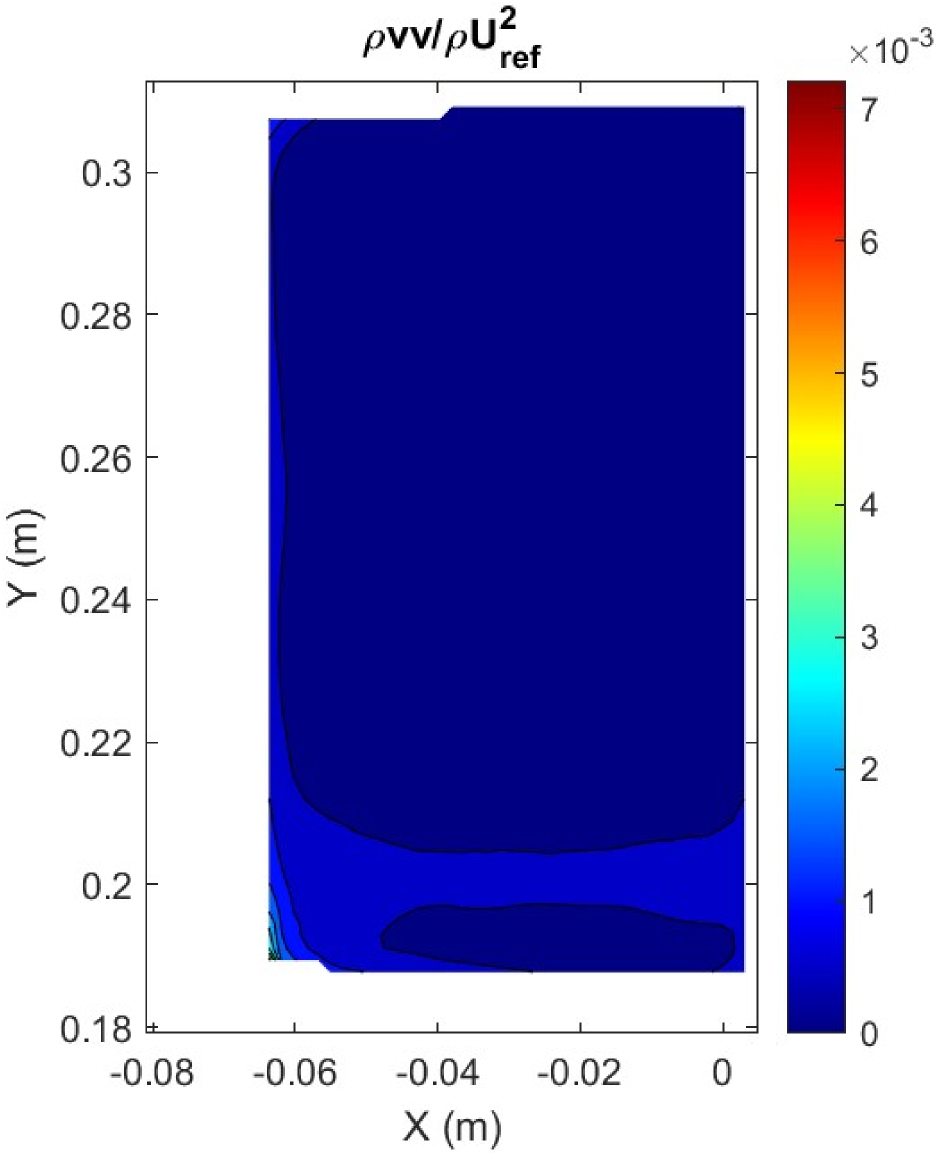

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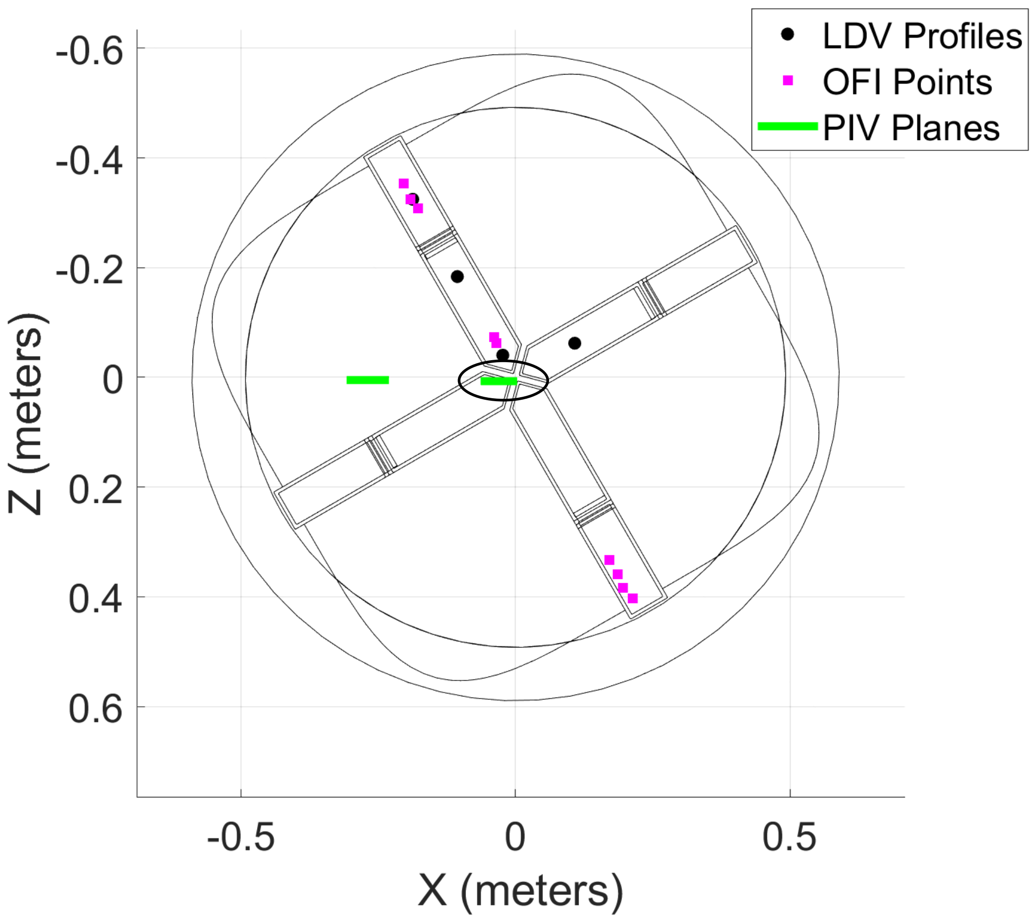

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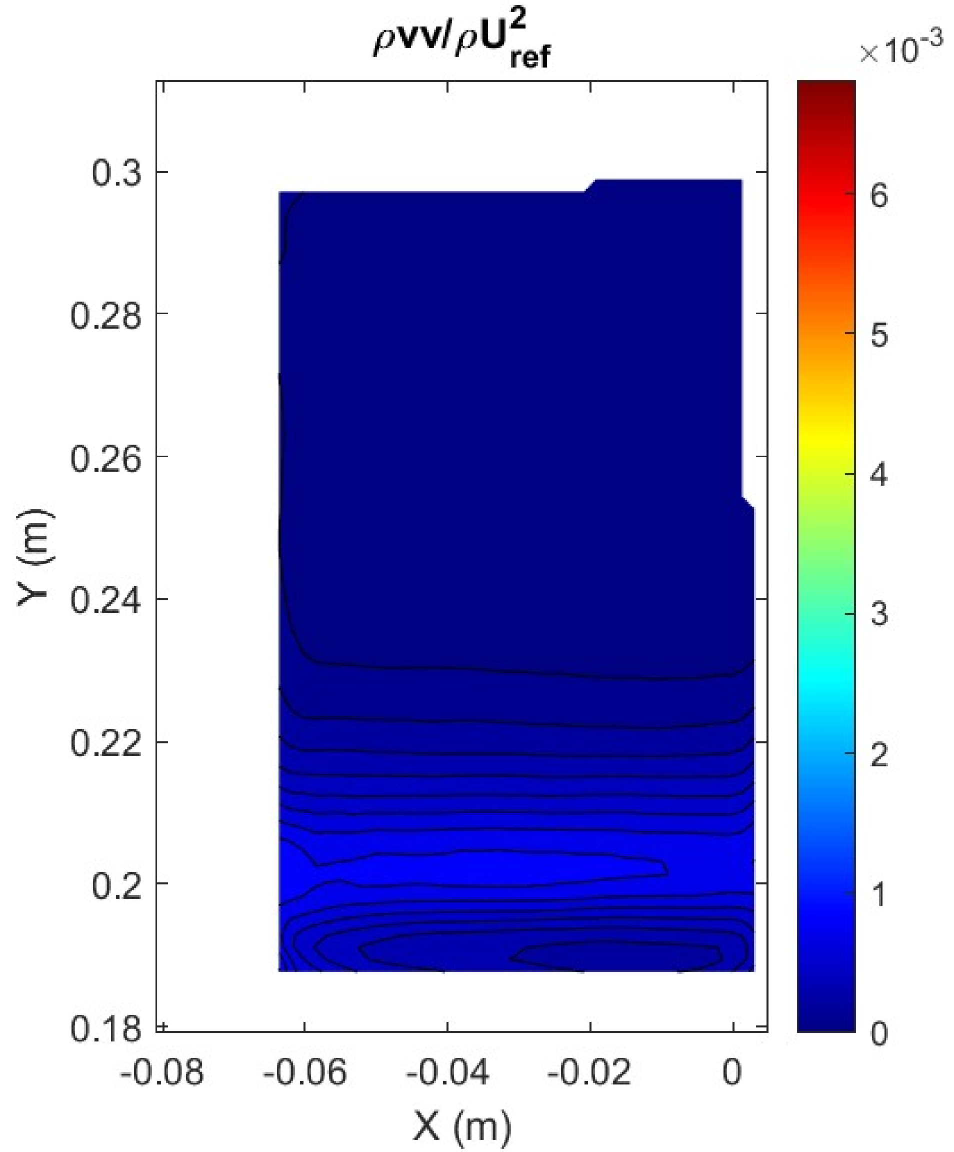

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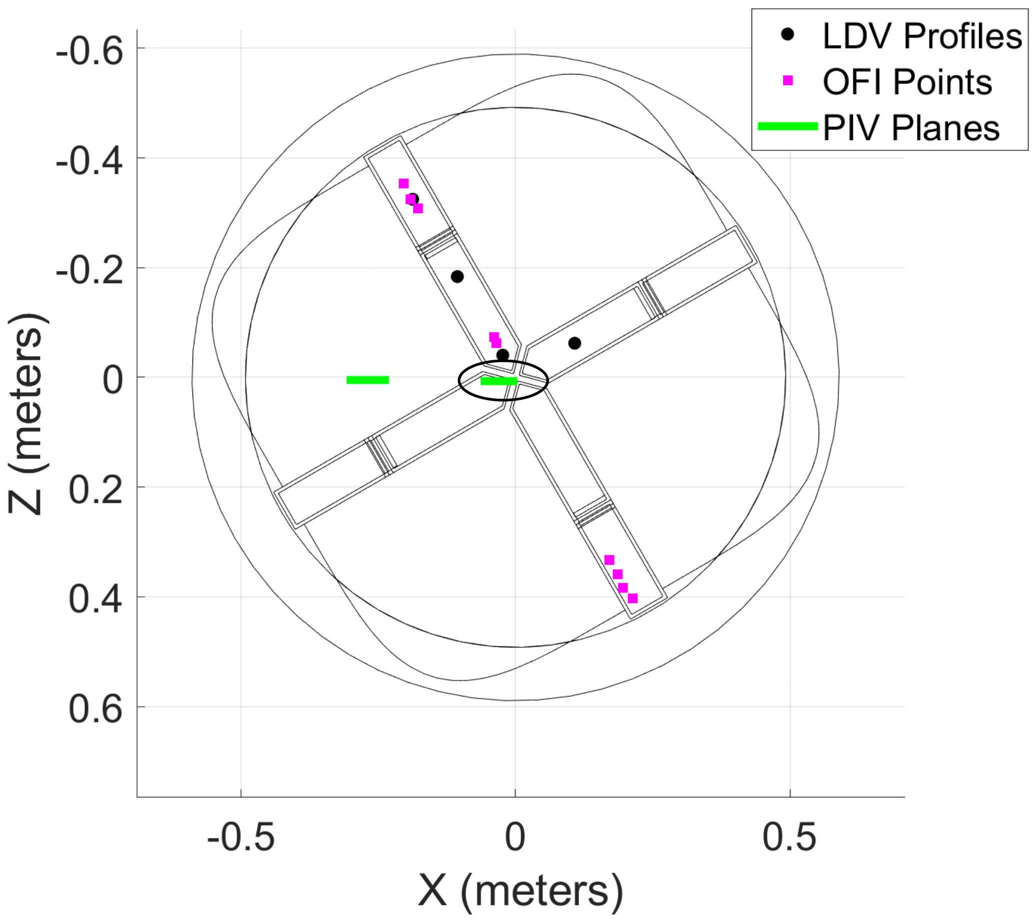

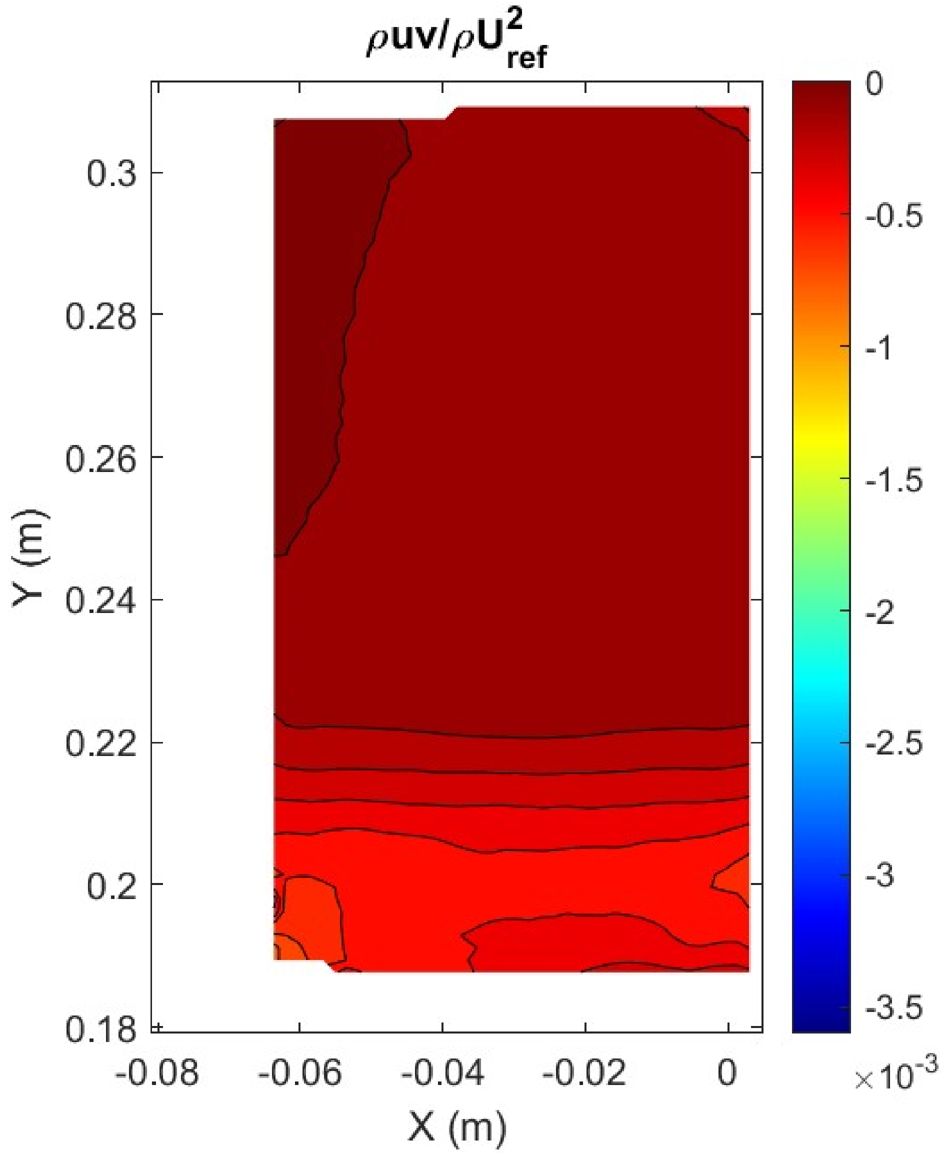

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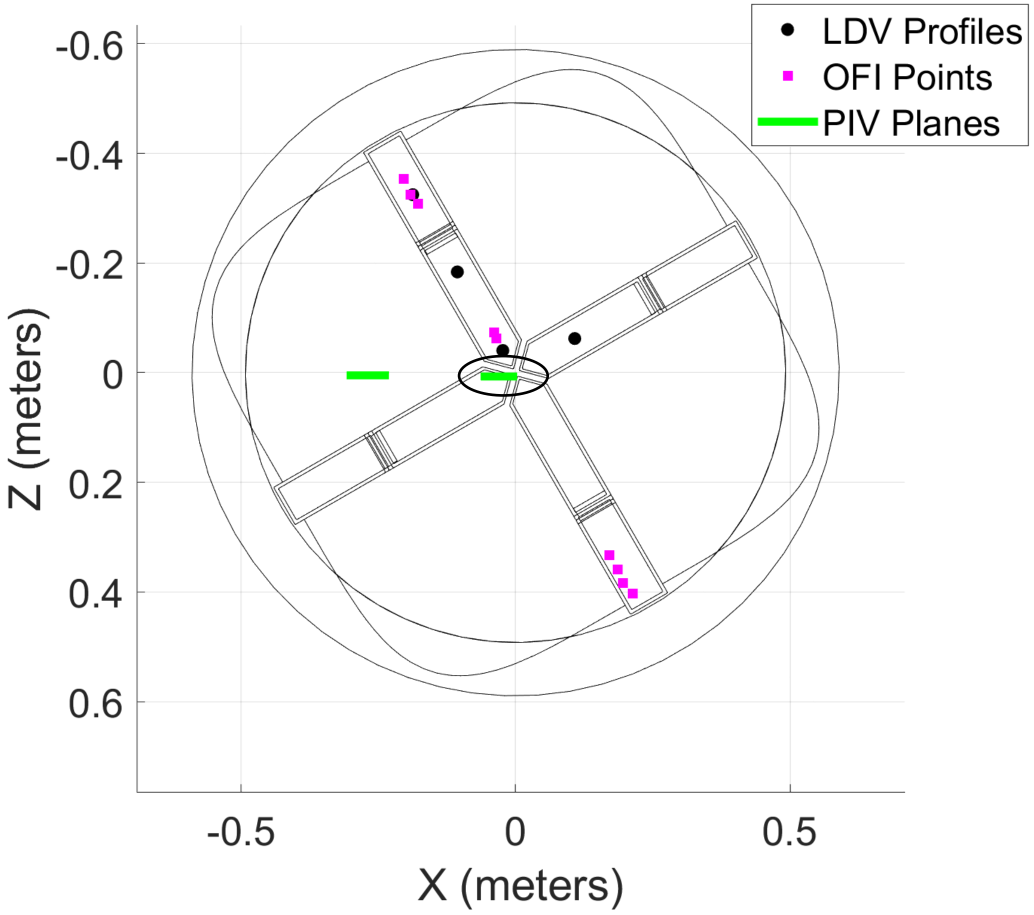
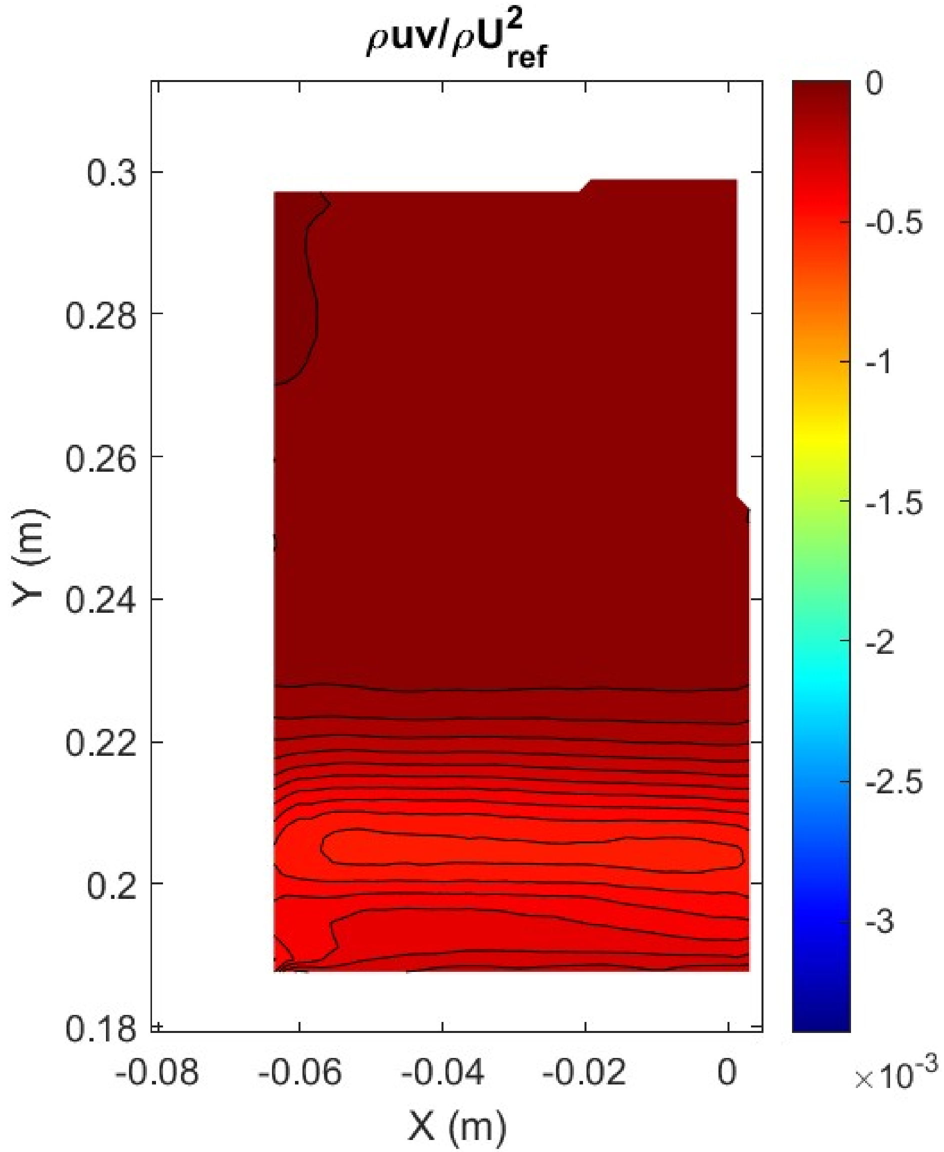
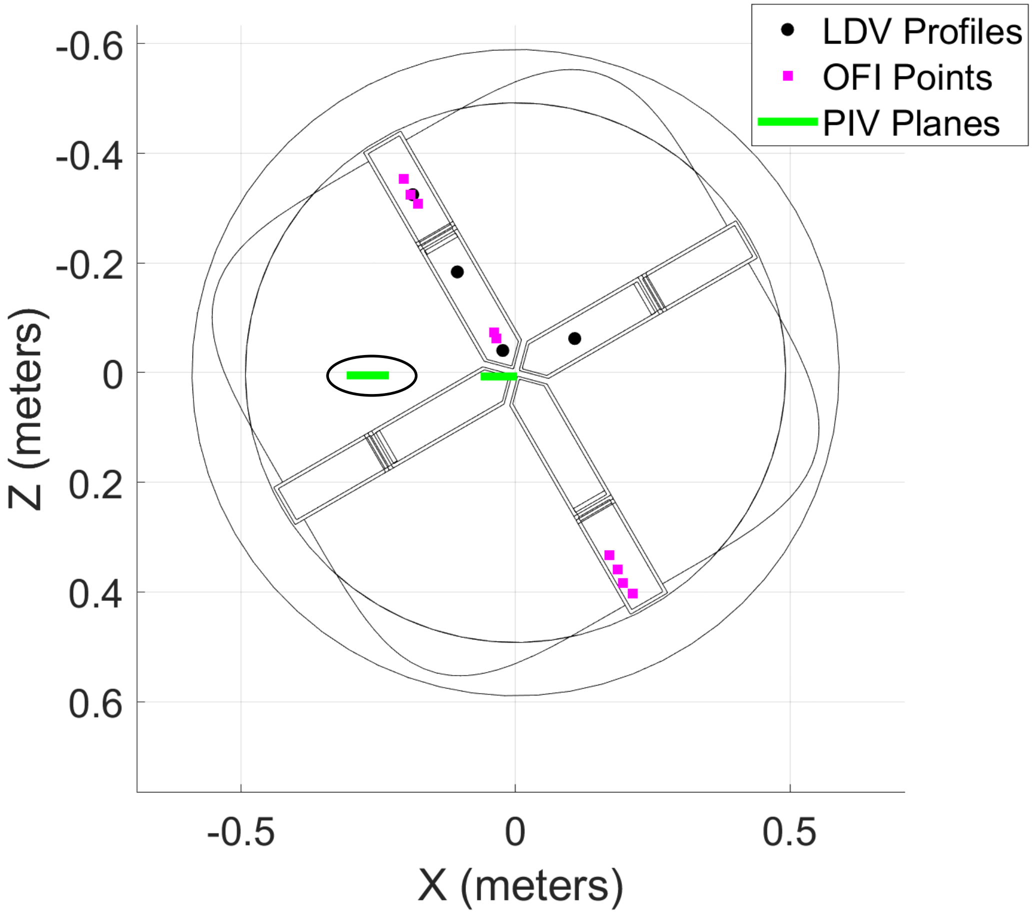
Re_H =650k

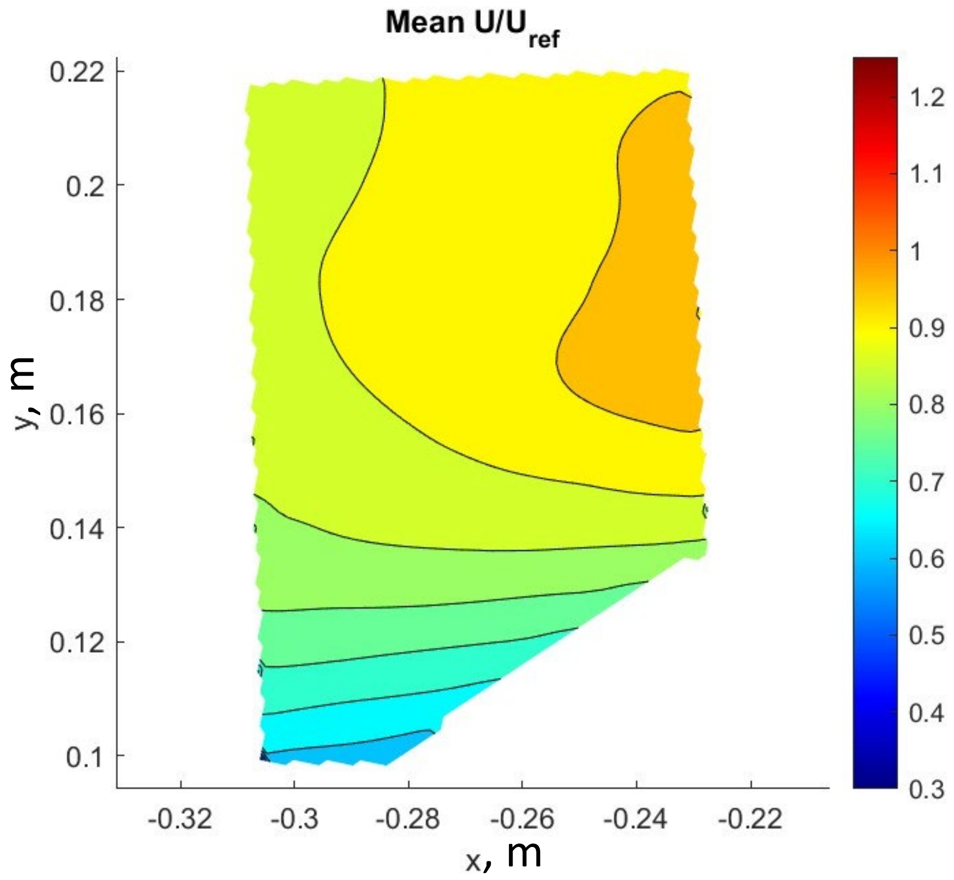




PIV Planar Results

Re_H =250k





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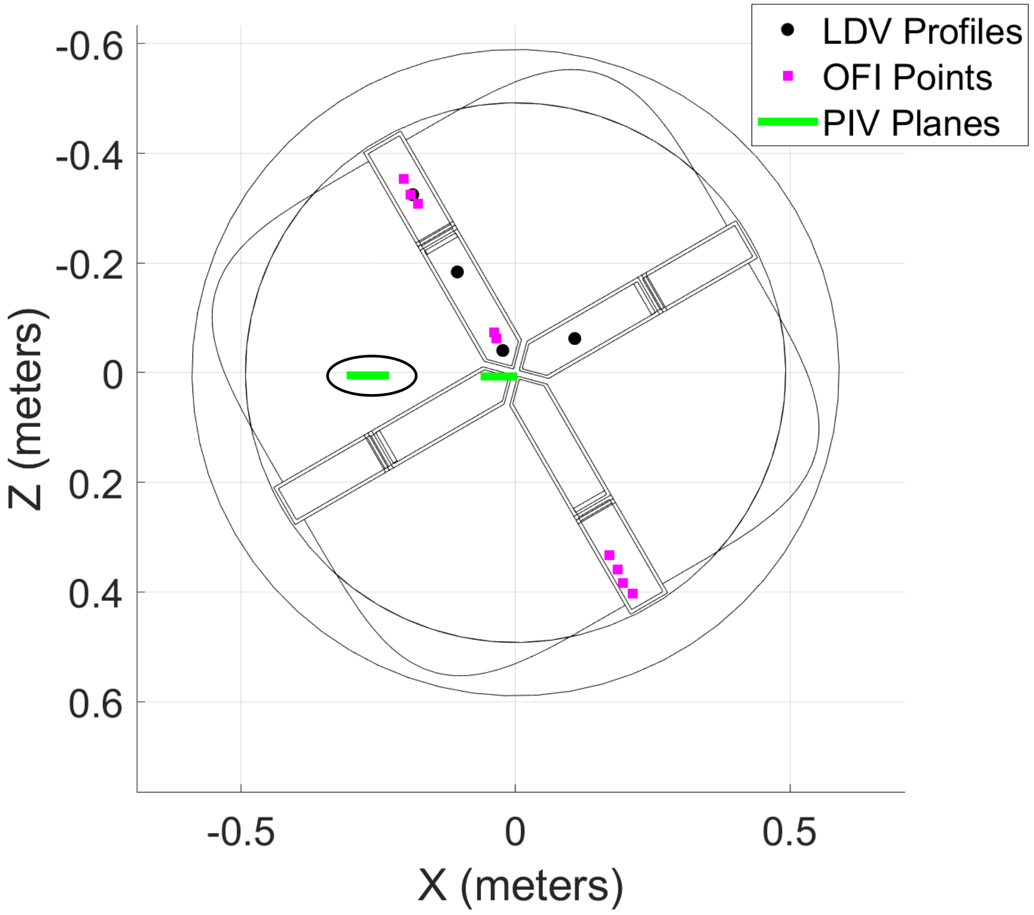

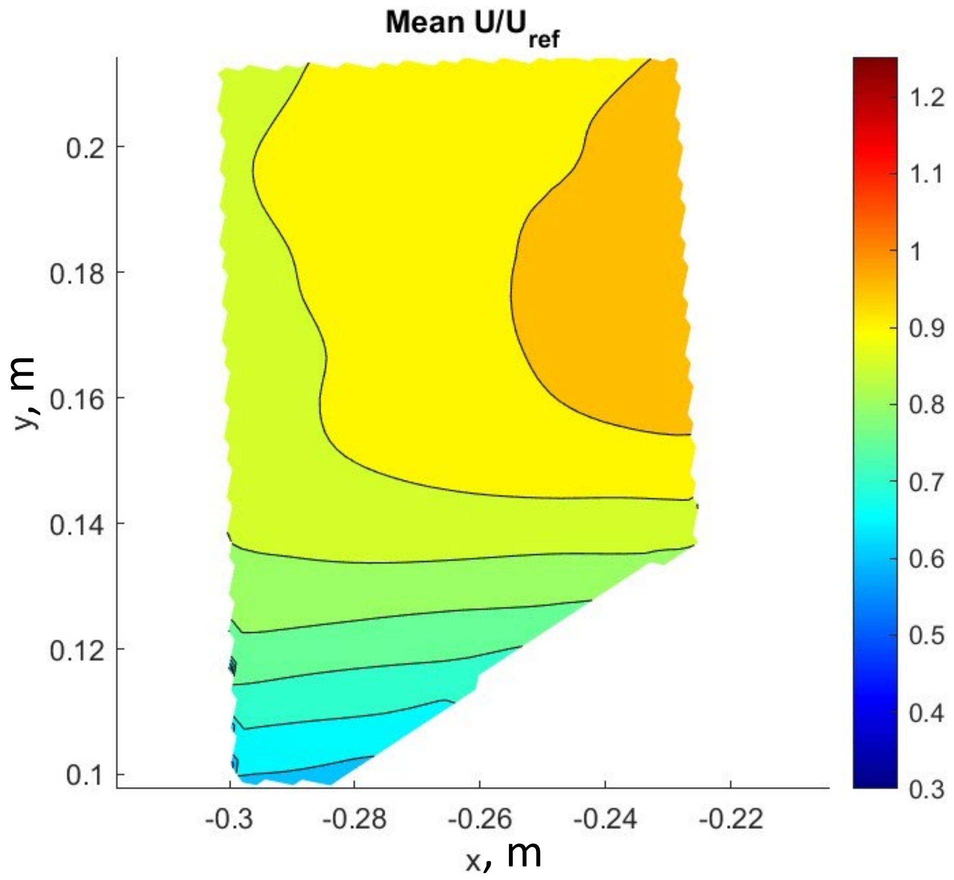

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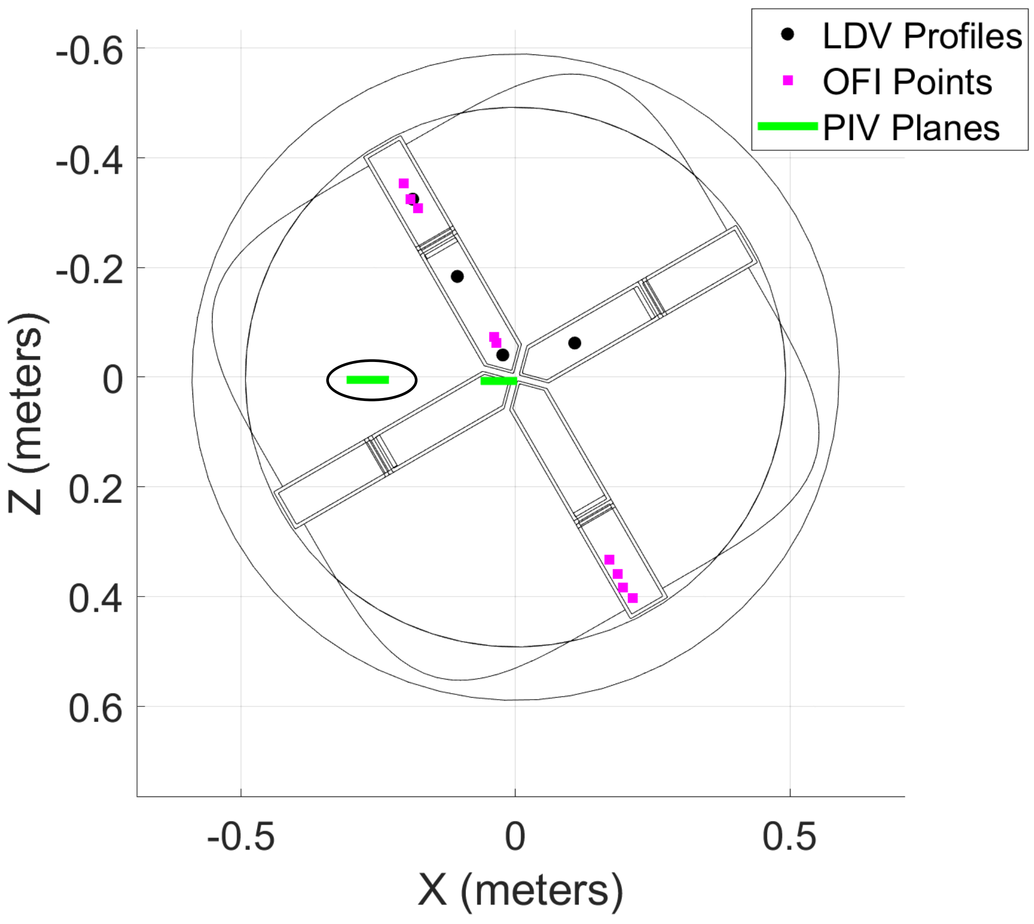
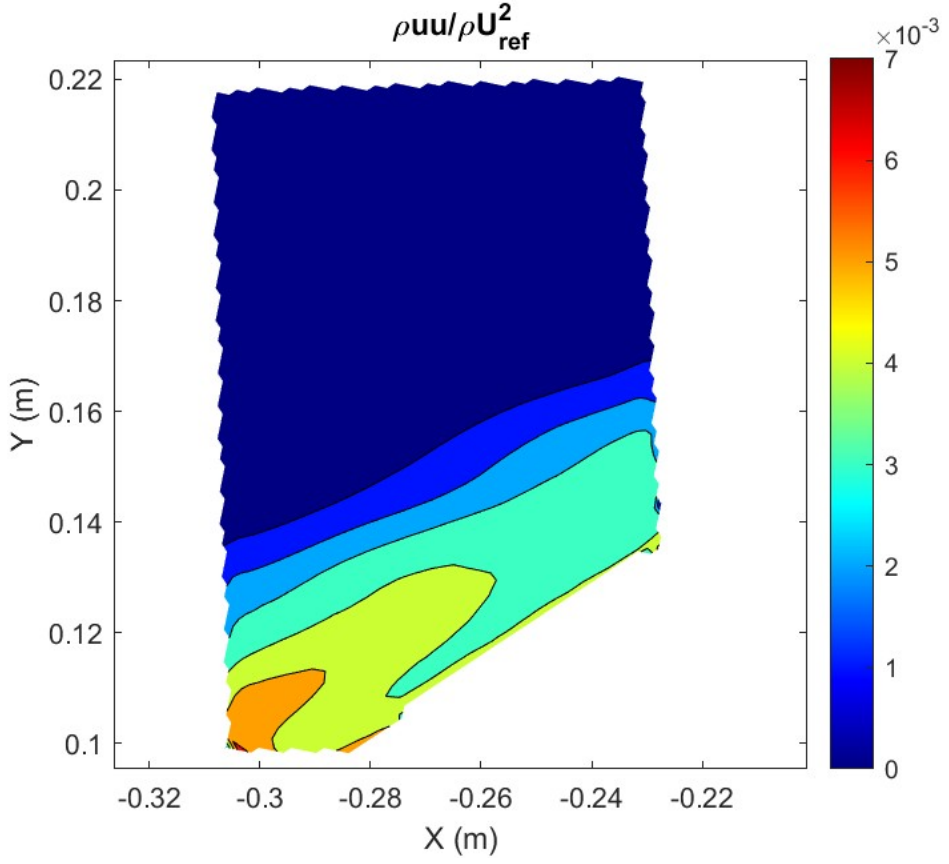
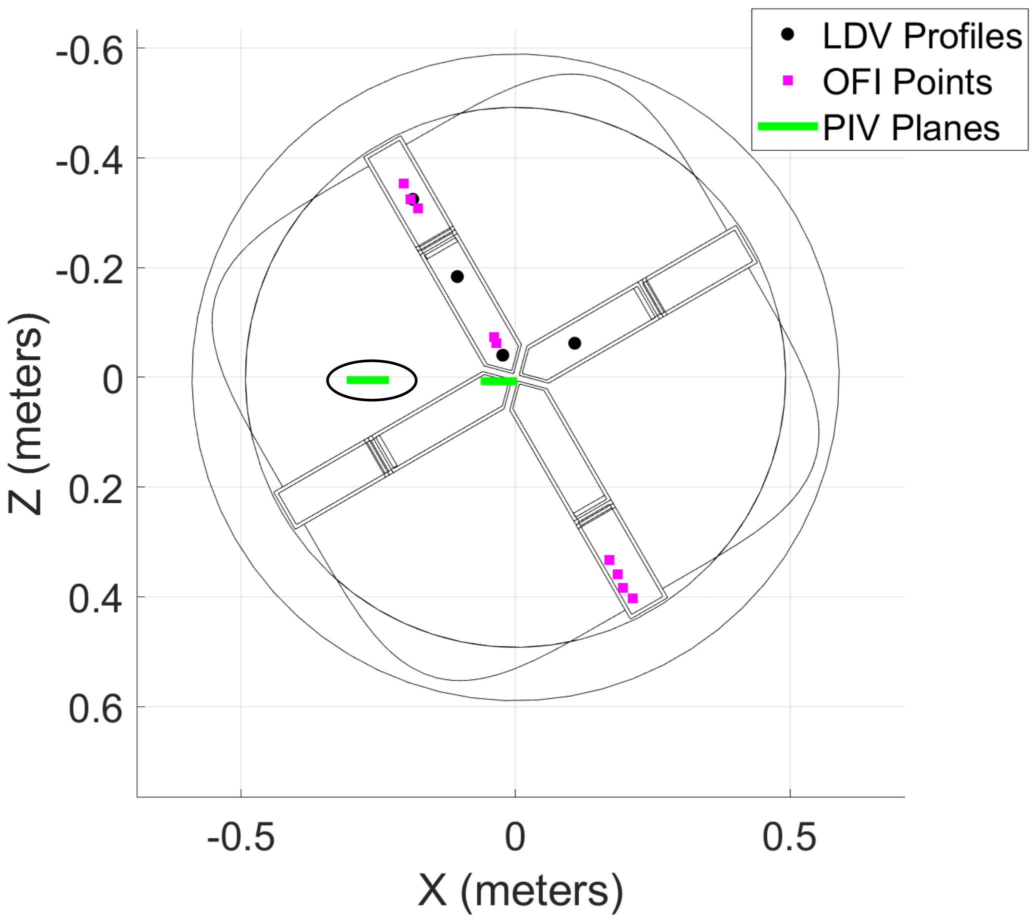
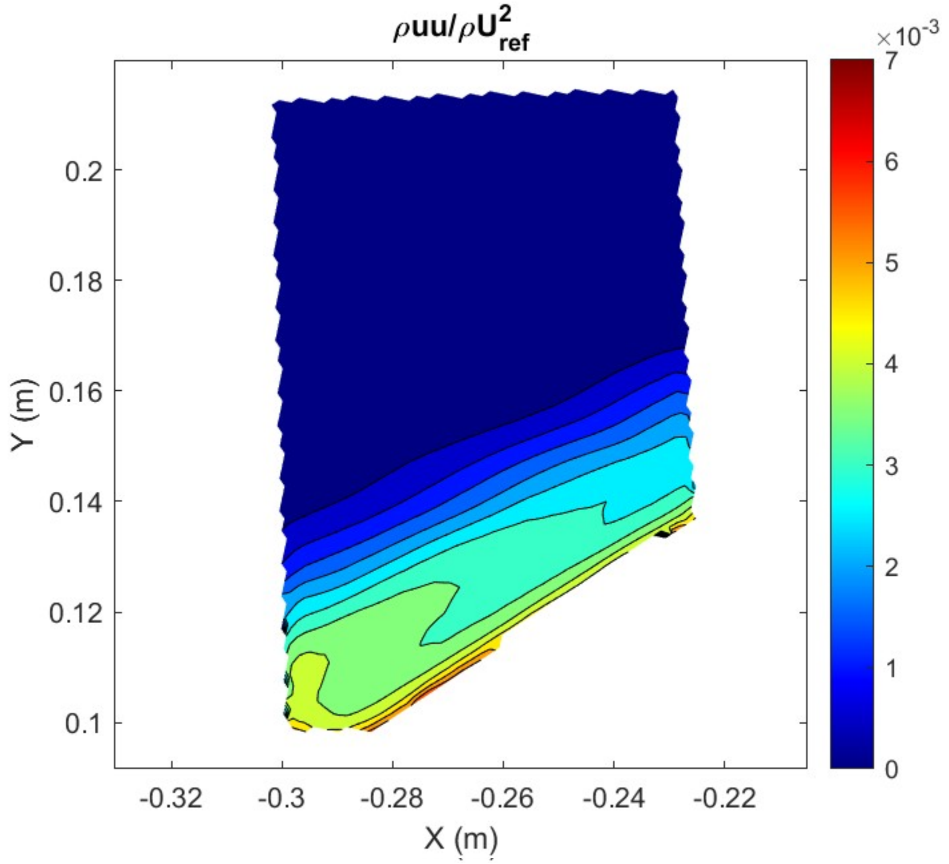




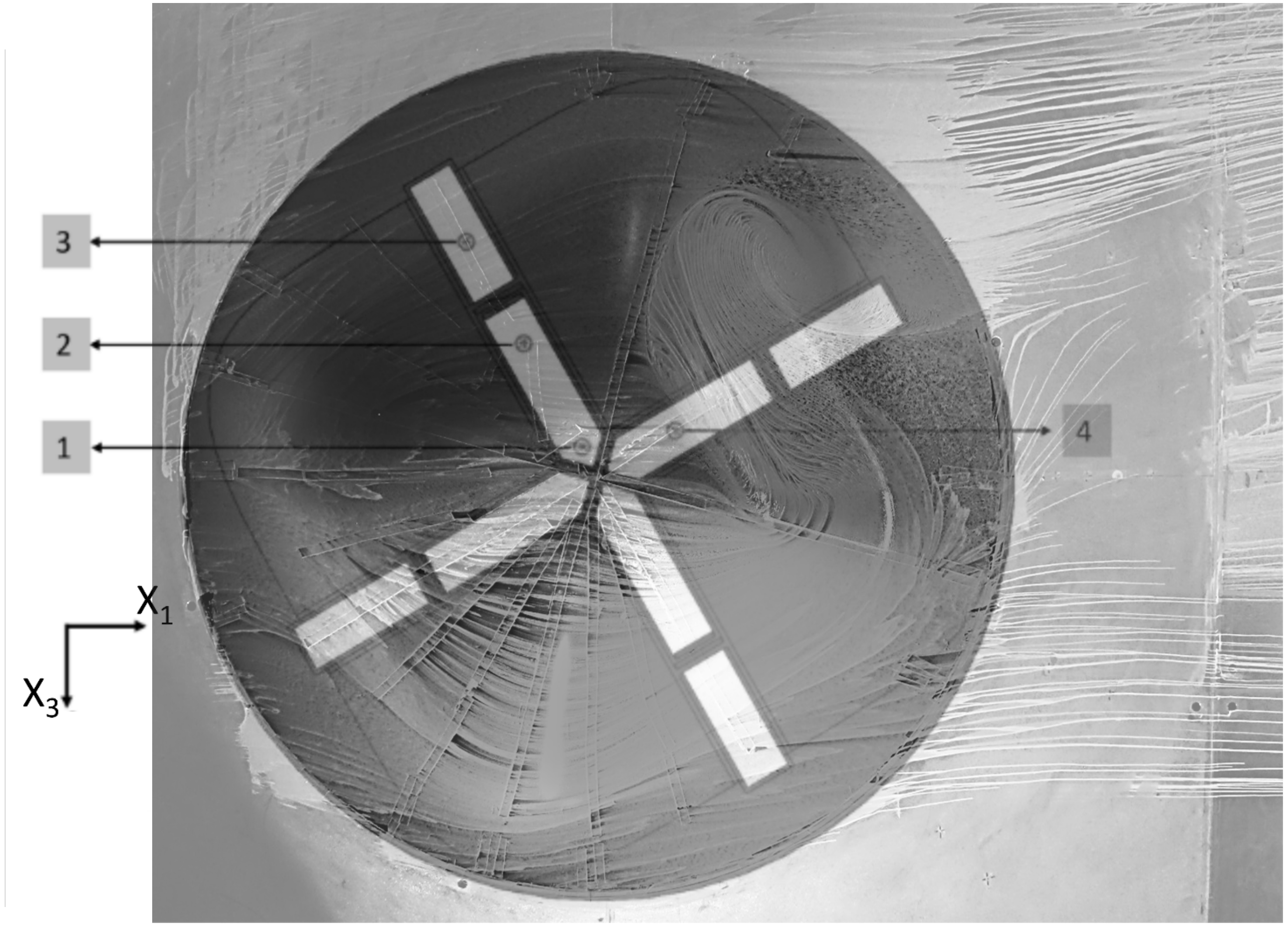
PIV Planar Results

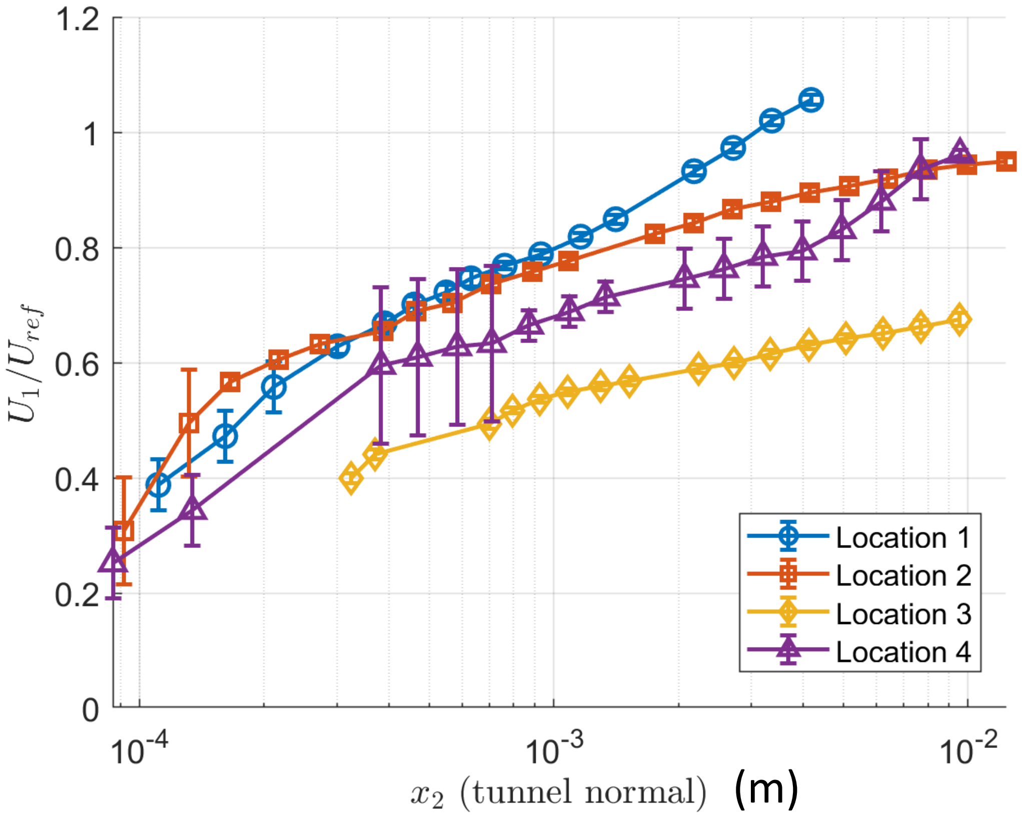
Re_H =650k





LDV Mean Velocity Profiles: $\mathrm{Re_H} = 250\mathrm{k}$





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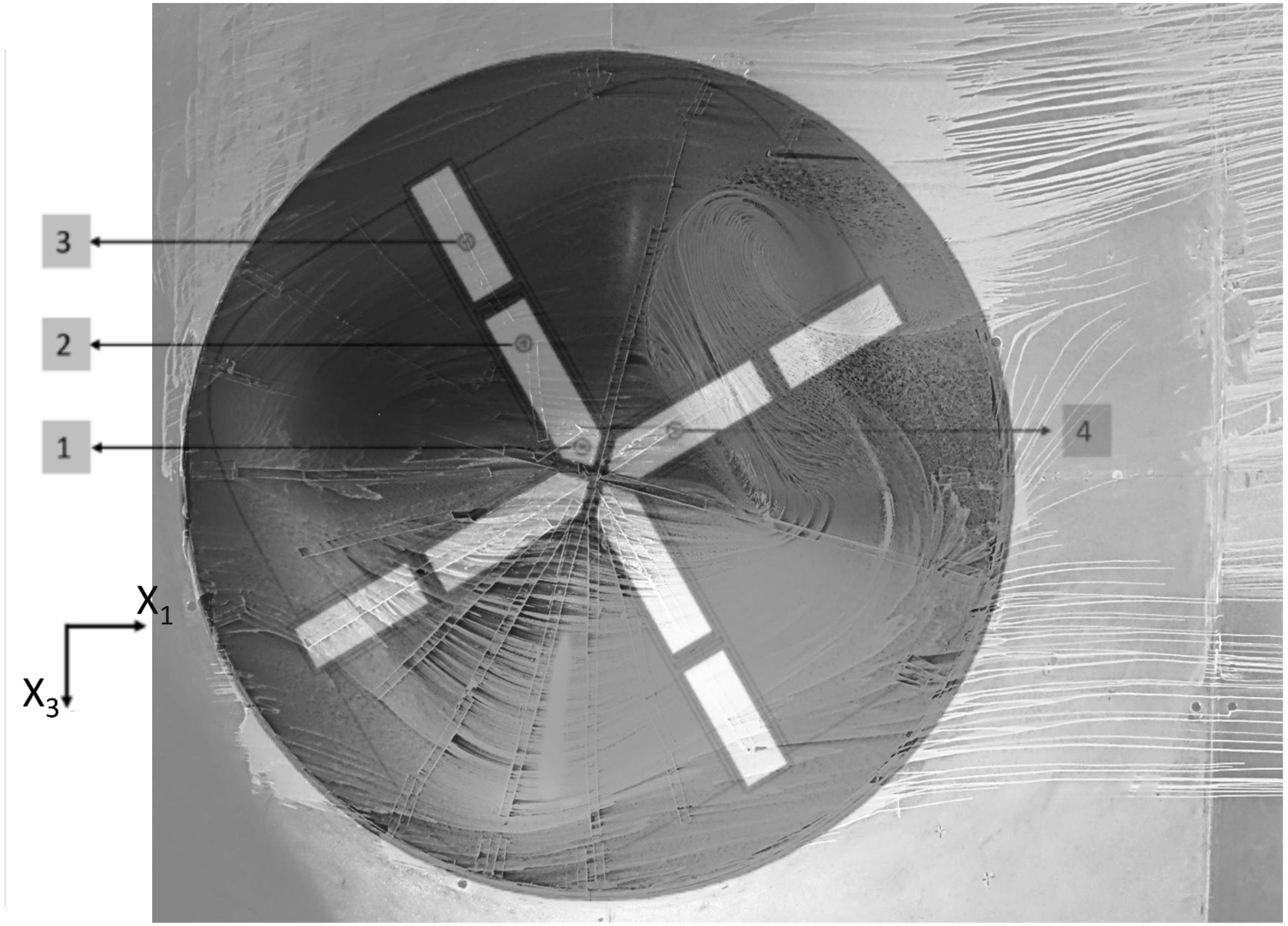

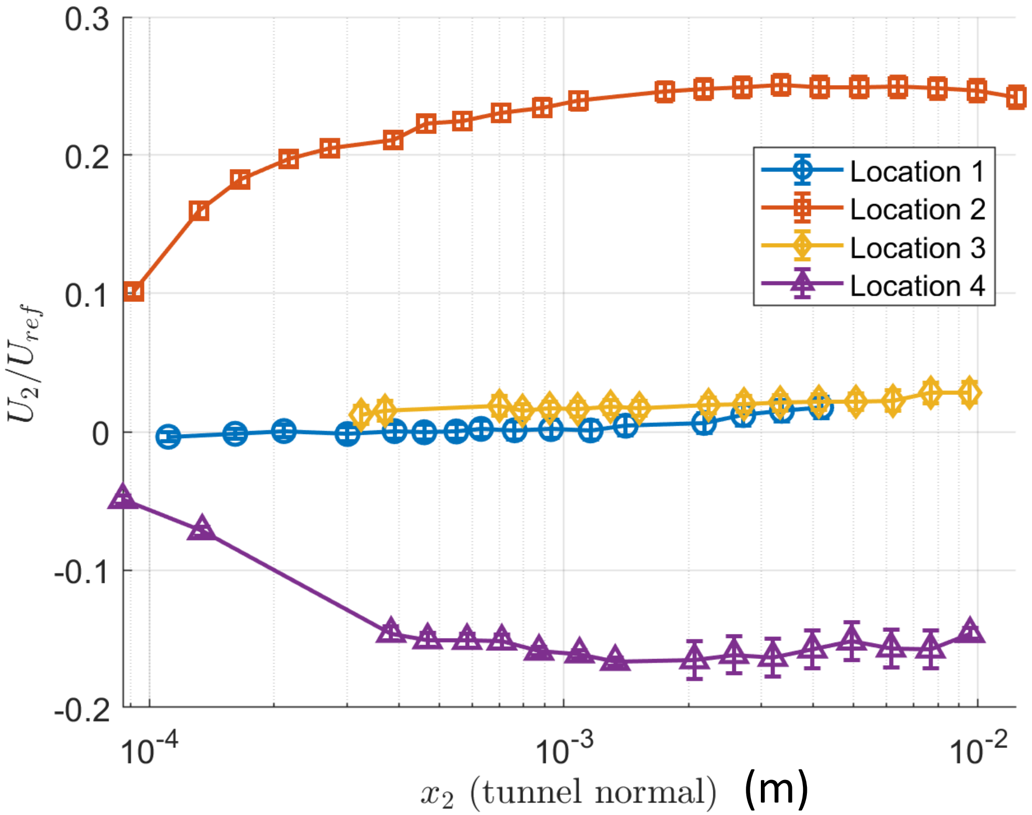

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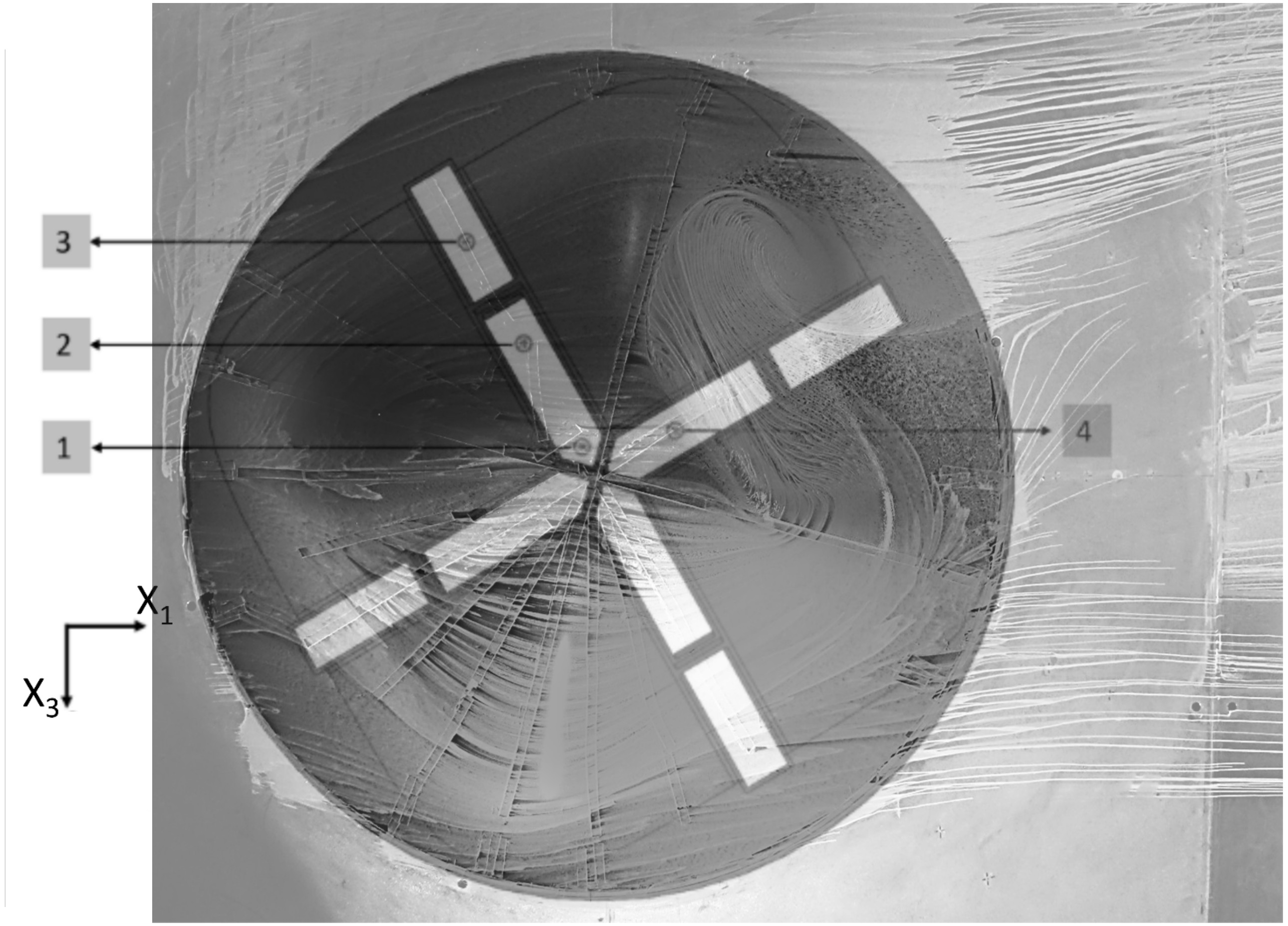

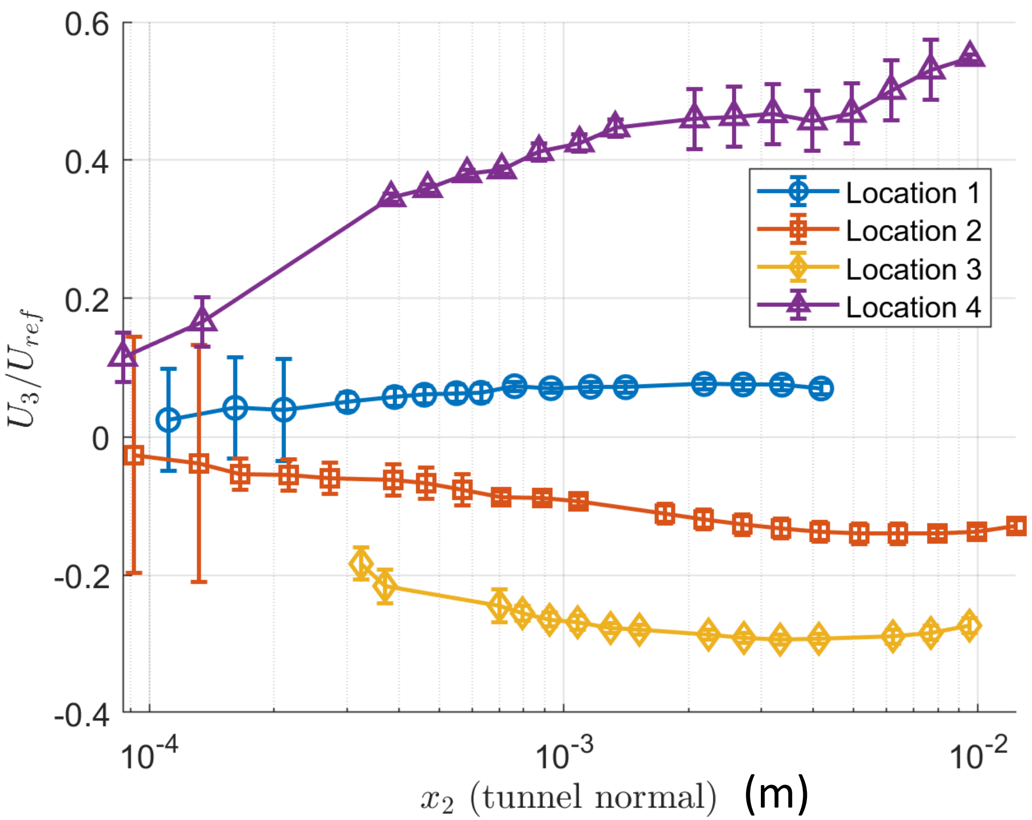

LDV Reynolds Stress Profiles: $\mathrm{Re_H} = 250\mathrm{k}$

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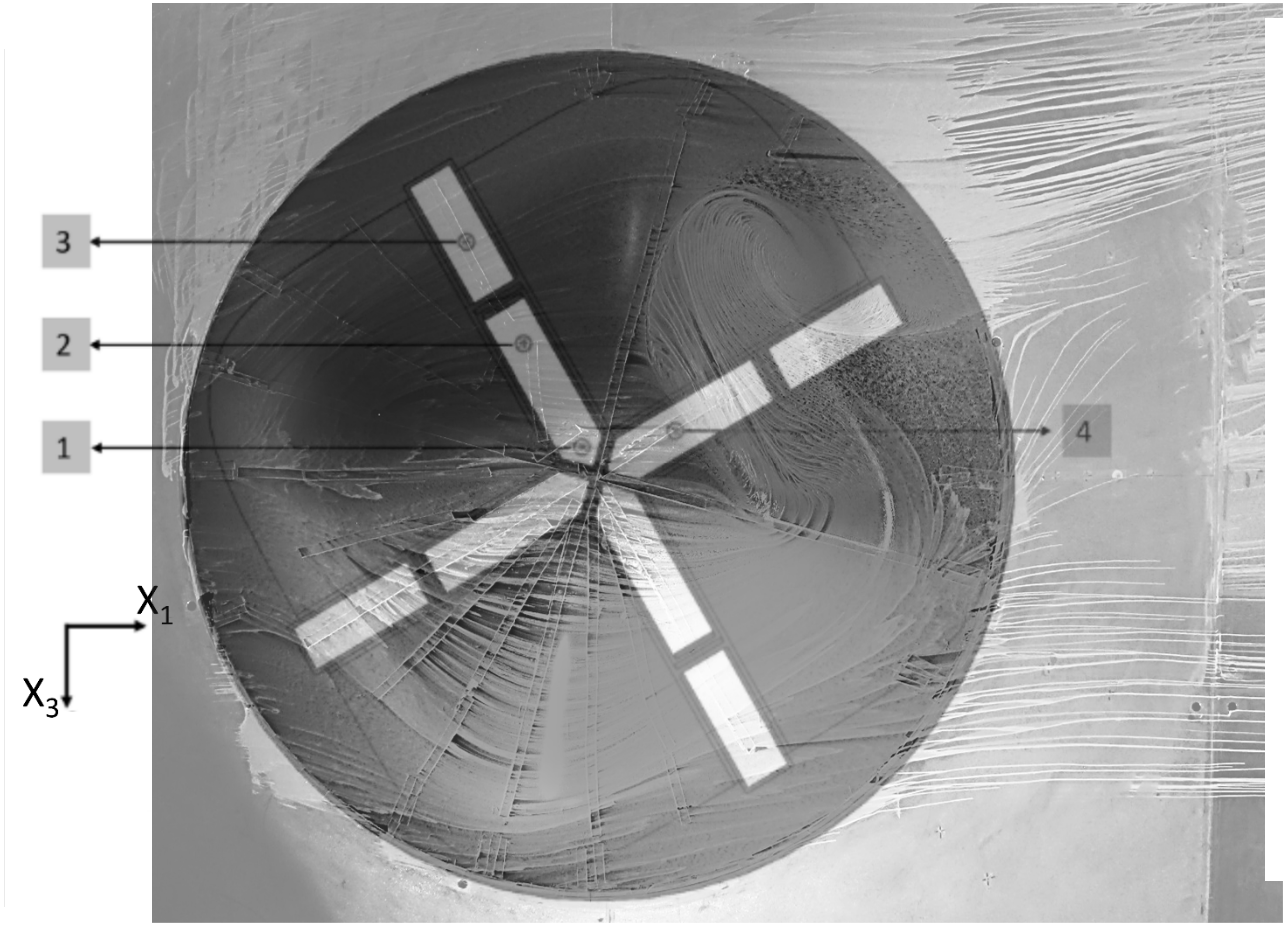

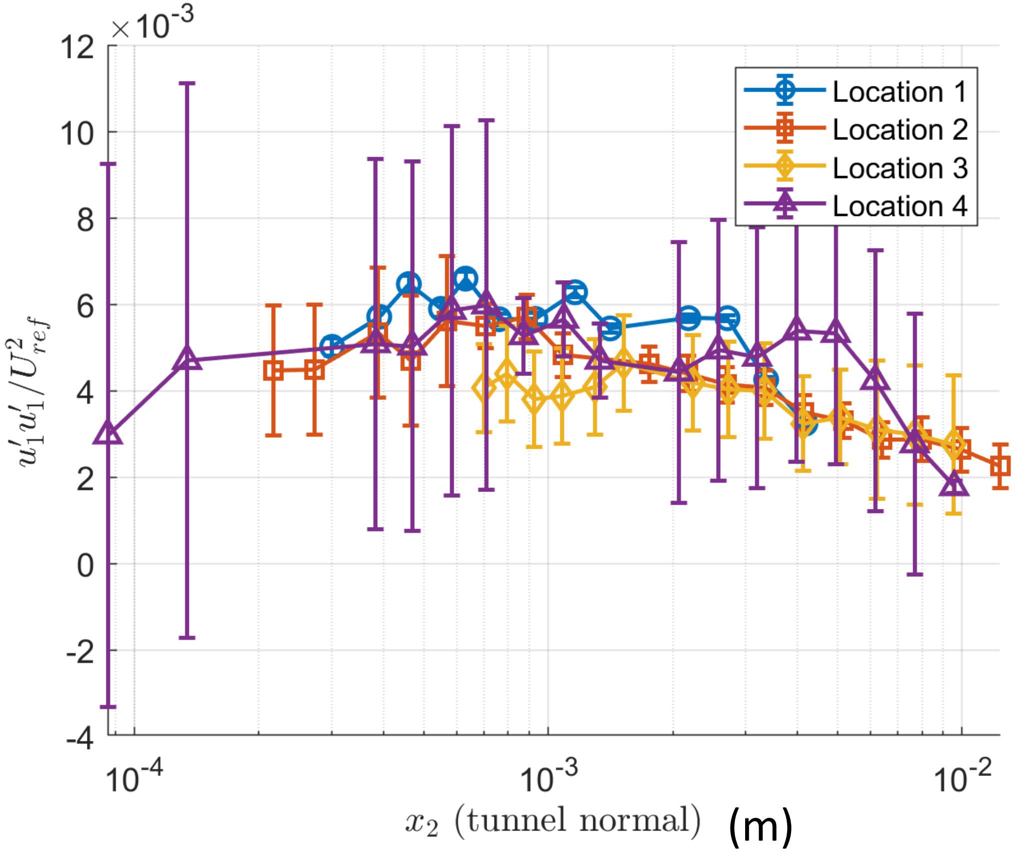

LDV Reynolds Stress Profiles: $\mathrm{Re_H} = 250\mathrm{k}$

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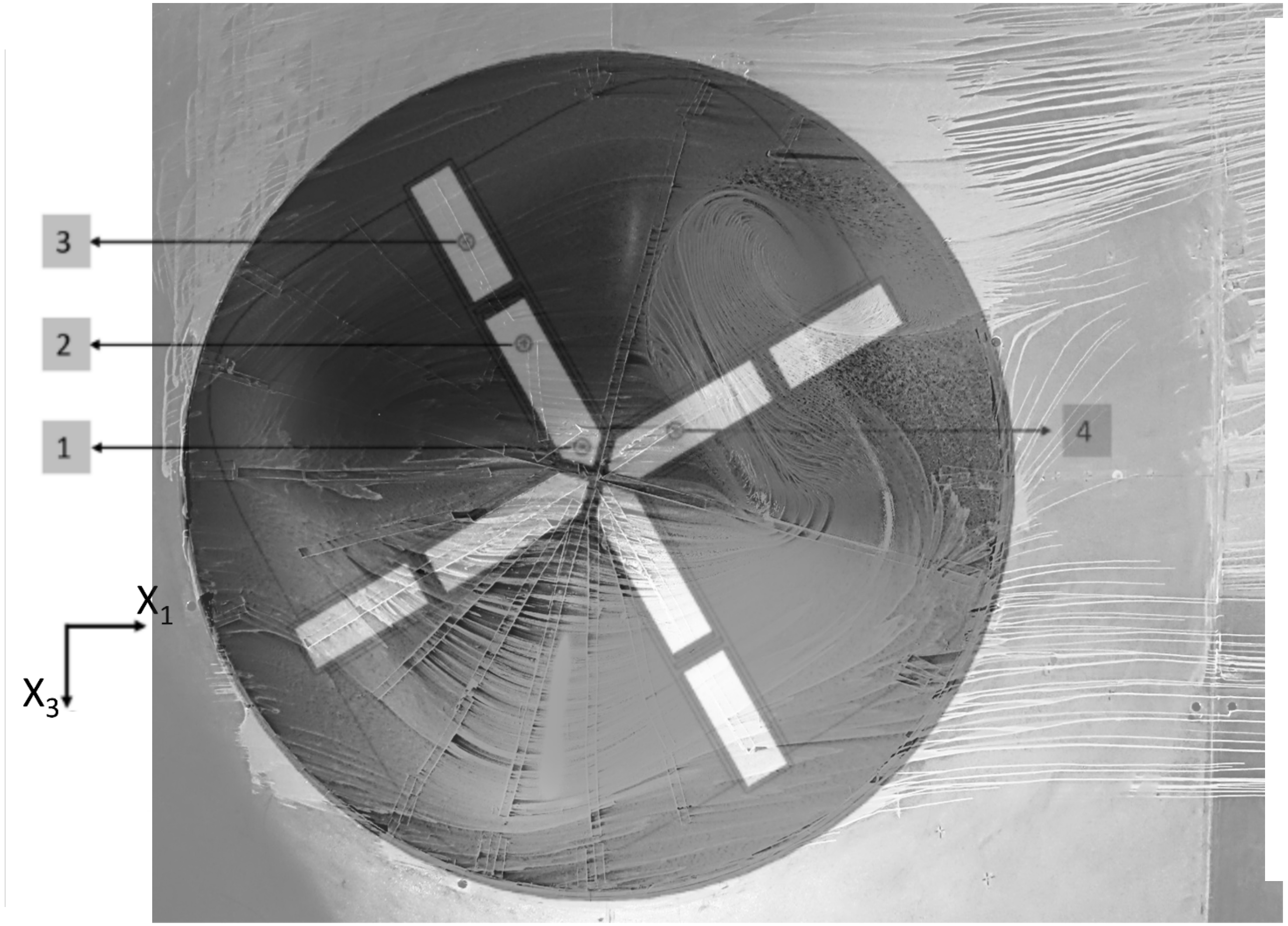
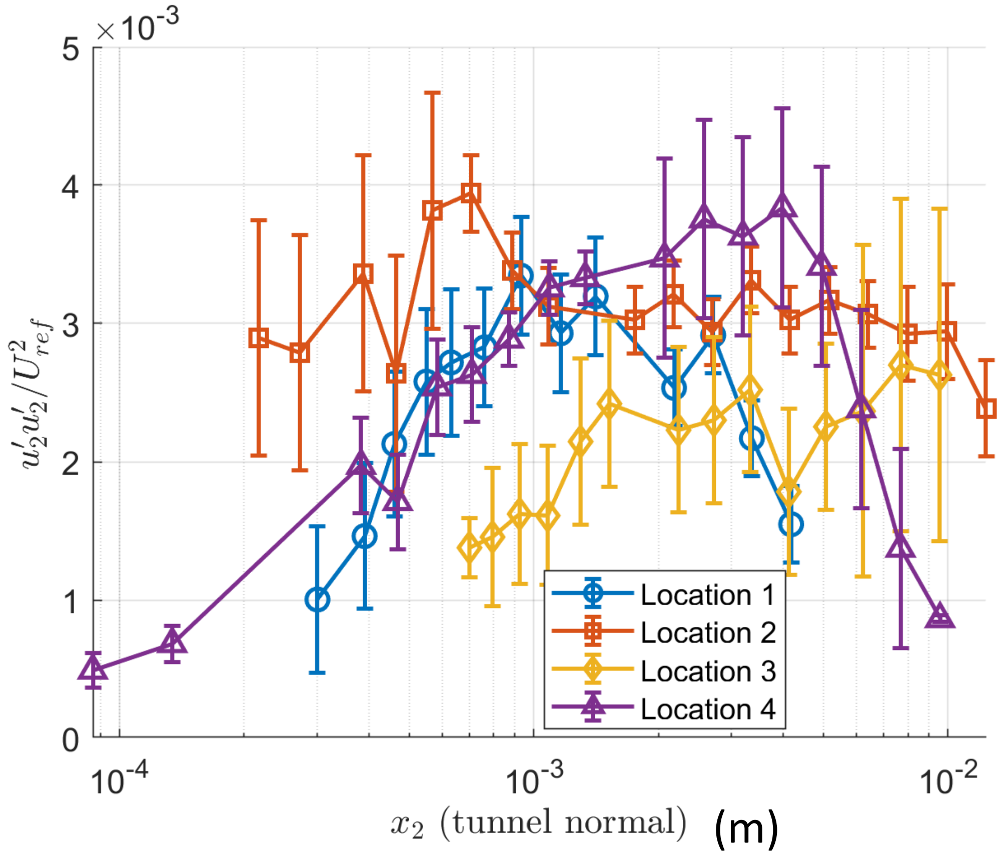
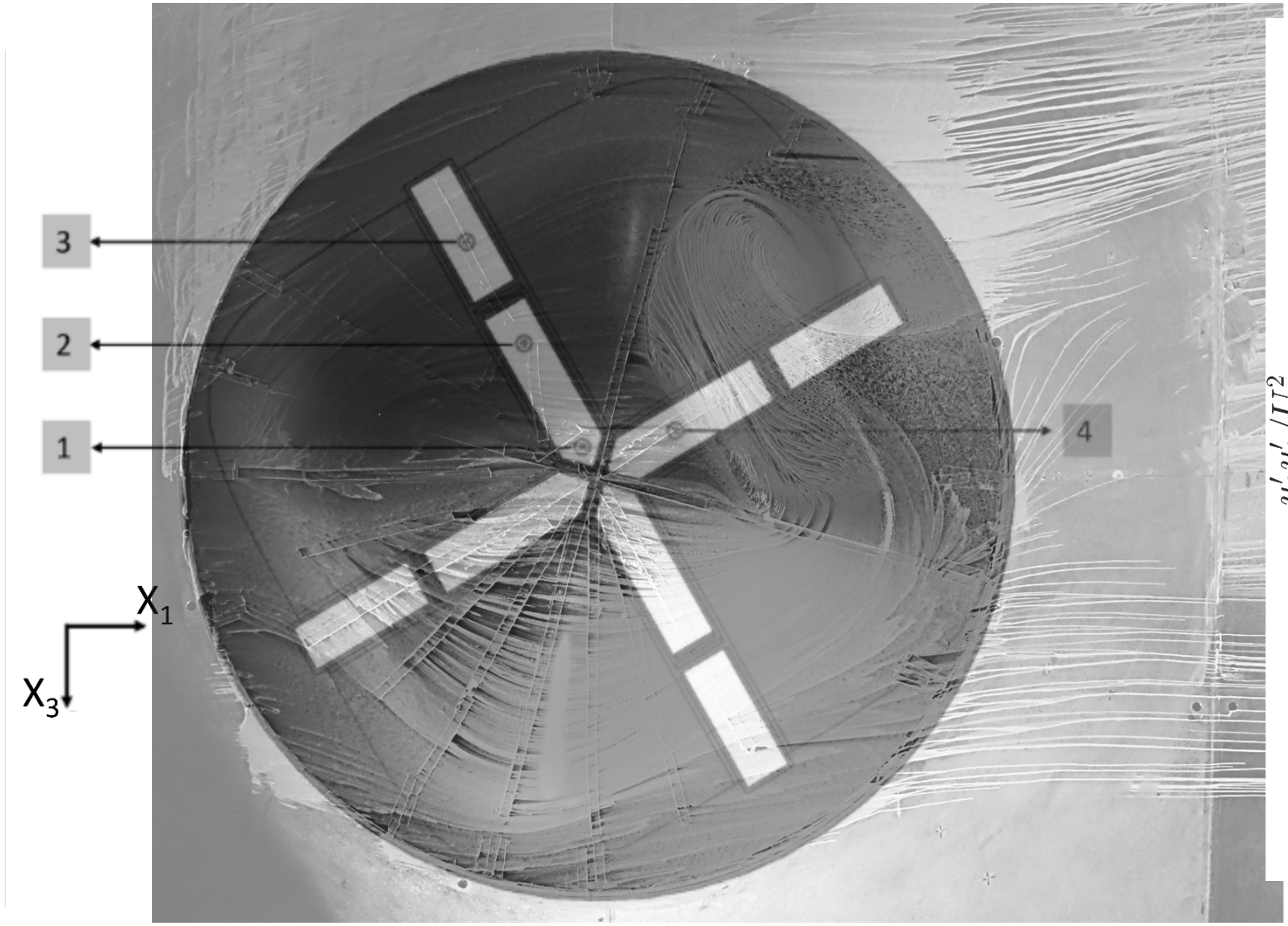
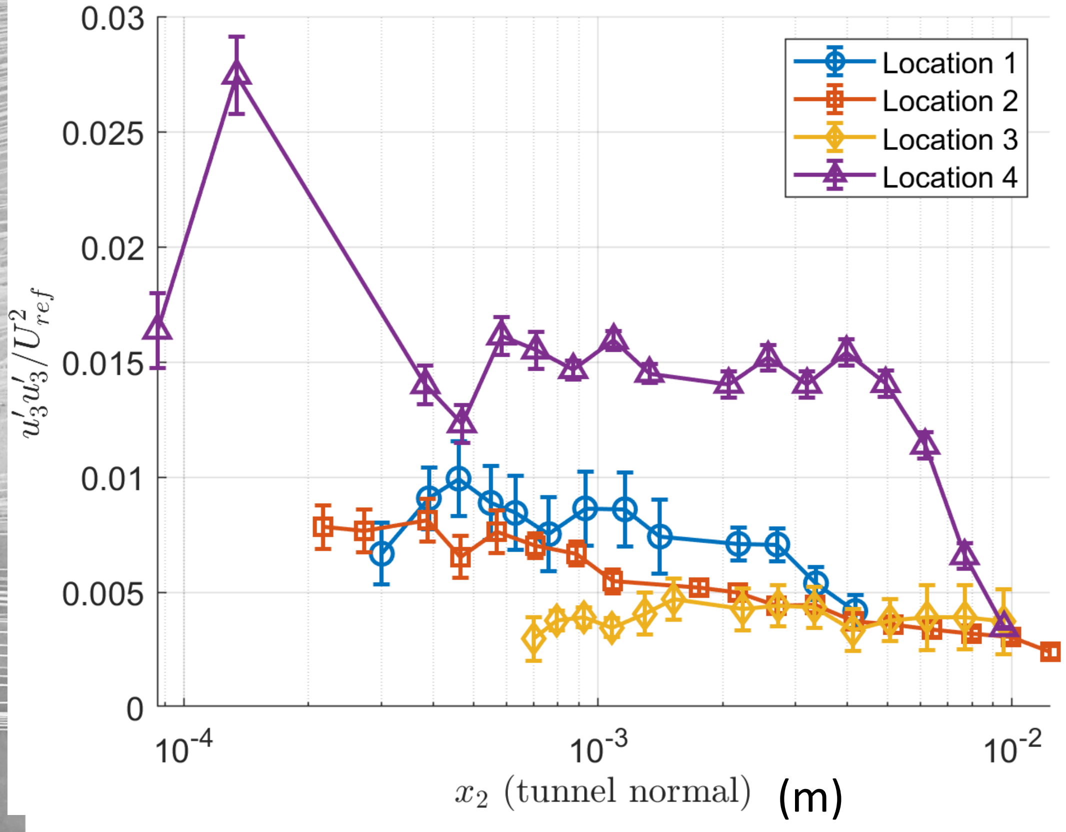


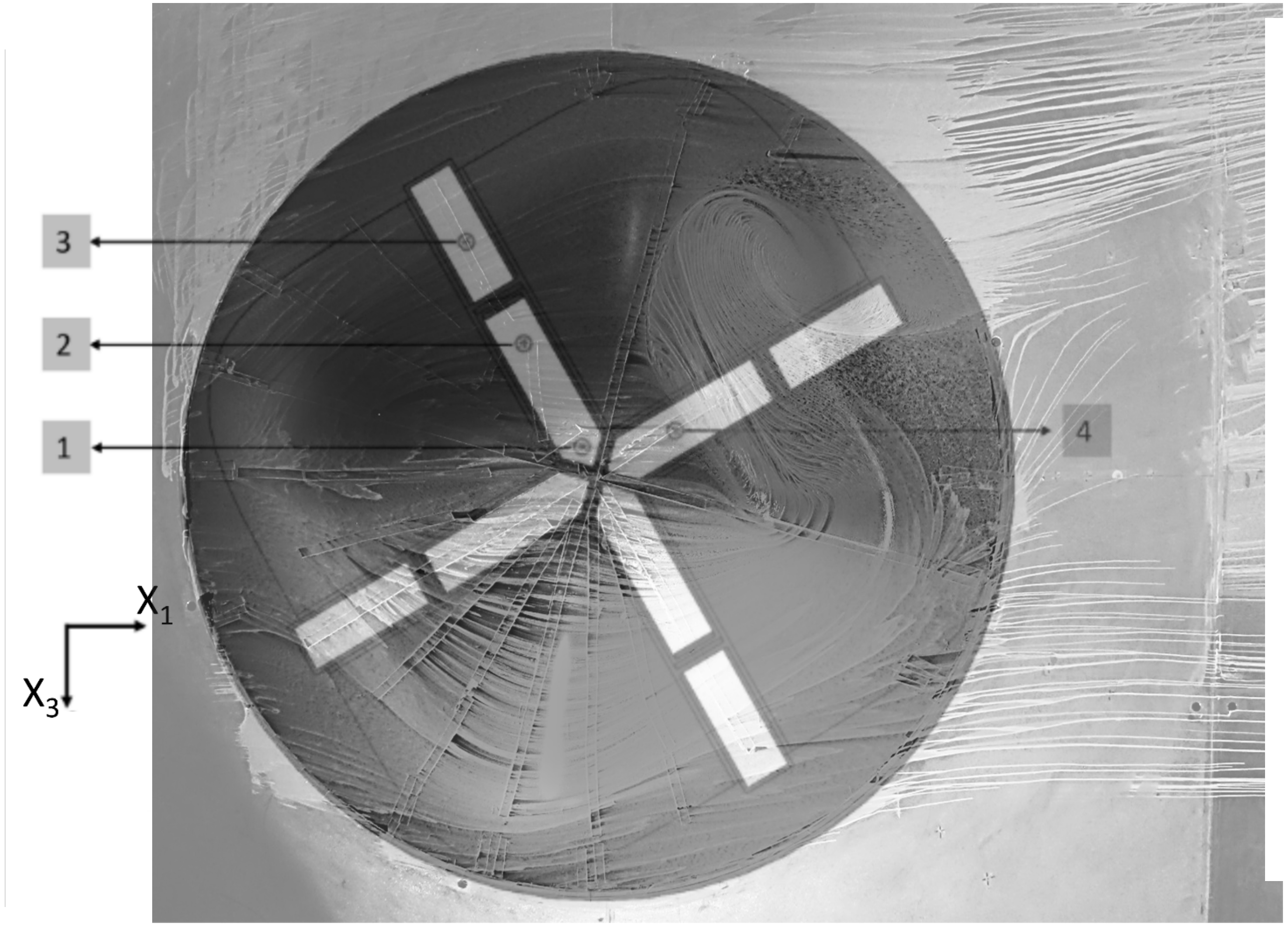


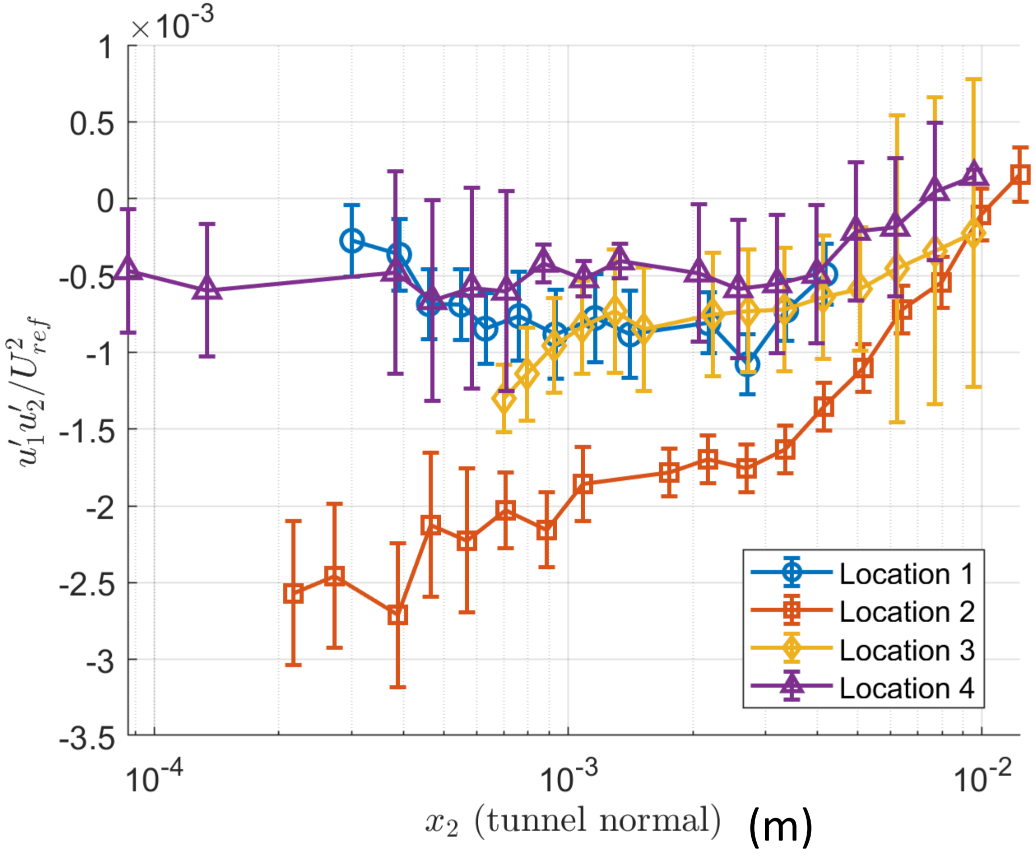
LDV Reynolds Stress Profiles: $\mathrm{Re_H} = 250\mathrm{k}$



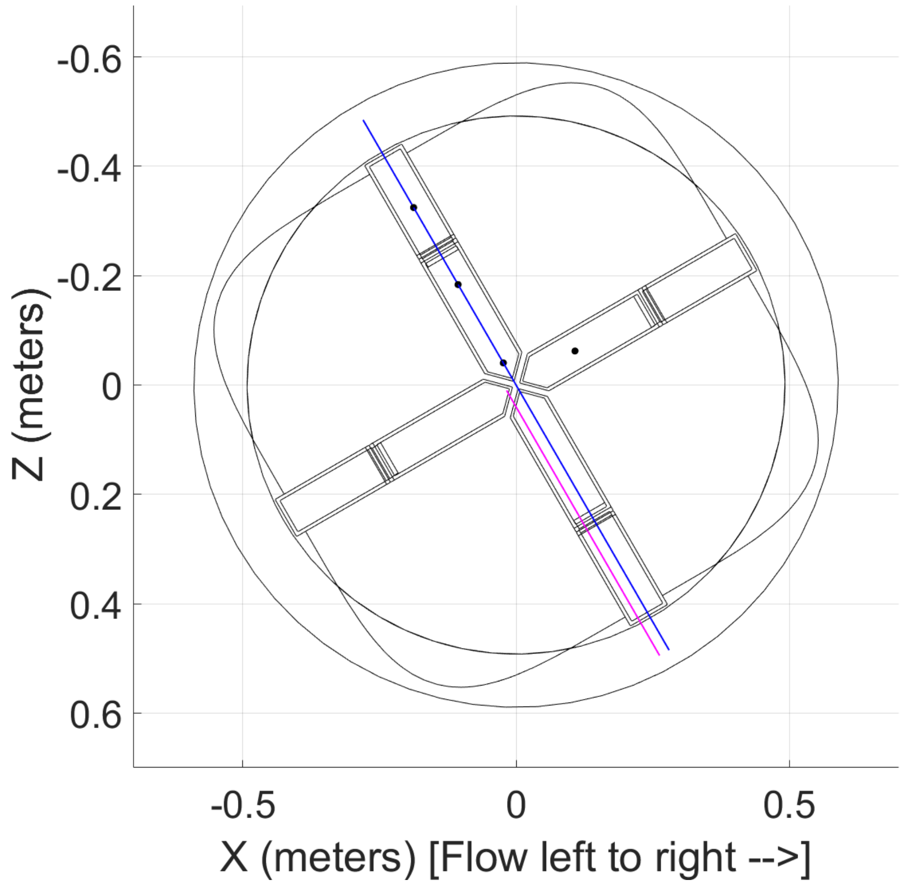


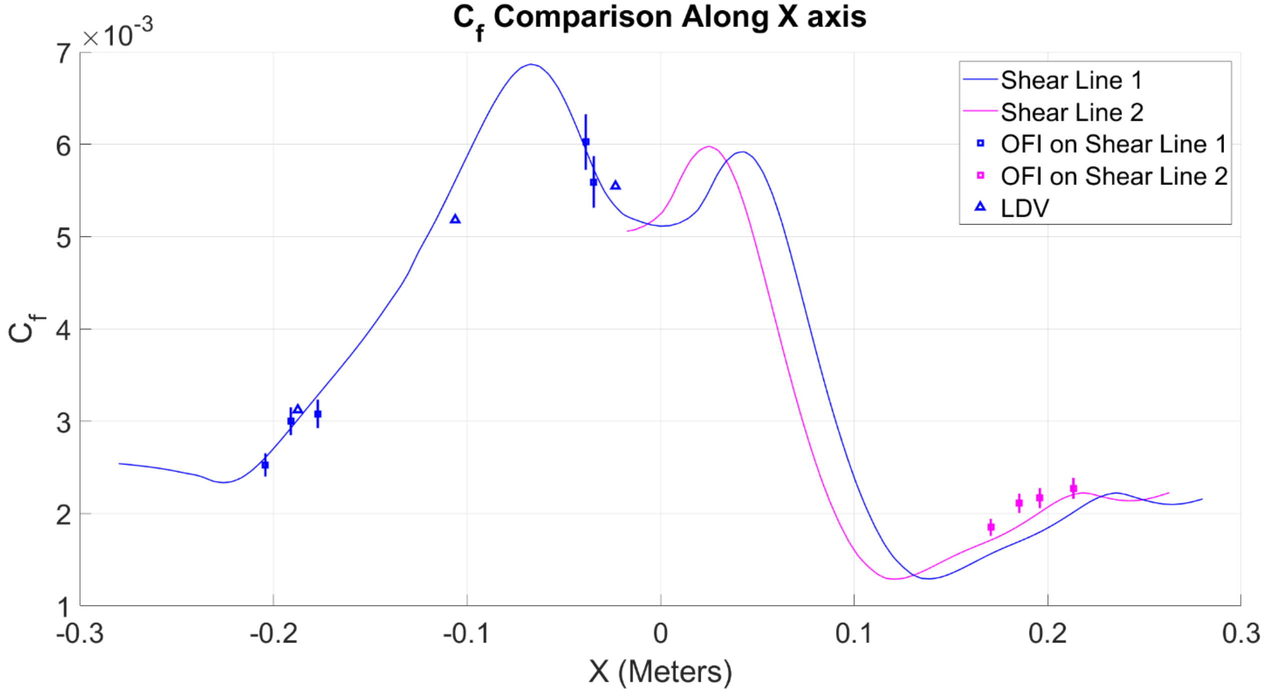
LDV Reynolds Stress Profiles: $\mathrm{Re_H} = 250\mathrm{k}$





OFI/LDV Wall shear comparisons





Wrap up

- Measurements were the culmination of several major wind tunnel entries focused on the BeVERLI Hill
- Results covered distinct regimes of interest on the Hill, providing a range of possible comparisons and model validation measures
- Moving forward, the data will be archived for further validation studies by the community

Thanks so much for the attention and all the engagement throughout the BeVERLI project.