

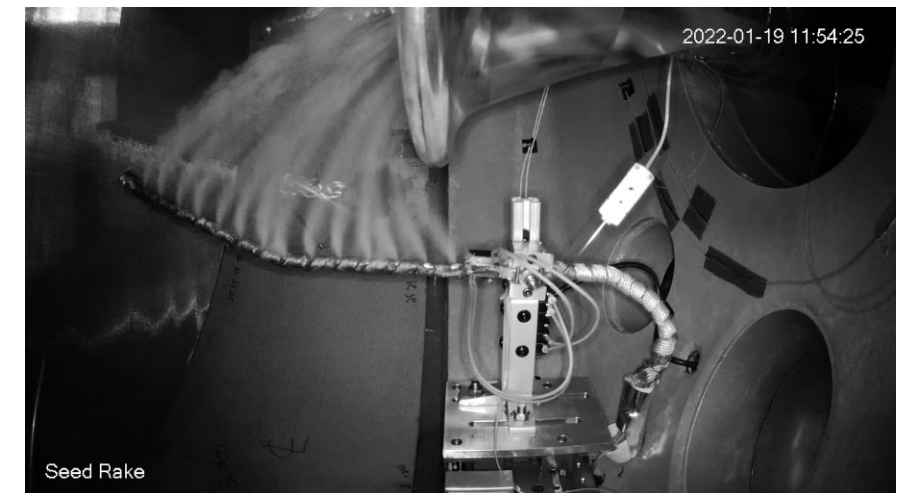
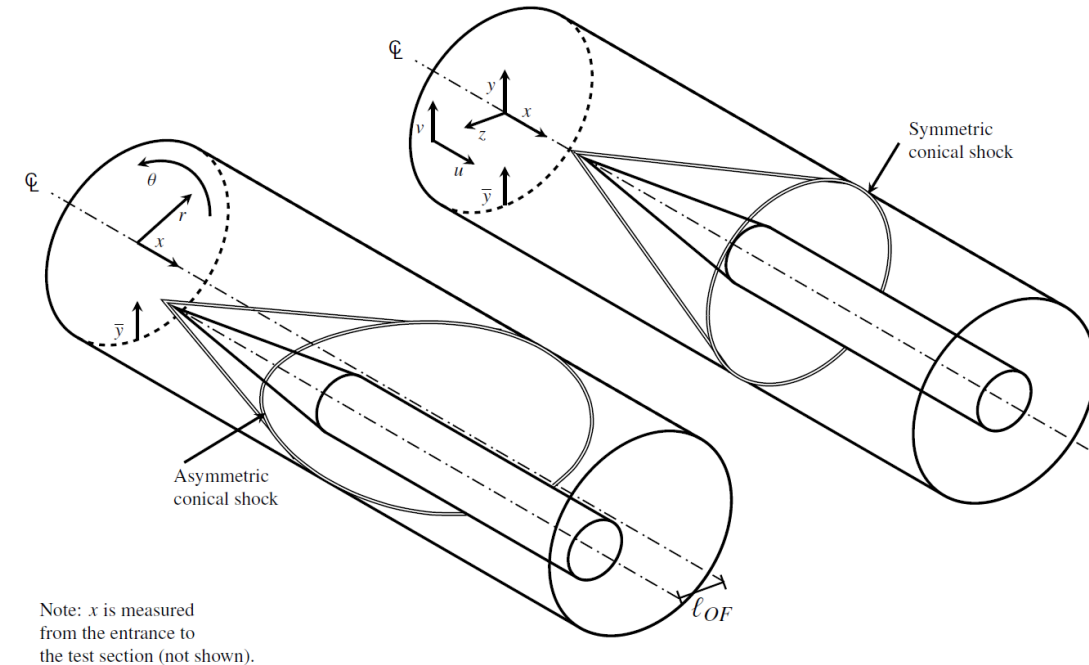


Development and Assessment of a New Particle Image Velocimetry System in the NASA GRC 225 cm² Wind Tunnel

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- Turbulent CFD Validation Experiments (TCFDVE)
 - Test program overview, CFD2030-02, Monday at 4
 - Detailed analysis of hot-wire measurements, AMT-25, Friday at 10:10
- Detailed, redundant measurements in a canonical flowfield with well-defined inflow conditions
- Particle Image Velocimetry (PIV) selected as a component measurement due to its capability to:
 - Directly quantify 3 components of flow velocity
 - Rapidly acquire data
 - Non-intrusively sample the flow
- Completely new apparatus required to apply PIV in this facility

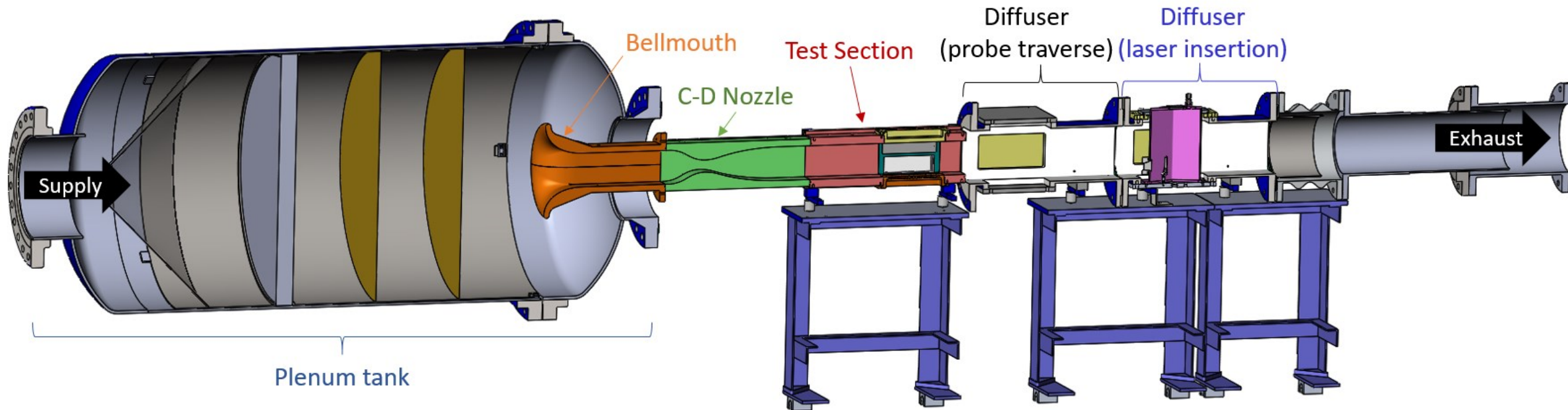


➤ NASA Glenn 225 cm² Wind Tunnel

- Continuous flow
- **Square**, circular, or octagonal cross-section
- Heated supply, closed-loop Reynolds number control

Square configuration used for current work due to:

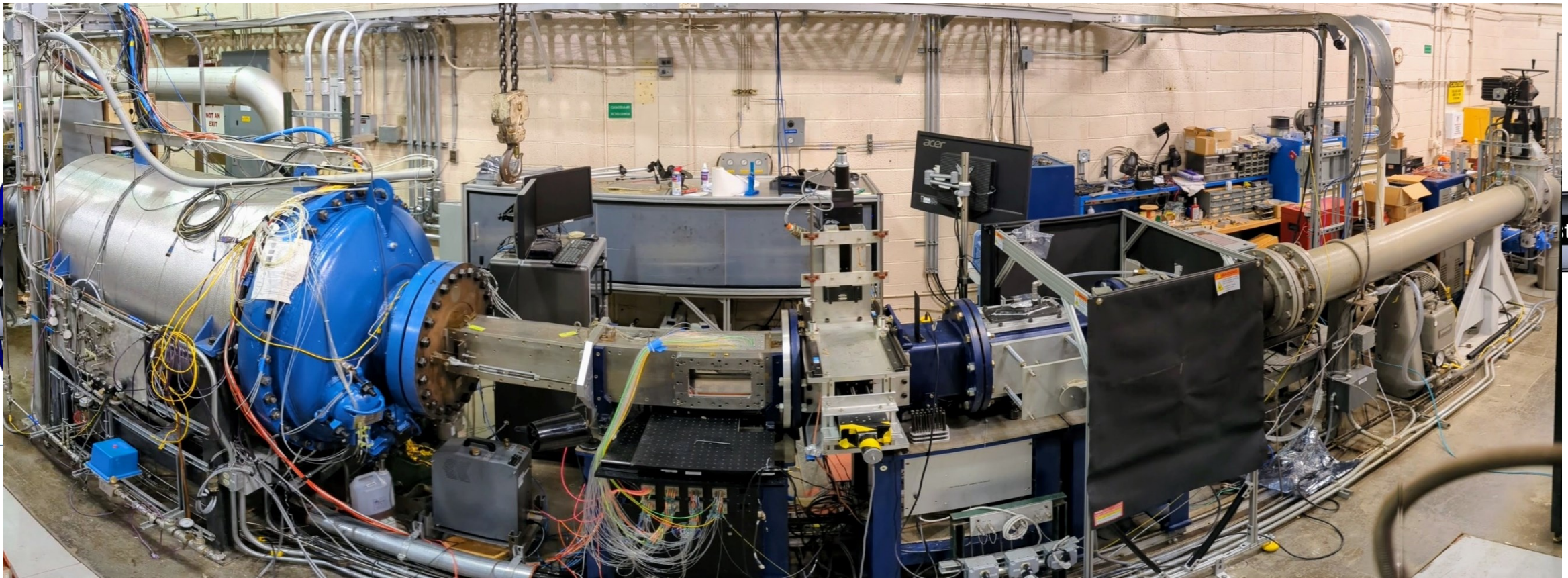
- Simplified optical access
- Existing shock generator hardware



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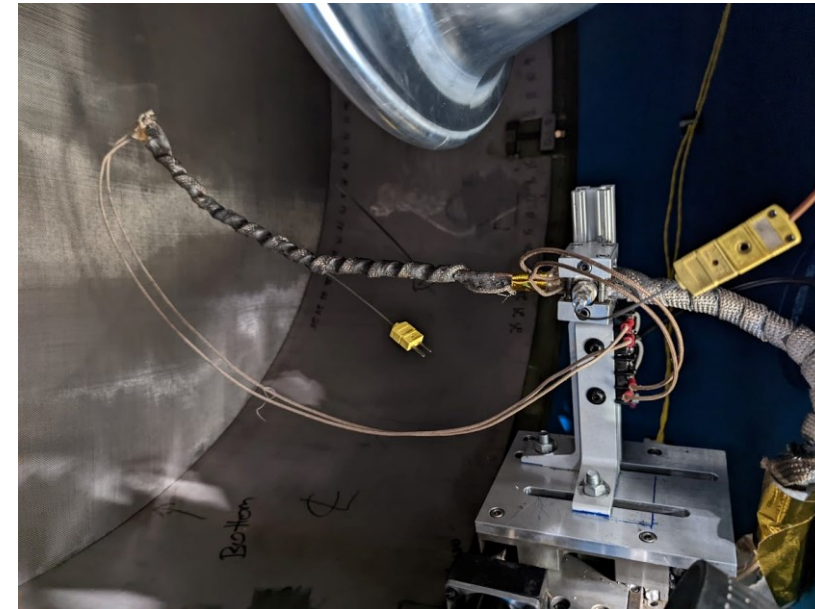
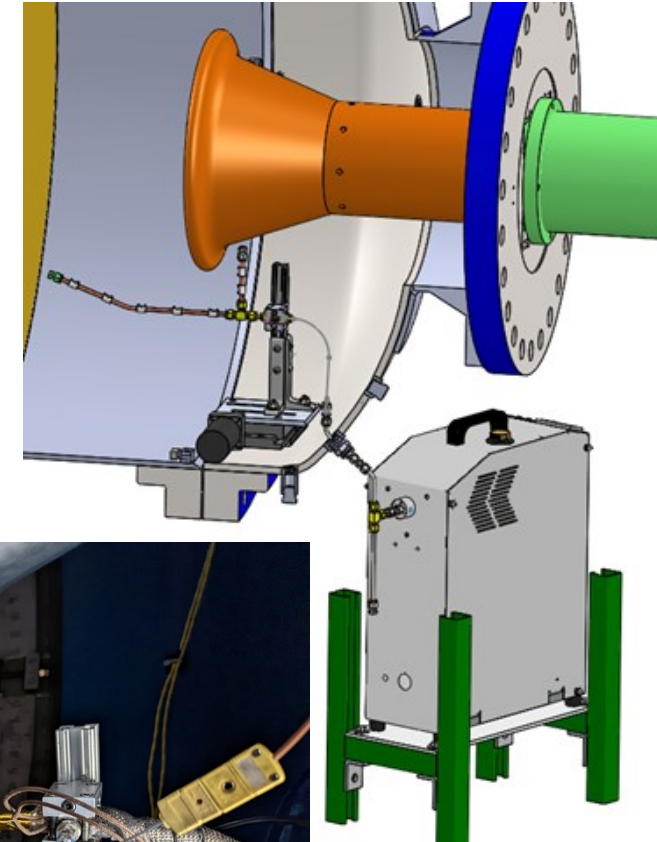
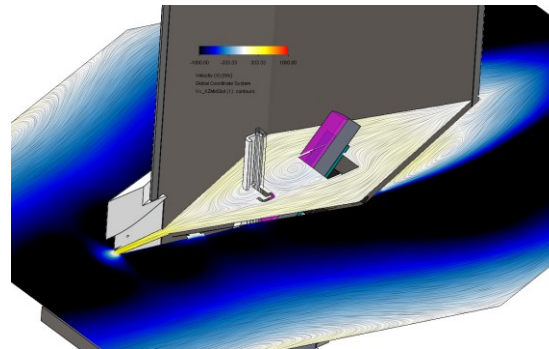
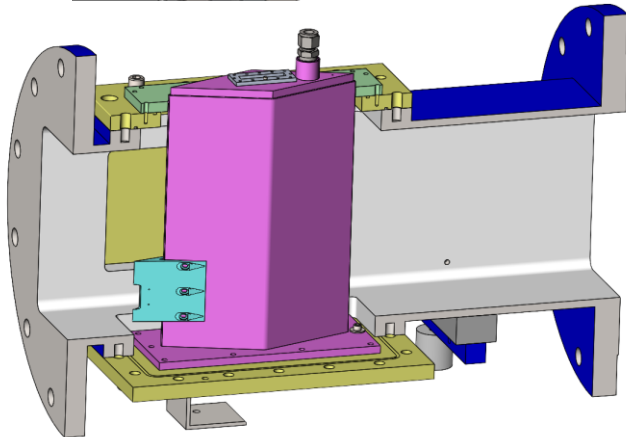
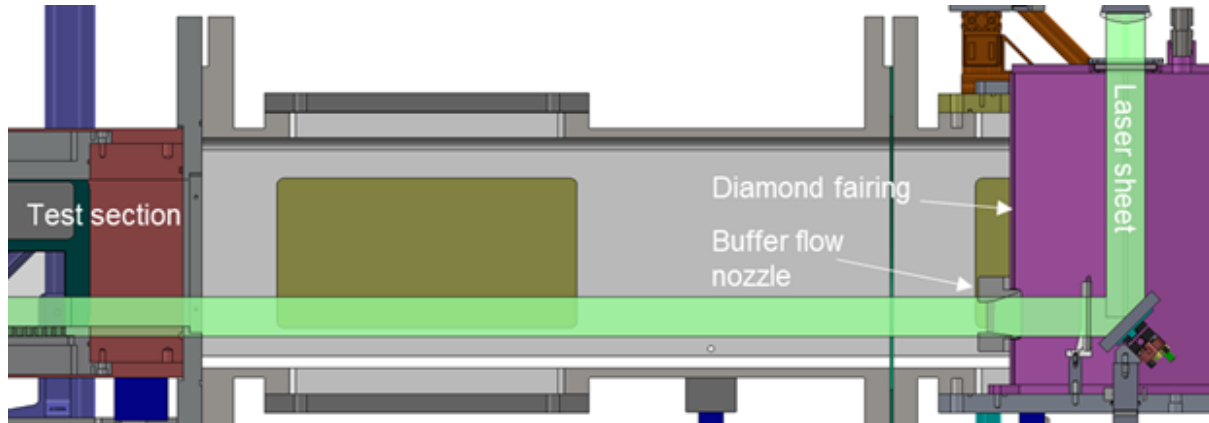
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PIV System Design

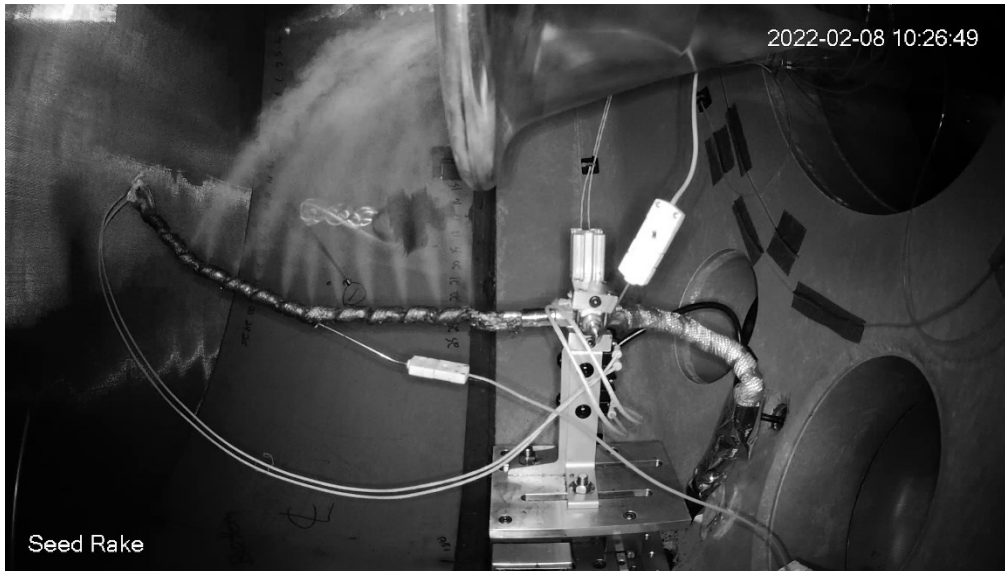
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- Applying PIV required multiple changes to the facility
 - New plenum tank end cap with access ports
 - Infrastructure for remote operation of commercial smoke generator
 - **Custom heated “rake” to disperse seed material (focus of this paper)**
 - Laser sheet insertion into wind tunnel diffuser section



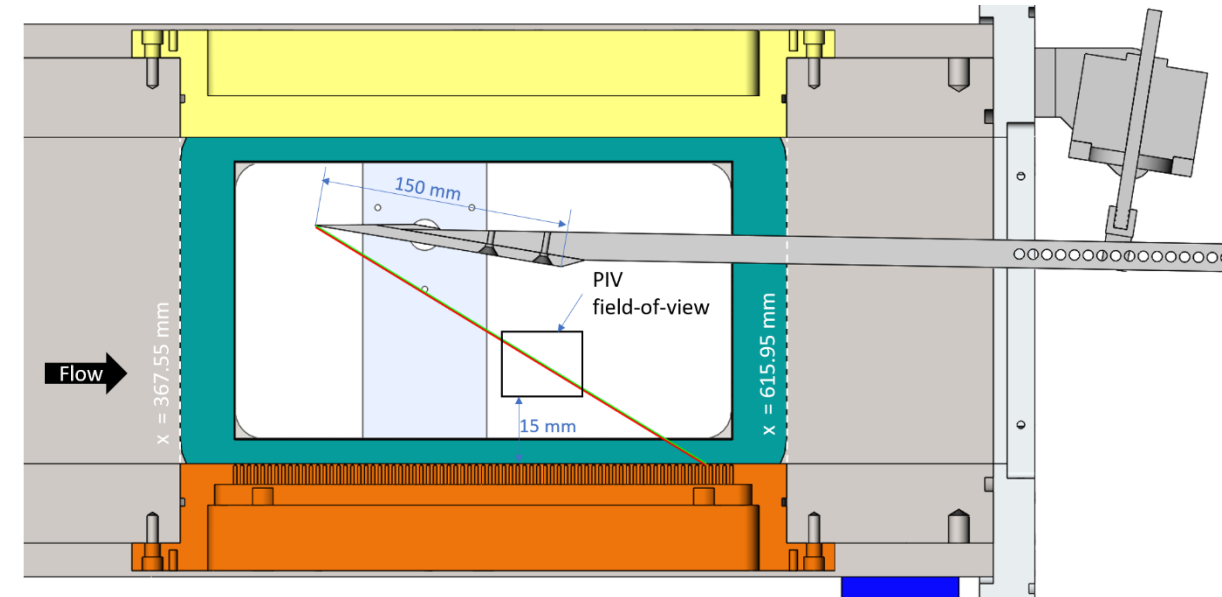
Seeding coverage & concentration

- Evolve rake design through CFD and testing to ensure particles are delivered to region of interest in test section
- Video recordings from within plenum tank were invaluable



Seed particle size optimization

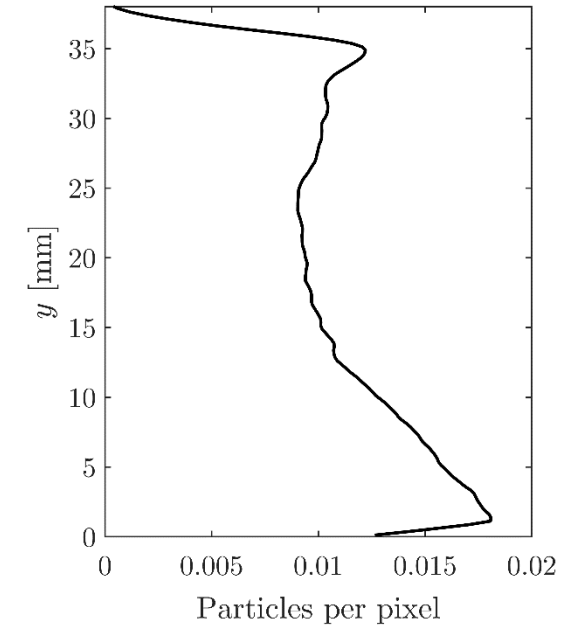
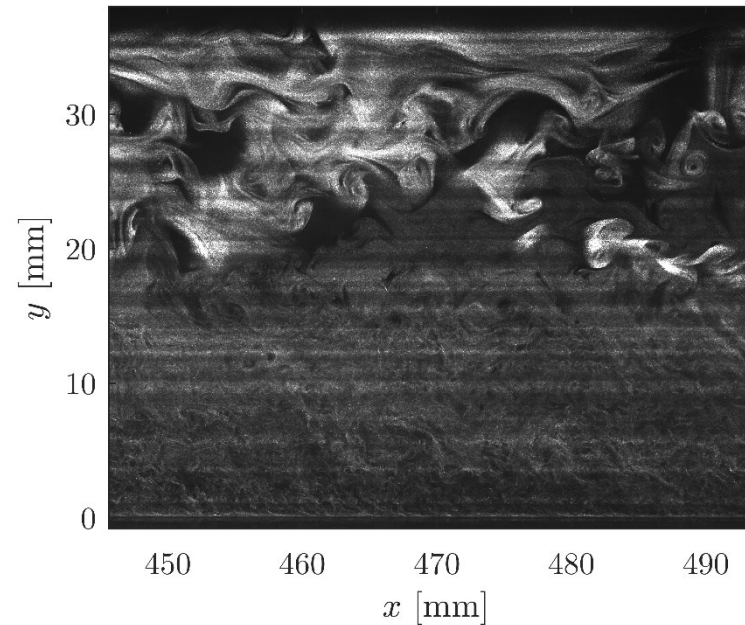
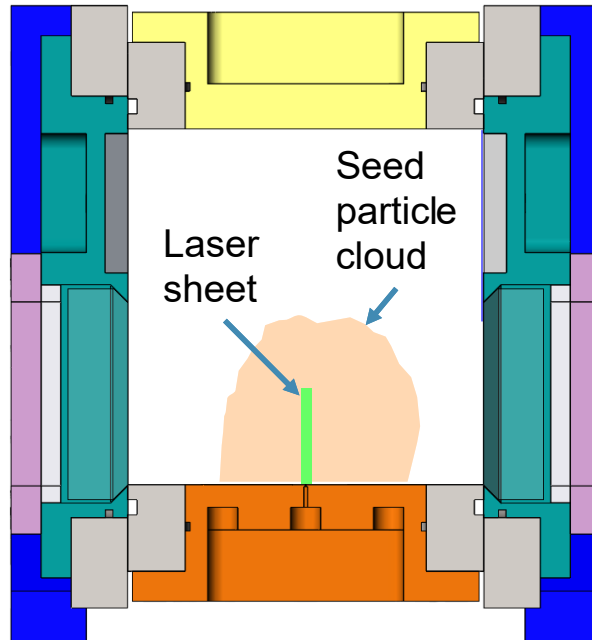
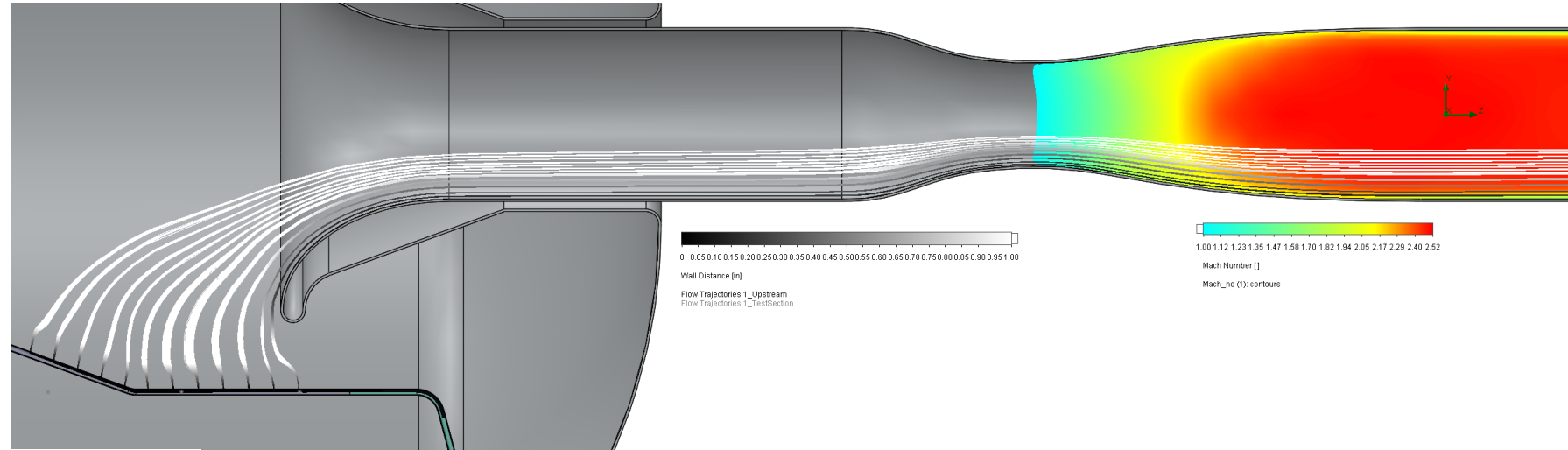
- Use PIV measurements across shock wave to quantify seed particle size
- Determine optimum operating parameters which minimize droplet inertia



Seeding coverage

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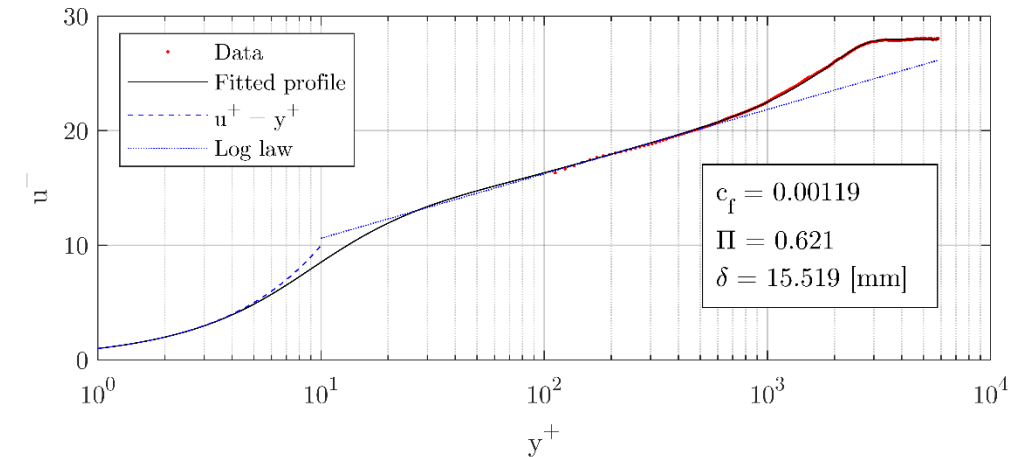
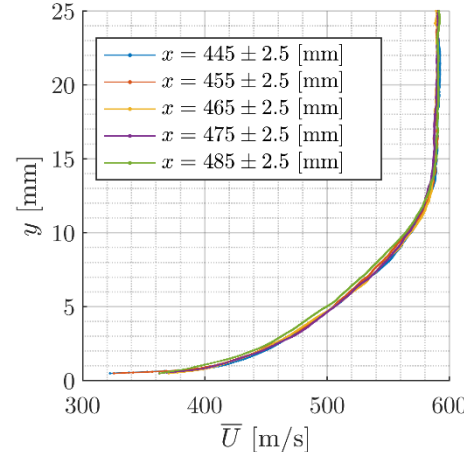
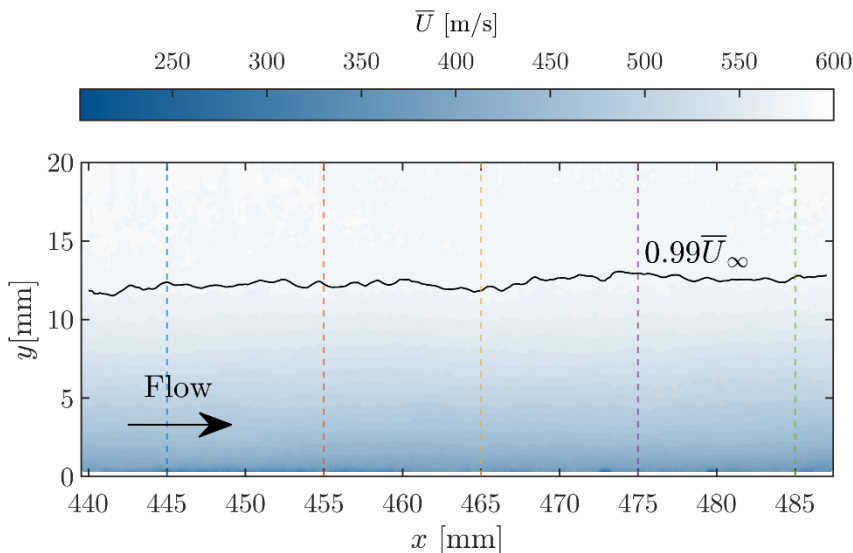
- CFD used for initial seed rake design
- Planar PIV images used to visualize particles at relevant test section station
- BL turbulence mixes particles well; freestream flow has large variation due to frozen structures carrying large quantity of seed



Test Section Floor Boundary Layer PIV

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- This dataset can also be used to confirm capability of PIV to resolve boundary layer profile
- PIV processing parameters:
 - 32×32 with 4:1 stretching (equivalent to 64×16 windows) and 75% overlap
 - Reject peak ratio < 2 and $> 1\sigma$ deviation within 8×8 sub-regions
- Vector yield is $> 90\%$ for $y > 0.7\text{mm}$
- Sample below is $Re_D = 4 \times 10^6$



Re_D	Re_τ	δ_{99} [mm]	δ^* [mm]	θ [mm]	H_i	Re_θ
2.0×10^6	2.68×10^3	15.9	4.37	1.25	1.32	16.1×10^3
3.0×10^6	3.75×10^3	14.3	3.98	1.10	1.33	22.0×10^3
4.0×10^6	4.92×10^3	13.2	3.45	0.96	1.35	25.7×10^3

Re_D values are nominal set points used to control the wind tunnel, $Re_\tau \equiv \frac{u_\tau \delta_{99}}{\nu_w}$, and $Re_\theta \equiv \frac{U_\infty \theta}{\nu_\infty}$.

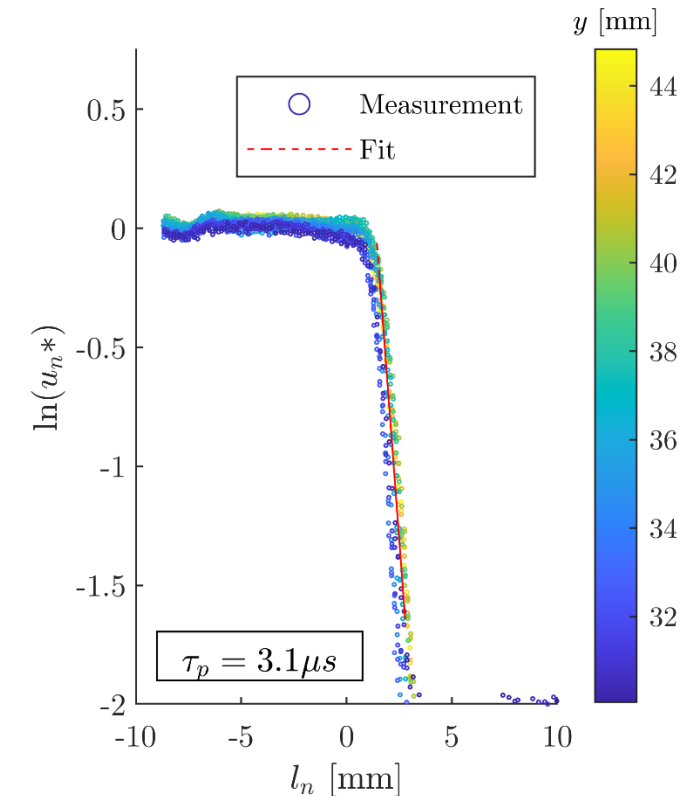
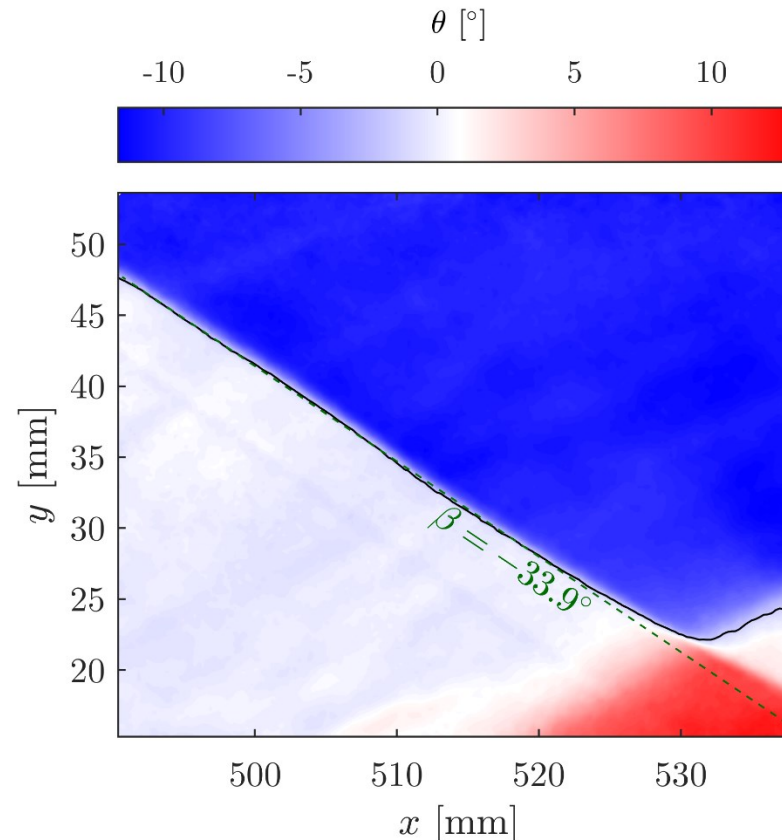
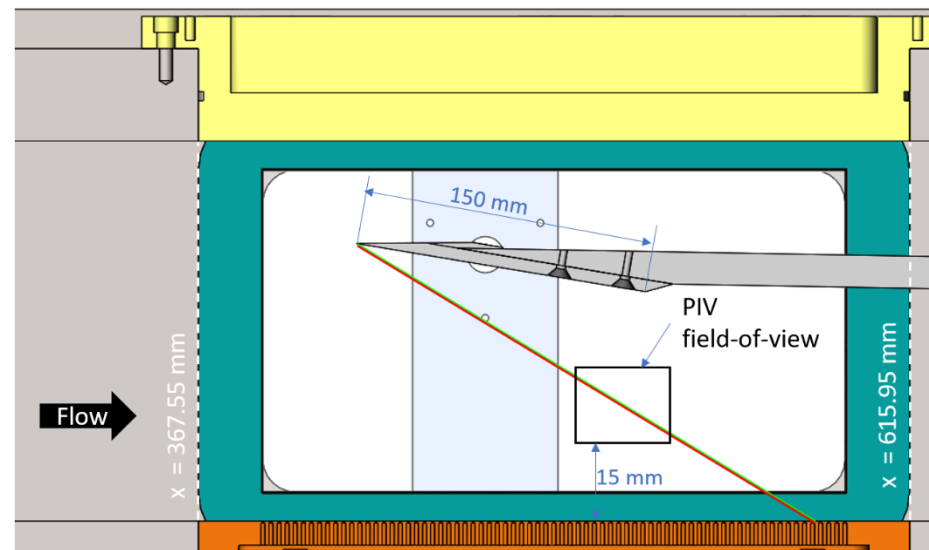
Particle Inertial Effects

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- Particle response to oblique shock wave quantified with PIV
- PIV processing parameters:
 - 32 × 32 with adaptive stretching and 50% overlap
 - Reject peak ratio <2 and >1σ deviation within 8 × 8 sub-regions

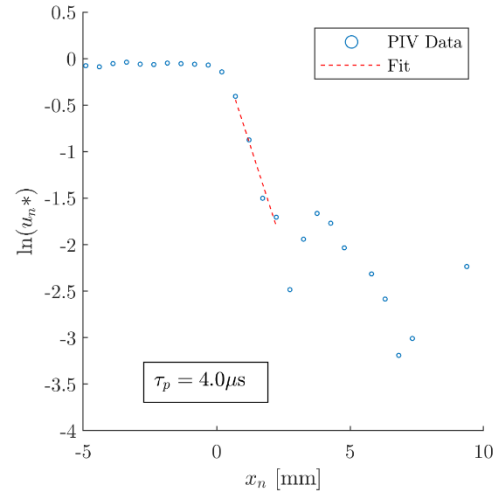
$$\frac{d\vec{U}_p}{dt} = -\frac{3}{4}c_D Re_p \frac{\mu}{\rho_p d_p^2} (\vec{U}_p - \vec{U}_f)$$

$$\ln(u_n^*) = \ln\left(\frac{u_n - u_{2n}}{u_{1n} - u_{2n}}\right) = -\frac{t}{\tau_p} \cong -\frac{l_n}{\xi_p}$$



Shock Response PIV Data Reduction

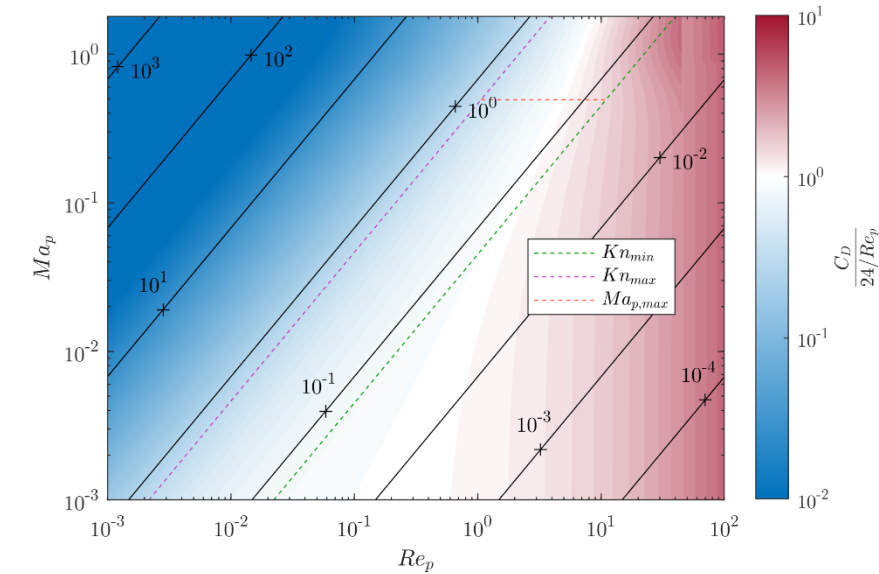
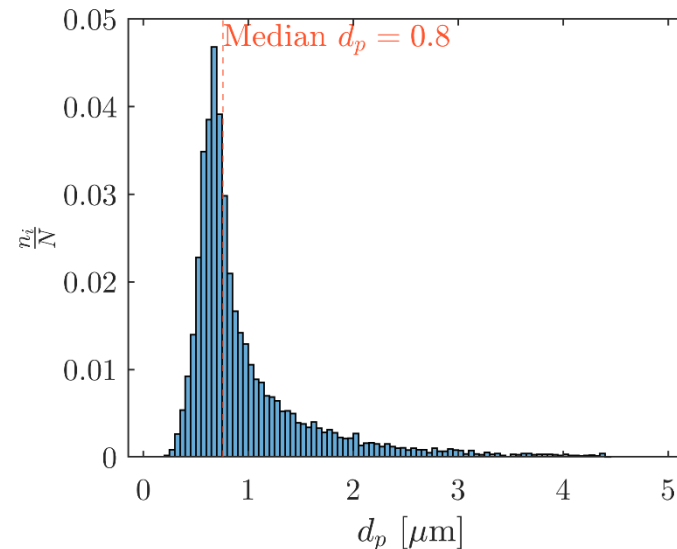
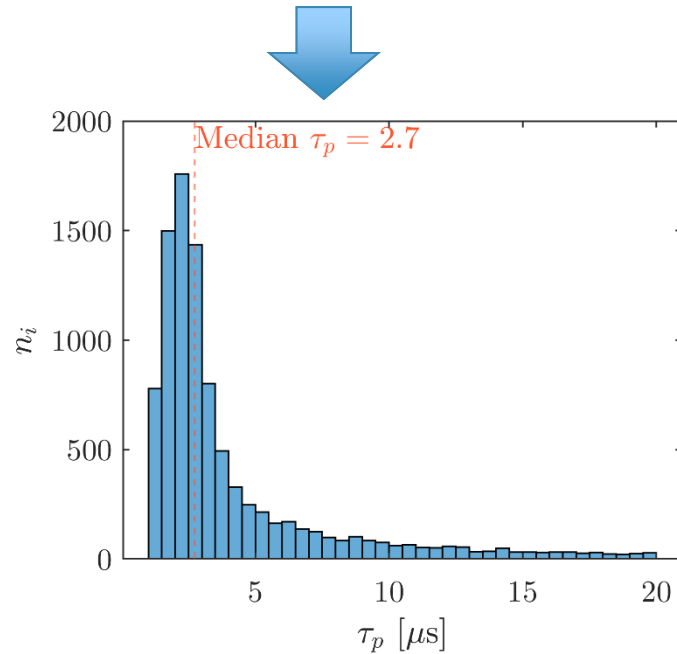
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- Fit performed line-by-line on entire dataset to compute ensemble statistics
- Lag time can be converted to diameter if drag coefficient is known

$$\frac{d\vec{U}_p}{dt} = -\frac{3}{4}c_D Re_p \frac{\mu}{\rho_p d_p^2} (\vec{U}_p - \vec{U}_f)$$

$$c_D = \frac{24}{Re_p(1 + Kn)}$$

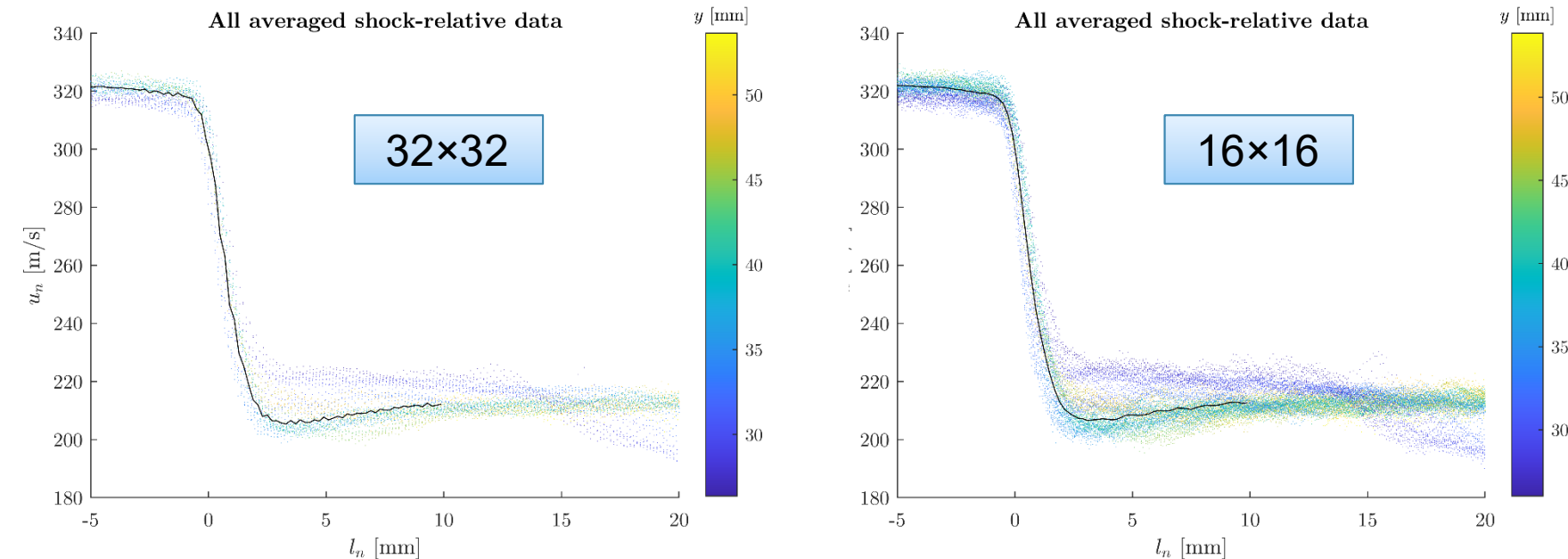


Particle Response Results

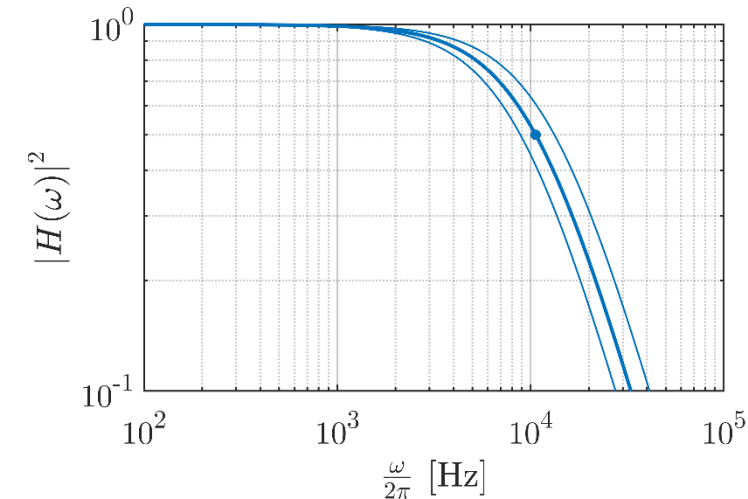
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- Median particle response was 3-4 μs at optimal settings for each Re condition
- Applying same line-by-line analysis to PIV vectors computed with 16×16 interrogations not possible due to noise/missing vectors, but average results unchanged

$\text{Re}_D (\times 10^{-6})$	2	3	4
P_{N_2} [psig]	95	115	120
τ_p [μs]	2.7	3.1	3.2
$d_{p,st}$ [μm]	0.77	0.78	0.80



Particle response function

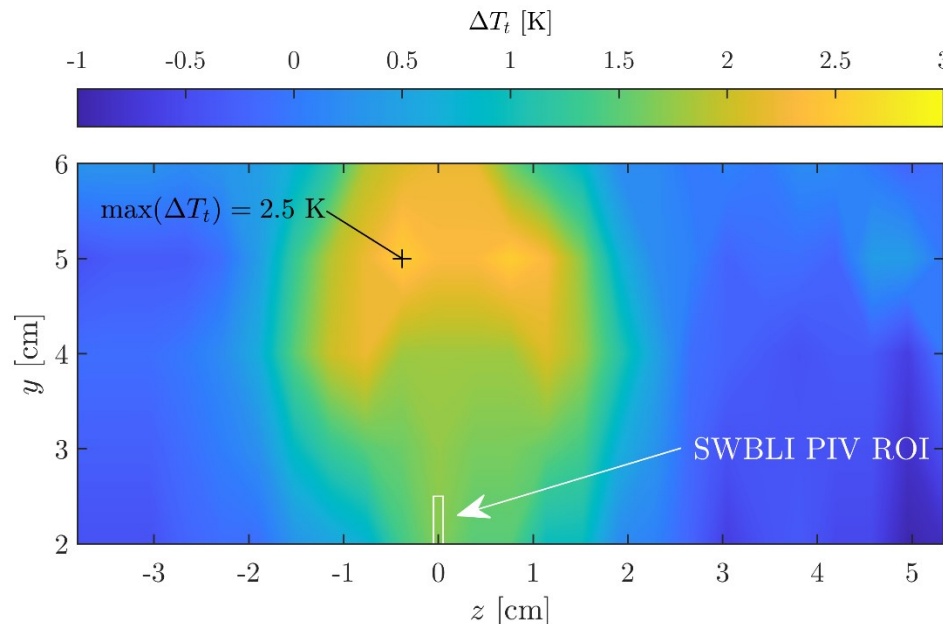


- Relative to BL outer timescale, δ/U_∞ , Stokes number $< 0.2 \rightarrow$ velocity error bounded to $< 2\%$ (Samimy & Lele 1991)
- High-frequency response damped by 50% around 10 kHz (Mei 1996)

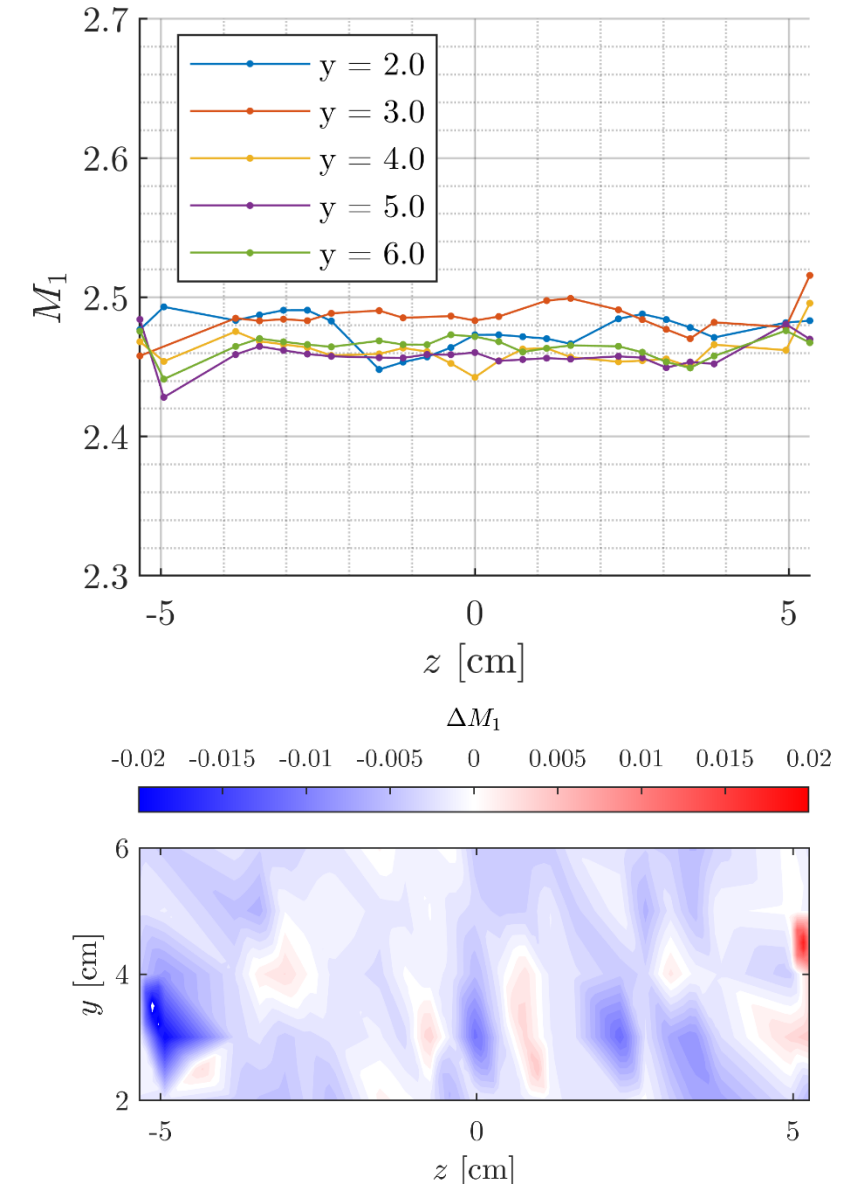
Seed Rake Influence

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- Cross-stream probe surveys performed to assess disturbance created by seed rake
- Spanwise Pitot and static pressure probe surveys characterized velocity wake
- Cold-wire probe used to identify thermal wake generated by hot rake



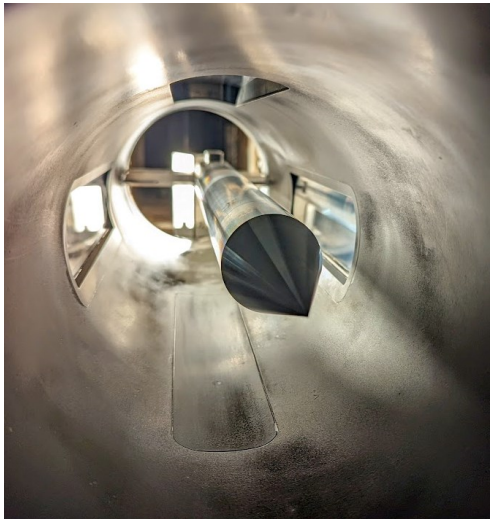
Typical values
 Tunnel $T_t = 311$ K
 $T_{\text{rake}} = 500\text{-}530$ K
 Rake $\Delta T \gg 2.5$ K



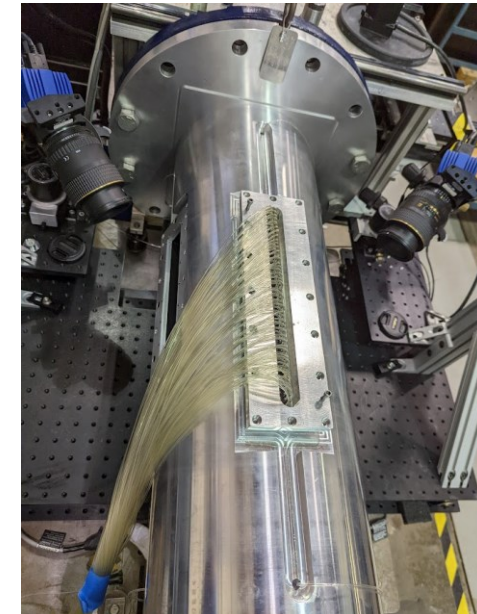
Conclusions & Acknowledgments

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- New PIV measurement capability added to the NASA GRC 225 cm² Wind Tunnel
 - Specifically designed to perform near-wall measurements for shock-wave/boundary-layer interaction studies
 - Local seeding maintains long test duration capability of wind tunnel by keeping viewing windows clean
- Effect of seed particle inertia was quantified and optimized
 - Sub-micron median particle size over range of operating conditions
- Perturbations to baseline wind tunnel flowfield due to seeding apparatus found to be negligible



Next : SWBLI measurements in circular test section



This work was made possible by:

- Funding by the NASA Transformation Tools & Technologies Project (T³) under the TACP
- Many insightful suggestions from Mark Wernet (NASA GRC)
- NASA Glenn Engine Research Building facility staff