Multipurpose Rotating Rake Arrays for Integrated Inlet and Fan Stage Performance Measurement

Supported by: NASA Advanced Air Transport Technology Project
Integrated Boundary Layer Ingestion Subproject

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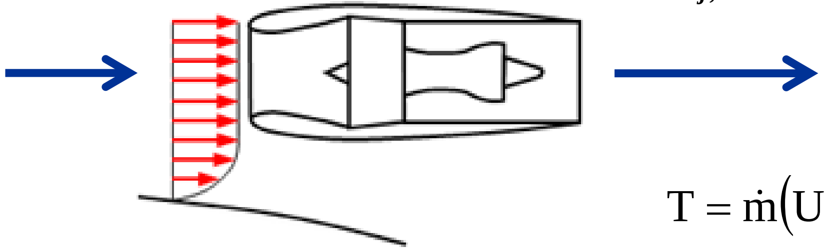
Boundary Layer Ingestion: Benefits and Application

Because average inlet velocity is lower for BLI, jet velocity is also lower when thrust and airflow are fixed.

BLI offers significant **propulsive** efficiency and fuel burn benefits relative to conventional propulsion.

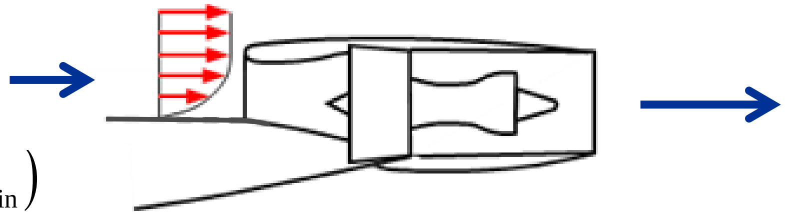
Conventional Propulsion

$U_{in,conv} = U_0$ $\qquad$ $U_{j,conv}$



Boundary Layer Ingesting Propulsion

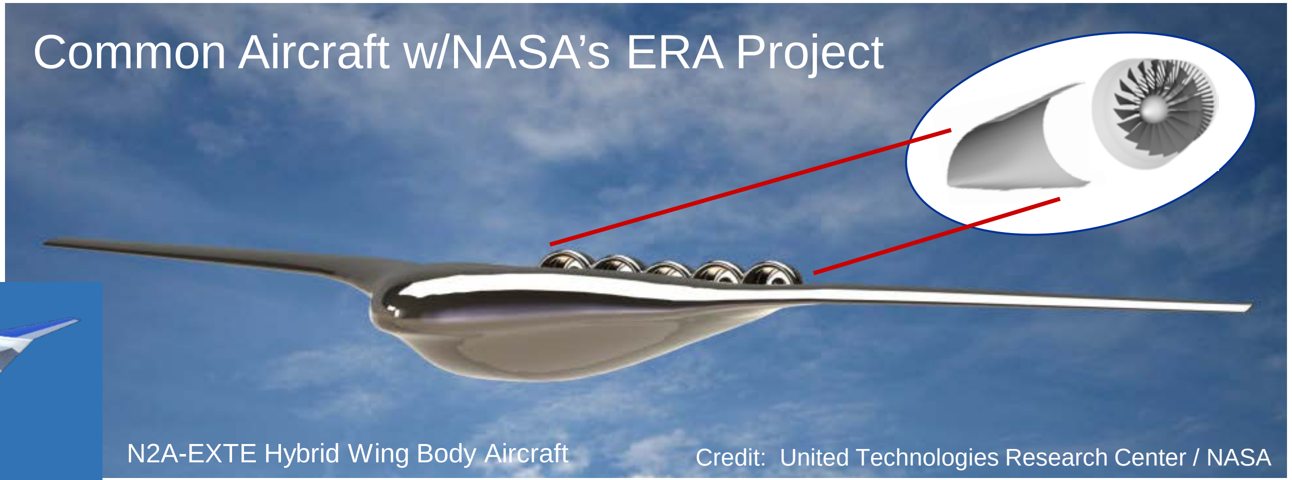
$\bar{U}_{in,BLI} < U_0$ $\qquad$ $U_{j,BLI} < U_{j,conv}$



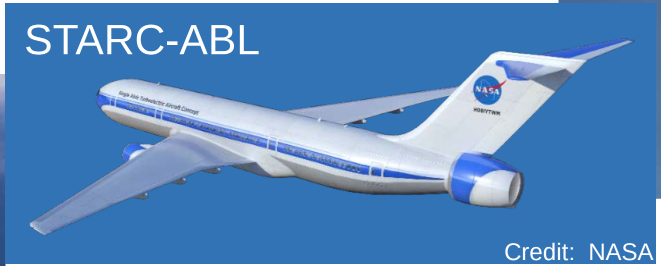
$$T = \dot{m}\left(U_j - U_{in}\right)$$

$$P = \dot{m}\left(U_j^2 - U_{in}^2\right)$$

Our reference configuration was the N2A-EXTE HWB aircraft, but other configurations could benefit from BLI.



Credit: United Technologies Research Center / NASA

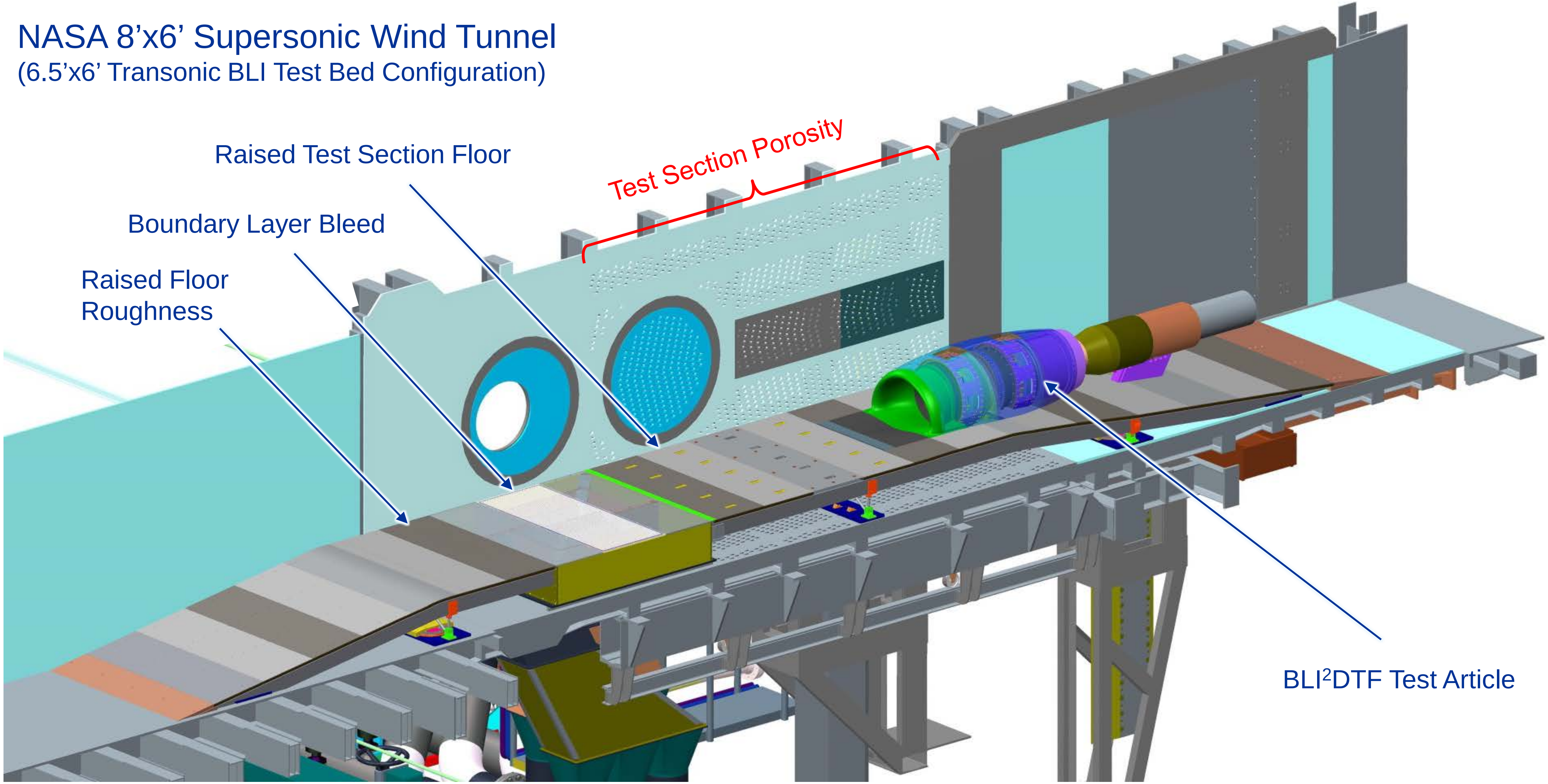


Credit: NASA

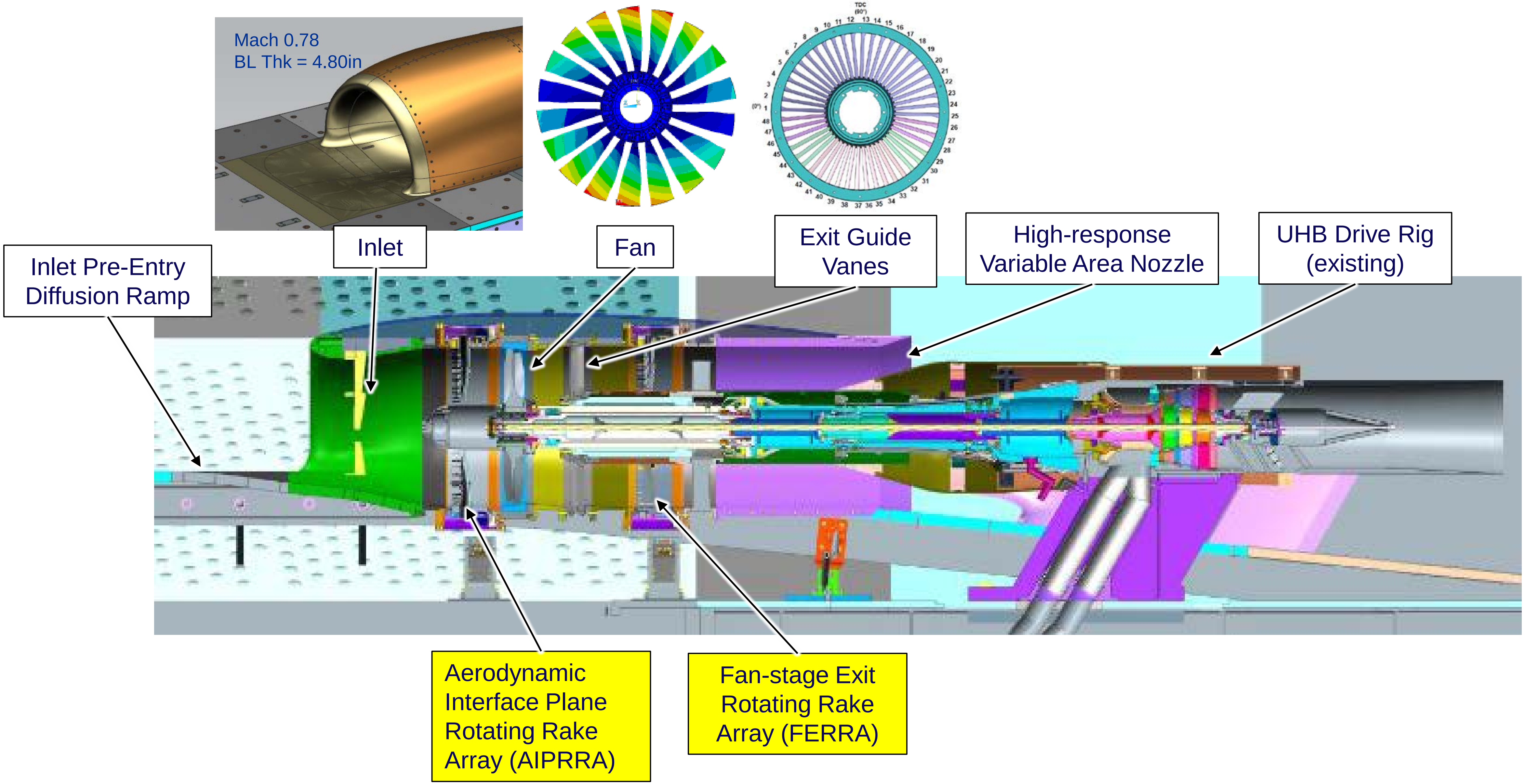
Credit: NASA / MIT / Aurora Flight Sciences

Boundary-Layer-Ingesting Inlet / Distortion-Tolerant Fan (BLI^{2}DTF) Experiment

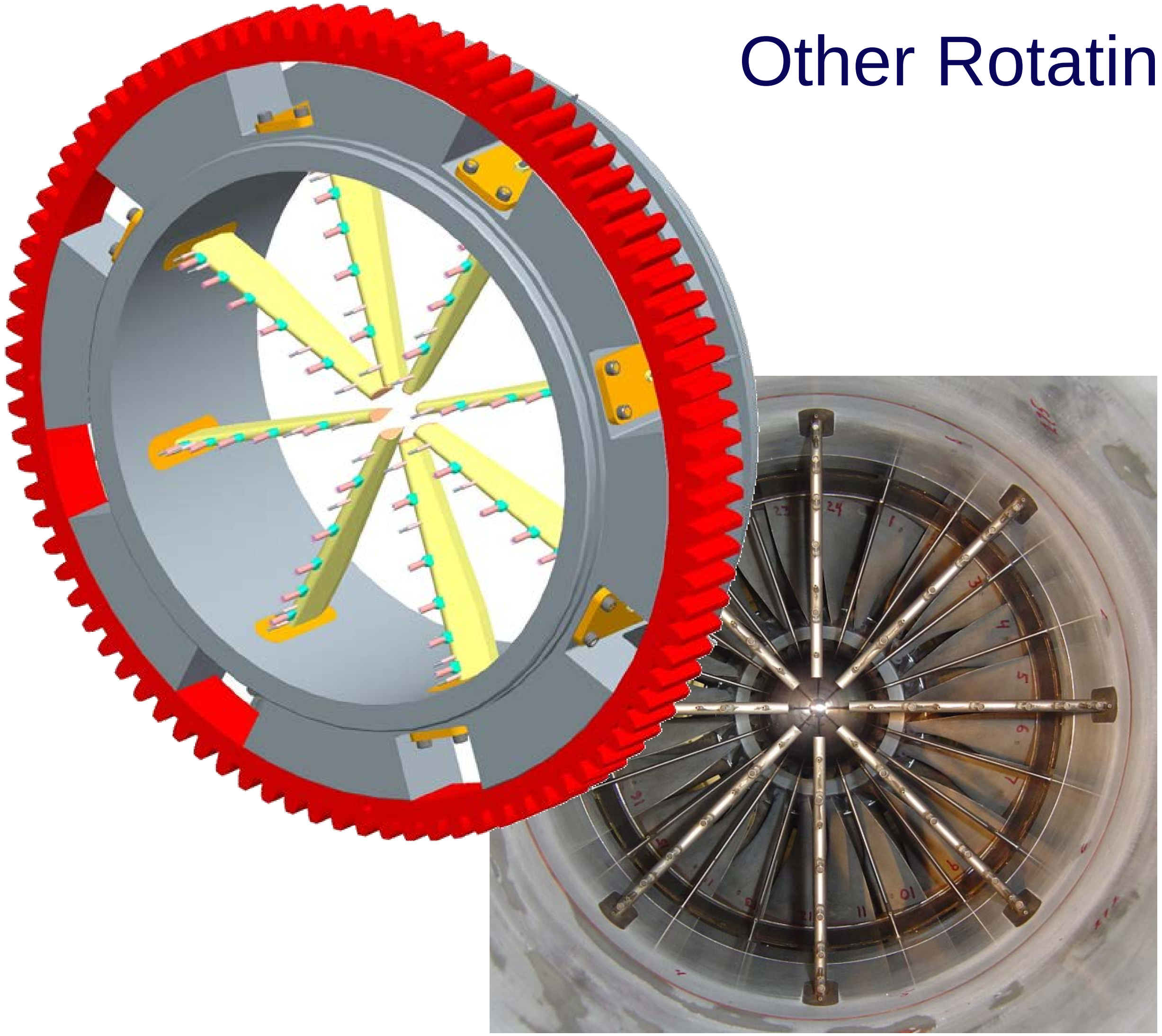
NASA 8'x6' Supersonic Wind Tunnel
(6.5'x6' Transonic BLI Test Bed Configuration)



Integrated BLI²DTF Test Article



Other Rotating Rake Arrays

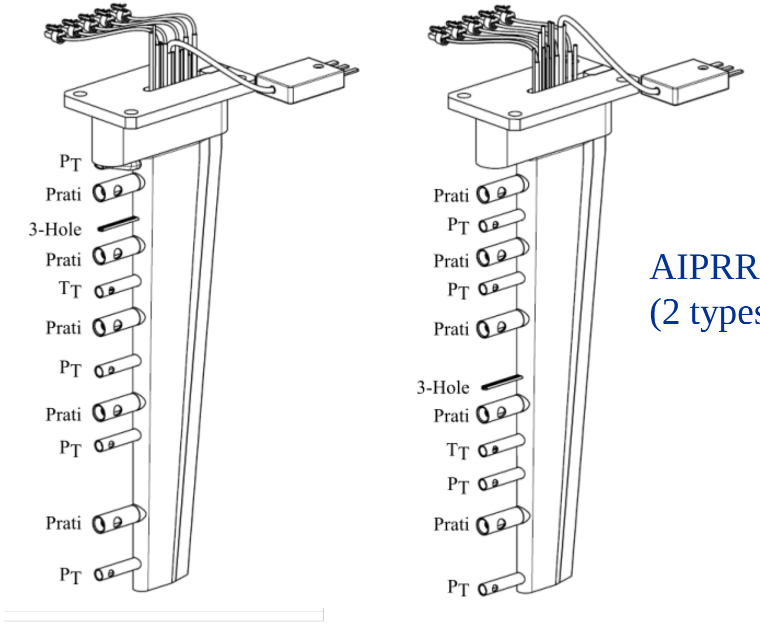


Active Inlet Flow Control Rig

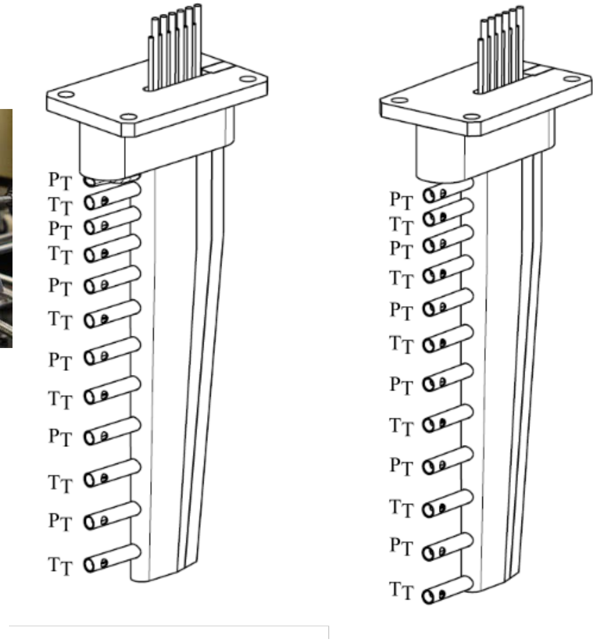
Active Noise Control Fan Rig
Rotating Microphone Rake

Rotating Rake Arrays

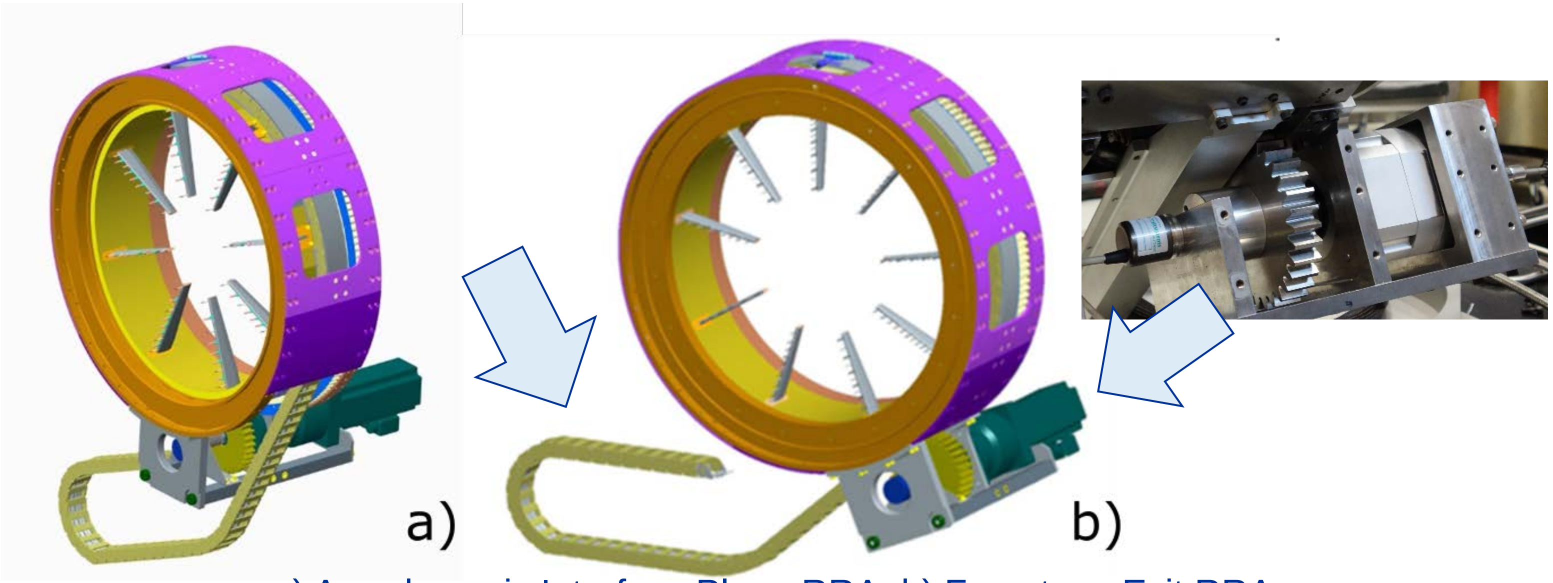
- Rotating Rake Arrays (RRA) measured P_T, T_T, P_S, angularity
- Adiabatic efficiency, flow rate, inlet total pressure recovery, and distortion are derived from RRA measurements upstream and downstream of the fan stage.
- High data density achieved through rotations and probe arrangements (FERRA 24 radial x 72 circumferential measurements; AIPRRA P_T 13 x 72)



AIPRRA Rakes (2 types)



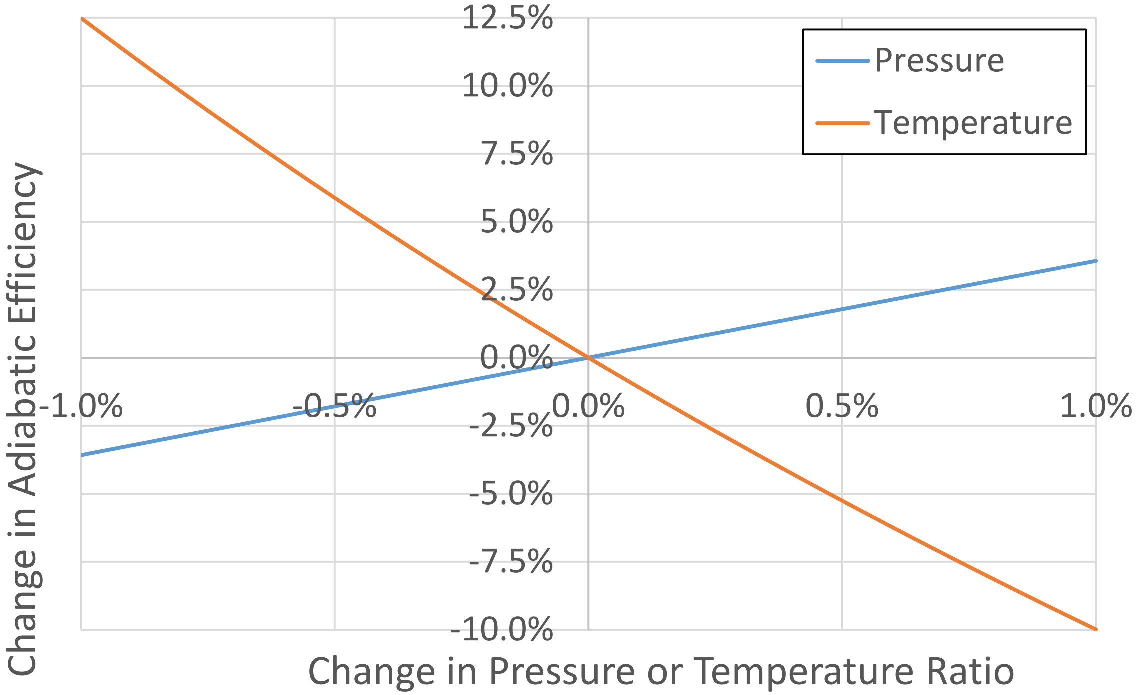
FERRA Rakes (4 types; P_T and T_T reversed on types not shown)



a) Aerodynamic Interface Plane RRA; b) Fan-stage Exit RRA

The Adiabatic Efficiency Measurement Challenge

- When fan stage pressure ratio (s_P) and stage temperature ratio (s_T) are close to unity, measurement of adiabatic efficiency becomes challenging
- Accurate measurement of entrance/exit conditions is critical



$$\eta_A = \frac{s_P^{\frac{\gamma-1}{\gamma}} - 1}{s_T - 1}$$

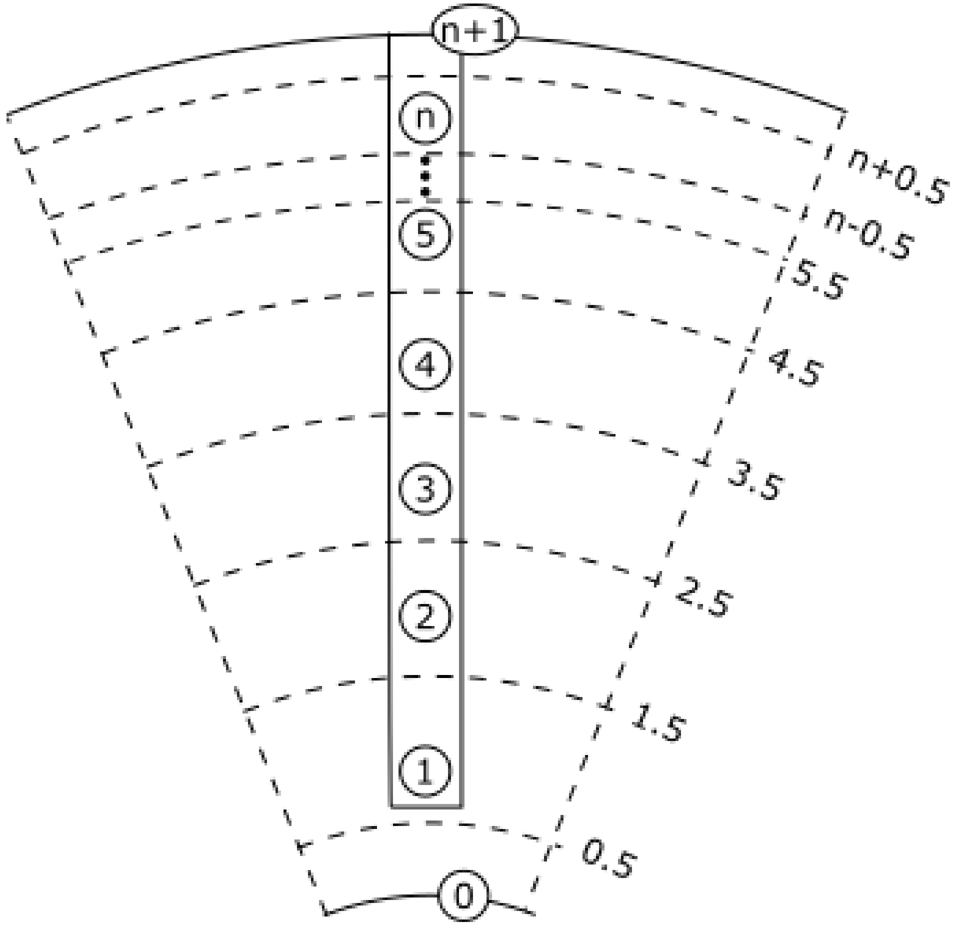
$$s_P = \frac{P_{T,Fan\_stage\_exit}}{P_{T,Aerodynamic\_interface\_plane}}$$

$$s_T = \frac{T_{T,Fan\_stage\_exit}}{T_{T,Aerodynamic\_interface\_plane}}$$

Methods

- Simulations of the rake surveys were performed by sampling from a CFD flowfield with a variety of rake measurement patterns
- CFD data for surveys were derived from time-averaged, full-circumference solutions by UTRC, using UTCFD, a Reynolds-averaged Navier-Stokes solver using the k-ω turbulence model.
- Two rounds of CFD solutions were used.
  - First round: conventional inlet and fan exposed to BLI flowfield
  - Second round: BLI^{2}DTF inlet and fan exposed to BLI flowfield

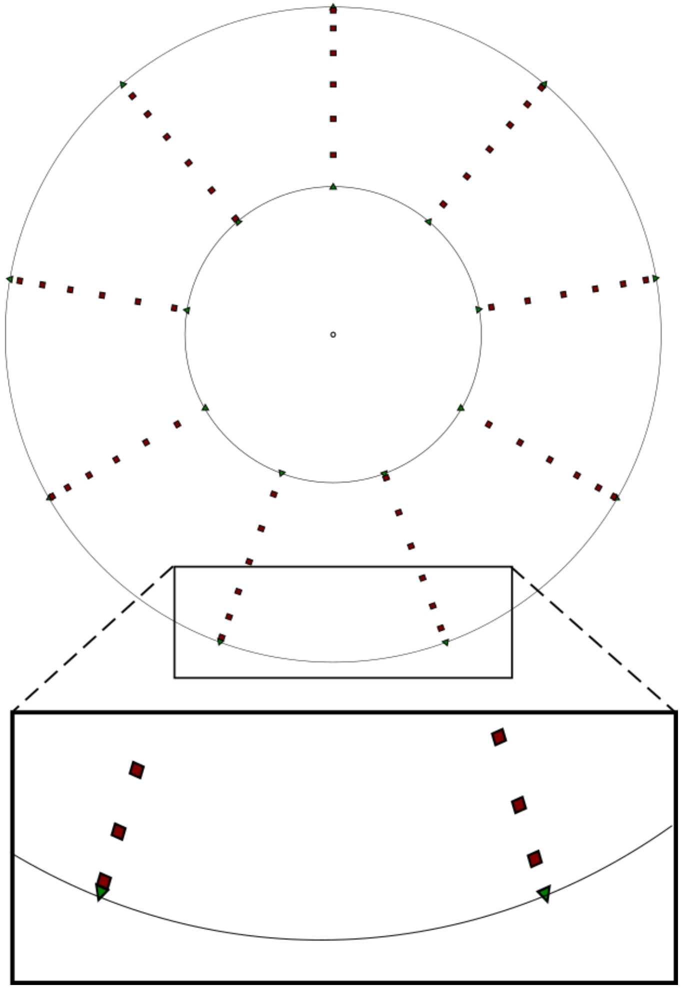
Area Weighting (Unstretched)

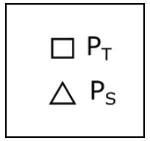


Vinokur, M., "On one-dimensional stretching functions for finite-difference calculations," *Journal of Computational Physics*, vol. 50, 1983, pp. 215–234.

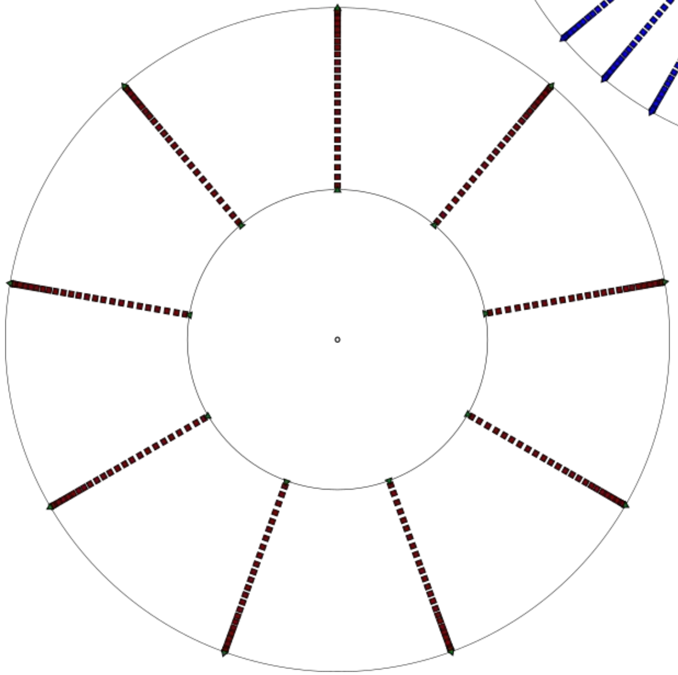
Methods: Simulated Survey Sampling

a) FERRA Rakes

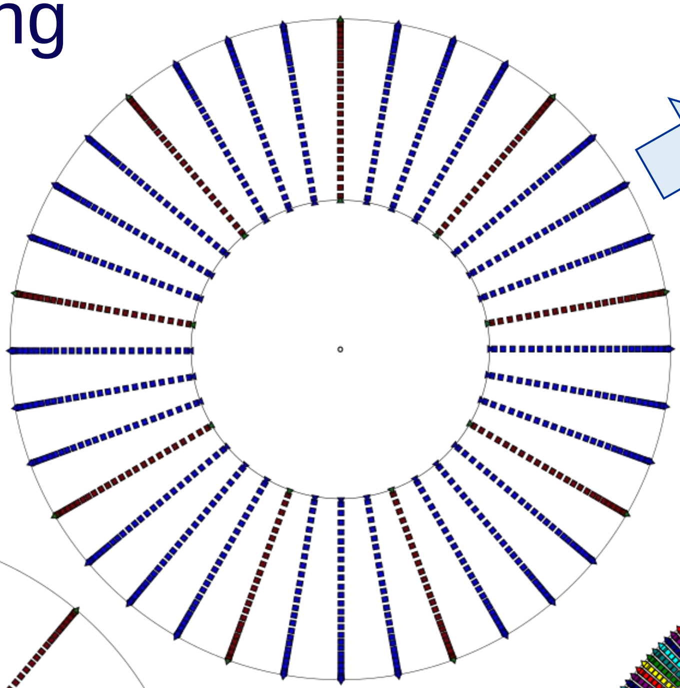




b) overlapped

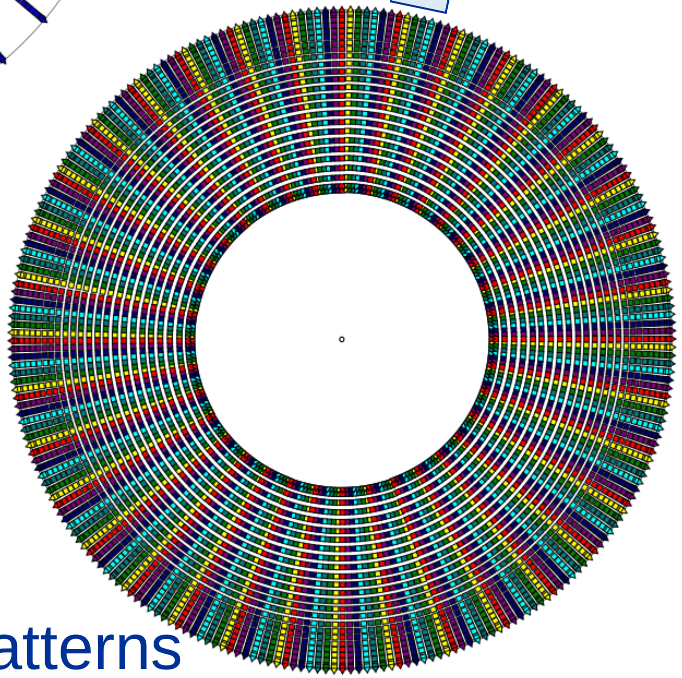


c) survey pattern



Mach, Massflow, Massflow-Averaged P_T & T_T

Standard Deviations of Variables



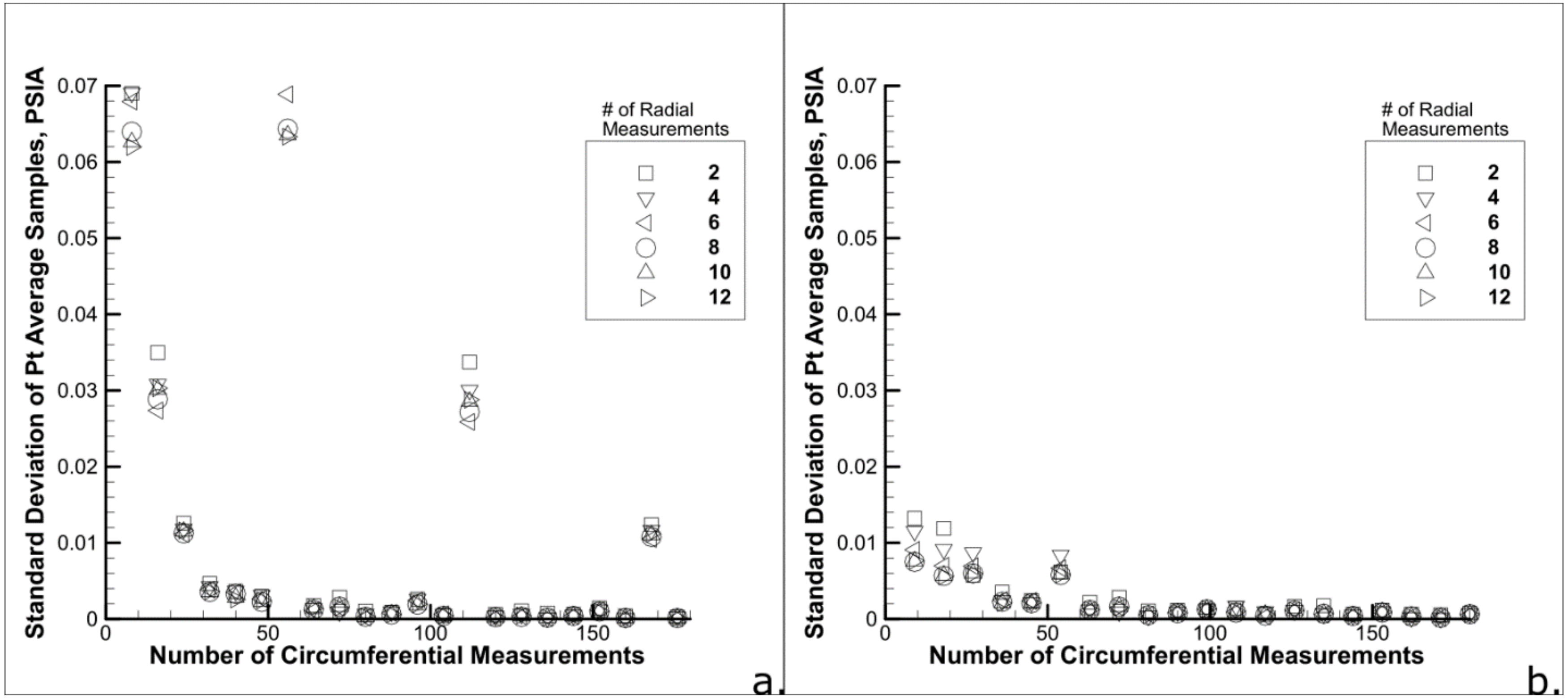
d) offset patterns

First Round Simulated Survey Results (FERRA) – Total Pressure

“Spikes” appear in data at 56, 112, 168 circumferential measurements

8 Rakes

9 Rakes

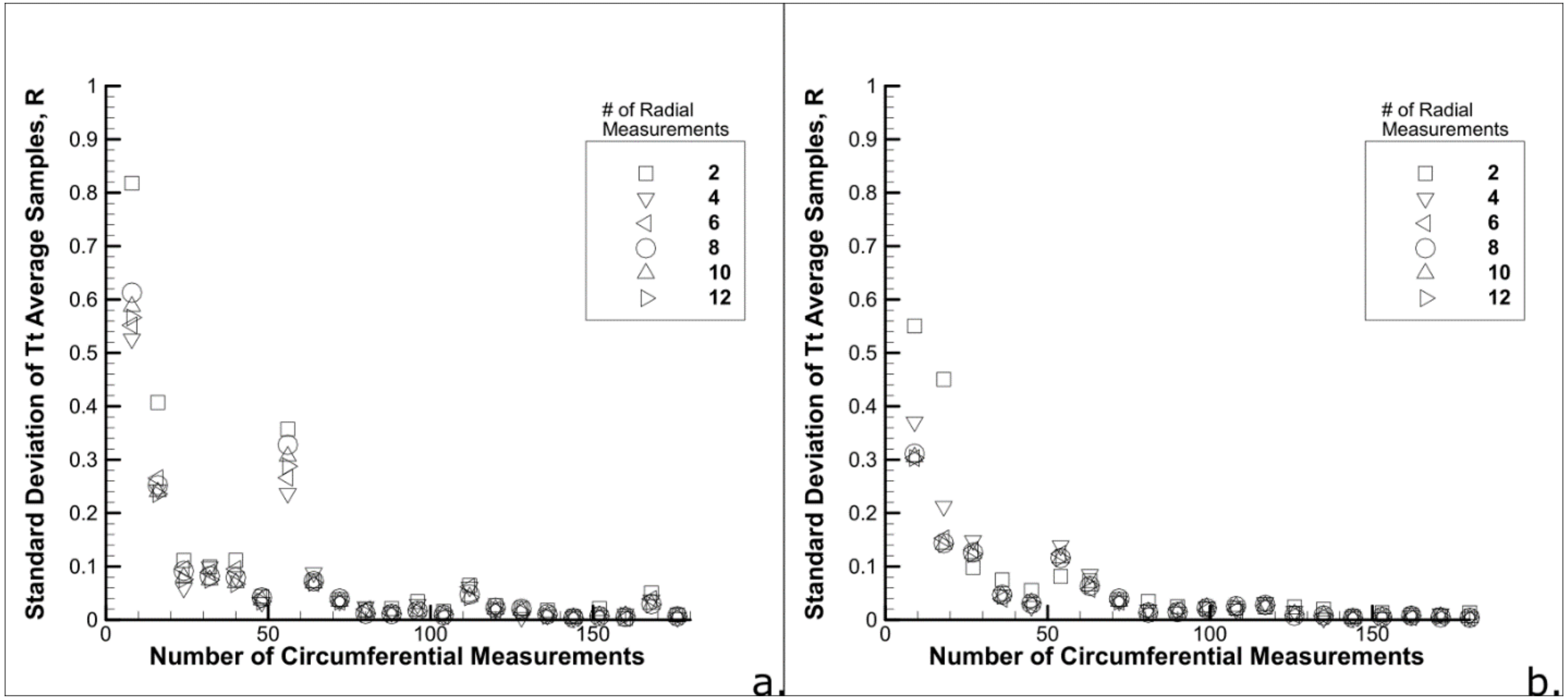


First Round Simulated Survey Results (FERRA) – Total Temperature

…Likewise for temperature, though less dramatic

8 Rakes

9 Rakes

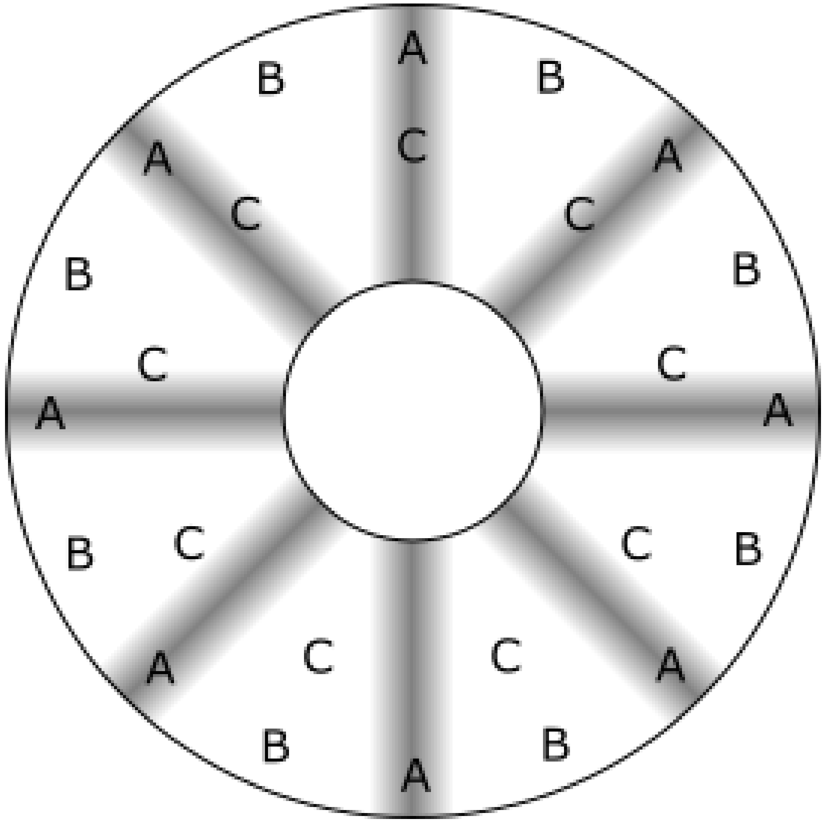


Explanation for 8-Rake vs. 9-Rake Difference

- Shadows represent wakes behind 8 exit guide vanes
- A represents 8 rakes, behind wakes
- B represents 8 rakes, away from wakes

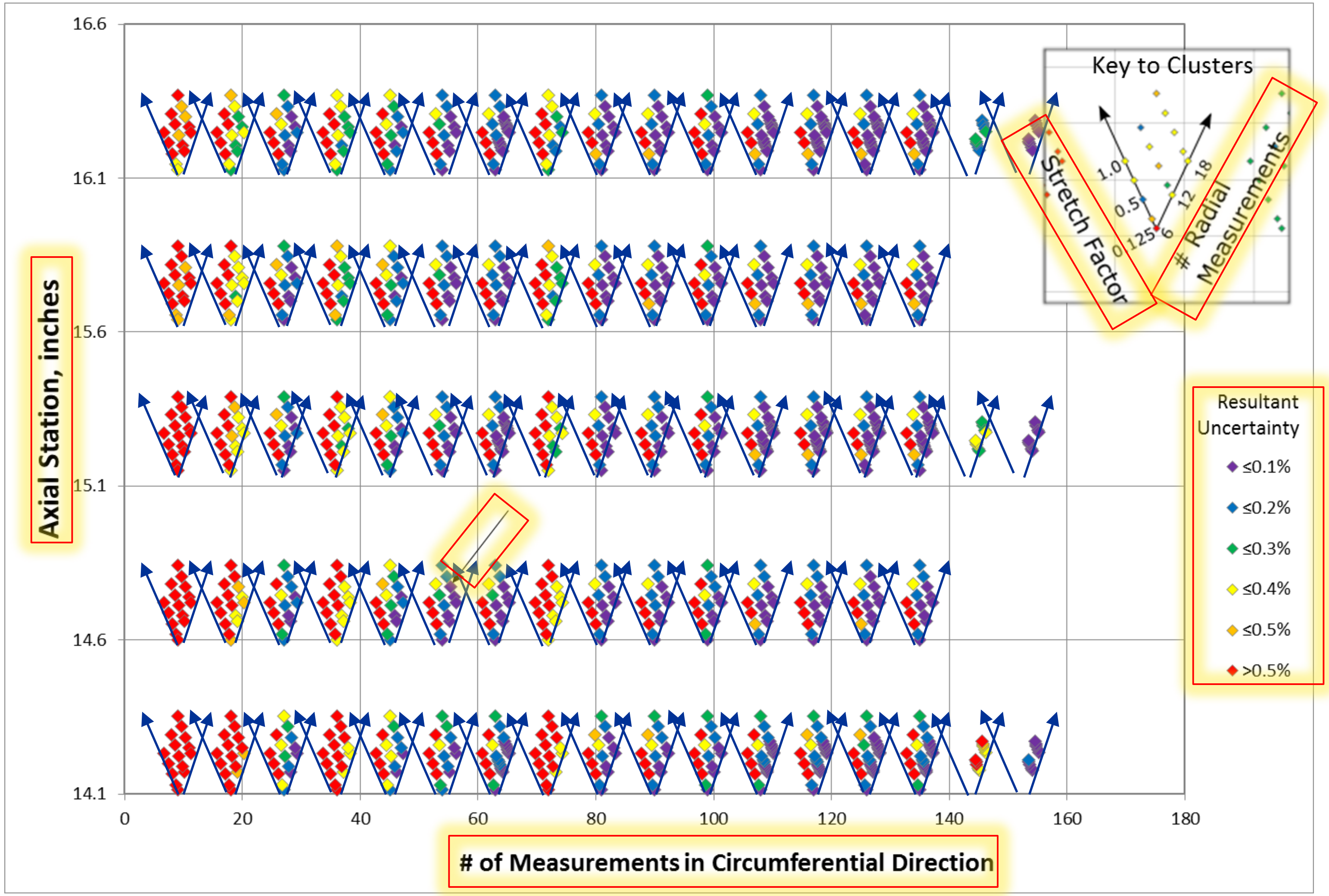
$\Big\}$ In-Phase Measurements

- C represents 9 rakes



Results from Second Round Simulated Surveys (FERRA) – Mass Flow Rate

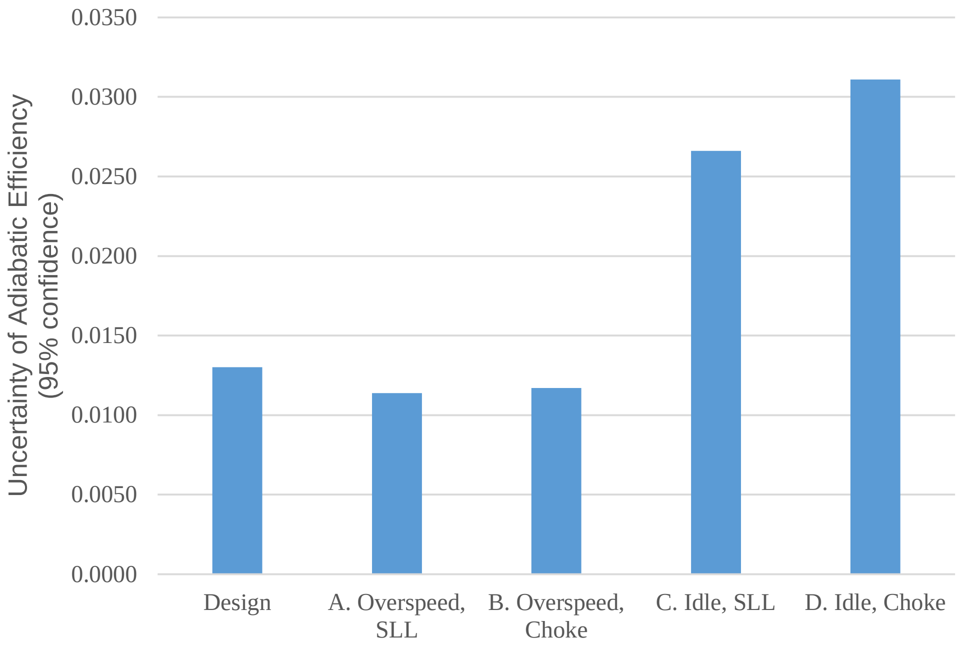
- Colors indicate calculated uncertainty due to four variables
- Goal is to reliably measure variables while minimizing measurements
- Arrow indicates selected option



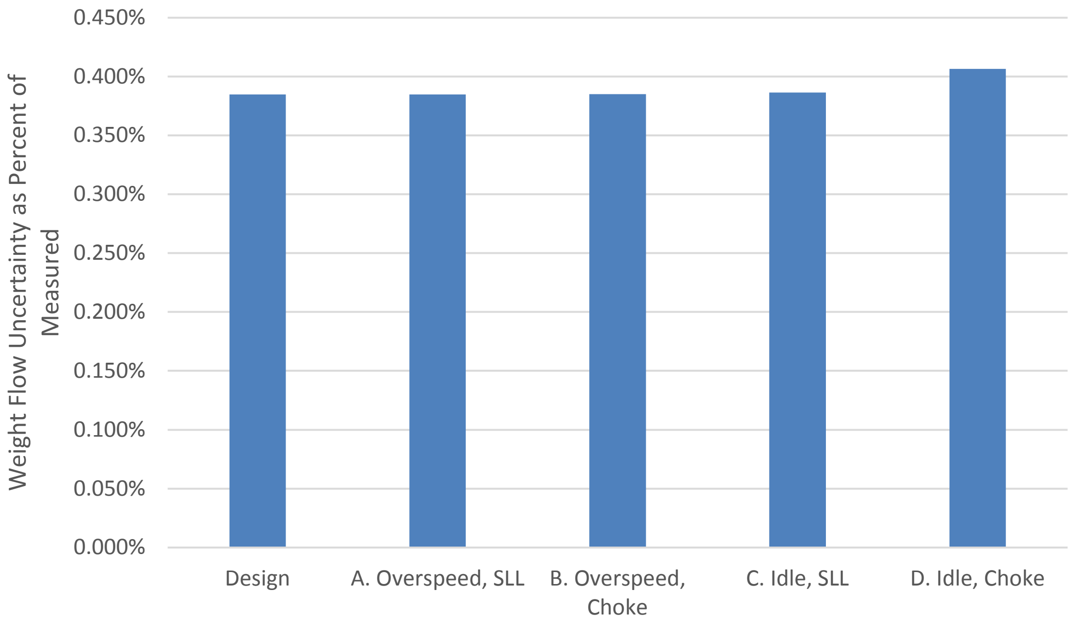
Uncertainty Estimates

- Estimates based on measurement and discretization uncertainties
- Efficiency estimates primarily influenced by pressure/temperature ratios
- Weight flow estimates relatively flat

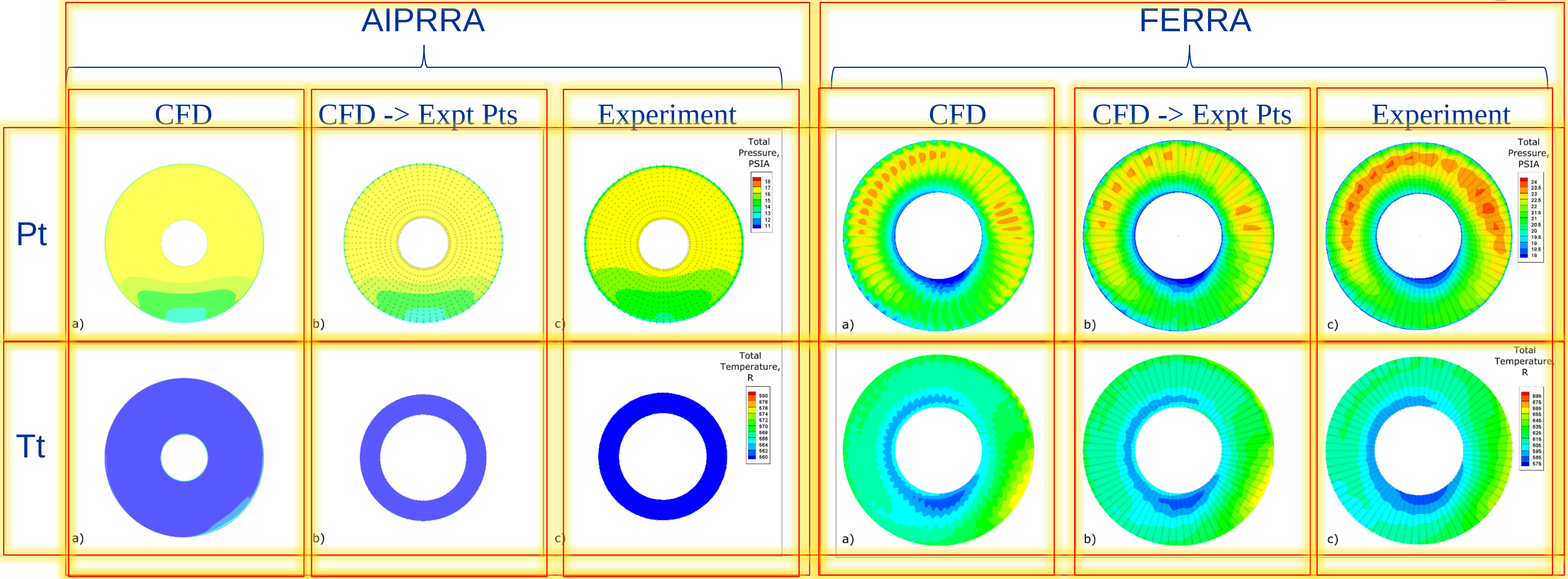
Adiabatic Efficiency



Weight Flow Rate



BLI²DTF Total Pressure and Temperature Contours



- Similar patterns between CFD and experimental data
- No apparent artifacts from the heterogeneous rake arrangements
- The sampled data does not capture all of the EGV wakes; however, a sufficiently representative sample has been obtained.

Conclusions

- Low-pressure-ratio fans require precise performance measurements for accurate calculations of fan-stage performance.
- When using rotating rake array measurements, care should be taken to avoid “in-phase” measurements. For this reason, the wakes of the EGVs strongly influenced the design of the FERRA.
- The density of measurements in the radial and circumferential directions is the next-most-important factor in reducing measurement error.
- AIPRRA distributions, driven largely by other factors, were checked using the simulated survey method and found adequate.
- Heterogeneous rake probe arrangements can achieve accurate measurement of flowfield variables, if sufficient control of test conditions is achieved.
- Uncertainty of the measurements was adequate for test objectives

For Further Details

- More on the rotating rake arrays:

  John D. Wolter, David J. Arend, and Stefanie M. Hirt, and John A. Gazzaniga. **Development of a Rotating Rake Array for Boundary-Layer-Ingesting Fan-Stage Measurements.** *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Jul. 2017.

- More on Boundary Layer Ingestion

  6.5'x6' Transonic Wind Tunnel Testbed for the Evaluation of Aircraft Embedded Propulsors

  Presenter: Mr David Arend - NASA GRC

  Airframe Propulsion Integration Testing Innovations Session

  Thursday, October 26, 2017

  1:30 PM - 2:00 PM