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Performance Characteristics and Aerodynamic Behavior of a Boundary Layer Ingesting Inlet – Distortion Tolerant Fan

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Author Contributions

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Outline of the Talk

- Background on closely coupled Propulsion/Airframe Integration and Boundary Layer Ingestion (BLI)
- Simulation domain and code coupling
- Comparison of BLI2DTF simulation to experimental data
  - Progression of the external flow toward the nacelle
  - Flow progression in the inlet duct
  - Flow aft of the propulsor
- Investigate the aerodynamic behavior of the propulsor operating in highly distorted flow
  - Distortion effects on blade loading
  - Fan performance and pressure recovery
- Conclusions

Background – Propulsion/Airframe Integration and BLI

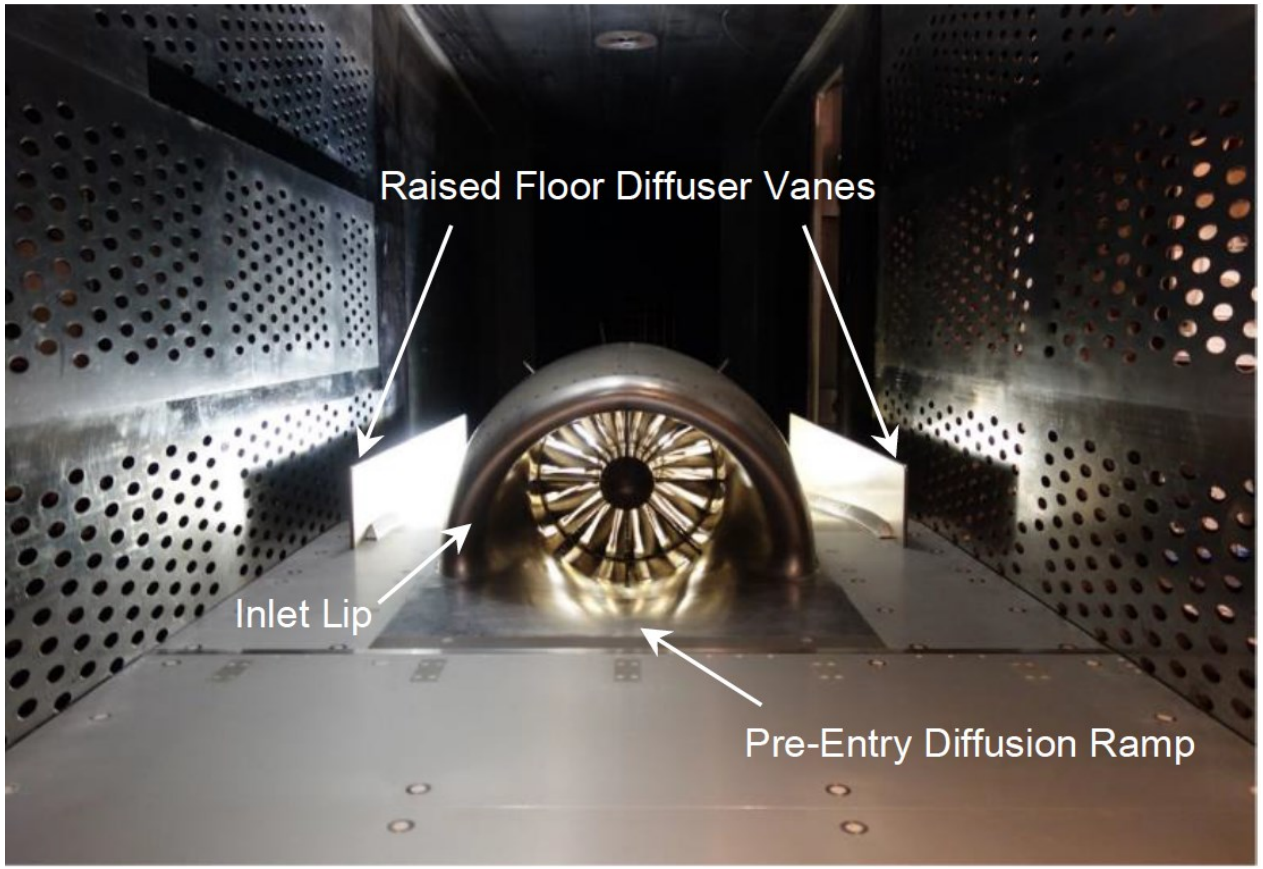


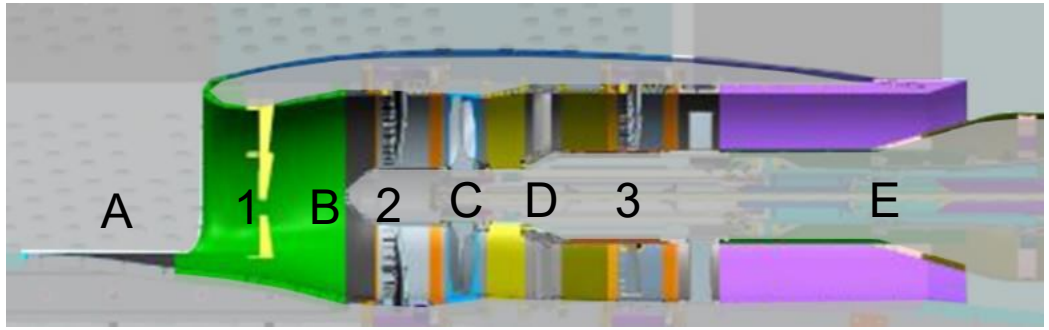
Credit: NASA

- Reduced fuel burn, noise, and emissions are the cornerstones of next generation aircraft design.
- The blended wing body with boundary layer ingesting engines could provide significant benefits to each category targeted for reduction.
- Slow moving boundary layer air is ingested by the fan resulting in an overall drag reduction and high flight efficiency.
- Reduced drag and noise from top mounted/embedded ultra high bypass fans.

Ref: Smith, L. H., Plas *et al.*

Background – 8x6 Supersonic Wind Tunnel Test





Hardware	Instrumentation
A - Pre-Entry Diffusion Ramp	1- Inlet Rakes
B - Inlet	2- AIPRRA
C - Fan Rotor	**3- FERRA**
D - Exit Guide Vanes	
E - Fan Exit Nozzle	

- Experimental test data of the Boundary Layer Ingesting Inlet – Distortion Tolerant Fan (BLI^{2}DTF) taken in 2016 at Glenn Research Center
- The embedded propulsor was tested in three phases
- This presentation focuses solely on a specific case where instrumentation is installed exclusively at the FERRA location

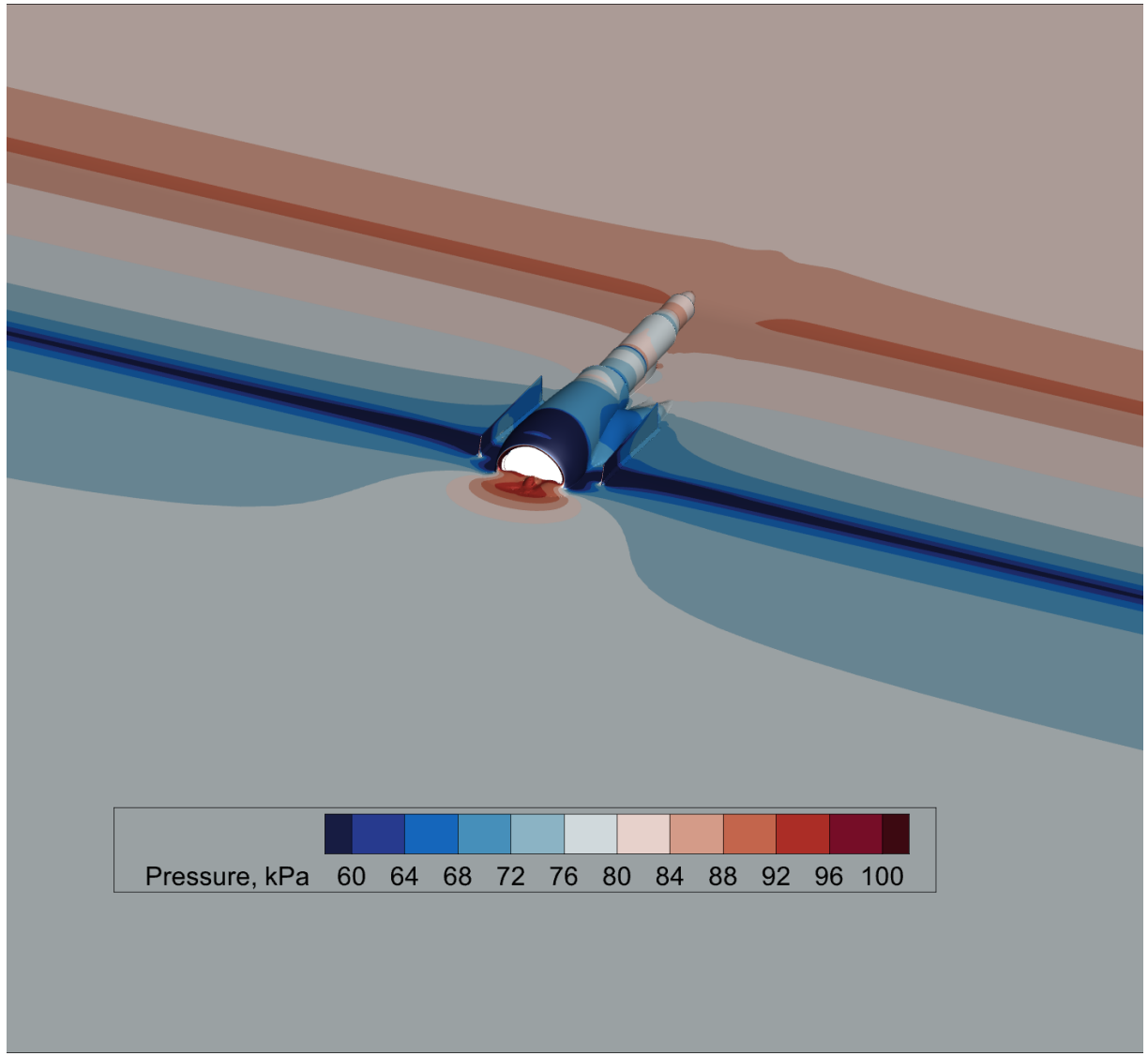
** David J. Arend, et al., "Experimental investigation of an ultra-high bypass ratio embedded boundary layer ingesting propulsion for subsonic cruise aircraft", ASME Turbo Expo 2020.*

Background – Simulation

- Simulating the airframe or propulsor as isolated entities is the most common method to determine the behavior and characteristics of each system
  - Computationally less expensive and in many instances a good approximation
- The BLI^{2}DTF is closely coupled system meaning the flow leading up to, and going through the propulsor, are dependent on the behavior of one another
- There is a disparity in the computational requirements when simulating airframes or propulsors
- The asymmetry of the ingested boundary layer interacting with the fan is a continuously unsteady process
- Two NASA CFD codes are coupled to simulate the behavior of the combined system; LAVA for the airframe/nacelle and TURBO for the propulsor
- To investigate the aerodynamic behavior of the propulsor operating in the distorted flow of a BLI system, the isolated propulsor is used

Simulation Domain and Code Coupling

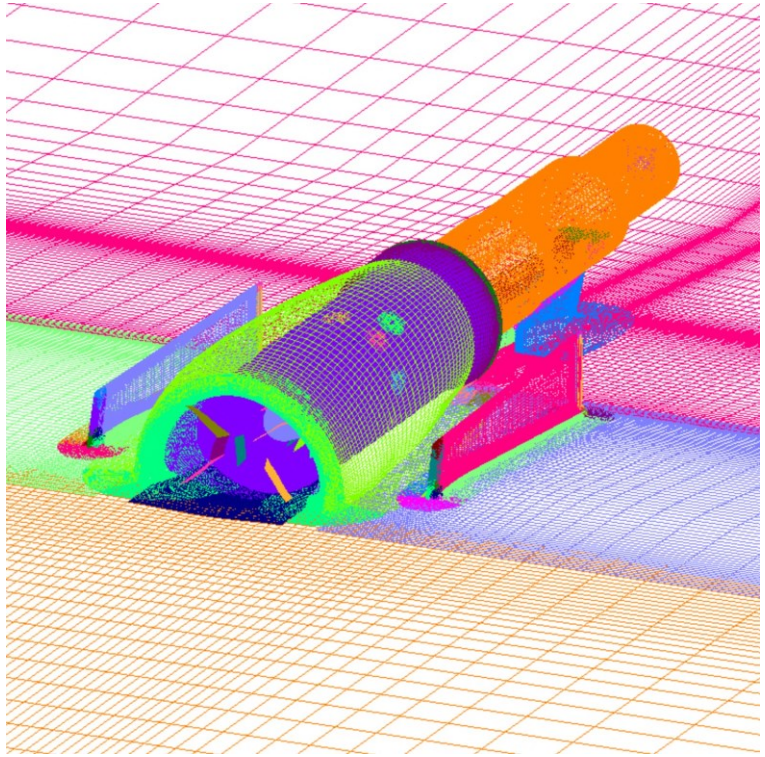
Simulation Domain - External Flow (LAVA Domain)



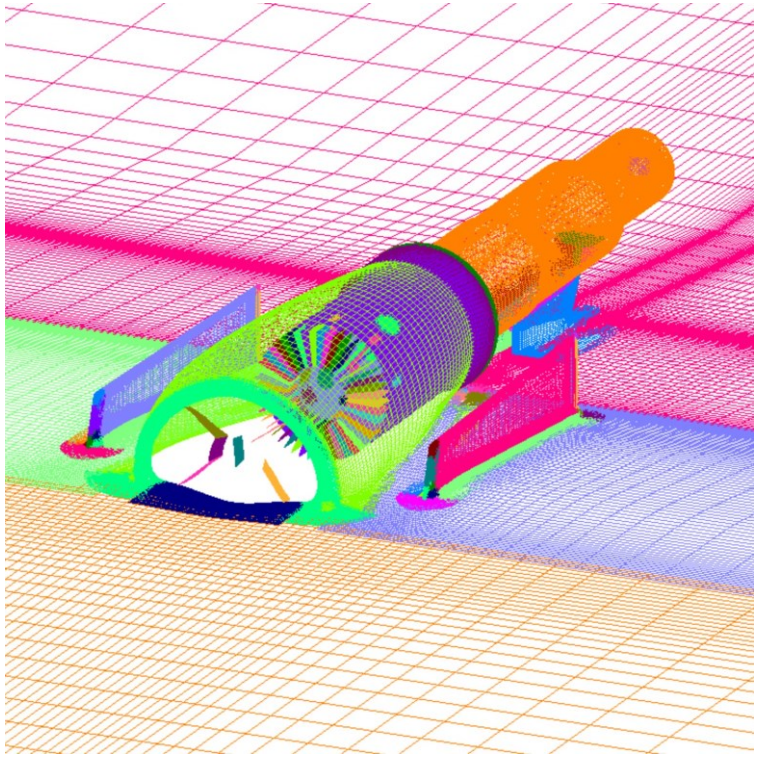
- The wind tunnel experiment used wall suction to limit blockage effects and replicate an isolated propulsor at cruise flight conditions
- The simulations forewent modeling the wind tunnel and chose to directly model an isolated propulsor
- All outer boundary conditions set ~200 fan diameters away from the nacelle
- Experimentally, the height of the incoming boundary layer was altered by turbulent trips and floor suctions
- The simulation altered the length of the viscous floor BC upstream of the nacelle to match the height of experimental boundary layer

Simulation Domain - External Flow (LAVA Domain)

LAVA – Actuator Disk Zone Model

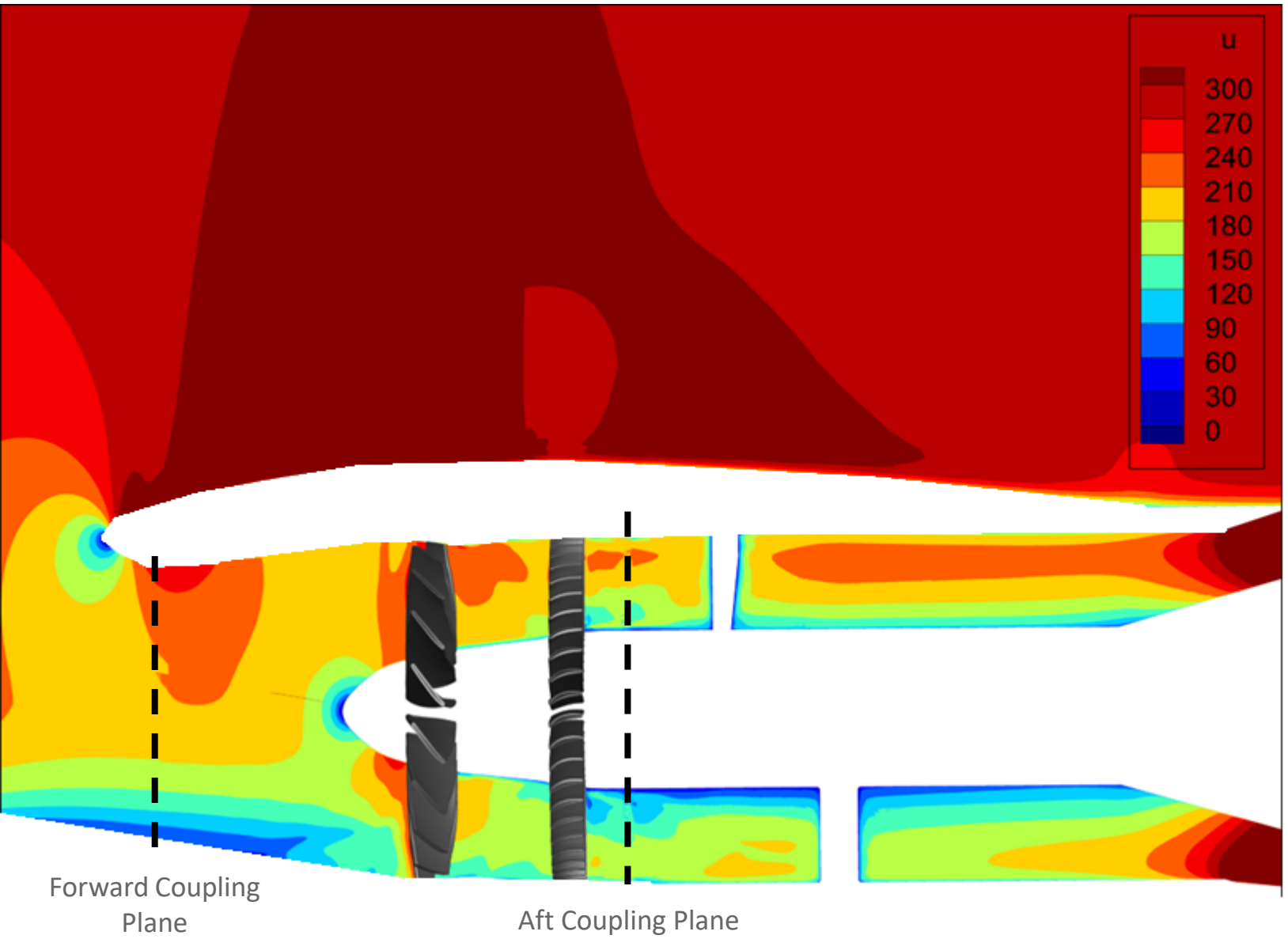


LAVA – Code Coupled Model



- A lower fidelity actuator disk zone (ADZ) simulation is performed first by LAVA only
  - Necessary to get the flow of the closely coupled system simulated correctly
  - This serves as a baseline comparison system and as an initial guess for the code coupled simulation
- Outside of the nacelle, the same grid is used for the code coupled simulation

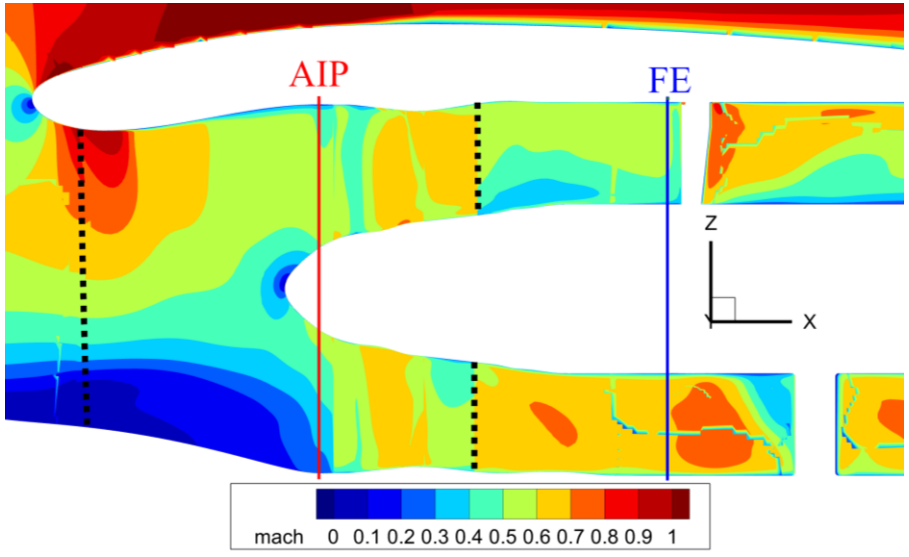
Simulation Domain - Internal Flow (TURBO Domain)

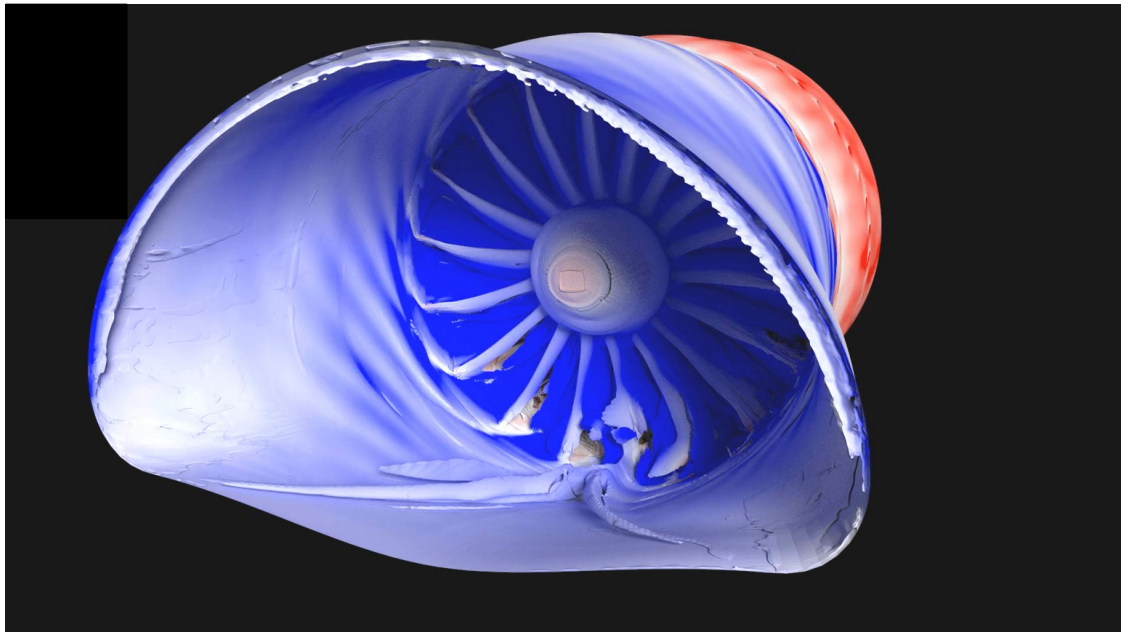


- The TURBO domain is focused on the internal flow of the inlet duct, the full annulus fan, and full annulus exit guide vanes (EGVs)
- 18 fan blades and 48 EGVs
- Op-line condition at 100% design speed
- Data is exchanged with the LAVA domain at the forward and aft coupling planes
- Spatial resolution mismatch as the coupling planes up to $O(10^2)$ from ADZ to full propulsor model
- LAVA domain computation is steady, whereas TURBO domain computation is unsteady

Code Coupling Implementation

- LAVA and TURBO utilize different methods in the foundation of their codes.
  - LAVA uses node centered finite difference
  - TURBO uses cell centered finite volume
- Grids can be constructed in the same manner between the two codes
  - Structured hexahedral meshes (TURBO can only use these elements)
  - LAVA is an unstructured code and can accept this requirement
- Boundary conditions are implemented in different locations
  - A half grid step due to the difference in data center locations
  - An Overset approach for the coupling grid is utilized



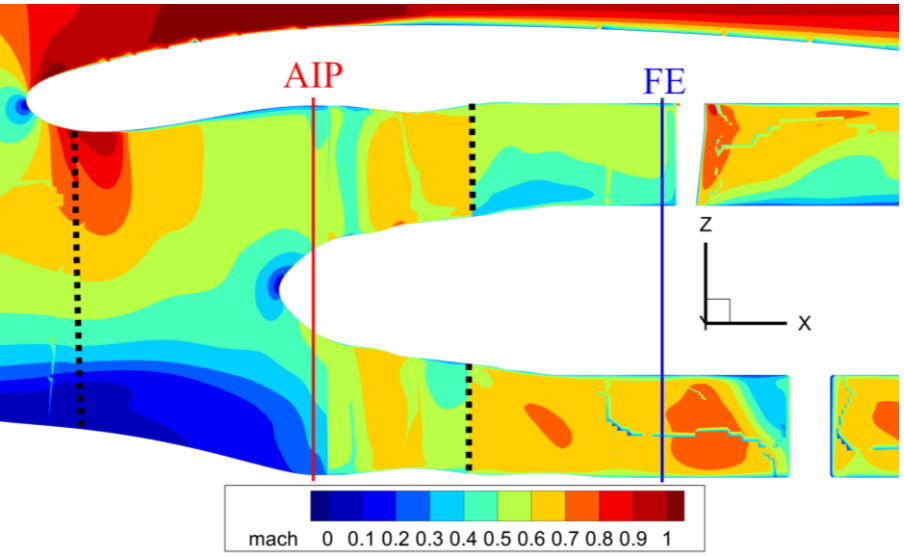


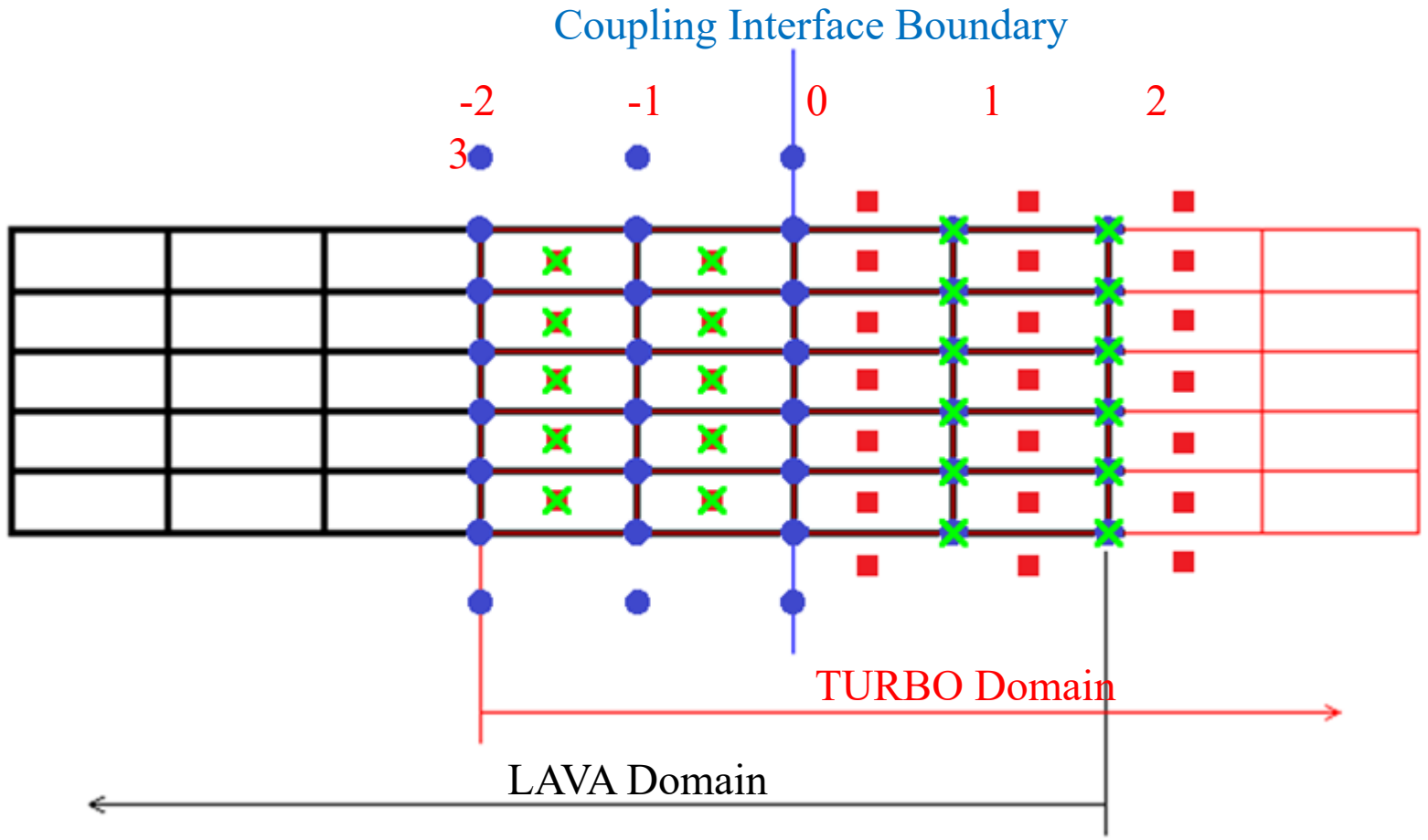
Interface Computational Domain

X updated ghost cells

TURBO cell centered variable location

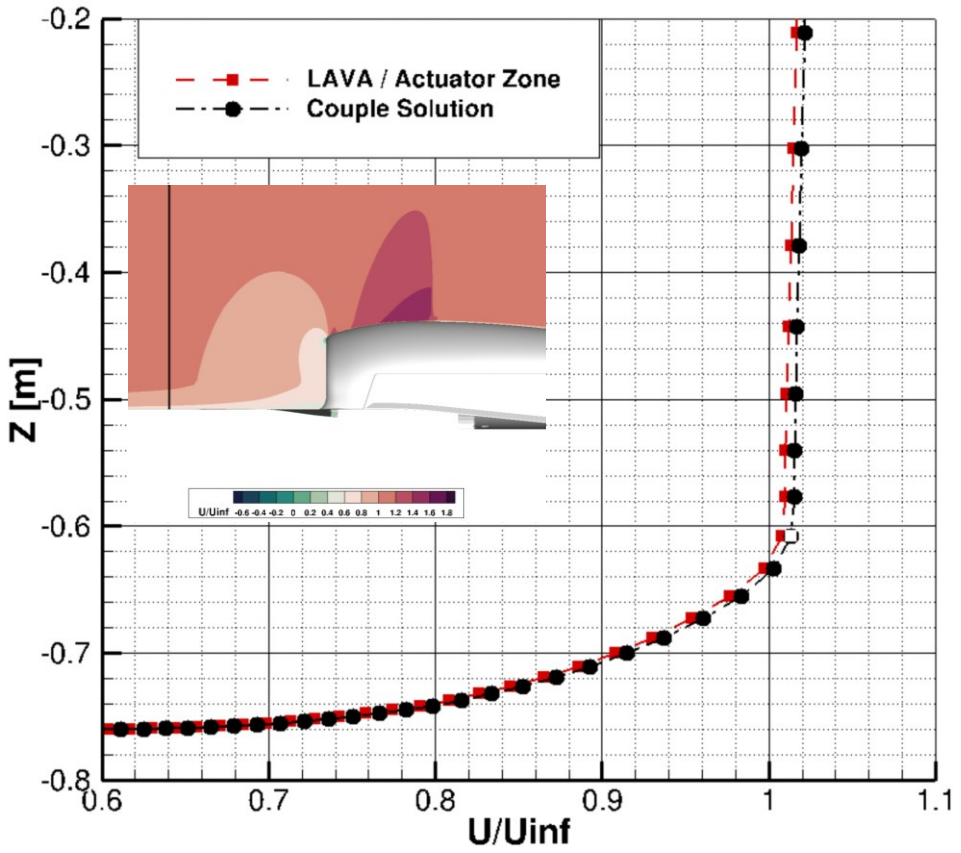
LAVA node centered variable location





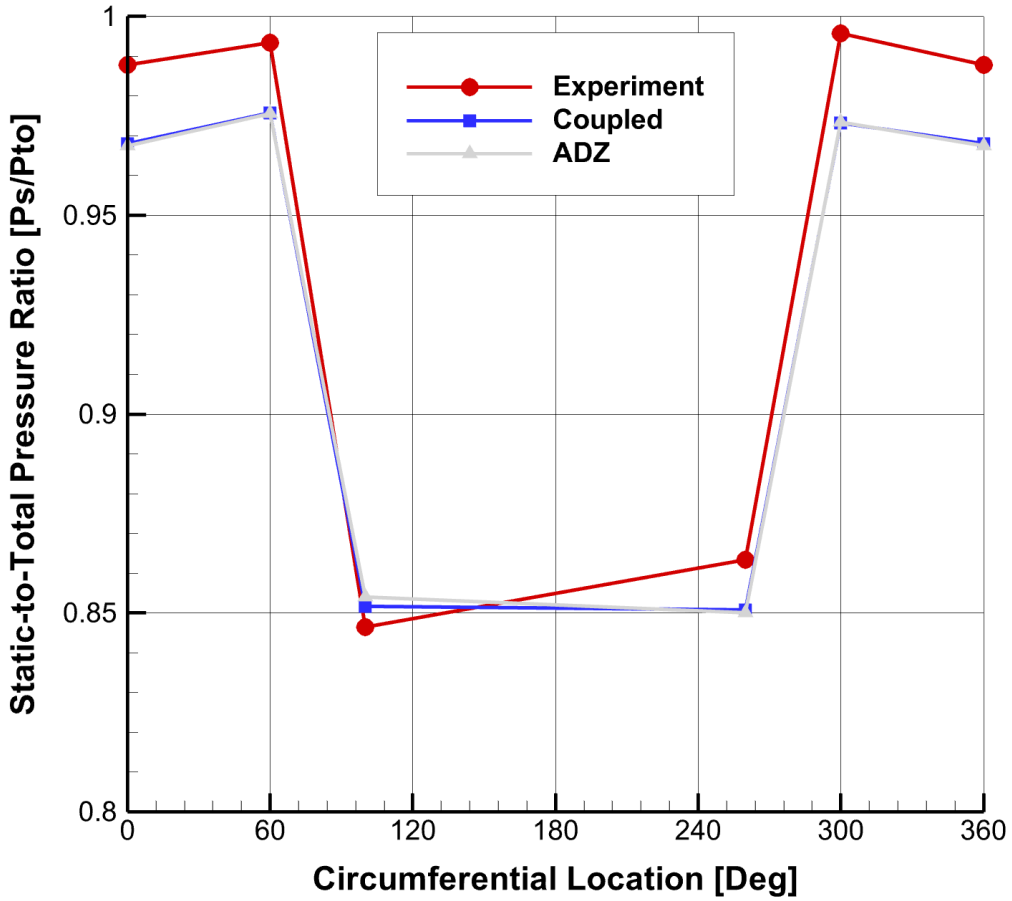
Comparison to Experimental Data

Upstream Boundary Layer

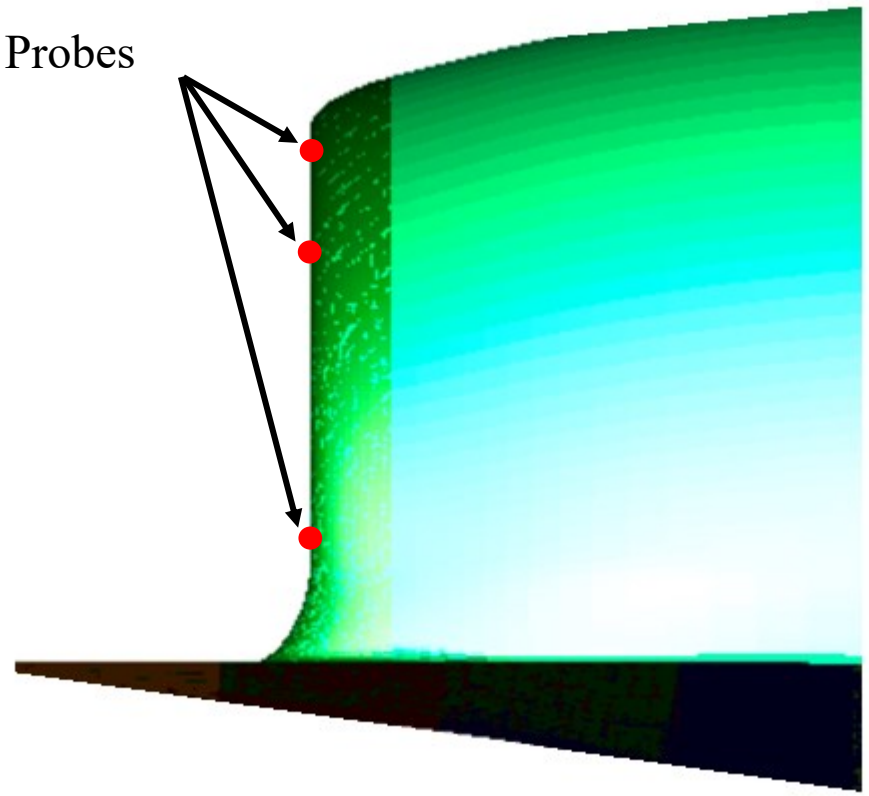


- The figure showcases the computed boundary layer at a position one meter ahead of the propulsor, comparing the LAVA Actuator Disk Zone (ADZ) solution with the LAVA/TURBO coupled solution. Both solutions demonstrate remarkably similar boundary layer behavior.
- It is important to note that no experimental boundary layer measurements were available during propulsor operation in the tunnel.
- The boundary layer height was able to be selected using wall suction and experimentally measured, in the clean tunnel, to be 0.1224m for nominal operation (Hirt *et al.*).
- Either the ADZ or coupled solutions exhibited a 0.1232m boundary layer height, or 0.7% different

Inlet Lip Stagnation Probes

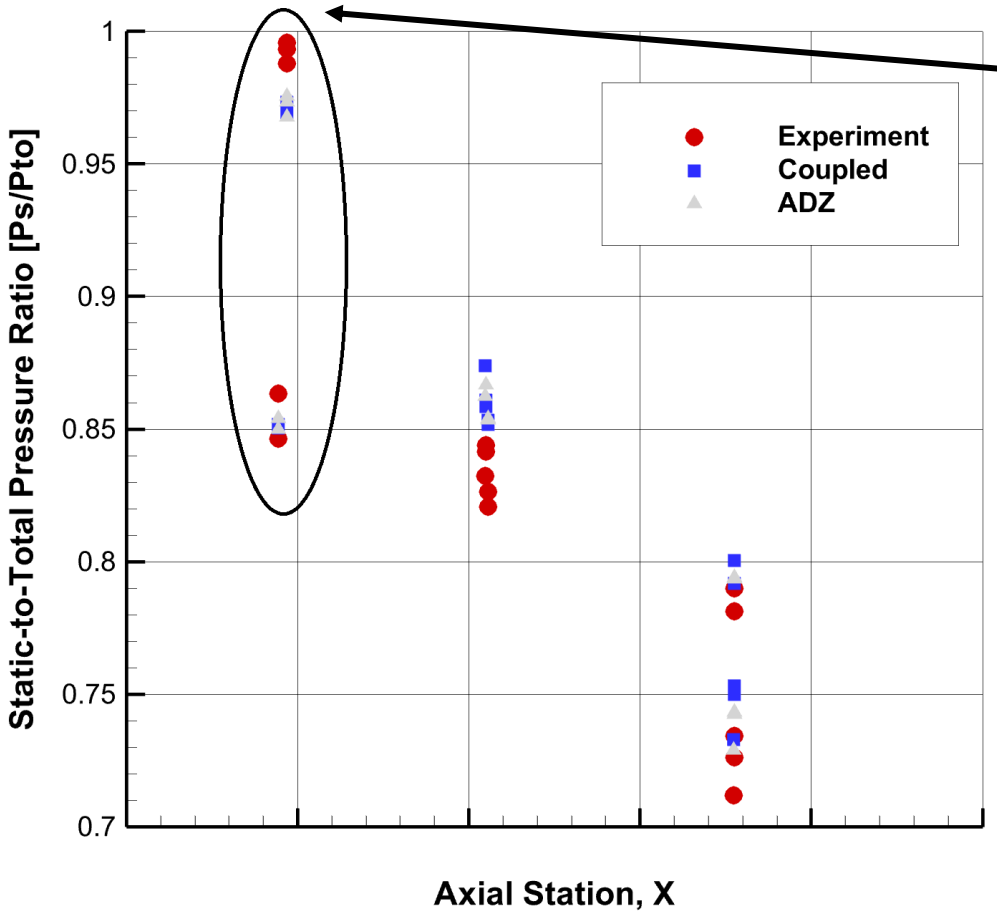


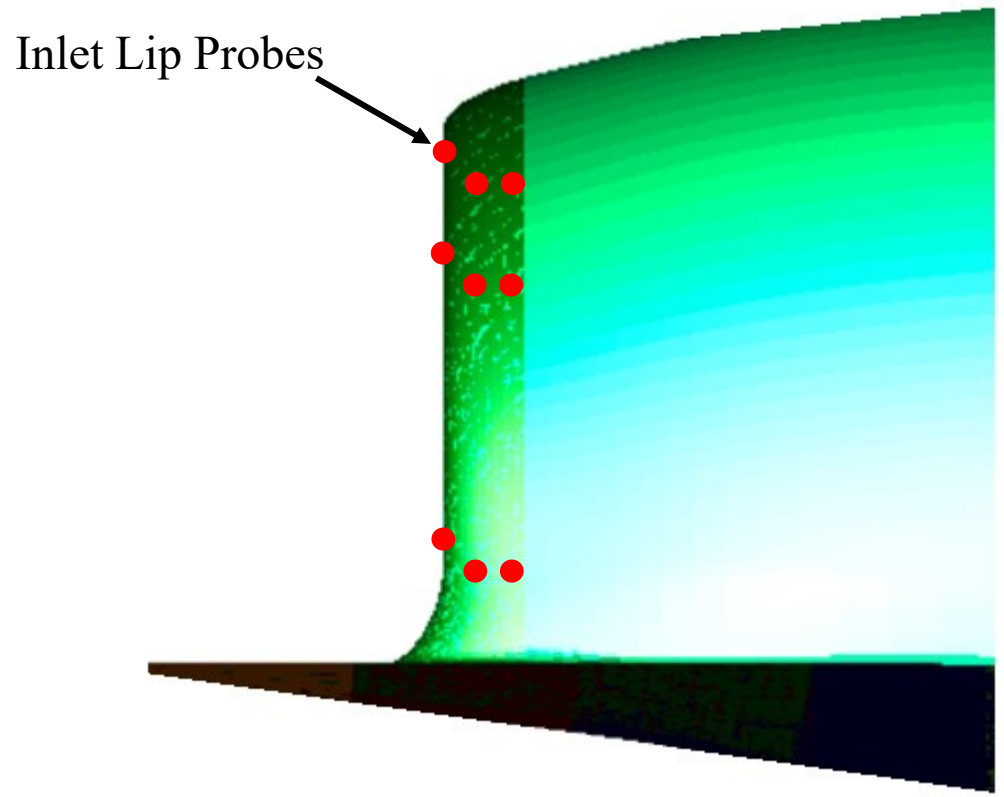
Stagnation Probes



- Both simulations under predict the static pressure on the inlet lip near the top of the duct, the portion seeing clean free-stream flow
- The probes near the bottom of the duct, closer to the boundary layer, display a much closer agreement
- Differences in the mass flow rate through the nacelle change the location of the stagnation point

Inlet Lip Probes

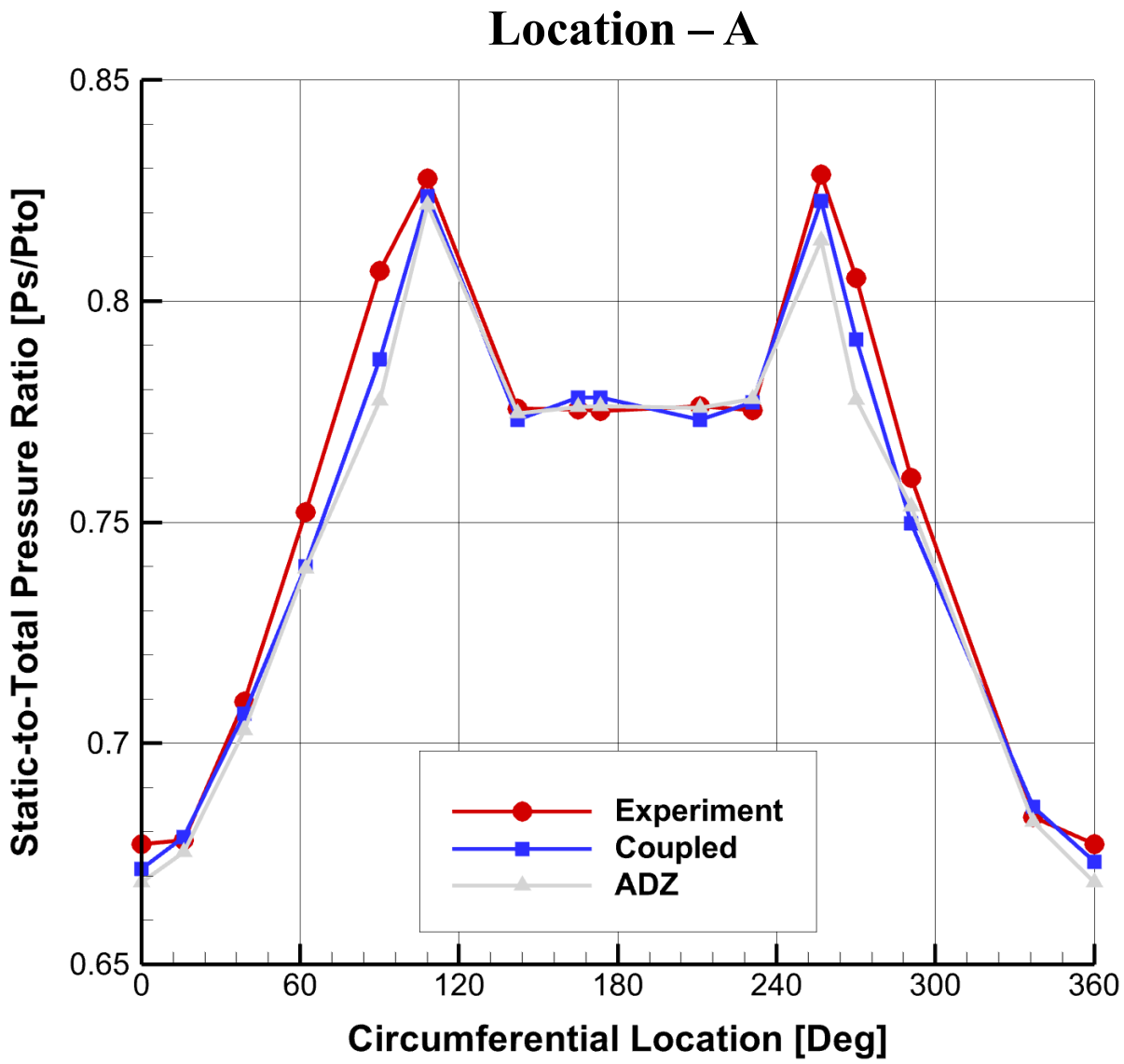




- If the simulation had a larger mass flow rate, the stagnation point outboard of the lip, then all following axial stations would show lower pressure
- A ~2% difference in mass flow rate through the nacelle of the simulation is the cause of the static pressure exhibiting an altered behavior

Inlet Duct – Circumferential Static Pressure Distribution



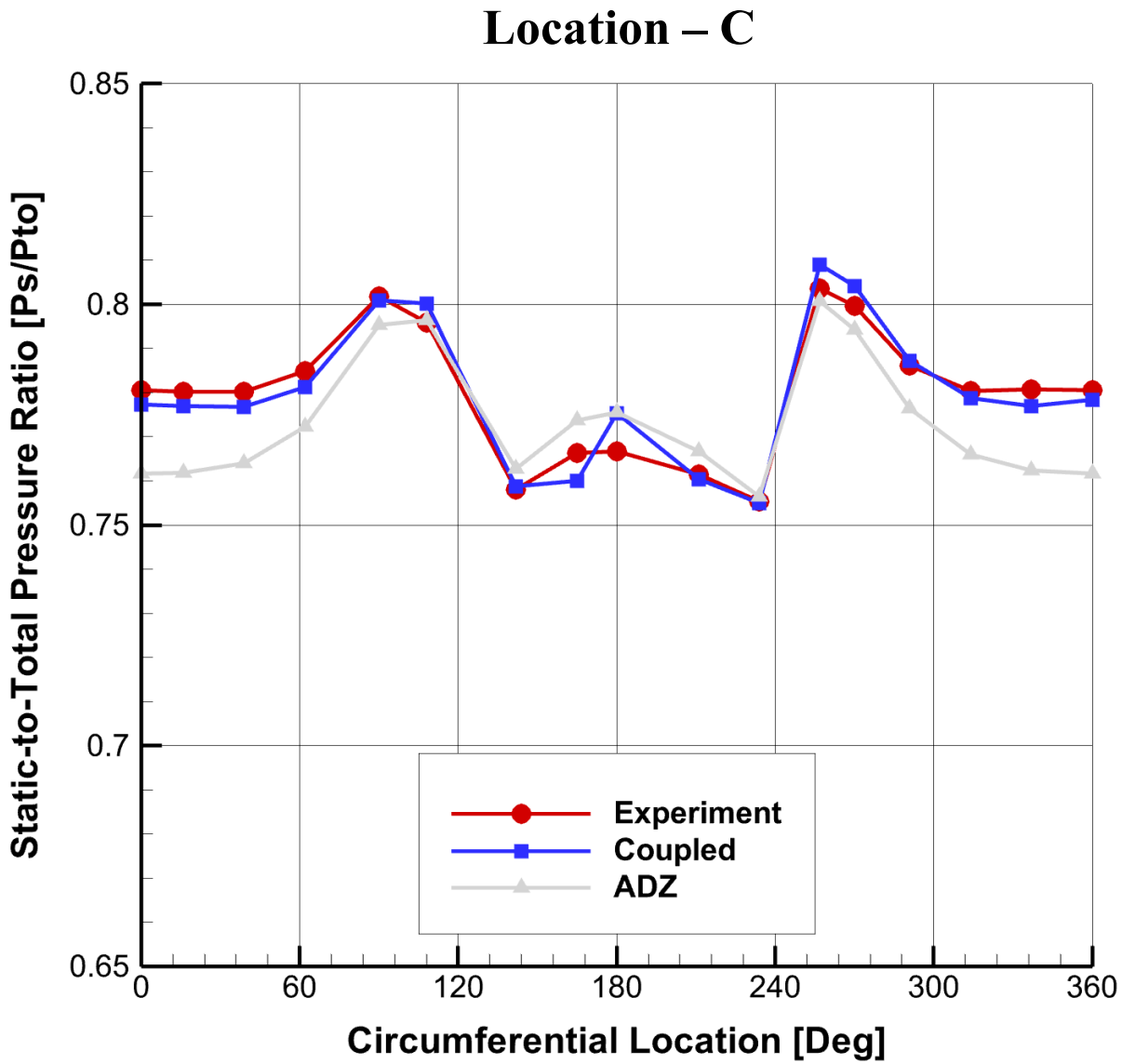


- Static pressure probes will be used to chart the progression of the flow through the inlet duct as
- At the first axial station, near the throat of the inlet, shows good agreement between the simulations and experiment
- The disagreement of static pressure on the inlet lip are lessened with propagation through the inlet duct

Inlet Duct – Circumferential Static Pressure Distribution



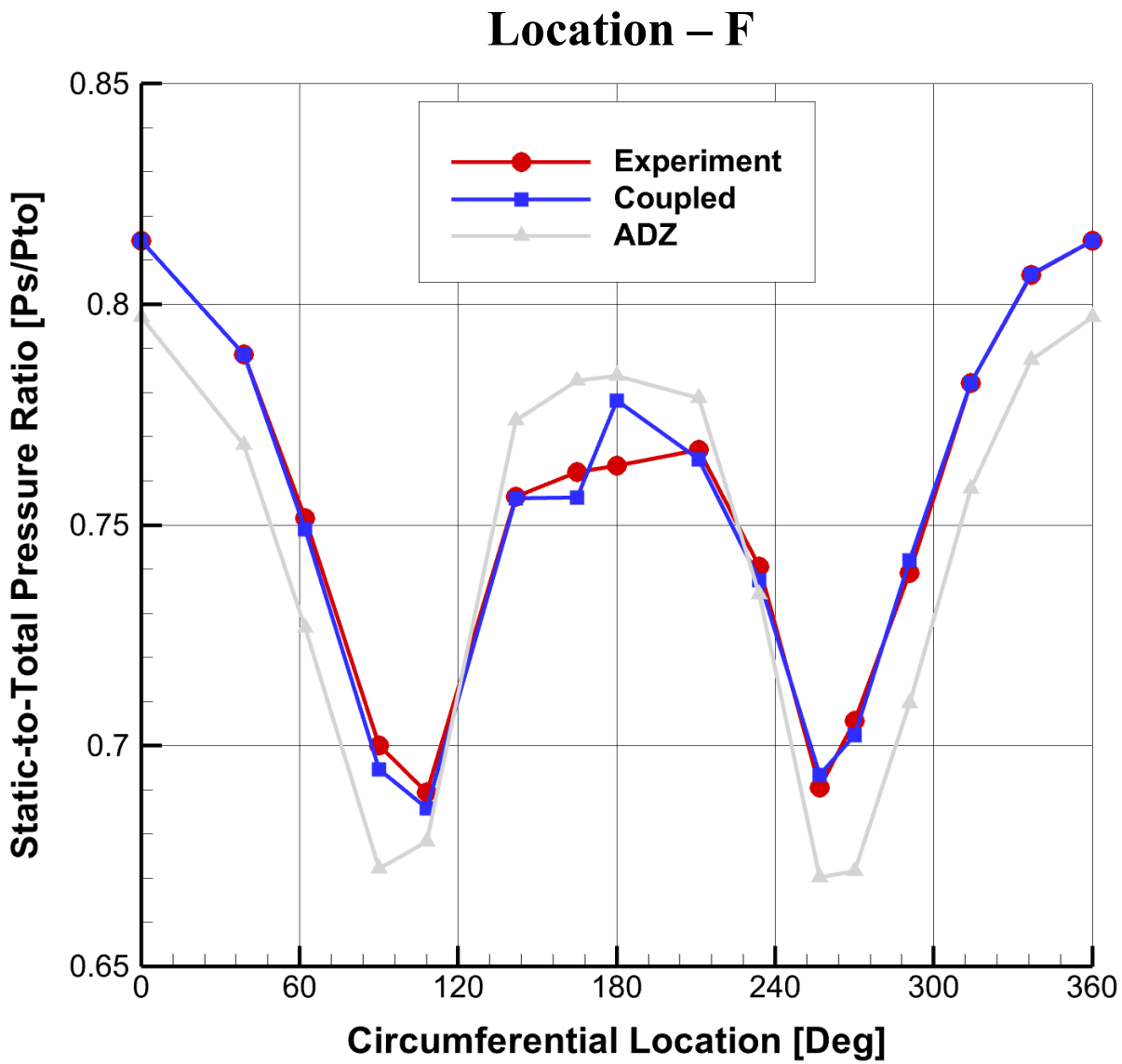
- Differences in flow behavior between the code coupled simulation and the ADZ model emerge as flow progresses through the inlet toward the fan
- Good agreement is seen between the experimental values and the code coupled simulation
- A small divergence can be seen at bottom of the inlet duct (180 deg) in the coupled simulation results



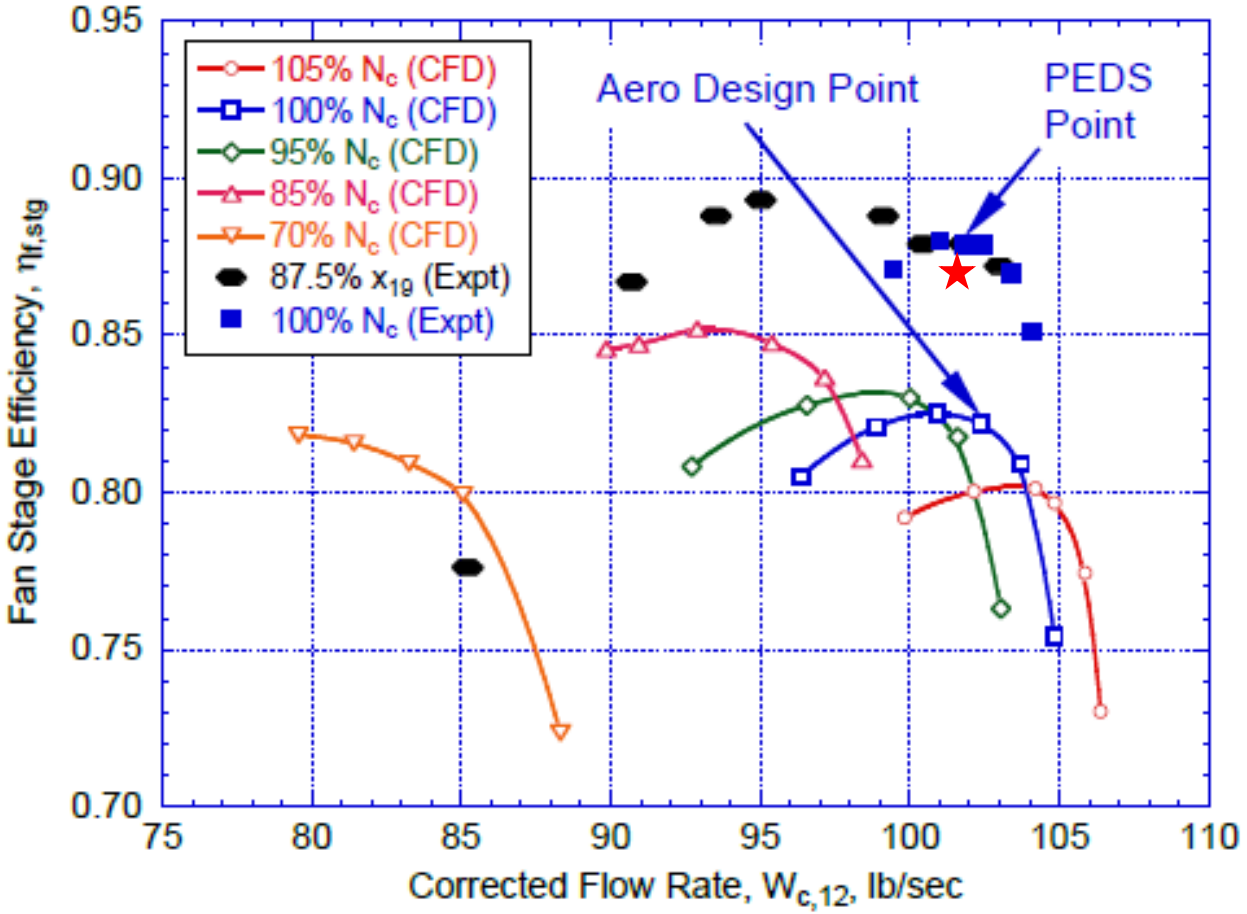
Inlet Duct – Circumferential Static Pressure Distribution



- The operation of the fan can be seen to affect the flow behavior in the inlet duct, not captured by the ADZ
- Good agreement in static pressure profile just upstream of the fan
- The discrepancy in static pressure at 180 deg is caused by stronger vortical flow uplifting lower momentum fluid

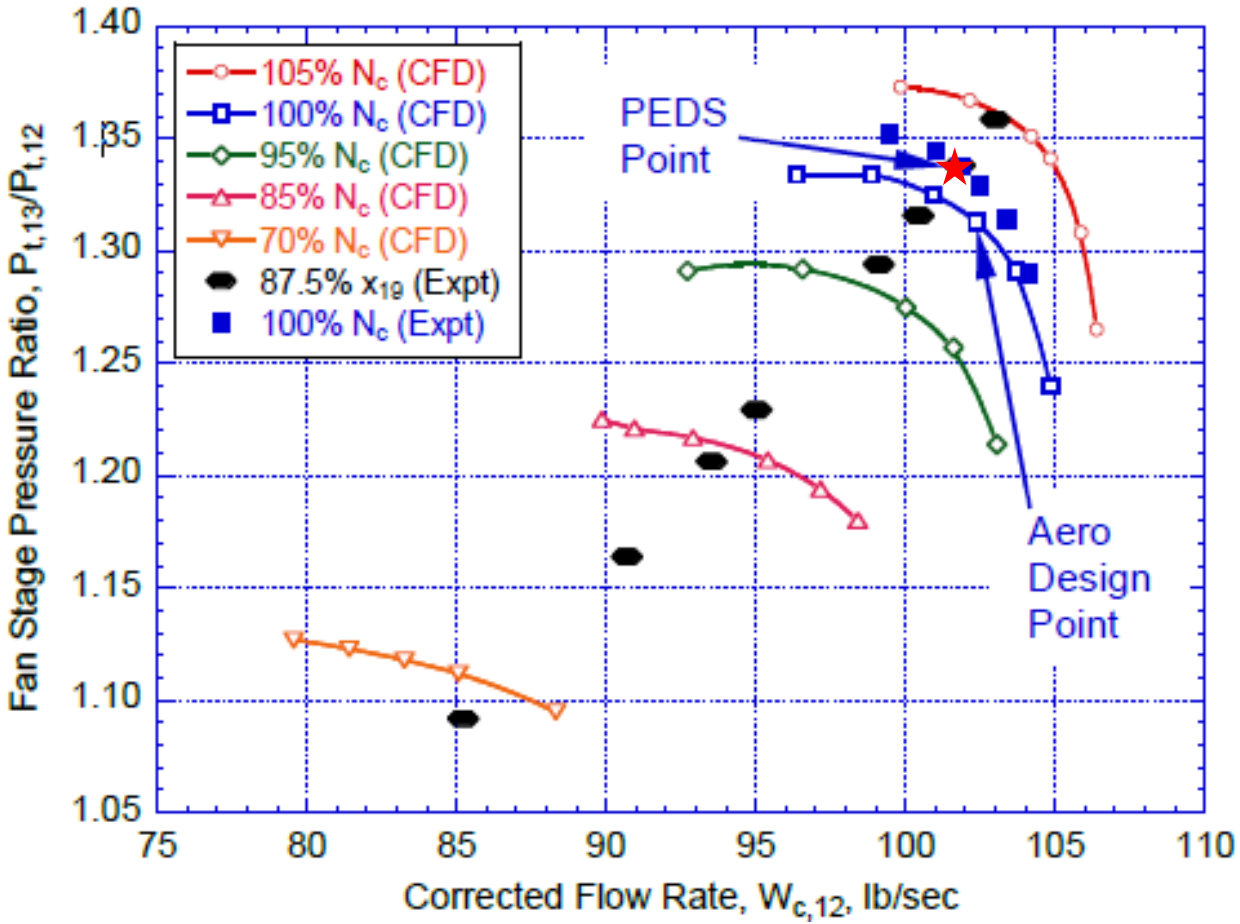


Propulsor Stage Characteristics



- Stage total pressure ratio was 1.339 for the experiment and 1.335 for the simulation
- Stage efficiency was 87.8% for the experiment and 86.7% for the code coupled simulation
- Efficiency difference appears to emerge from total temperature

★ Current code coupled simulation



Images taken from Arend *et. al.* **Experimental Investigation of an Ultra-high Bypass Rat Boundary Layer Ingesting Propulsor for Subsonic Cruise Aircraft,** 2020, GT2020-1569

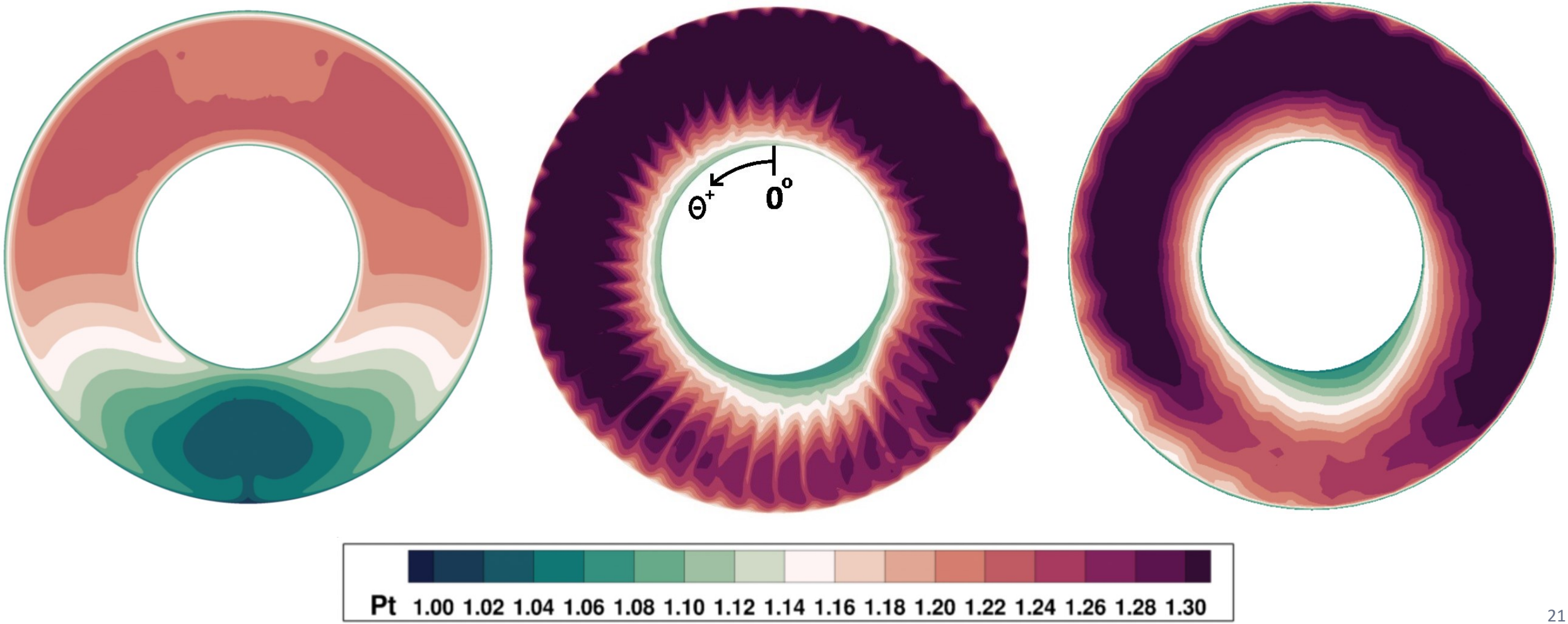
BLI2DTF – Boundary Layer Ingesting Inlet/ Distortion Tolerant Fan

➢ The comparison involves the computed non-dimensional total pressure and the measured values at the FERRA location

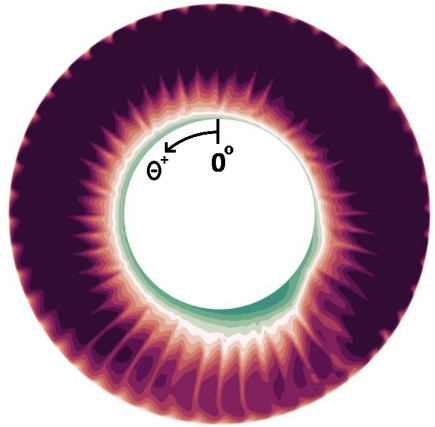
LAVA – ADZ

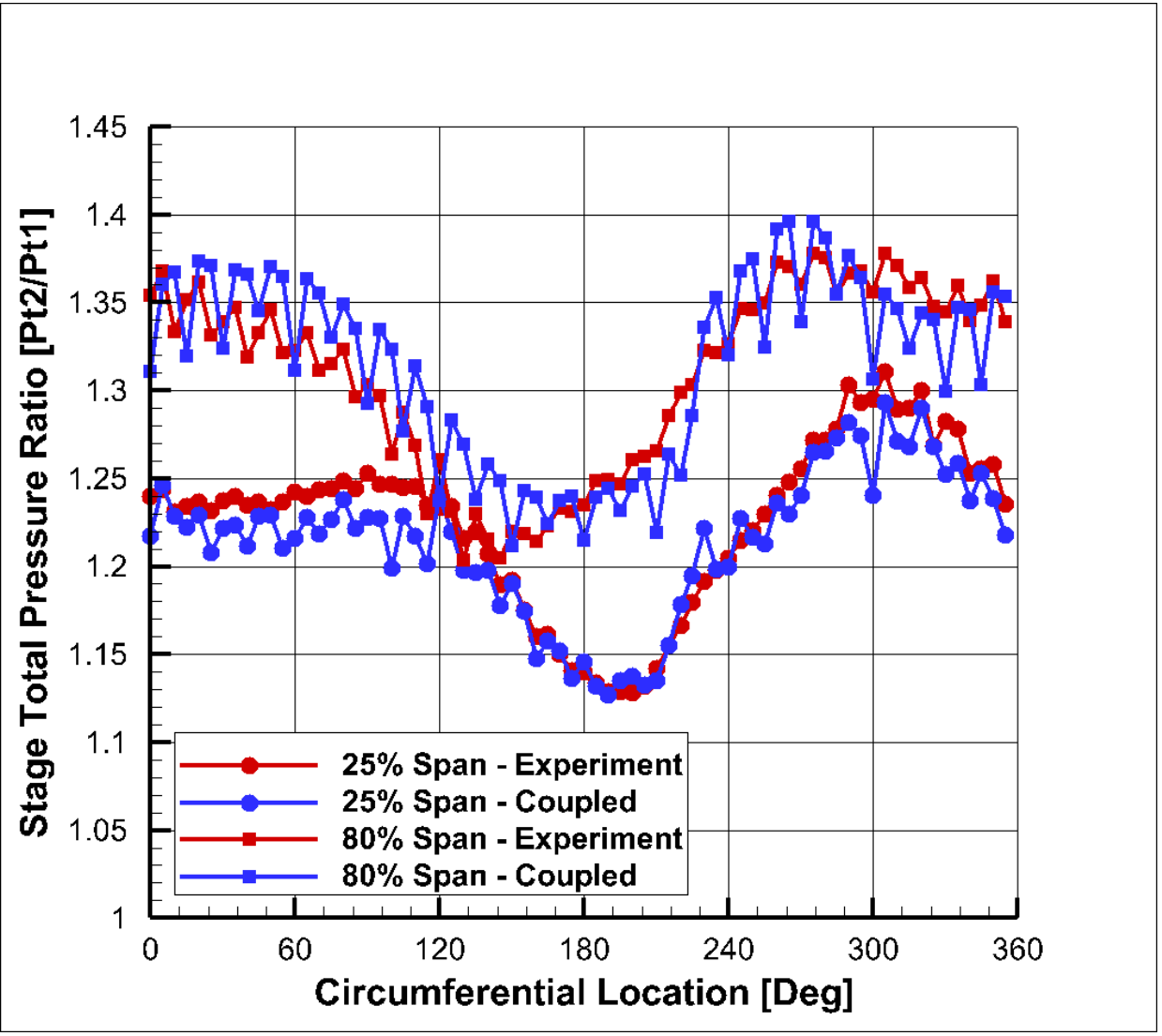
LAVA / TURBO Coupling

Experimental



Comparison to Experimental Data – Total Pressure Profiles





- Good agreement in total pressure contours at FERRA location
- Performance decrease in the distortion region evident at all spanwise sections
- The higher resolution in CFD results show the wakes from the EGVs are still significant at the FERRA plane
- Slight under-prediction in total pressure rise entering the distortion at low spanwise sections
- Slight over-prediction in total pressure rise in the same region for the higher spanwise sections

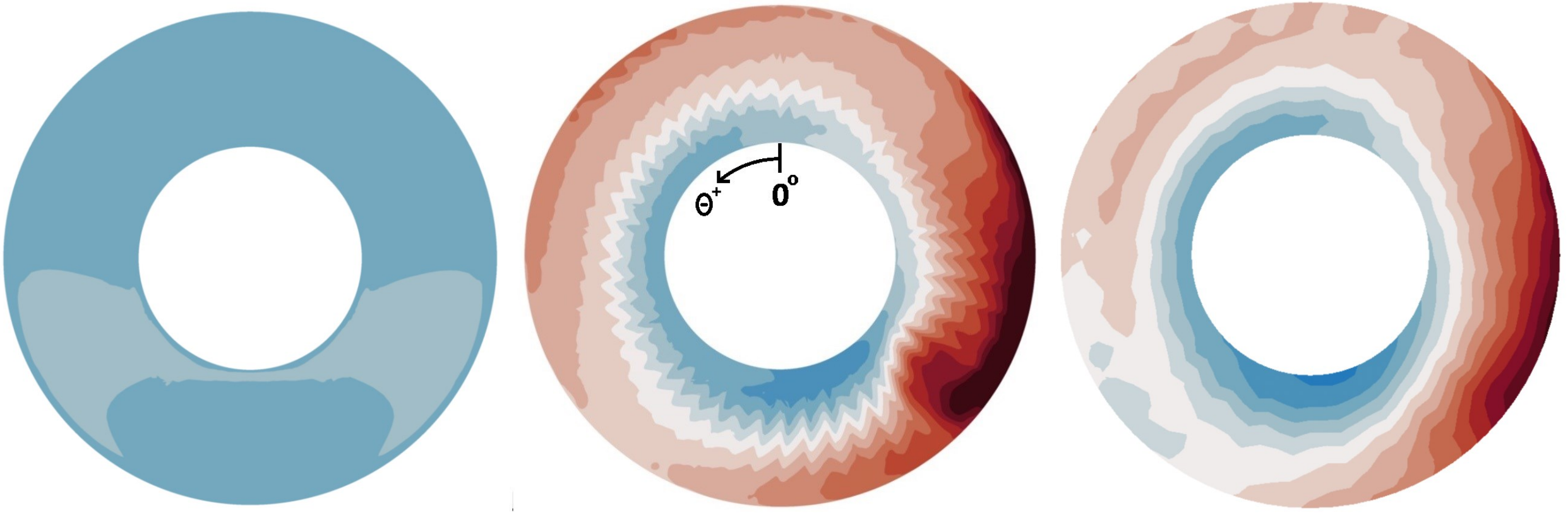
BLI2DTF – Boundary Layer Ingesting Inlet/ Distortion Tolerant Fan

➢ The comparison involves the computed non-dimensional total temperature and the measured values at the FERRA location

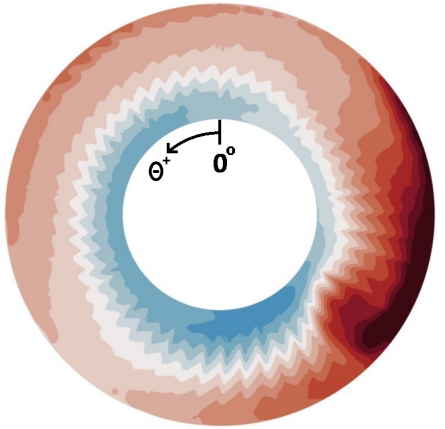
LAVA – ADZ

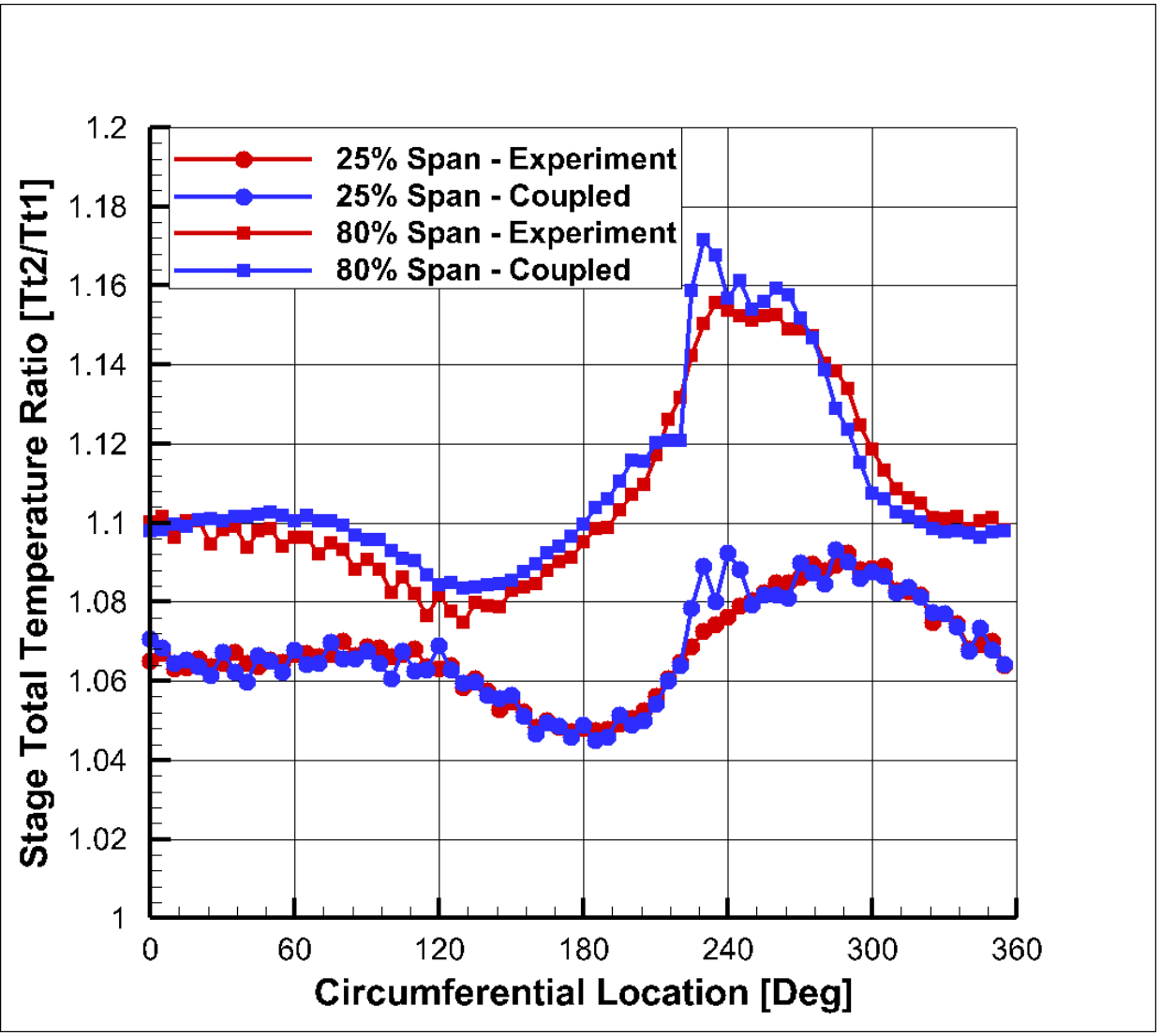
LAVA / TURBO Coupling

Experimental



Comparison to Experimental Data – Total Temperature Profiles

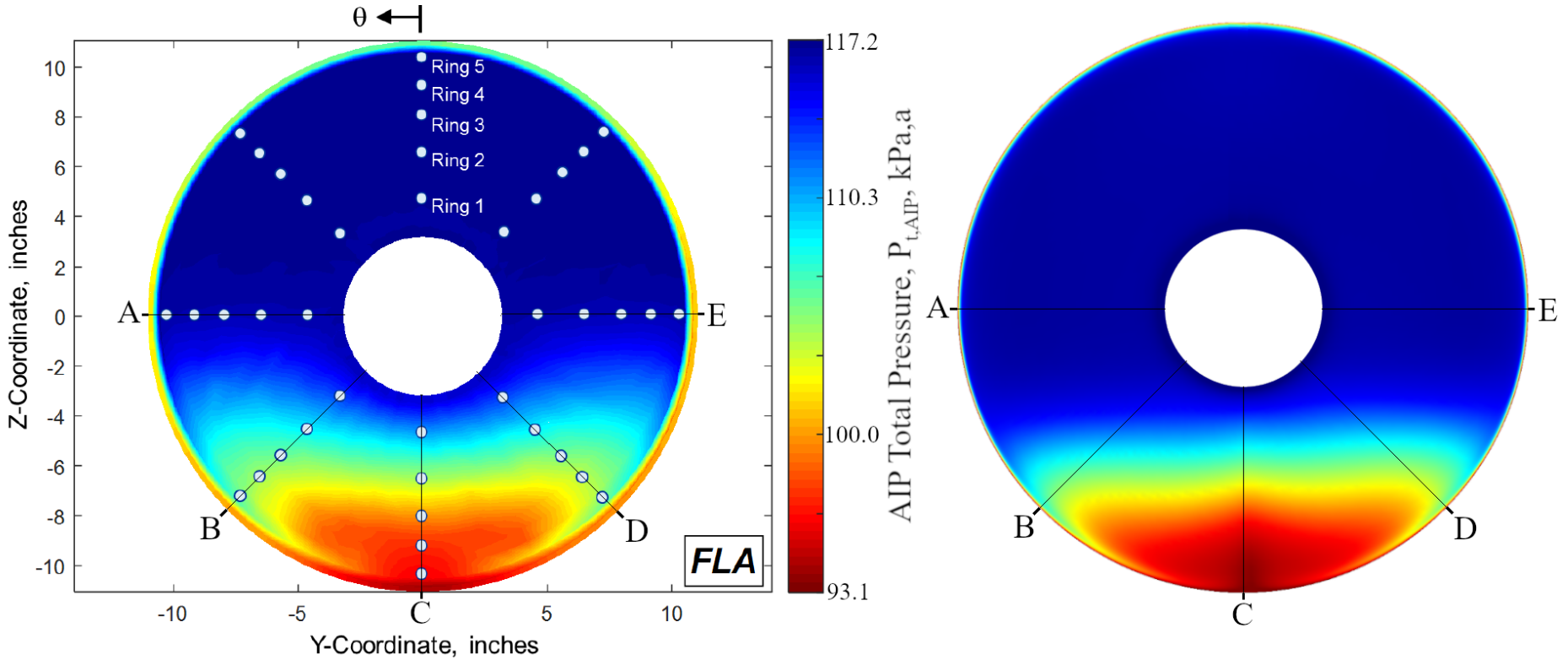




- Good agreement in total temperature ratio contours at FERRA location
- Higher total temperature ratio at outboard spanwise sections of the fan coming out of the distortion
- Good agreement in low spanwise section profile outside of a spike around 240deg
- Slight over-prediction in total temperature ratio leading into and through the distortion for the higher spanwise sections

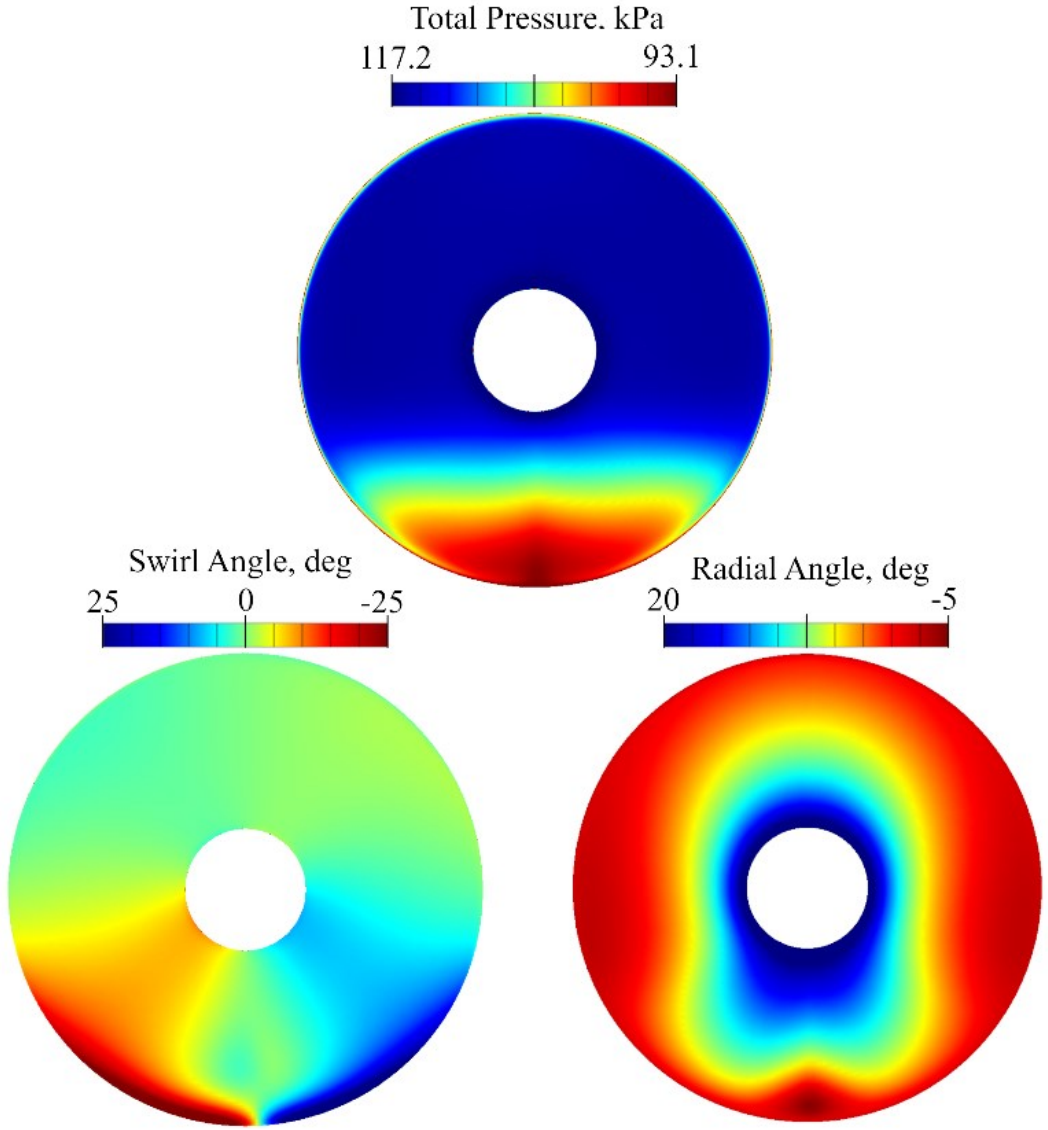
Distortion Tolerant Fan – Aerodynamic Behavior

Total Pressure Distortion Comparison at the AIP



- The AIP distortion is from an isolated TURBO run and the experimental measurements were obtained in an altered configuration
- The simulated total pressure distortion (right) is similar to that observed in the experiment (left) showing that physically meaningful progression of the distortion is occurring in the inlet duct.
- The experimental distortion is more diffuse (larger circumferential area) and has a higher total pressure in the distortion (by ~3%) than the simulation.

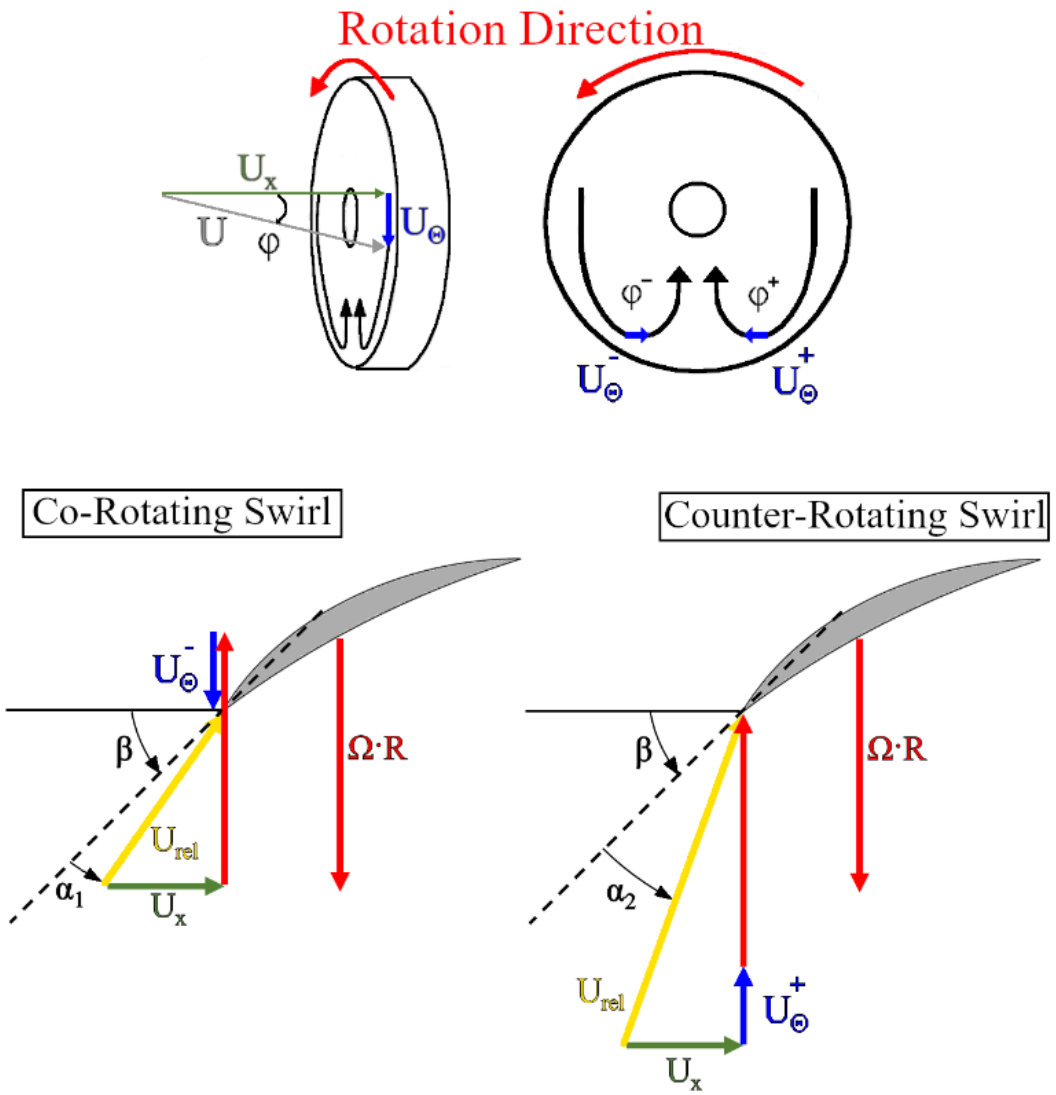
Aspects of the Distortion at the AIP



- The three main aspects of the distortion profile are total pressure, circumferential angle, and radial angle
- The total temperature did not show significant variation from the mean value at the face (~0.5%).
- The distortion intensity is a measure of the distortion severity :
  - Peak intensity values are: total pressure – 8.5%, swirl angle – 9.2%, and radial angle – 1.6%
- The total pressure and swirl distortions are more severe than the radial distortion.

$$PAV_i \int_0^{360} P(\theta) d\theta \qquad Intensity = \left(\frac{PAV - PAV_{low}}{PAV} \right)_i$$

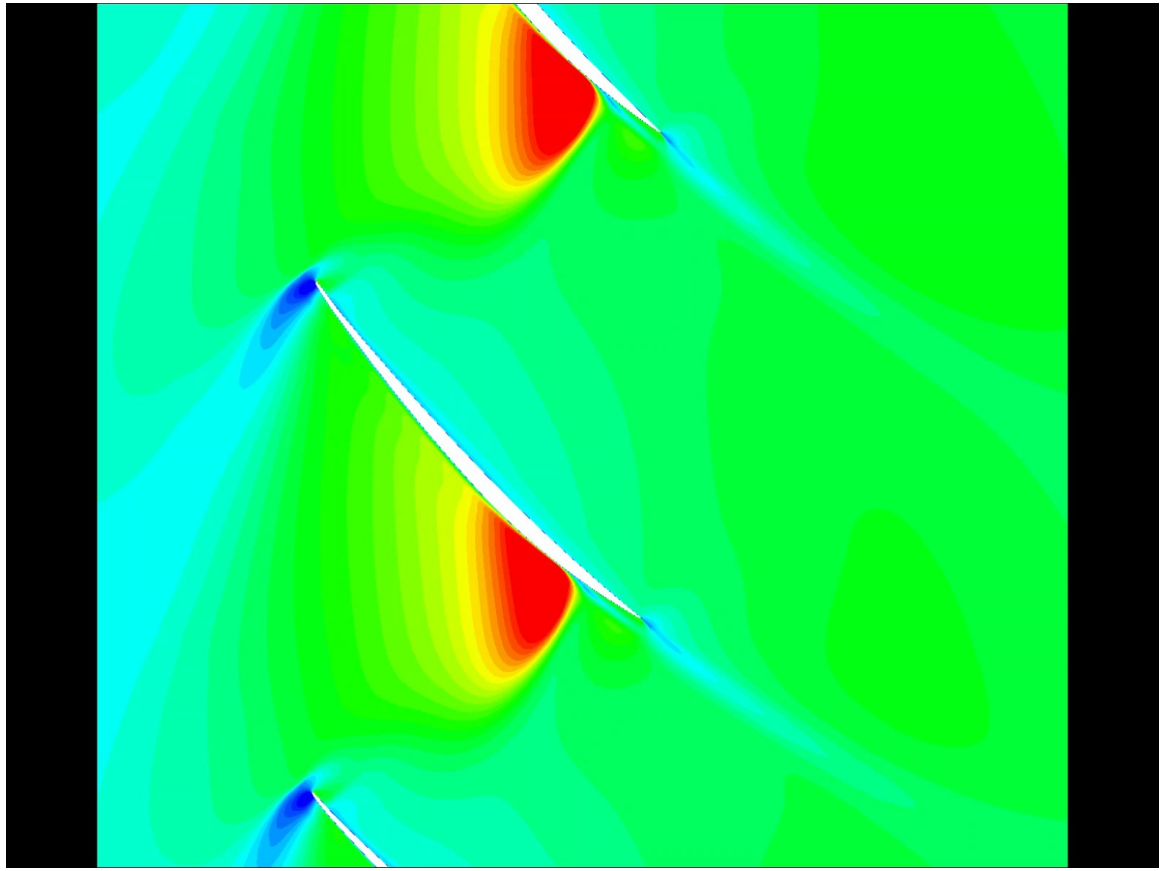
The Effect of the Distortion on Rotor Incidence Angle

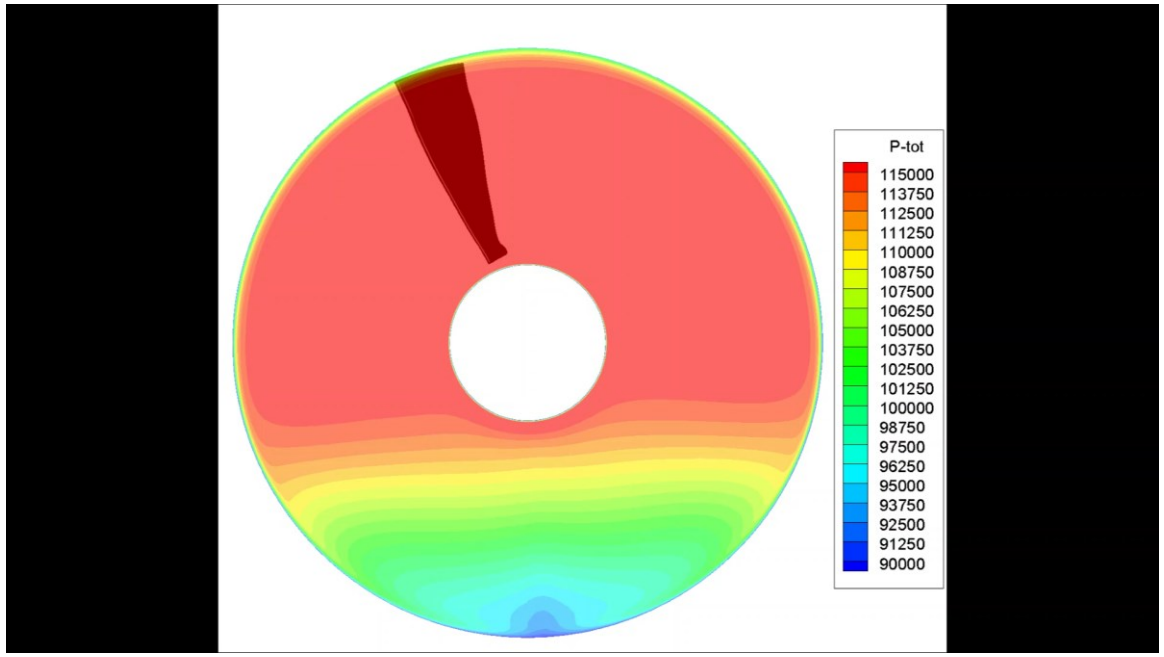


- The total pressure and swirl distortion have the largest intensity and should thereby have the greatest impact on the aerodynamic behavior of the blades.
- The total pressure distortion is related to the axial velocity. Lower axial velocity acts to increase the incidence angle and vice versa.
- The swirl distortion also influences the incidence angle due to its impact on the relative velocity perceived by the blades.
- Co-rotating swirl, U_θ^-, is the circumferential velocity in the same direction as the rotation and acts to decrease the incidence angle, α_1.
- Counter-rotation swirl, U_θ^+, is opposite to the rotation direction and acts to increase the incidence angle, α_2.

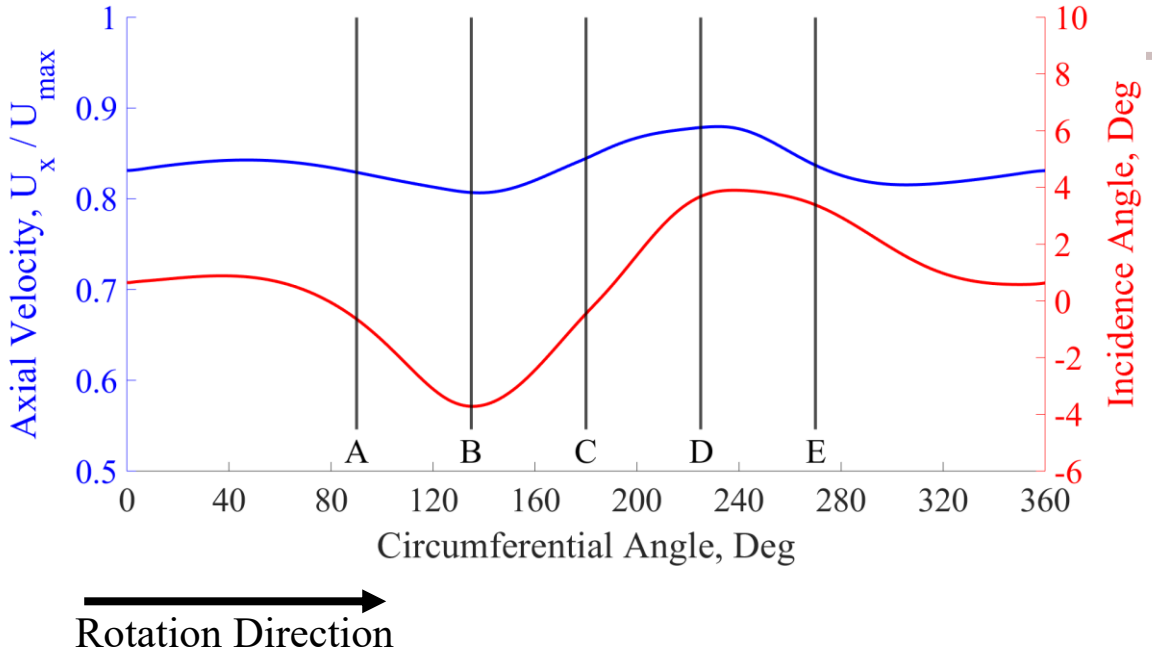
Coupled Inlet/Fan Behavior

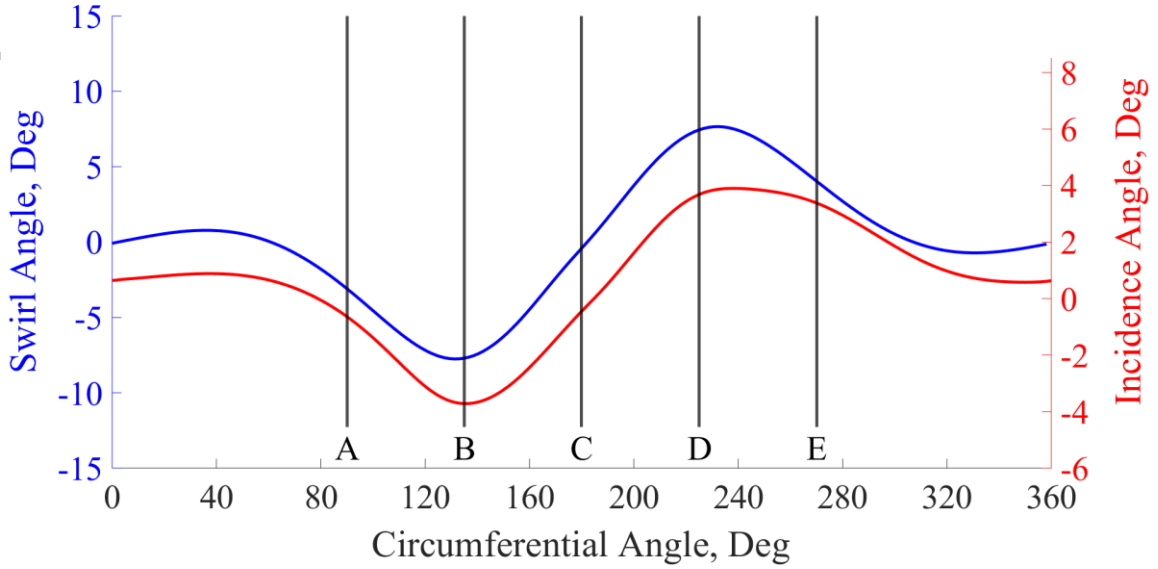
Mach Contours at 80% Span for Aerodynamic Design Point





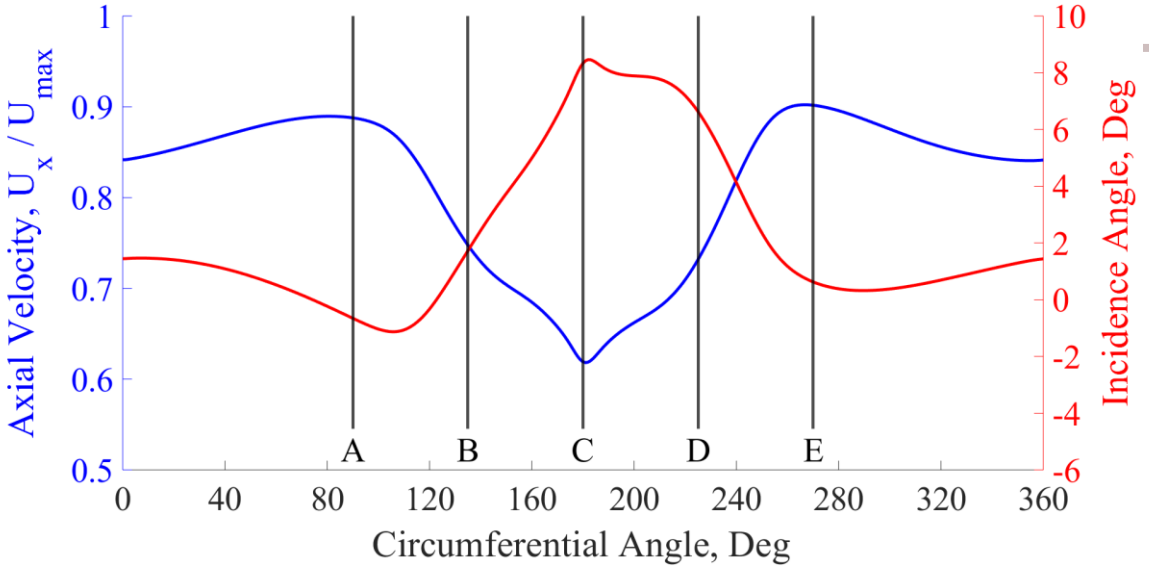
Incidence Angle at 20% Span

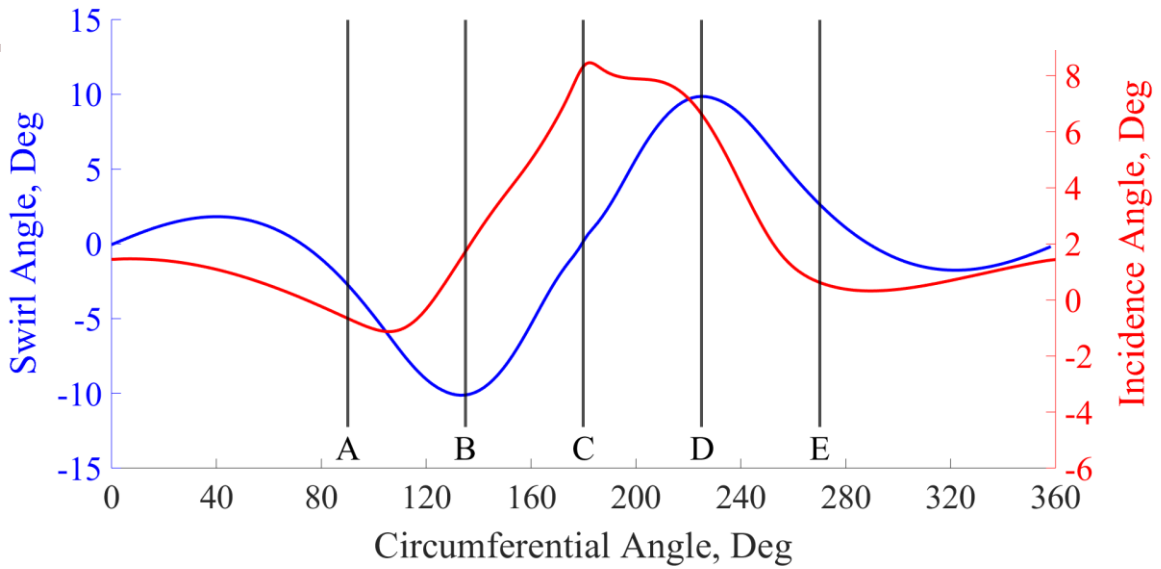




- The axial velocity at 20% span (close to the hub) is relatively uniform around the circumference.
- The incidence angle shows a sinusoidal pattern with large variation, unlikely to have been caused by the axial velocity by itself.
- In contrast to the axial velocity, the swirl angle exhibits the same profile as the incidence angle.
- The strong correlation between incidence angle and swirl angle shows that the behavior of the flow at inboard spans is dictated by incidence angle.

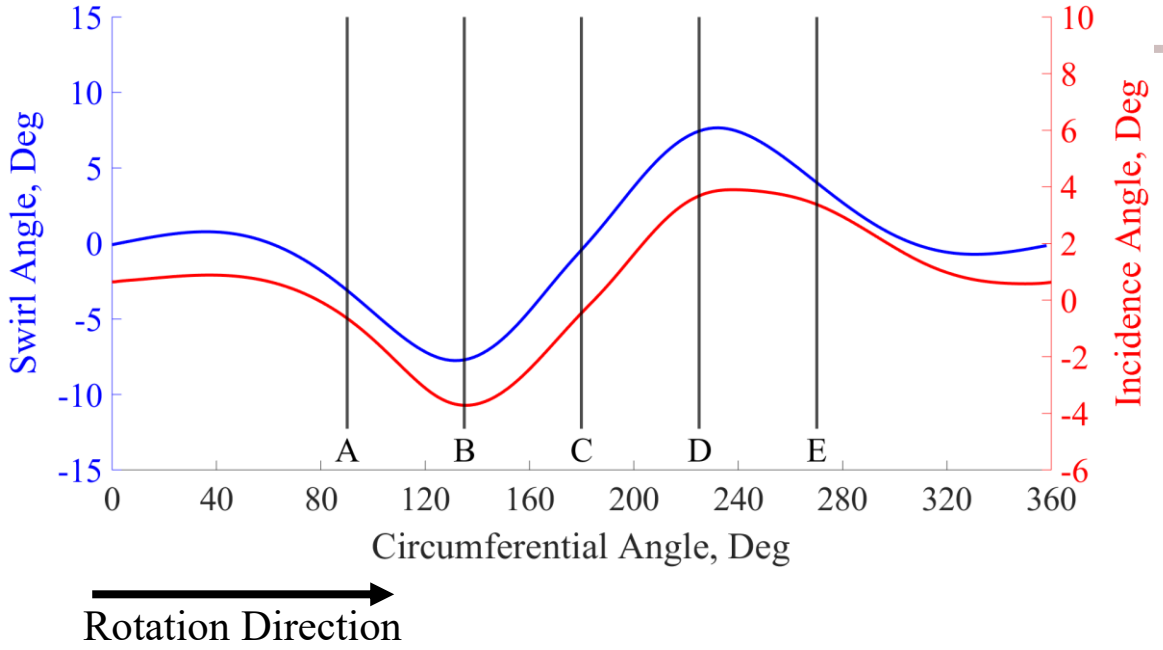
Incidence Angle at 80% Span



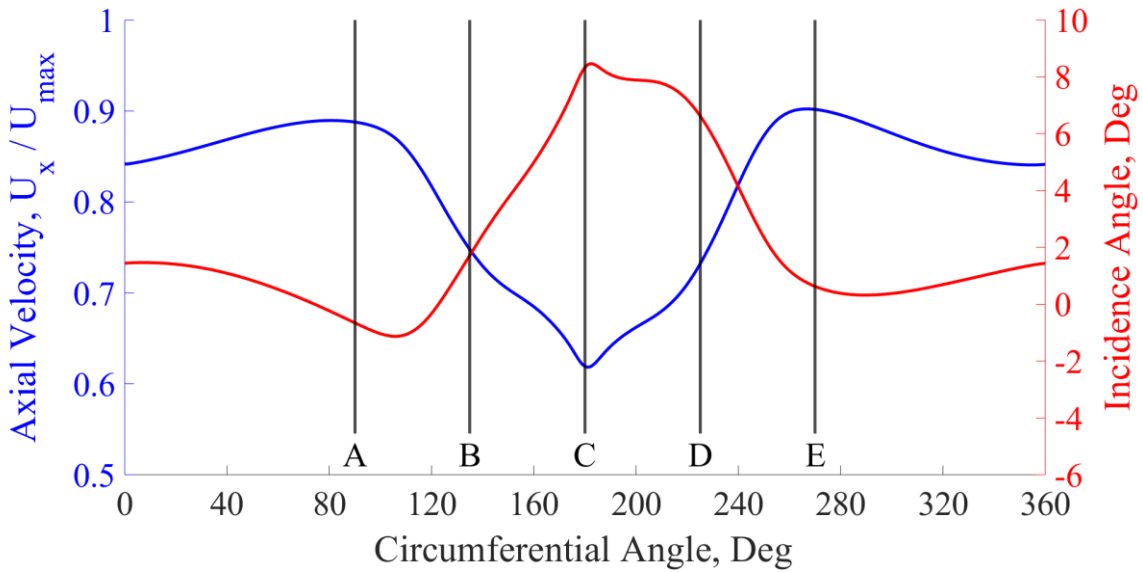


- The axial velocity at 80% span (close to the casing) is non-uniform around the circumference due to the distortion.
- The incidence angle shows a pattern which is similar to the inverse of the axial velocity, indicating that the behavior is axial velocity dominated.
- In comparison to the axial velocity, the swirl angle exhibits a phase shifted and more sinusoidal curve compared to the incidence angle.
- The peak in swirl angle corresponds to the overprediction in total temperature observed the same location, indicating an additional loss mechanism induced by swirl.

20% Span



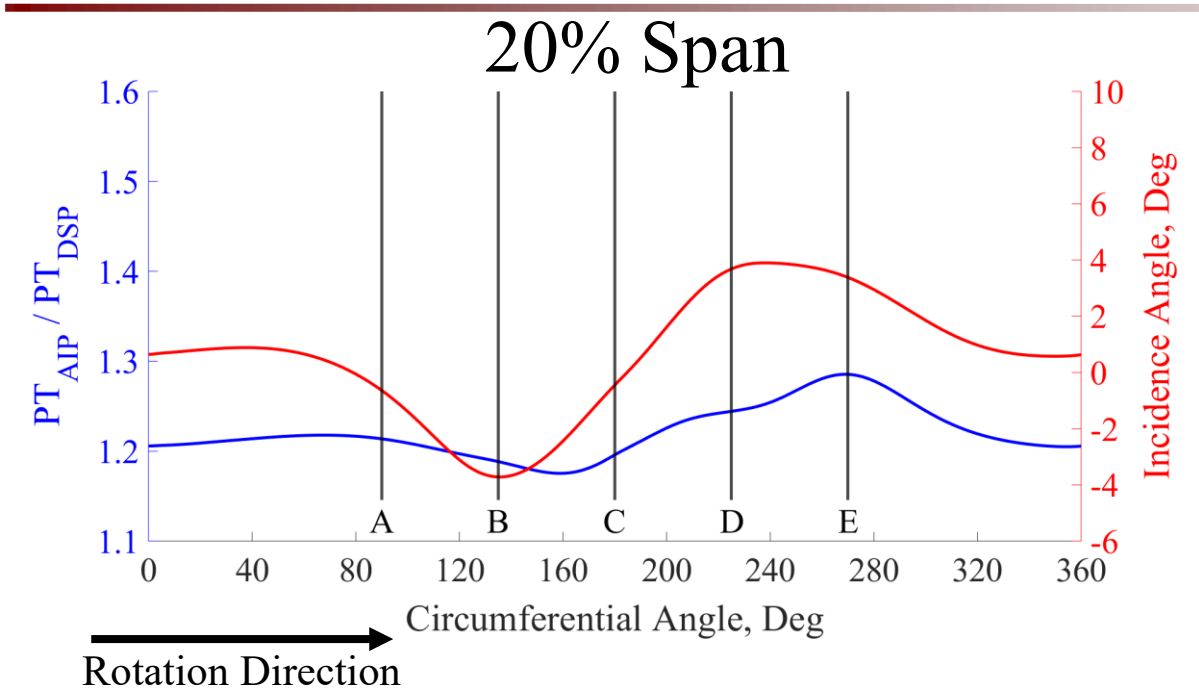
80% Span

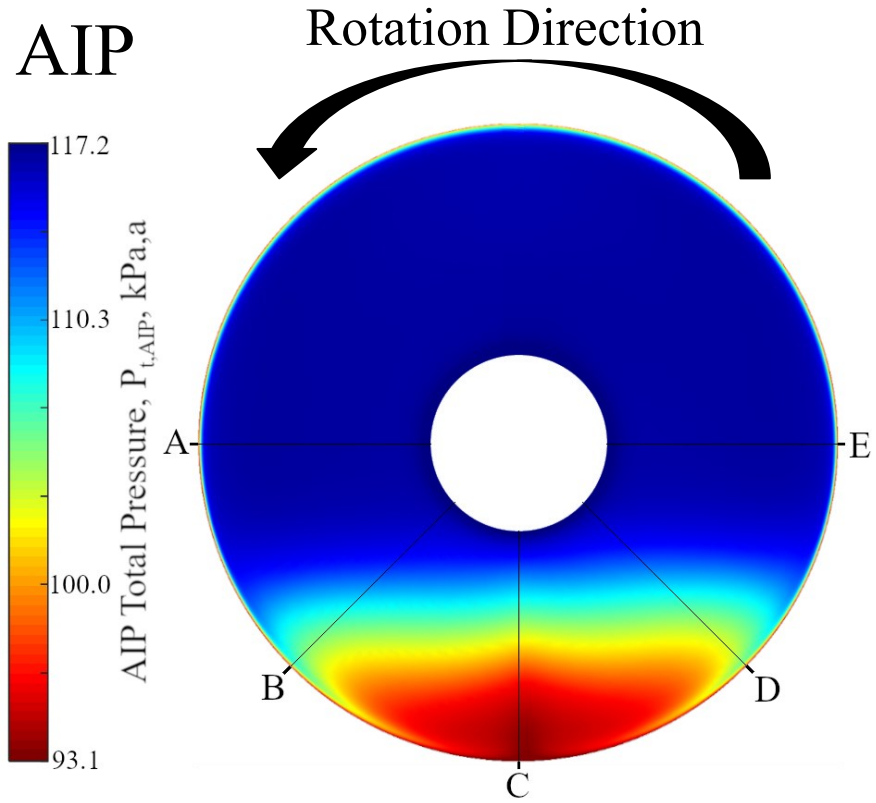


- The incidence angle behavior for the inboard span sections are swirl dominated
- The incidence angle behavior for the outboard span sections are axial velocity dominated.
- Both of these aspects can be obtained from the distortion profile at the AIP.

- This indicates that an estimation of the incidence angle on the blades can be obtained with knowledge of the distortion aspects.
- Better baseline blade designs could be obtained in the future with knowledge of the distortion.

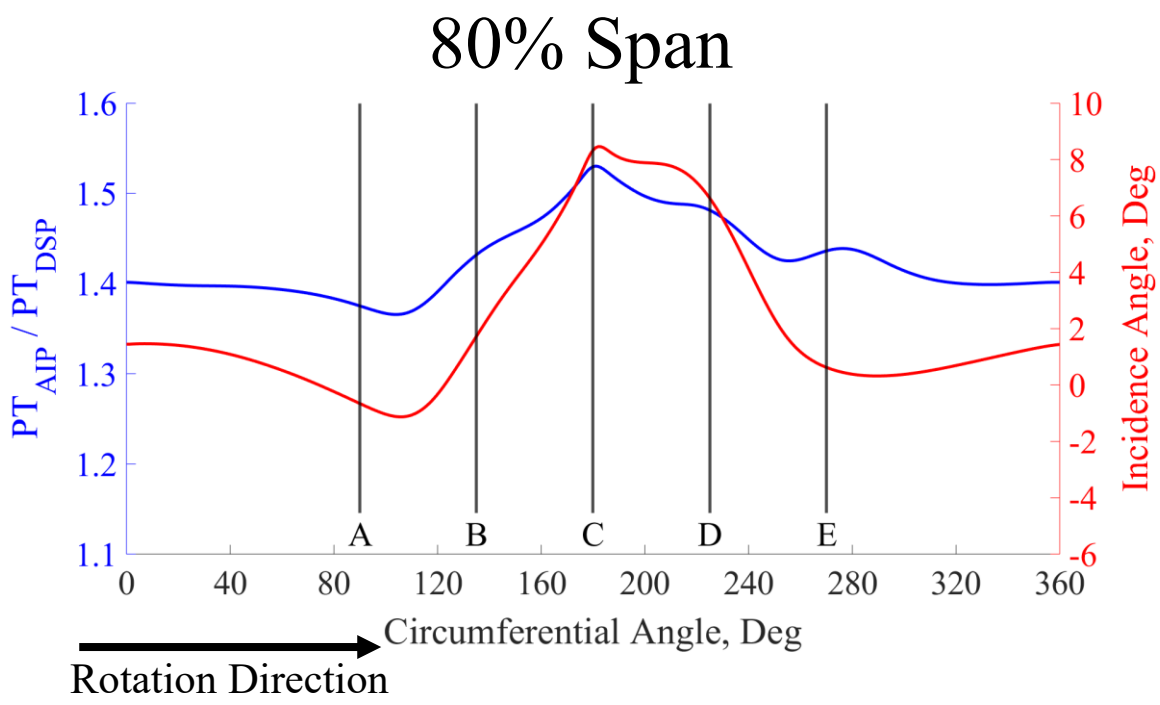
Total Pressure Ratio from the DSP relative to the AIP

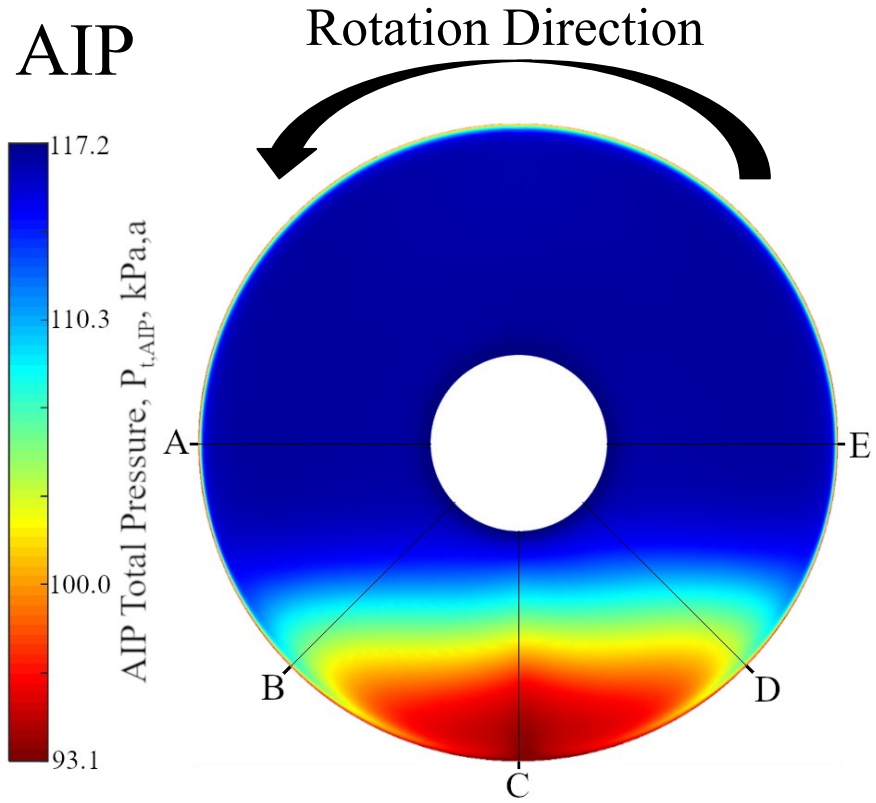




- The incidence angle correlates to the distortion and should also correlate to the total pressure ratio.
- An increase in incidence angle should impart more work into the flow and an increase in total pressure should be exhibited, and vice versa.
- For 20% span, the total pressure ratio curve appears to be similar to the incidence angle curve.
- A low total pressure ratio and incidence angle occurs at location B which rise to a peak between locations D and E.
- The general behavior in the clean flow region (E to A) of incidence angle and total pressure ratio shows good agreement.

Total Pressure Ratio from the DSP relative to the AIP

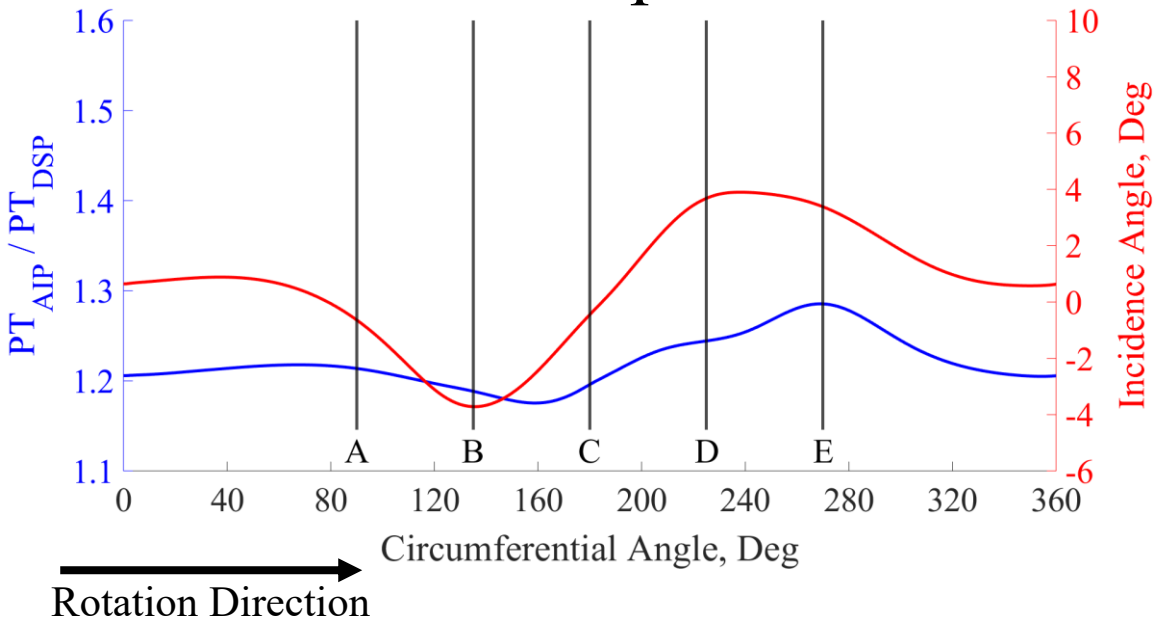




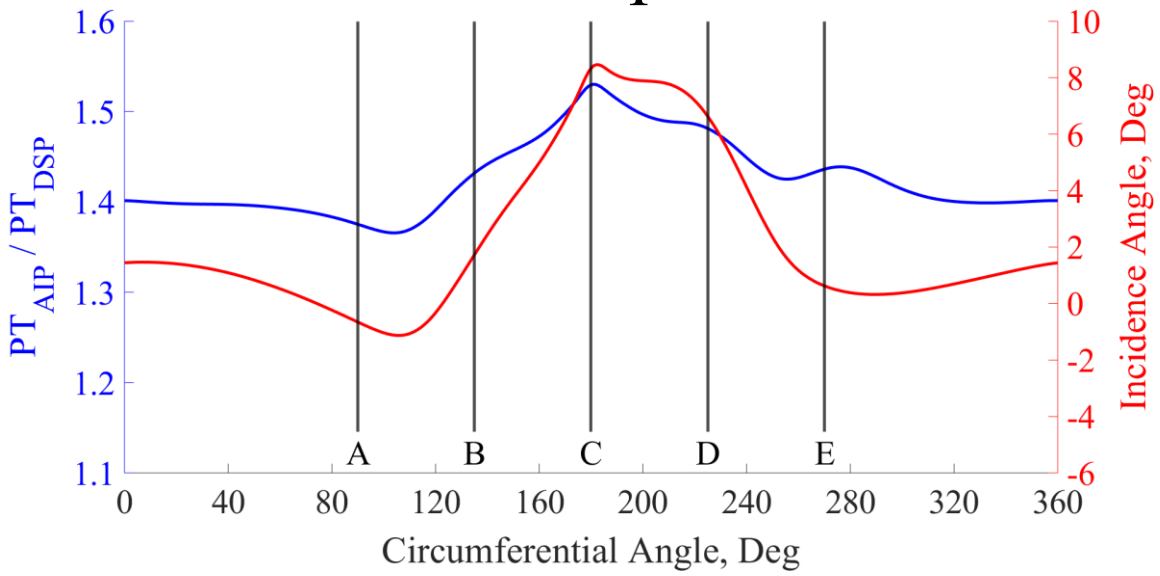
- In the same manner as 20% span, 80% span shows that the general behavior of the total pressure ratio is similar to the incidence angle.
- The curves reach a low between locations A and B then rise to a peak at location C.
- There exists a region of different total pressure ratio behavior near location E that does not match well with the incidence angle.
- This could be due to changes in the local flow around the blade while exiting the distortion that induce the apparent rise.

Total Pressure Ratio from the DSP relative to the AIP

20% Span



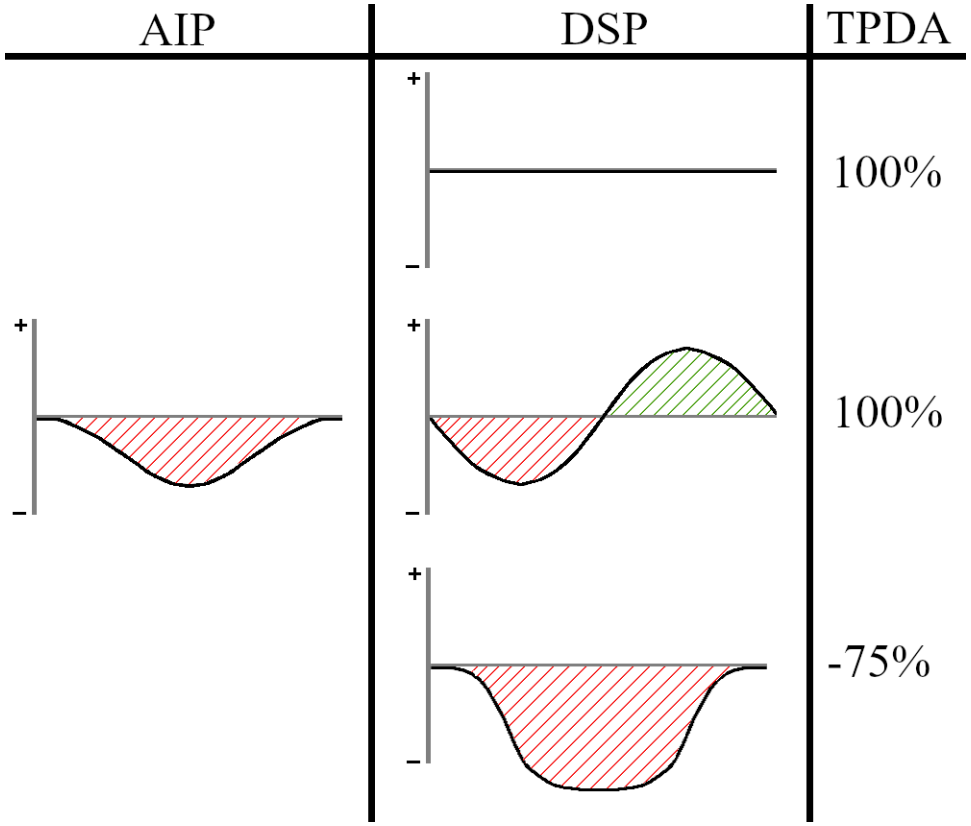
80% Span



- The incidence angle appears to generally correlate to the total pressure ratio imparted by the fan.
- While there are secondary and non-linear effects which effect the total pressure ratio, an estimate can be obtained from the incidence angle curve.
- This indicates that an estimation of, not only the incidence angle, but also the total pressure ratio can be obtained with knowledge of the distortion.
- A better baseline fan blade can be designed for future distortion profiles.

Distortion Profile Downstream of the Fan

Total Pressure Distortion Attenuation



- The total pressure distortion attenuation, TPDA, is a metric designed to give insight into how the distortion is acted upon by the fan.
- The TPDA is the ratio of the distortion at the AIP to the distortion after interacting with the fan at the DSP (as a percentage).
- The ratio is found by integrating the circumferential curve of, $\widetilde{PT}$, at every radial location.
- The TPDA was found based on the radius to give some measure of how the different spanwise sections of the blade handle the distortion.

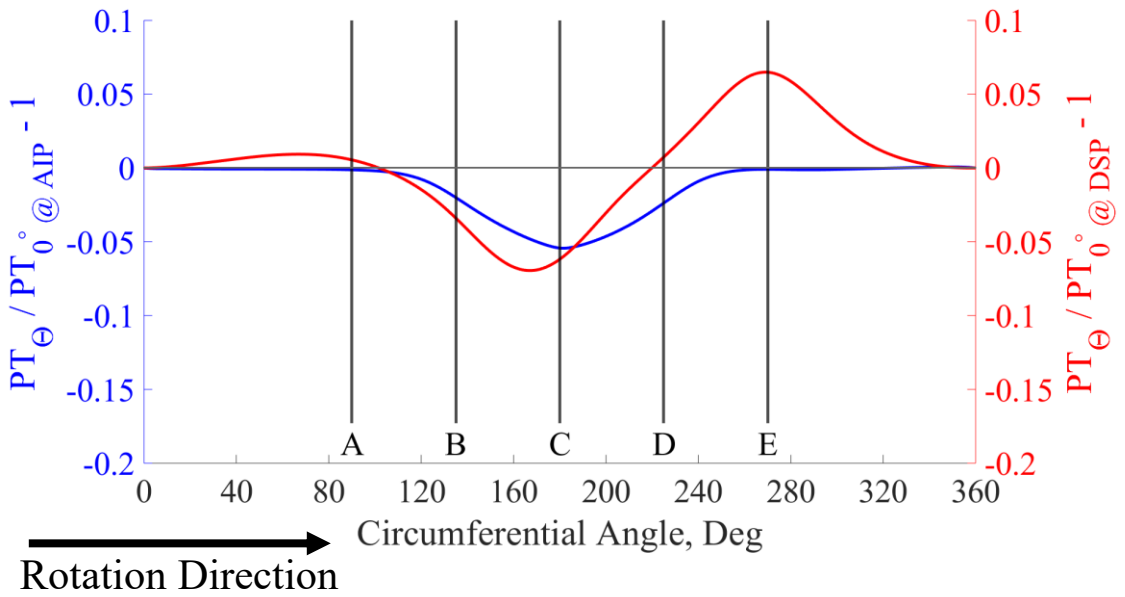
$$\widetilde{PT}(\theta_k) = \frac{PT(\theta_k)}{PT(0°)} - 1$$

$$I_{AIP} = \sum_{k=1}^{N-1} \frac{\widetilde{PT}_{AIP}(\theta_{k+1}) + \widetilde{PT}_{AIP}(\theta_k)}{2}(\theta_{k+1} - \theta_k)$$

$$TPDA = \left(1 + \frac{I_{DSP}}{|I_{AIP}|}\right) \cdot 100$$

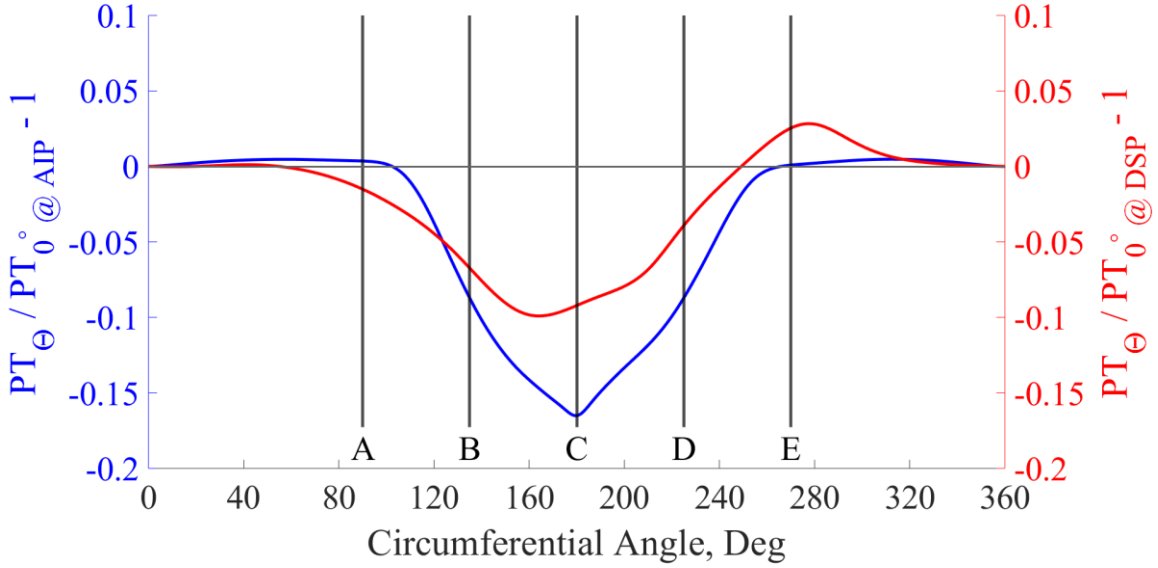
Total Pressure Distortion Attenuation

20% Span



- The upstream distortion is in blue and the downstream distortion is in red.
- For 20% span the downstream distortion has a significant overpressure region near location E.
- The overpressure is higher than that attained in the clean flow region.

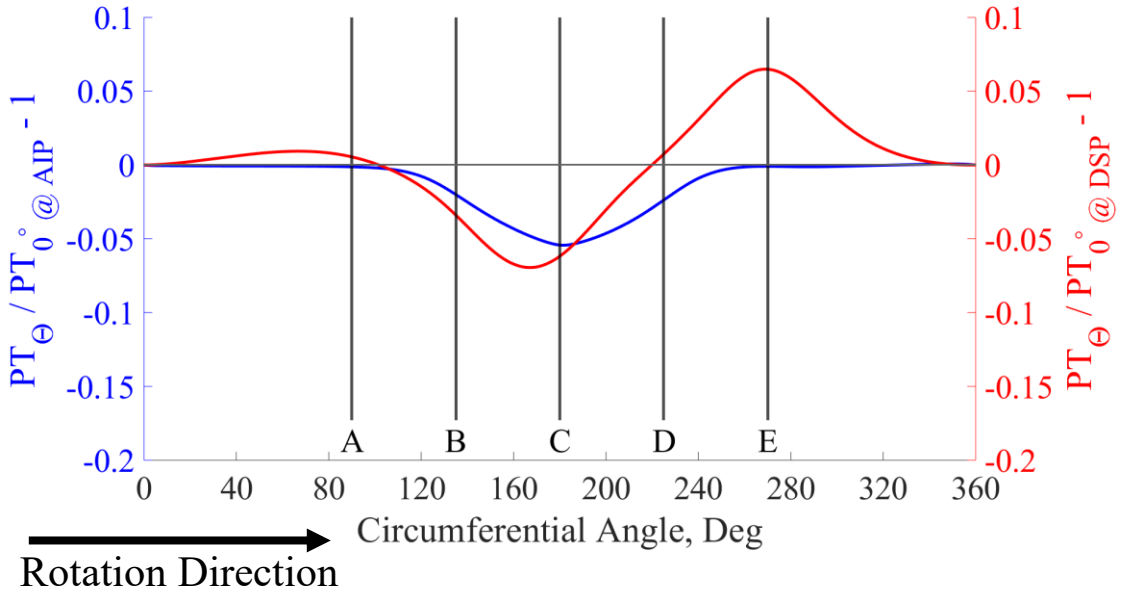
80% Span



- 80% span also shows an overpressure region but it is smaller than 20% span.
- However, 80% span displays a much larger decrease in the distortion after interacting with the fan, peak of 18% to a peak of 8%.

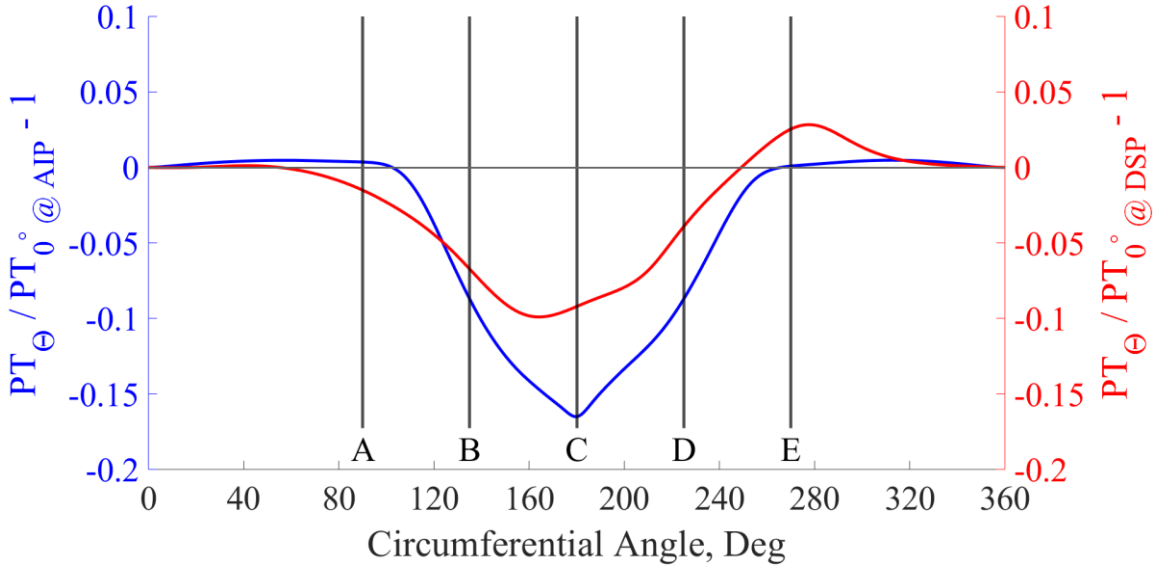
Total Pressure Distortion Attenuation

20% Span



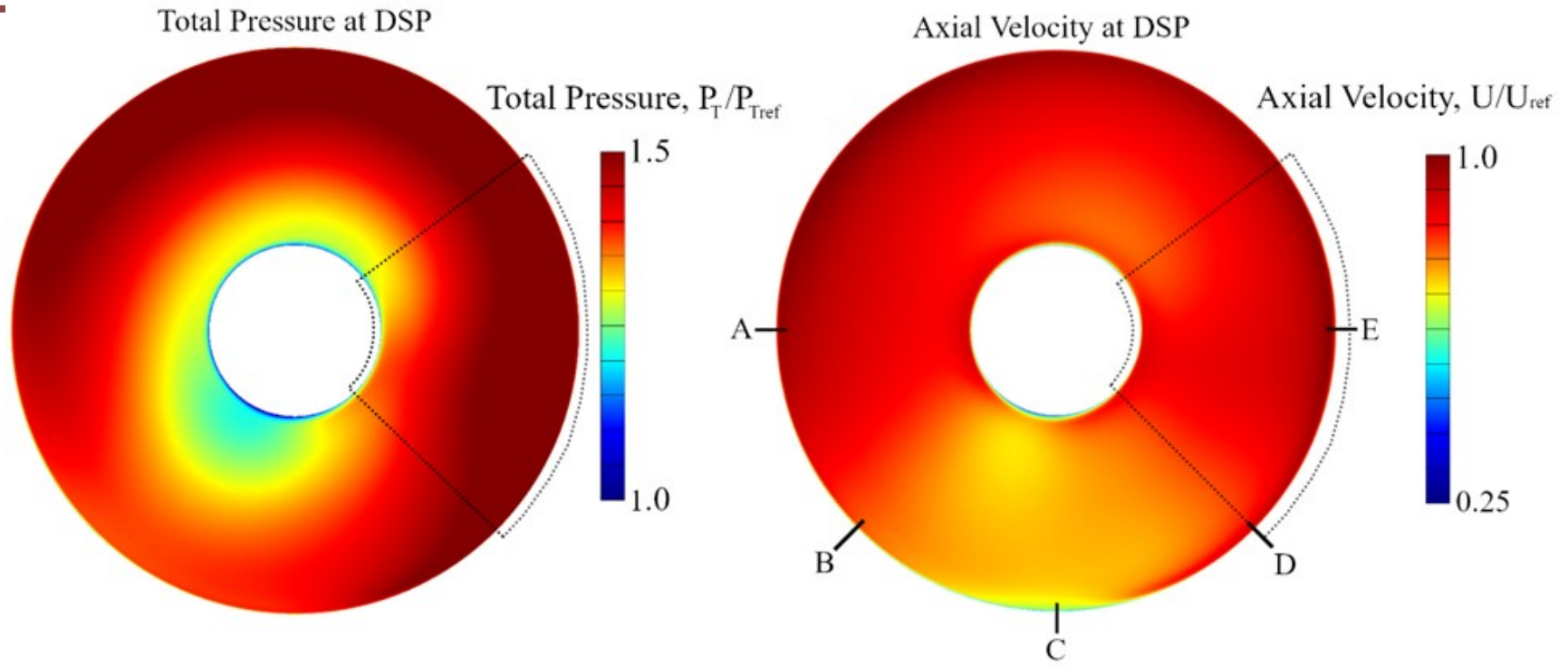
Rotation Direction

80% Span



- The overpressure for 20% span resulted in a TPDA of 102.7%.
- Due to the larger distortion region and smaller overpressure region, the TPDA for 80% span is 38.7%.
- The downstream total pressure is the combination of the distortion at the AIP and the total pressure rise.
- This means that with the incidence angle and total pressure able to be estimated from the distortion the TPDA can also be estimated based on the incidence angle.

Total Pressure Distortion Attenuation



- Non-uniform flow downstream of a propulsor is not normally considered beneficial but the TPDA counts it as a benefit.
- The overpressure region is at a higher pressure resulting in an overall higher total pressure ratio average for the fan.
- The overpressure region is also at a higher velocity meaning that it will have a stabilizing effect on downstream turbomachinery, i.e. moving away from stall.

Conclusions

- A simulation of the Boundary Layer Ingesting Inlet – Distortion Tolerant Fan was performed for the op-line condition at 100% design speed
- Static pressures in the inlet duct, for the coupled simulation, matched with experimental values but were not well predicted by the lower fidelity ADZ simulation
- The total pressure rise of the propulsor predicted by the coupled simulation matched very well with the experiment
- The predicted stage efficiency was close but lower than the experimental value and appeared to be due to higher total temperature as the fan blades exited the distortion
- The incidence angle is dictated by the swirl angle at low span of the blade and is dictated by axial velocity at high span.
- Estimations of fan performance can be created by knowing/using the distortion profile and may help future designs/models.
- The attenuation of the distortion downstream of the fan is affected by radial location on the blade.
- Lower spans have greater overpressure and higher spans decrease the distortion to a greater extent.

Questions?

