PIV Investigation of a High Speed Centrifugal Compressor Diffuser: Spanwise and Loading Variations

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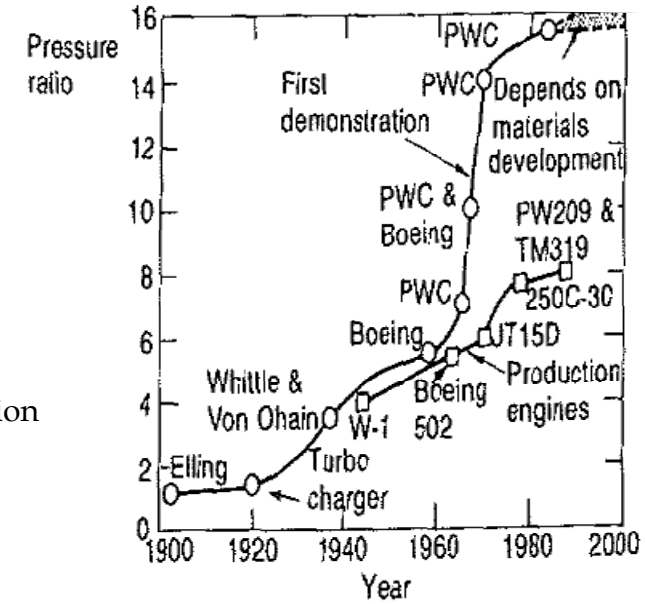
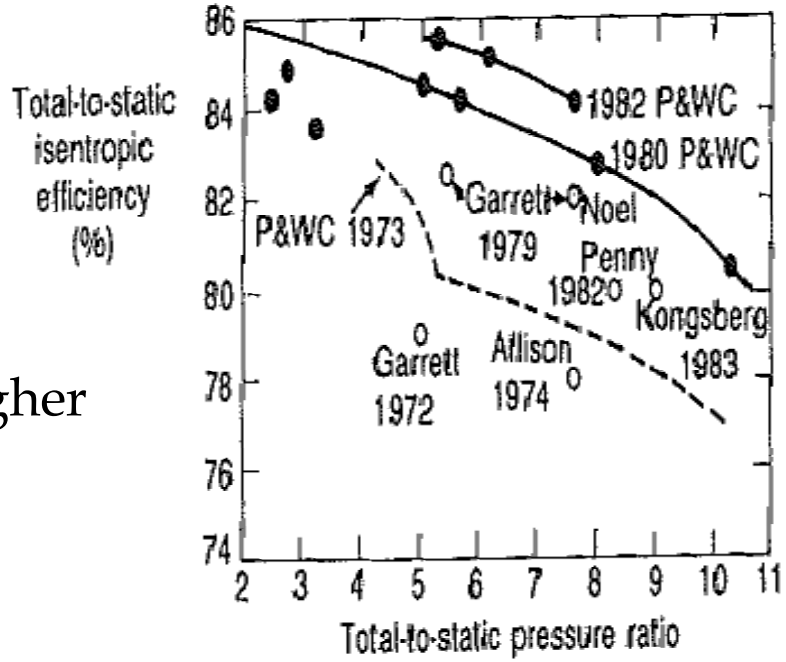
Funded in part by
Rolls-Royce Corporation, Indianapolis

Centrifugal Compressors

- Some Advantages of Centrifugal Compressors
  - Compact, Light Weight
  - Lack of Mechanical Friction
  - Lower Maintenance, Higher Reliability
  - Simplicity and Ruggedness
  - Higher Pressure Ratio per Stage
    - mechanism of energy transfer being less dependent on relative diffusion
- Favored for Small gas Turbine Engines

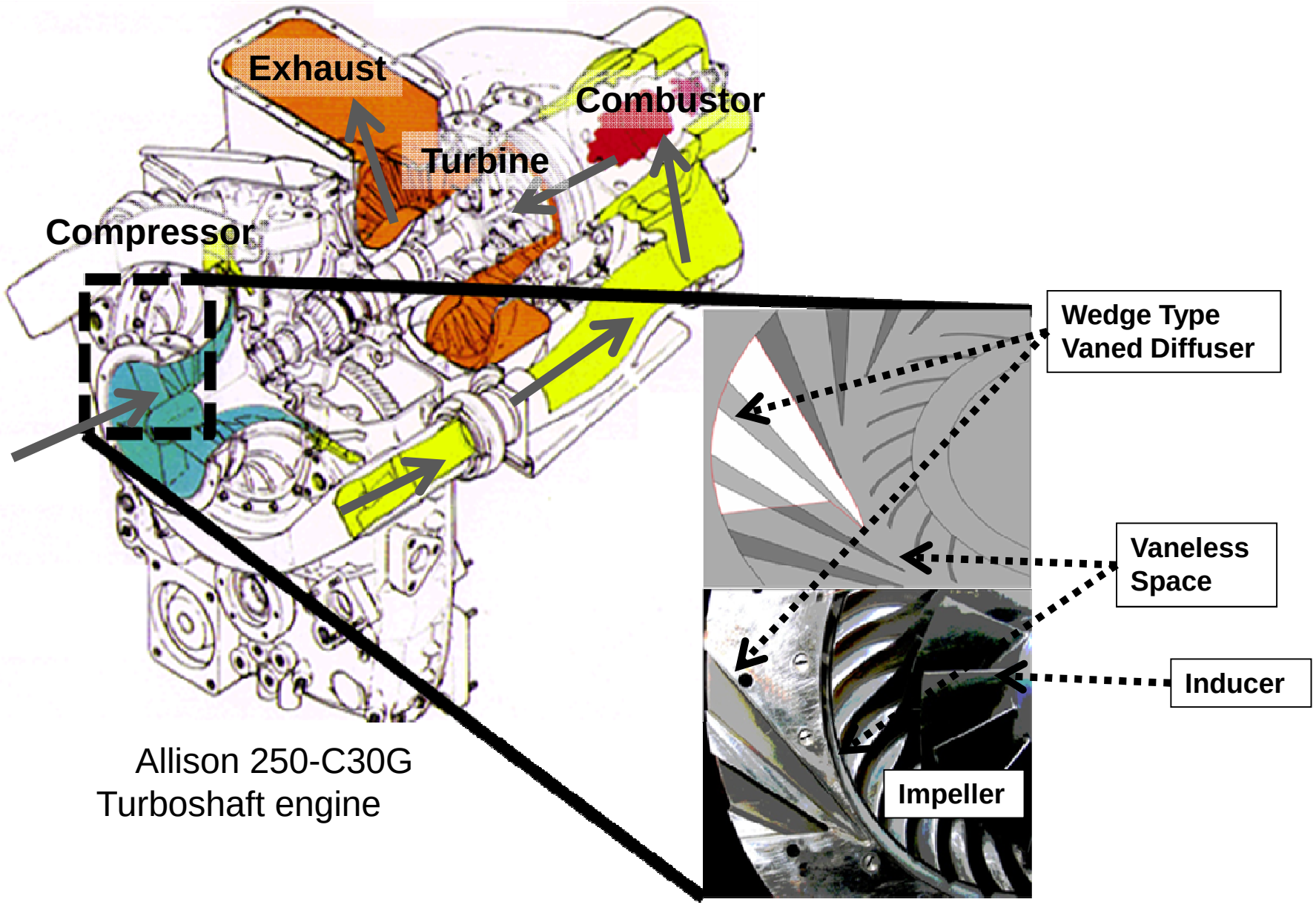


- Complexity
  - Three dimensional Flow Field
  - Viscous forces are important
  - Highly unsteady
  - Impeller-Diffuser Interaction



- The future of small gas turbines rely on higher efficiency and pressure ratio centrifugal compressors

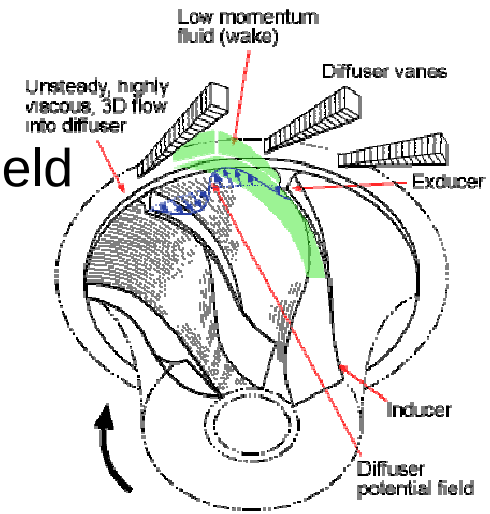
Centrifugal Compressors



Allison 250-C30G
Turboshaft engine

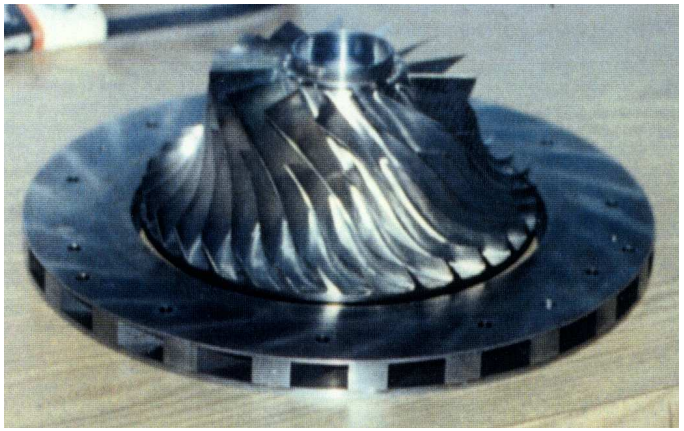
Introduction & Objective

- An efficient diffuser is essential to the performance, durability and operability of a centrifugal compressor stage.
  - Often the flow range of a centrifugal compressor is limited by stall or choke of the vaned diffuser.
- The effects of the diffuser geometry on the compressor stage are hard to predict
  - Coupling between the impeller and diffuser
    - Analysis as isolated components unrealistic
  - Impeller exit flow is a function of diffuser potential field
    - Diffuser geometry
    - Unsteady diffuser loading
      - Produced by the impeller
  - Enhances the value of empirical data
    - Performance
    - Durability



Objective: Characterize the circumferential variations along with spanwise distribution at several loading conditions for the diffuser flow field

Research Compressor



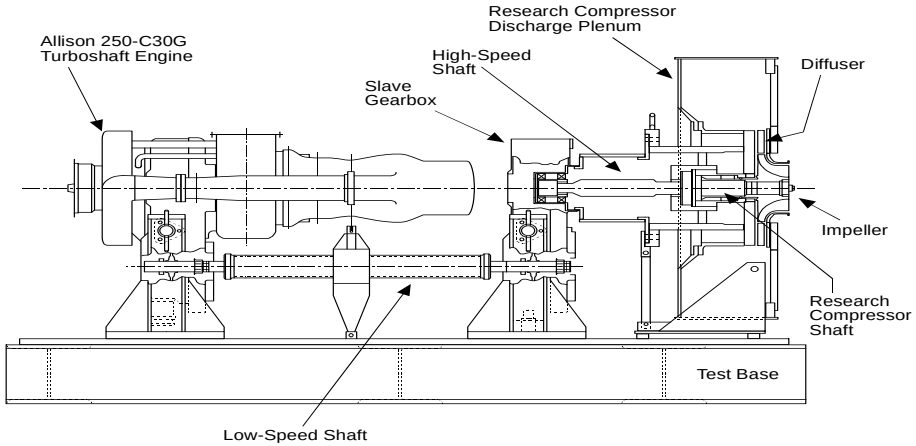
IMPELLER	
Tip Diameter	21.65cm
Inlet Diameter	14.2cm
Number of Blades	15 w/ splitters
Design Speed	48,450 rpm
Backsweep	50°
WEDGE DIFFUSER	
Inlet Diameter	23.67cm
Exit Diameter	34.5cm
Axial Passage Width	1.38cm
Number of Vanes	22
Radial Gap ratio	1.094
Diffuser Inlet Vane Angle	79.4º
Wedge Diffuser Opening Angle	7.85º

- High efficiency, pressure ratio compressor
  - -Impeller exit flow/diffuser entry flow field typical of modern transonic compressors

Experimental Method

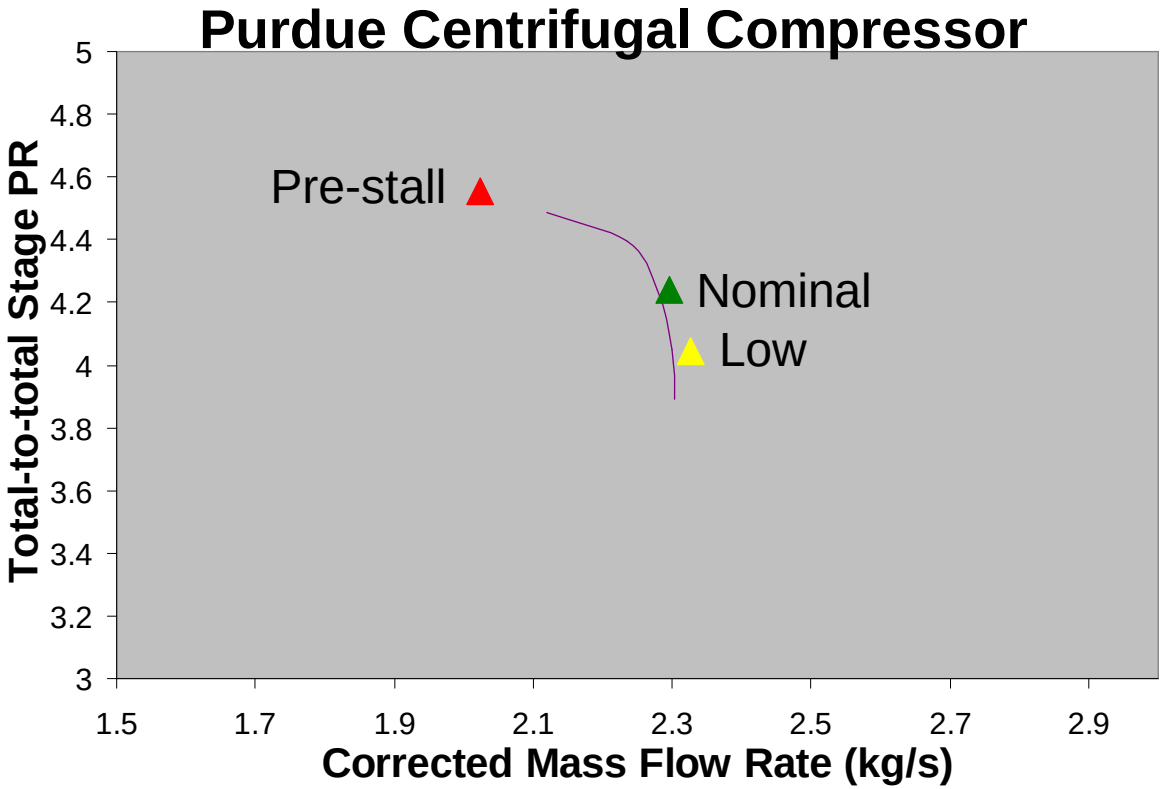
- Loading Conditions

Loading	N_{cor}	m_{cor}	PR
Low	101.87%	2.326	4.045
Nominal	101.23%	2.296	4.241
Pre-stall	101.08%	2.023	4.556



- Spanwise Locations
  - 25% from hub
  - 50% from hub
  - 75% from hub

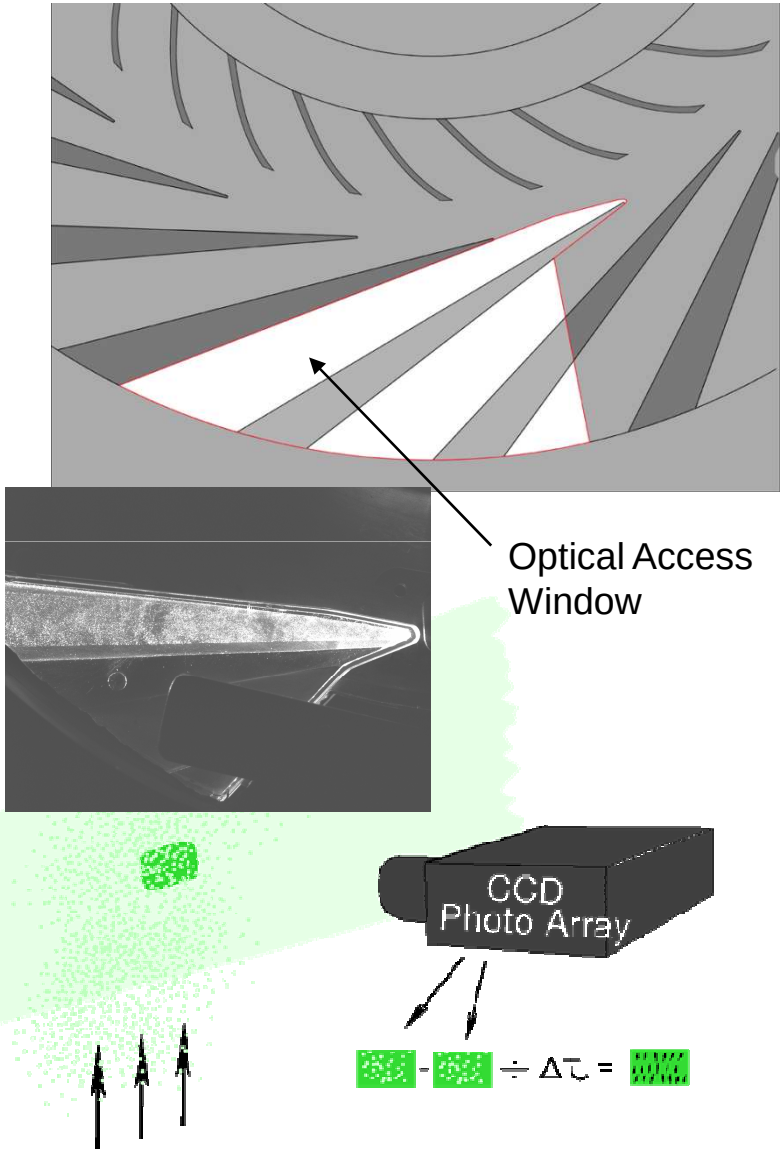
- 5 relative diffuser-impeller posns (delays)
  - 2 blade passages
    - 1 full blade & 1 splitter blade
  - 20% increments



Particle Image Velocimetry (PIV)

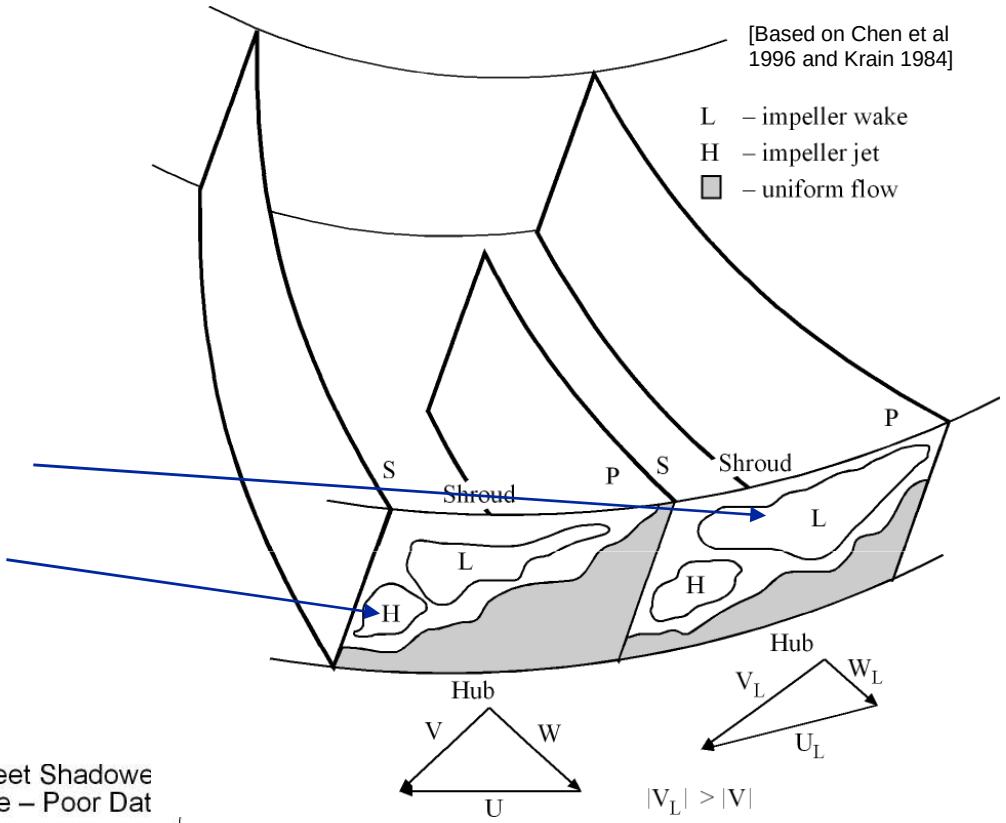
- Components
  - Sub-Micron Flow Tracking Particles
    - DiEthyl Hexyl Sebacate (DEHS)
      - d=0.25μm
      - In regions bounded by the sonic velocity:
      - up to 1.09% of the true velocity for 0.5mm flow features
  - Planar Illumination
    - Converging Light Sheet with Thickness Tailoring
  - Double Pulsed Nd:YAG Laser
  - Double Exposure Digital Camera

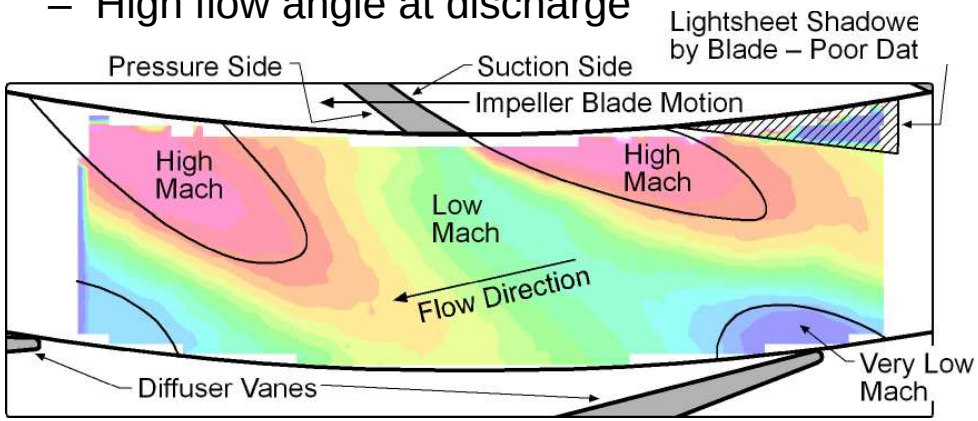
- Data Processing
  - Iterative multi grid cross correlation routine with window offsetting
  - 200 Images acquired for Ensemble Average
  - 25 valid vectors for interrogation region to report a velocity

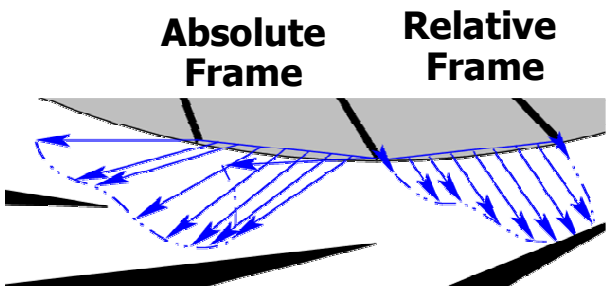


Impeller Discharge Flow

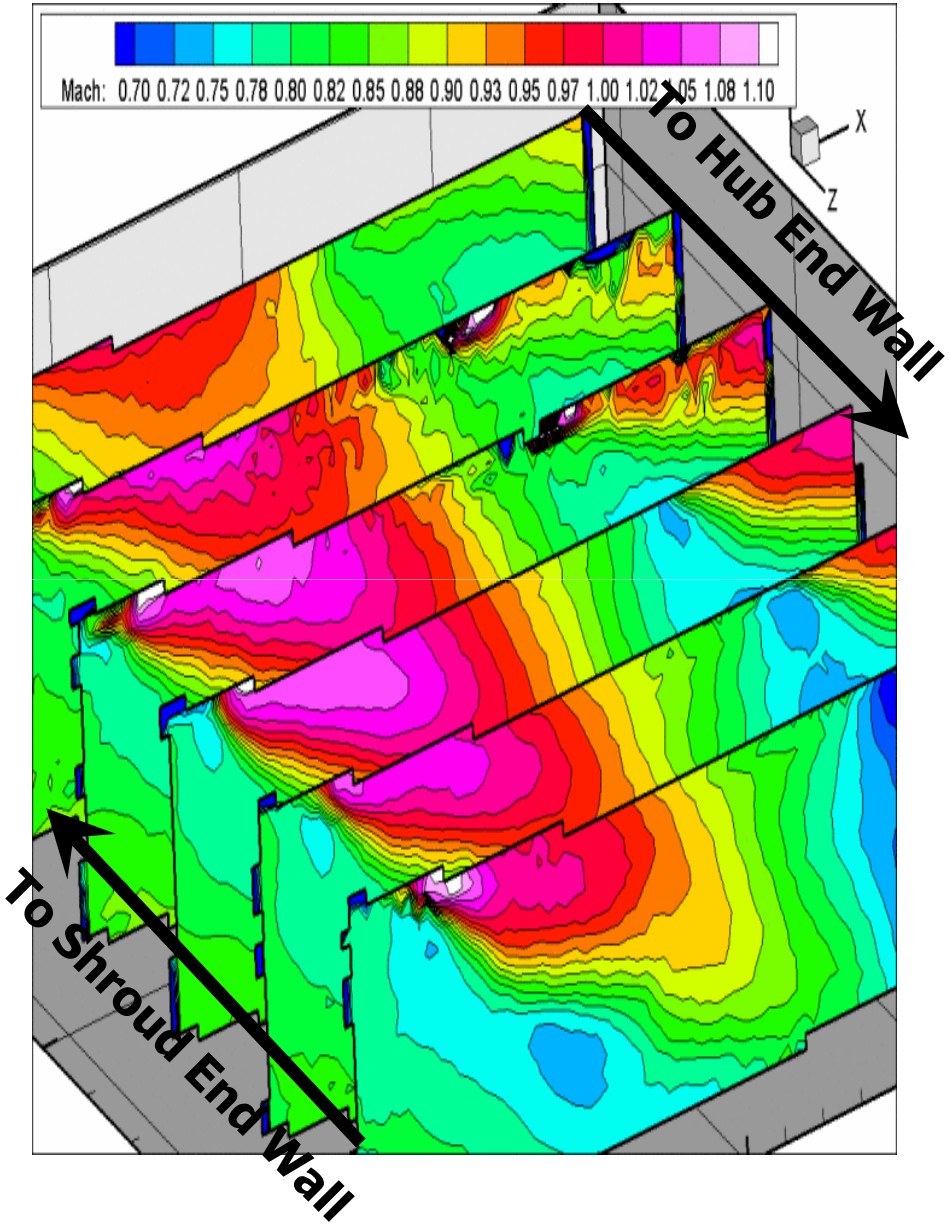
- Relative Frame
  - High momentum fluid concentrated near PS hub
  - Low momentum fluid gathers near SS shroud
- Absolute Frame
  - Large swirl velocity causes
    - Low momentum fluid to appear as high velocity region
      - Low flow angle at discharge
    - High momentum fluid appears as low velocity region
      - Larger radial component
      - High flow angle at discharge

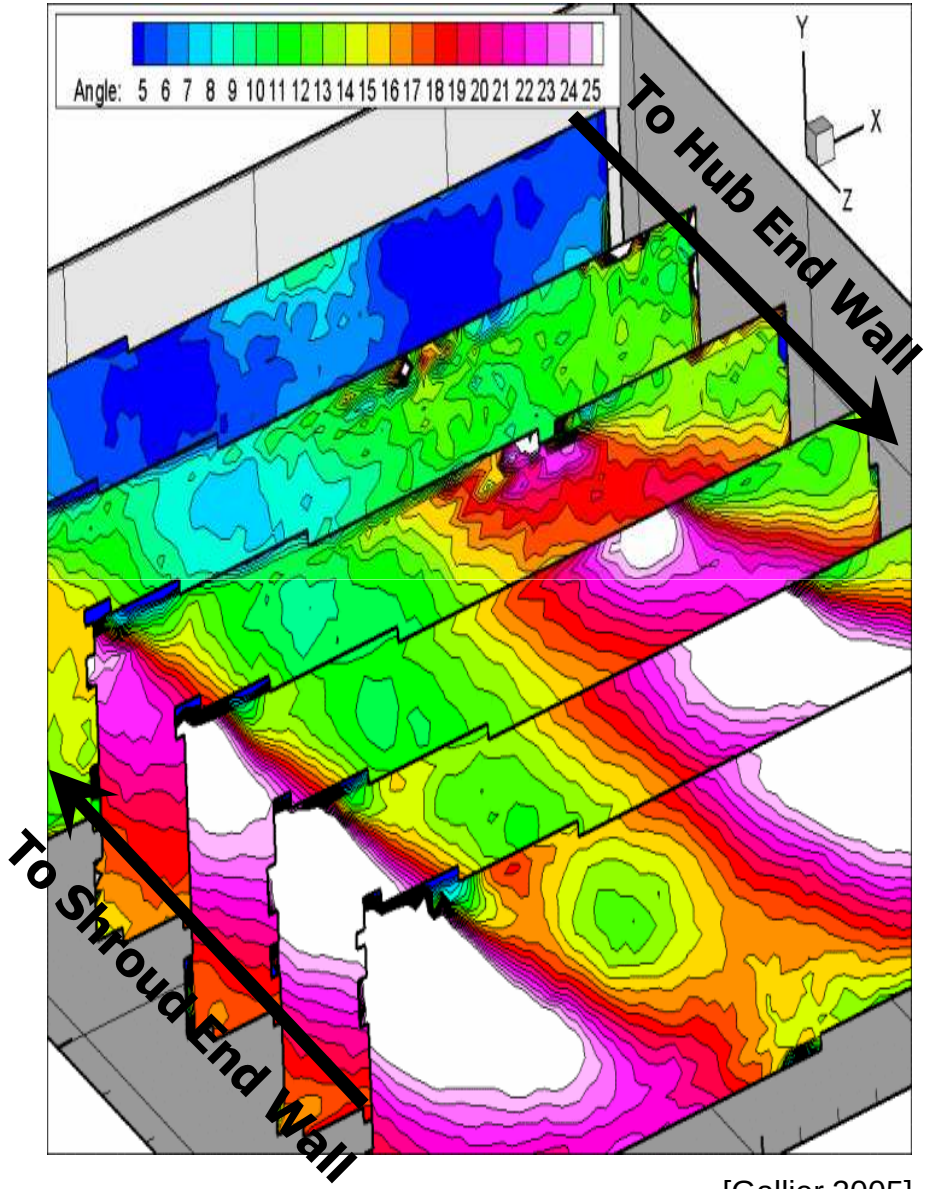






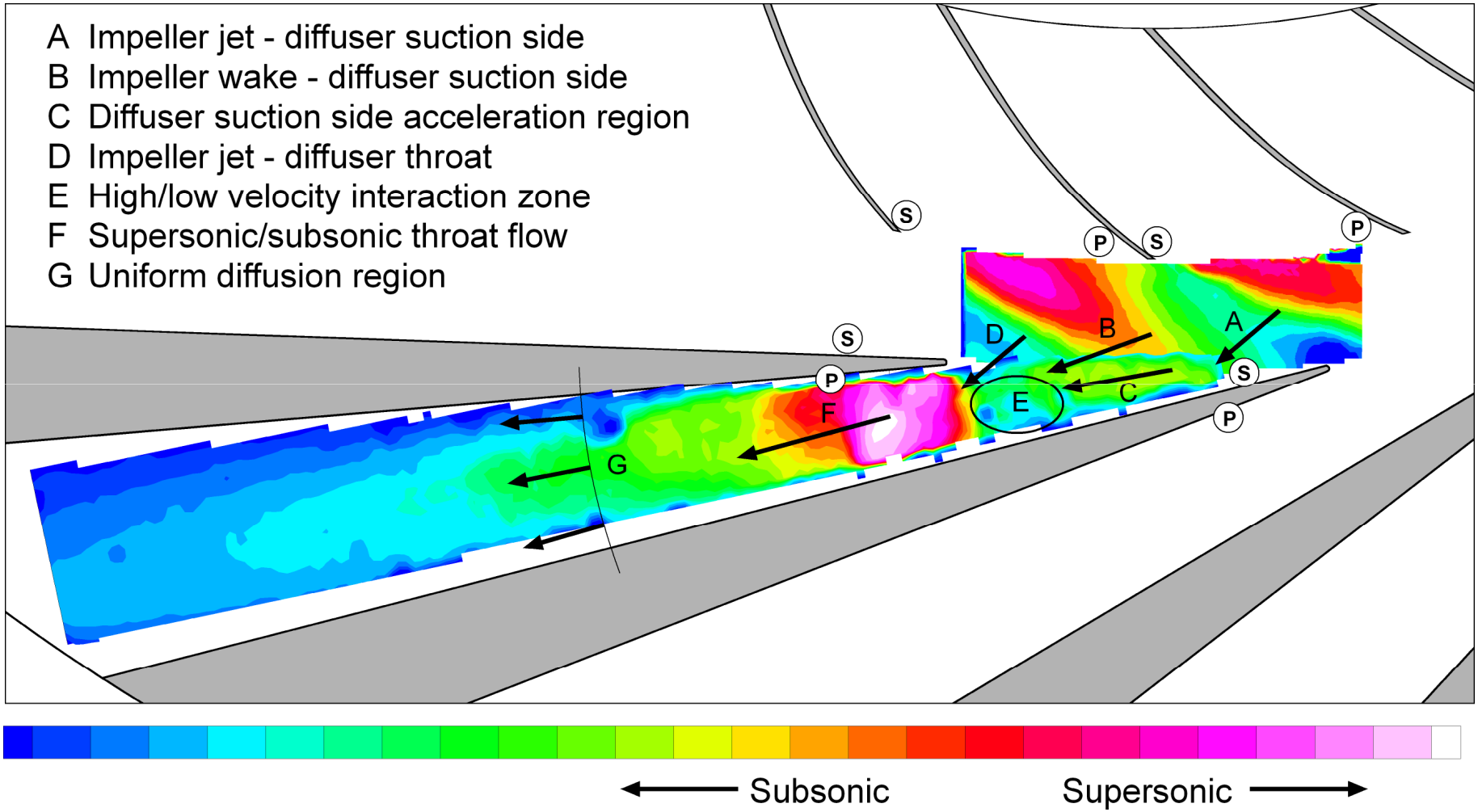
Vaneless Space





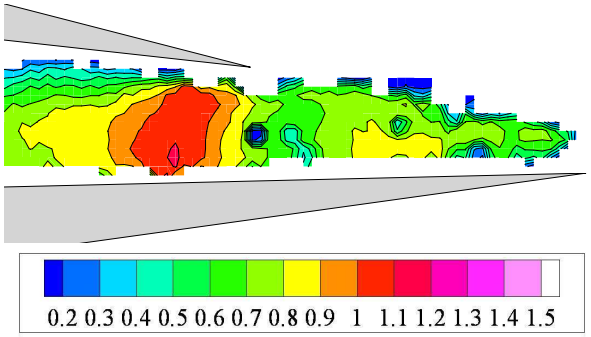
[Gallier 2005]

Impeller-Diffuser Interaction Overview



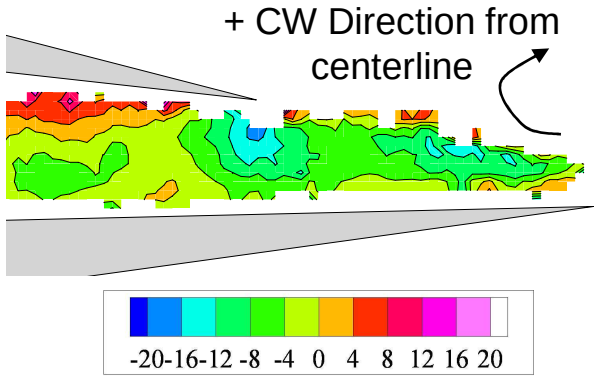
Nominal Loading – Near Hub

Lets take a look at these mentioned flow features in nominal loading, near hub measurement plane



Ma

- Semi-Vaneless Space Acceleration Region
  - Mach number is around 0.9
  - Flow is following the suction side vane
  - Consistent with geometry-driven acc. of the flow
  - Design criteria suggests avoiding supersonic flows
    - Shock structures/their adverse effects on boundary layer growth.

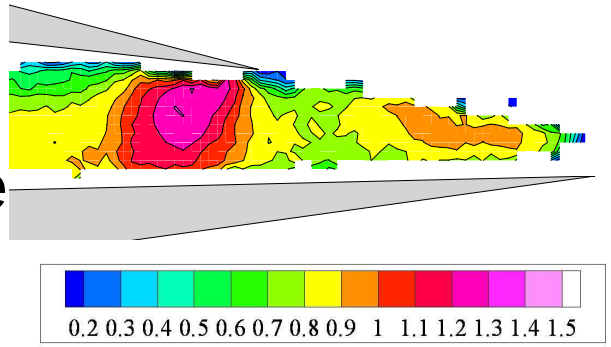


α (deg)

- Impeller Jet Flow
  - The impeller jet flow is characterized by deviation:
    - Flow angle: -8º from mean
    - Mach number: -15% from mean
- Prior to the throat
  - Flow decelerates from Mach 0.85 to 0.75
    - Partly a function of the area increase with increased radius
  - Main cause: Rapid adjustment zone
    - Two different types of flow fields interact
      - Jet flow: Large incidence & lower Mach
      - SS acceleration region: Smaller incidence & Higher Mach

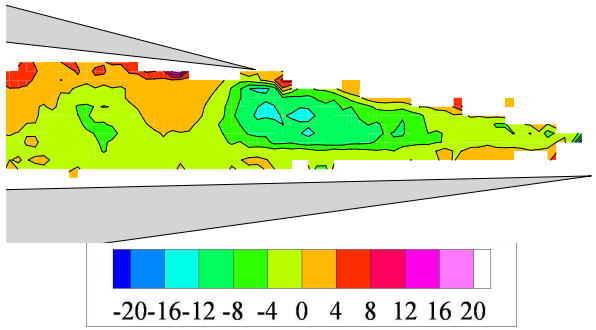
Nominal Loading – Mid Span

- Mach number in the semi-vaneless space and the throat are elevated
  - Consistent with the higher momentum levels at mid-span



Ma

- Highly negative flow angle regions cease to exist
  - Gallier showed that the flow in the vaneless space became more uniform around the mid-span
  - Jet flow reduces to -4º deviation from the mean flow
    - Minimum negative flow angle has become more tangential



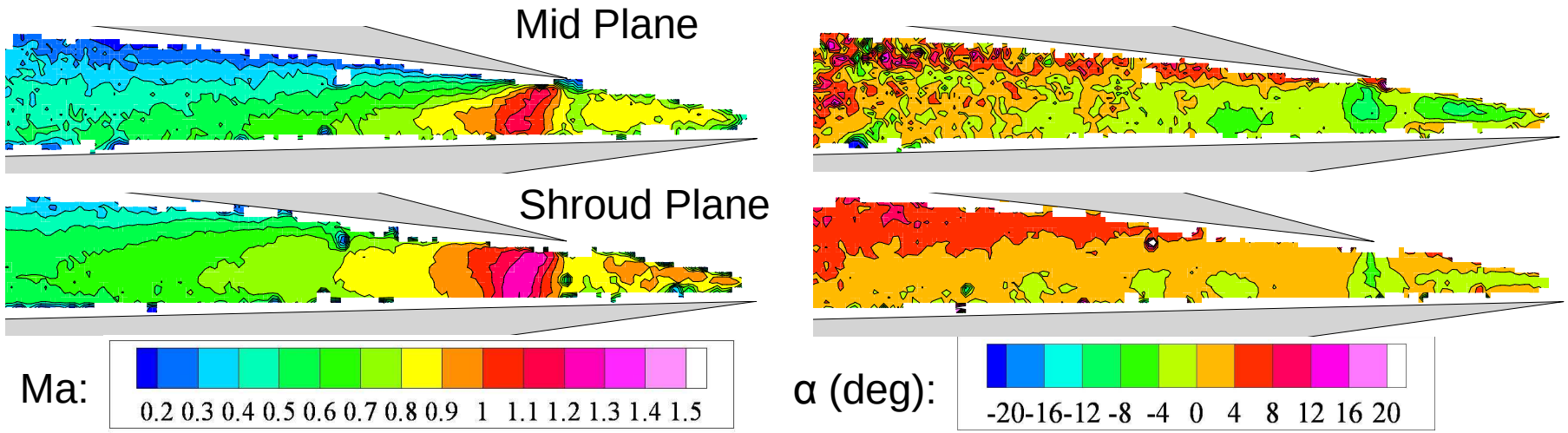
α (deg)

- Diminishing effects of impeller jet flow in the mid span

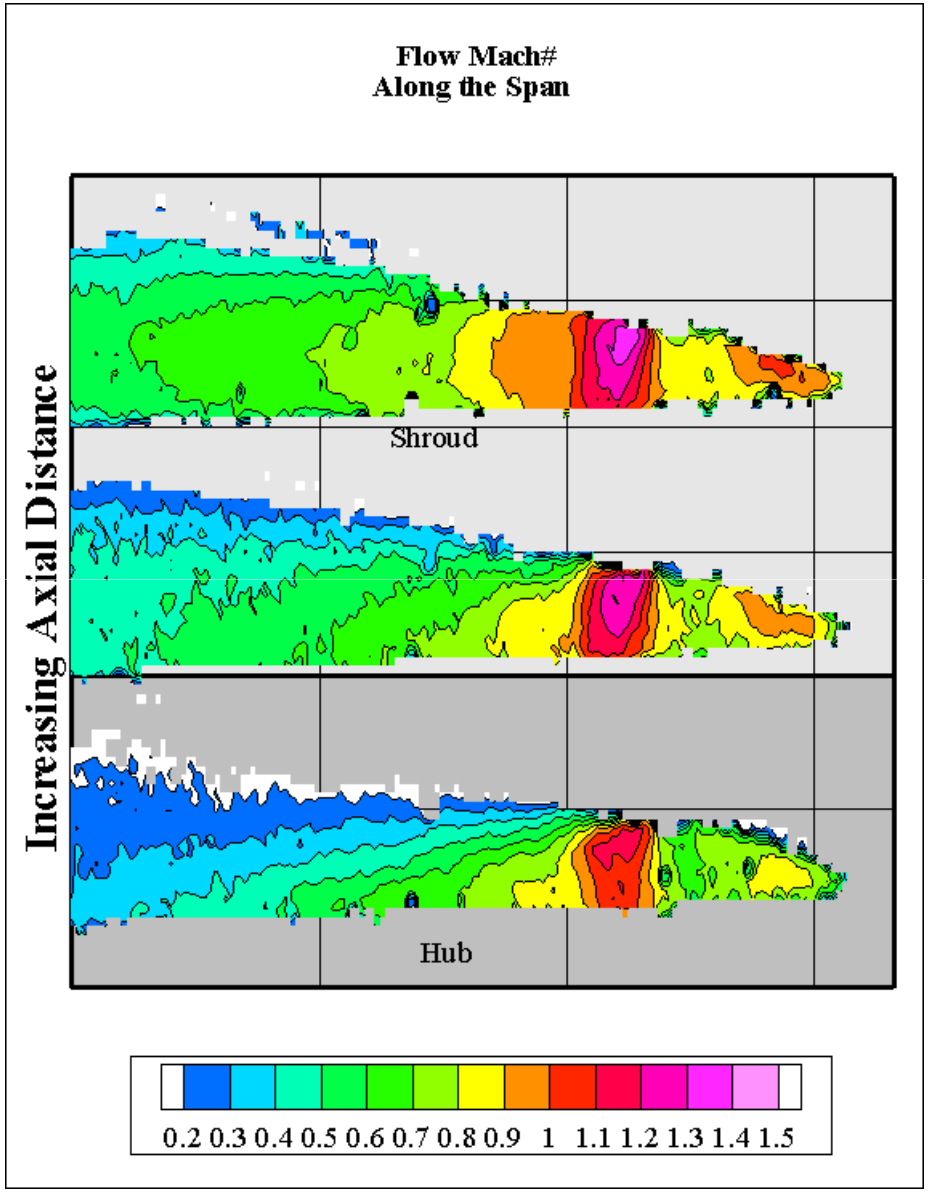
Nominal Loading – Near Shroud

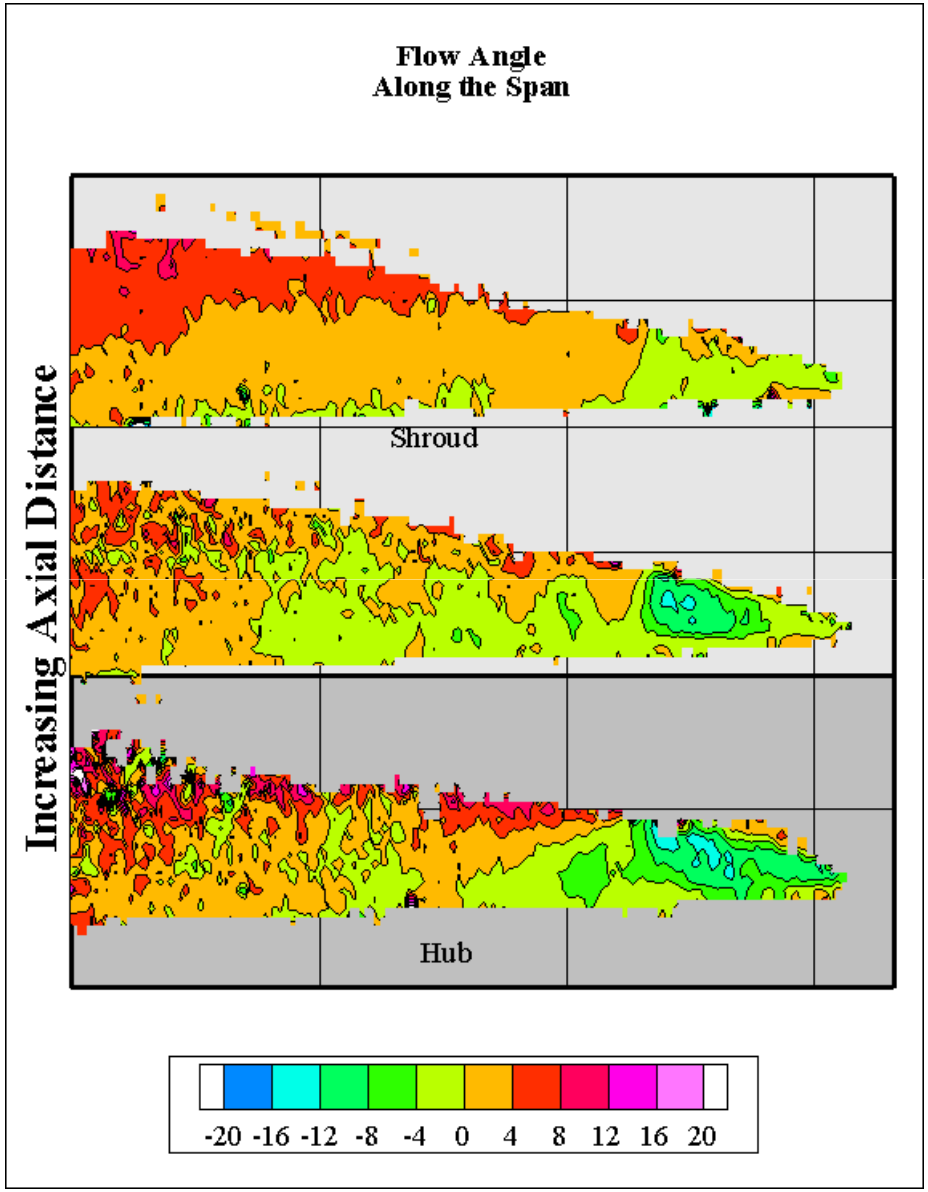
- Increase in overall Mach from mid-plane to shroud plane
  - Semi-vaneless space acceleration zone extends
  - Velocities downstream of the throat augments
  - No high/low momentum interaction zone
    - Effects of jet flow are diminished

- Artifact of the impeller wake ingression into the diffuser
  - Impeller wake associated with high velocity & smaller radial component
    - Lower incidence regions in near shroud, wrt mid-span
      - Decrease in incidence angle is 10º

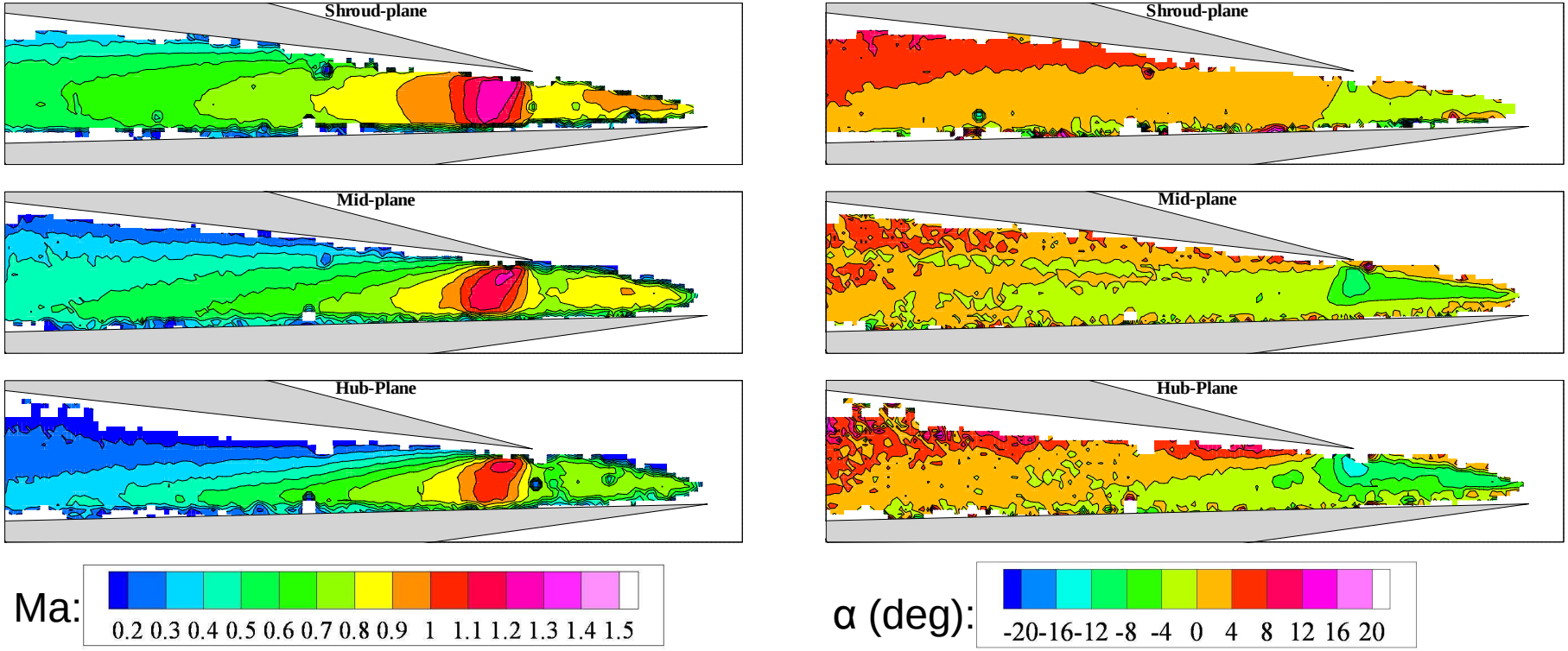


Nominal Loading Animation





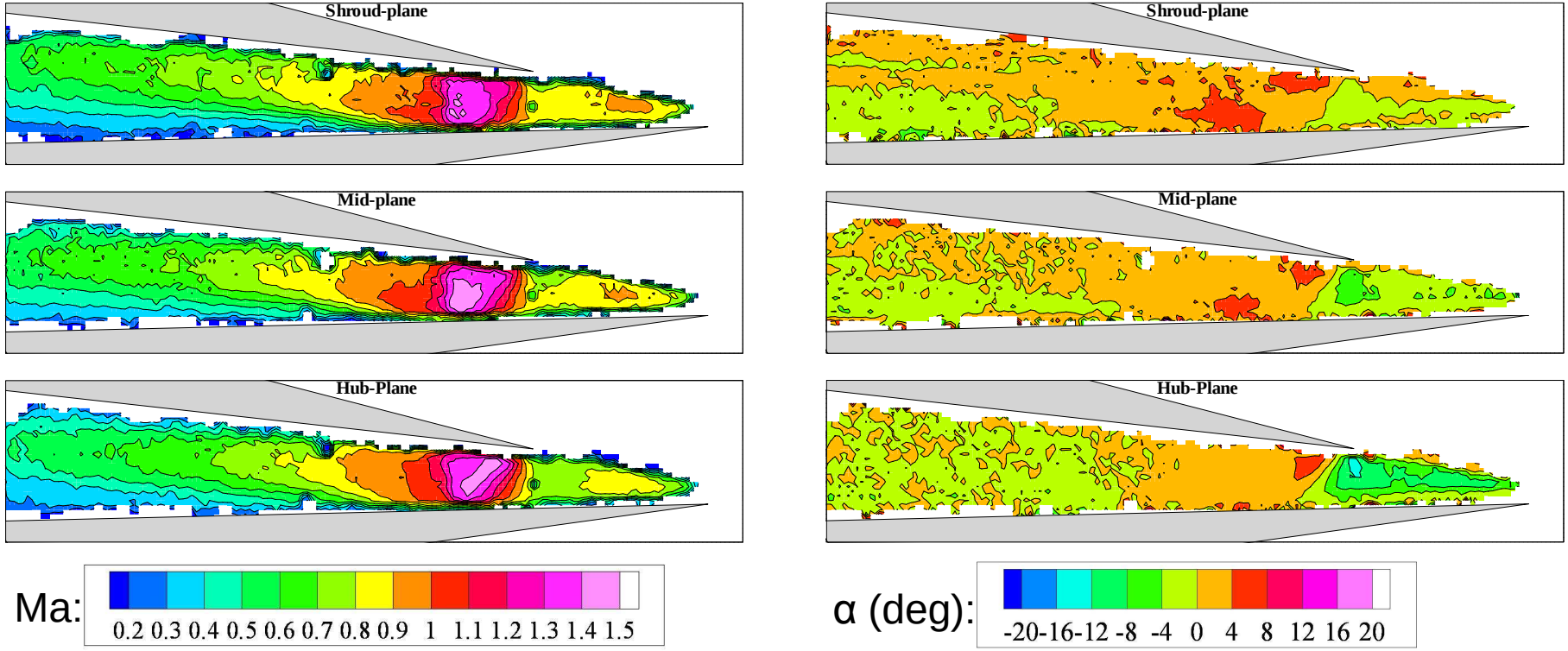
Nominal Loading-Phase Ave. Dist.



Averaged phase resolved PIV data – delay independent, circum. mean

- Large spanwise variation due to impingement of:
  - Low and high momentum flow produced by the impeller
    - Jet: Low momentum (high flow angle), concentrated near the hub
    - Wake: High momentum (low flow angle), concentrated near the shroud
- Upper vane pressure side / Lower vane suction side

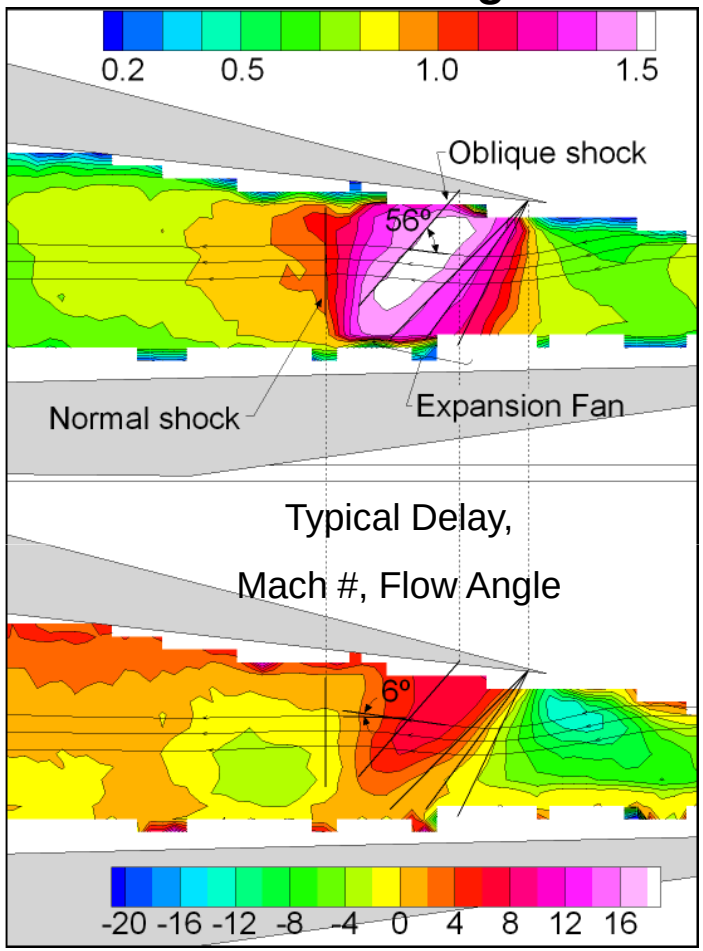
Low Loading-Phase Ave. Dist.



- Higher Mach numbers compared to nominal loading
  - Expected with the increased mass flow rate
- Mach number increase is mainly in the hub and mid plane
  - Reduction in spanwise Mach variation
- The role of the upper and lower surface of the vanes reversed
  - Upper vane suction side / Lower vane pressure side

Throat Structures – Loading Comp.

Low Loading



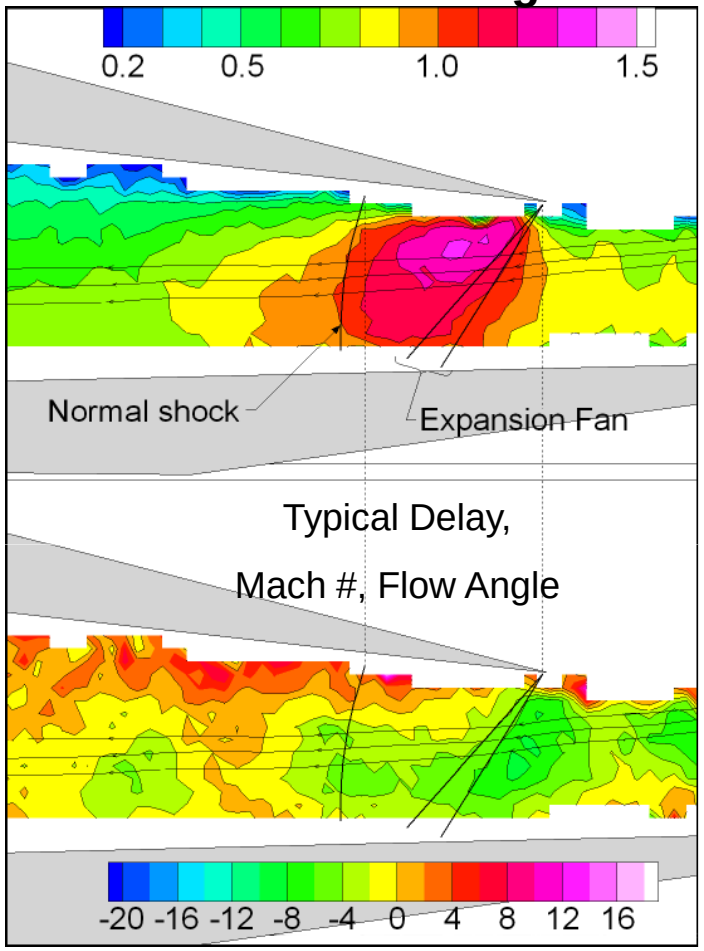
Sup. Acceleration

- Supersonic Mach increase
  - Effective flow area increase
- Flow is turning "away" from itself
- Expansion waves
  - Originating about the leading edge

Subsonic Transition

- Weak Normal Shock

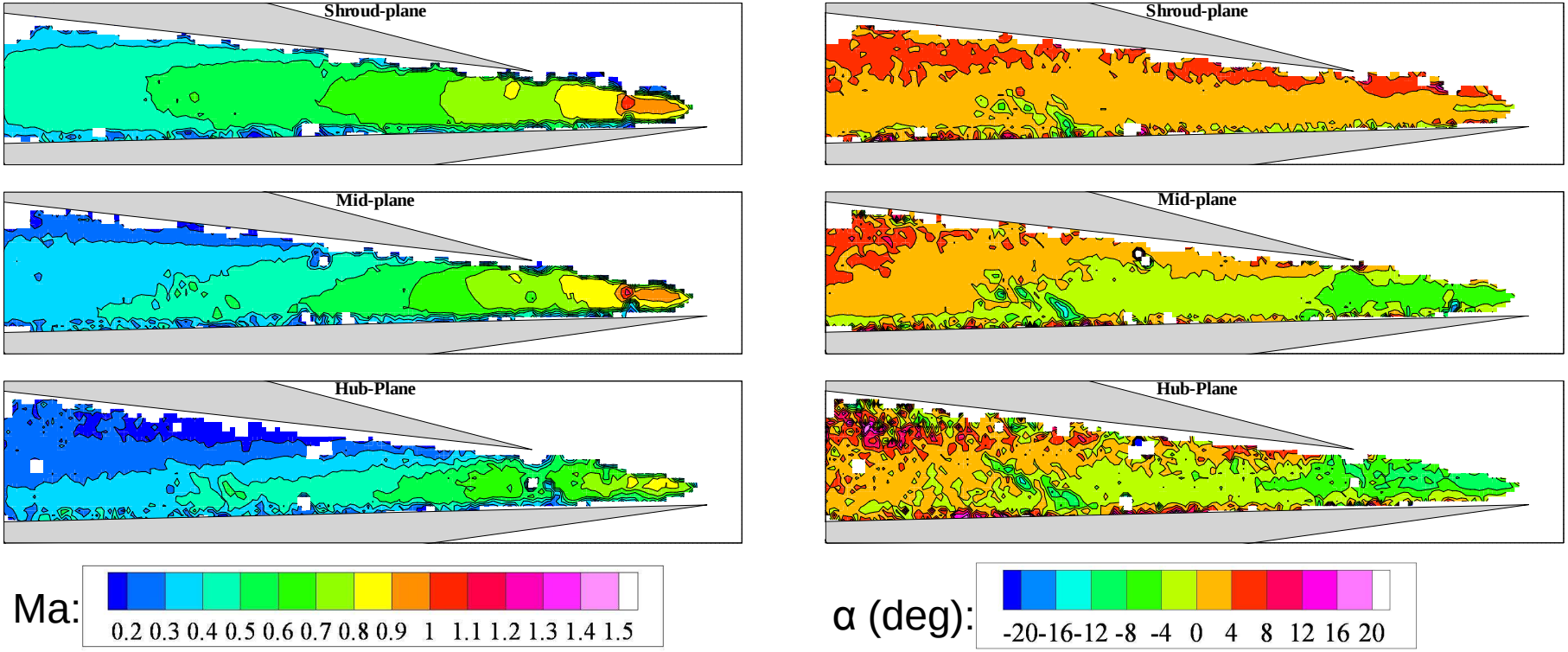
Nominal Loading



- Higher Mach # in the throat
- Abrupt Supersonic Deceleration
  - From Mach 1.4 to 1.1 in a short distance
  - Flow is turning "towards" itself
  - → Oblique shock ($\beta \approx 56^o$, $\theta \approx 6^o$)

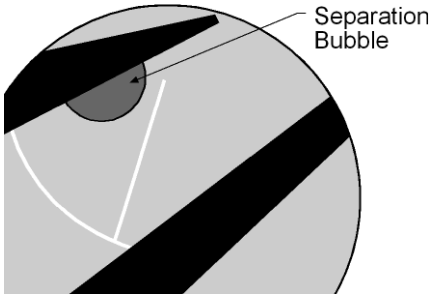
- Lower Mach #, Lower mass flow rate
- Gradual Supersonic deceleration followed by
  - Normal shock (perp. diffuser walls)

Prestall Loading-Phase Ave. Dist.



- Along the span: General trend of increase in flow Mach
  - Increased spanwise variation in Mach number wrt lower loading conditions
- No throat shock/sub. flow (Max Mach # occurs at the semi-vaneless space)
- Operational limits of compressor are reached, possible endwall separation regions
  - Diffuser hub region is the most likely location
  - At the mid and shroud planes decreased chance of separation because of
    - Higher inlet flow Mach numbers
    - More favorable incidence imposed on the PS leading edge
    - Less non-deterministic unsteadiness in flow angle

Separation Bubble

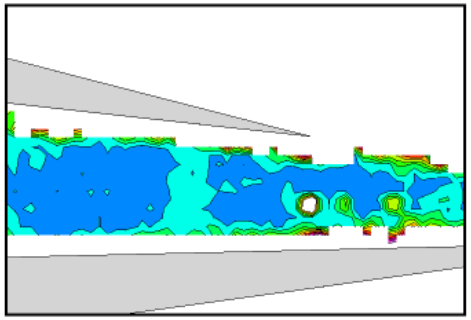


- Separation Bubble
  - Seen prior in literature (Justen[1999], Dawes[1994], Krain[1984])
  - Explains:
    - The upper throat flow turning and accelerating
    - Diffuser throat region acts as a convergent divergent nozzle
      - Rather than a simple increase in effective flow area
- Couldn't resolve the separation bubble in measurements
  - Seeding difficulty, much lower velocities (about 25%) relative to the mainstream flow [Krain 1984]
- Evidenced by the flow surrounding the separation zone
  - The bubble time scales is not phase locked to the impeller [Dawes 1994]
  - Observe through the increase in statistical variance in the ensemble averaged data

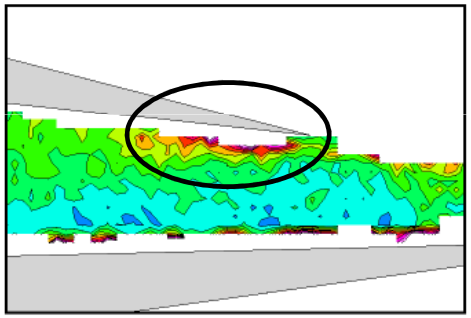
Separation Bubble at Nominal Load.

- Near Hub
  - High variance zone at the hub
    - Result of the mean flow deflecting due to a transient leading edge bubble
    - Locally this portion of the vane is aerodynamically suction surface
- Mid Span
  - Reduced magnitude wrt the hub separation
- Near Shroud
  - High variance region does not exist
    - Occurrences in this axial plane are mostly impeller phase locked
    - In agreement with incidence angle, locally pressure surface

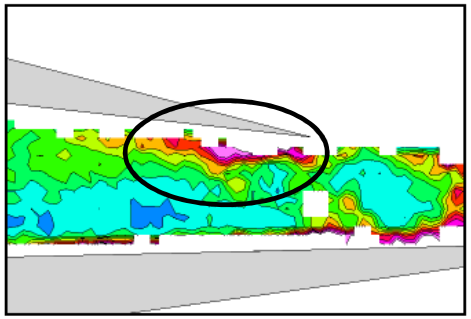
Shroud plane



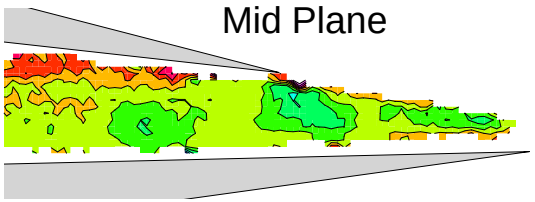
Mid-plane



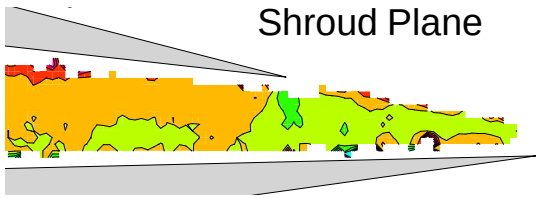
Hub-plane



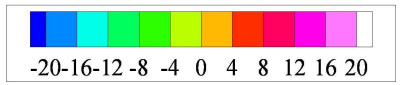
Mid Plane



Shroud Plane



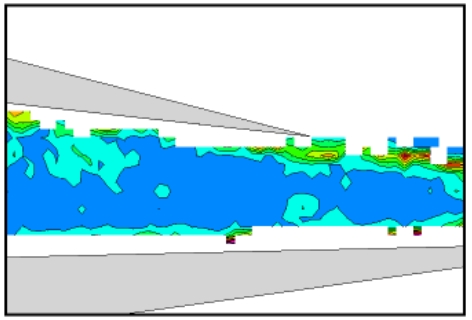
α (deg)



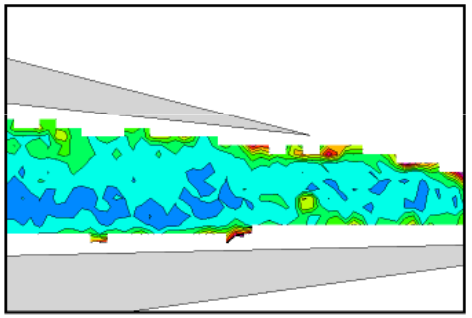
Separation Bubble at Prestall Load.

- Near Shroud
  - Variance seems as low as in the prior lower loading condition
- Near Hub
  - Large high variance zone
    - Indicates major unsteadiness, not phase locked to impeller
  - Precursors of compressor stall
    - Nominal loading: Small separation bubble
    - Higher loading: Highly separated flow
  - Hub flow is breaking down as the compressor is throttled
- Mid span
  - Variance lower than in nominal loading
    - As the hub becomes separated & has more blockage
      - May cause the fluid to rush in to other spanwise locations
        - » Locally increase the mass flow rate
        - » Create more favorable incidence

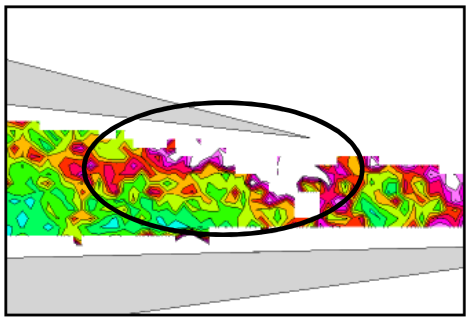
Shroud plane



Mid-plane



Hub-plane



Summary & Conclusions

- In Diffuser Flow Field, Strong momentum variations still exist in spanwise and circumferential directions
- Vaned diffuser flow field
  - Upstream of throat
    - Significant unsteadiness phase-locked to impeller position
  - Downstream of throat
    - Unsteadiness decayed more rapidly
- Circumferential variations
  - Increased near the hub: Due to multiple flow features (jet/wake) inherent to the system
  - Near Shroud region: Circumferential variations are of lesser magnitude
- Spanwise variations are due to
  - Low and high momentum flow produced by the impeller
    - Low momentum (high flow angle), concentrated near the hub
    - High momentum (low flow angle), concentrated near the shroud
  - Variations are enhanced for higher loading conditions
    - Towards stall, the flow breaks down in diffuser hub region
- Diffuser throat structures vary significantly with loading, spanwise location and relative impeller position

QUESTIONS ?