# Computational Analysis of the Large Scale Low-Boom Supersonic Inlet

This presentation describes two computational fluid dynamic (CFD) analyses done in support of a supersonic inlet test performed at NASA Glenn Research Center in the fall of 2010. The large-scale-low-boom supersonic inlet was designed for a small supersonic aircraft that would cruise at a Mach number of 1.6. It uses an axisymmetric, external compression spike to reduce the Mach number to 0.65 at the fan face. The inlet was tested in the 8x6 supersonic wind tunnel at NASA GRC using conventional pressure probes, pressure sensitive paint, and high-speed schlieren.

Two CFD analyses of the inlet were performed before the test, and compared to the experimental data afterwards. Both analyses used the WIND-US code. First, an axisymmetric analysis of the inlet, diffuser, cold pipe, and mass flow plug was performed to predict the performance of the entire system in the wind tunnel. Then a 3-D analysis of the inlet with all its interior struts was performed to predict details of the flow field and effects of angle of attack.

Test results showed that the inlet had excellent performance, with a peak total pressure recovery of 96 percent, and a buzz point far outside the engine operating range. The computations agreed very well with the data, with predicted recoveries within 0.3 – 0.5 points of the measurements.

National Aeronautics and Space Administration

# Fundamental Aeronautics Program

*Supersonics Project*

**Computational Analysis of the Large Scale Low-Boom Supersonic Inlet**

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**NASA GRC Inlets and Nozzles Branch, SUP Propulsion Subproject**

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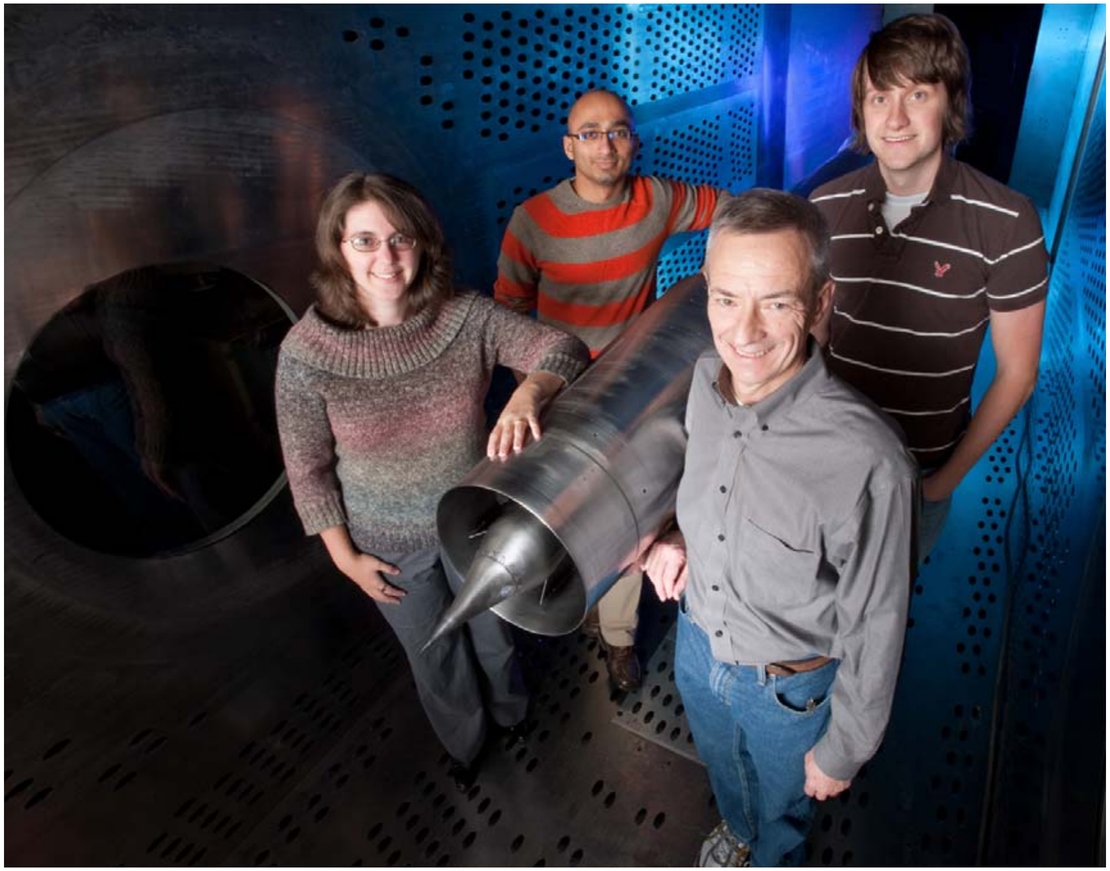
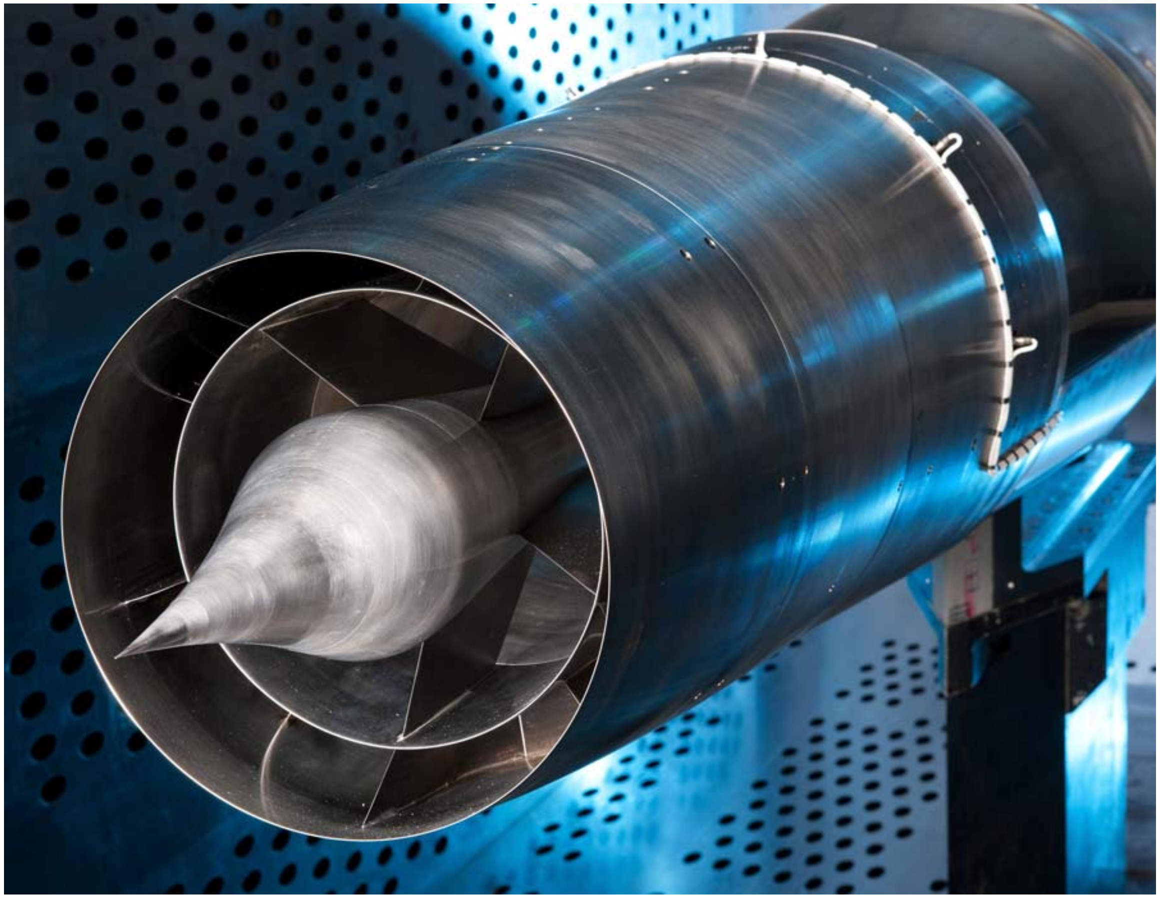
# Low Boom Inlet in NASA GRC 8x6 Supersonic Tunnel



L – R: Stefanie Hirt, Manan Vyas, Rodrick Chima, Robert Reger

Low boom inlet developed by Gulfstream Aerospace Corporation (GAC)
- Designed for Mach 1.6 cruise at 45,000 ft
- Over wing Mach number = 1.7
- Tested in 8x6 supersonic wind tunnel at NASA Glenn Research Center, Oct. – Nov. 2010

# Inlet Design



- Isentropic compression spike produces weak shock at hub, strong shock at tip.
- Primary (center) stream would lead to engine.
- Bypass stream diverts lossy tip flow around engine gear box.
- Low cowl angle minimizes boom.

Micro ramps, struts, and vortex generators not considered here

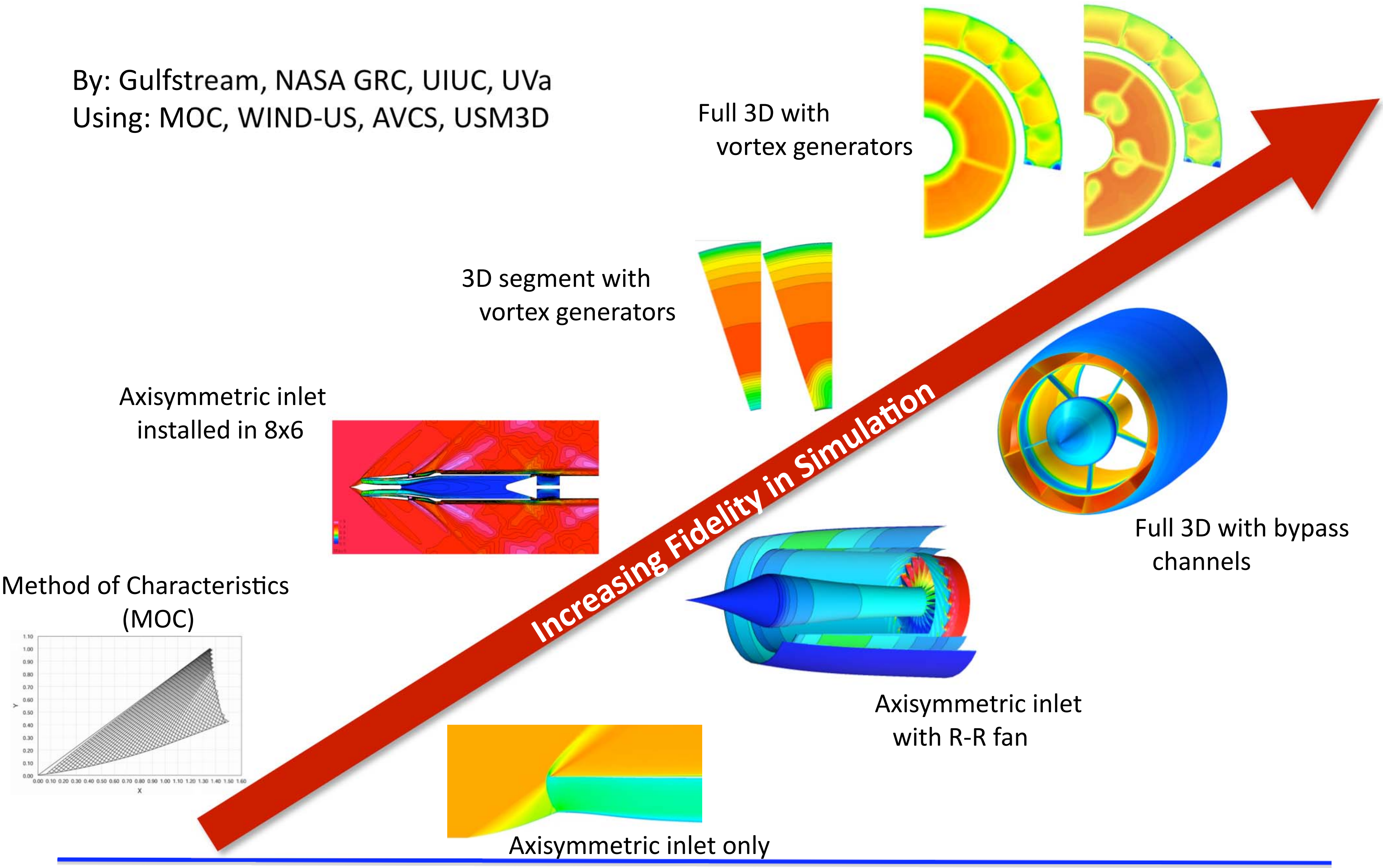
Primary stream throttled with 16” mass flow plug (MFP)

Bypass stream would duct flow around large engine gearbox.

Bypass stream exits through choked plates

# CFD Analyses

By: Gulfstream, NASA GRC, UIUC, UVa
Using: MOC, WIND-US, AVCS, USM3D

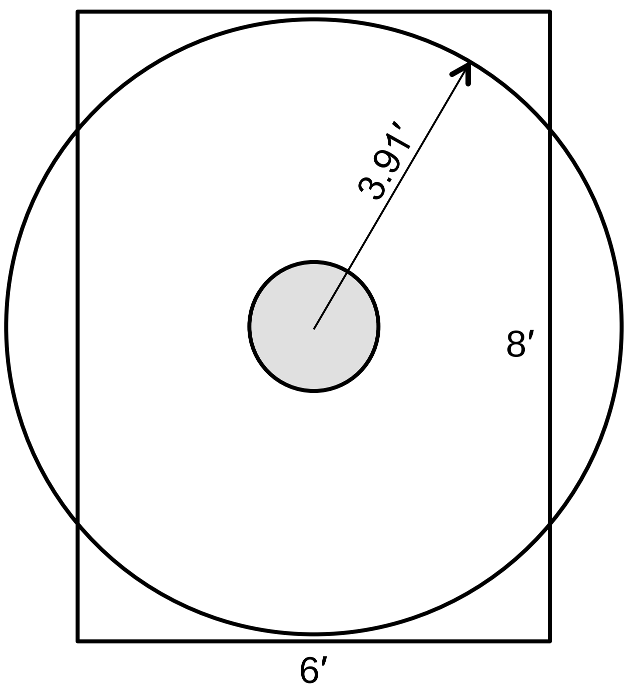


# Axisymmetric CFD Model

Axisymmetric model of the Gulfstream low boom inlet in the 8x6 wind tunnel including:

- Tunnel walls. Equivalent circular area is almost the same height as the tunnel.
- Bypass duct and exit plates
- Inlet, subsonic diffuser
- Cold pipe, mass flow plug (MFP)
- Mounting strut and tunnel wall porosity were ignored.

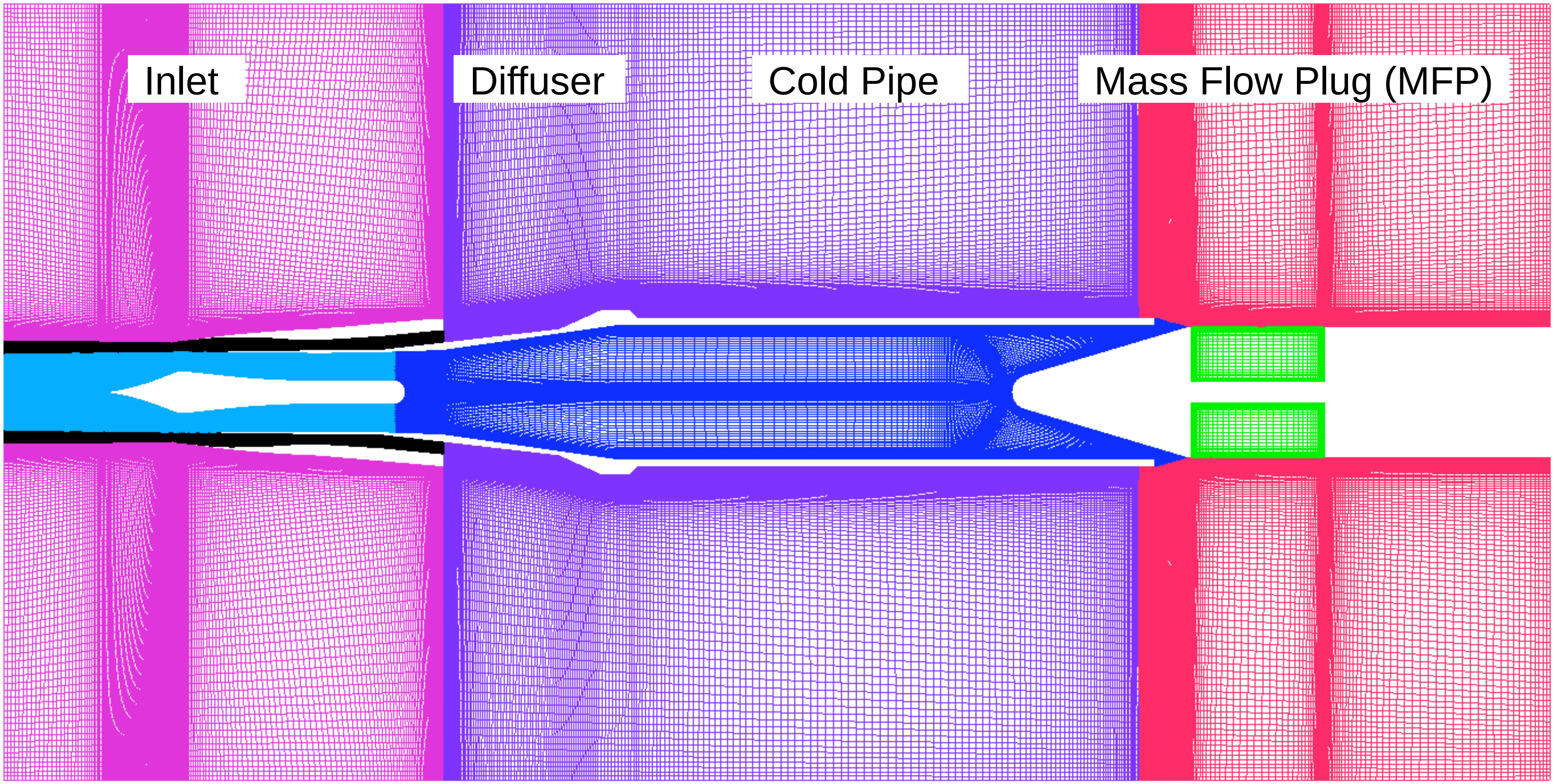
Results were used for initial sizing of bypass exit plates and positioning of MFP.




Axisymmetric section with same area as 8x6 tunnel has nearly the same height as the tunnel.

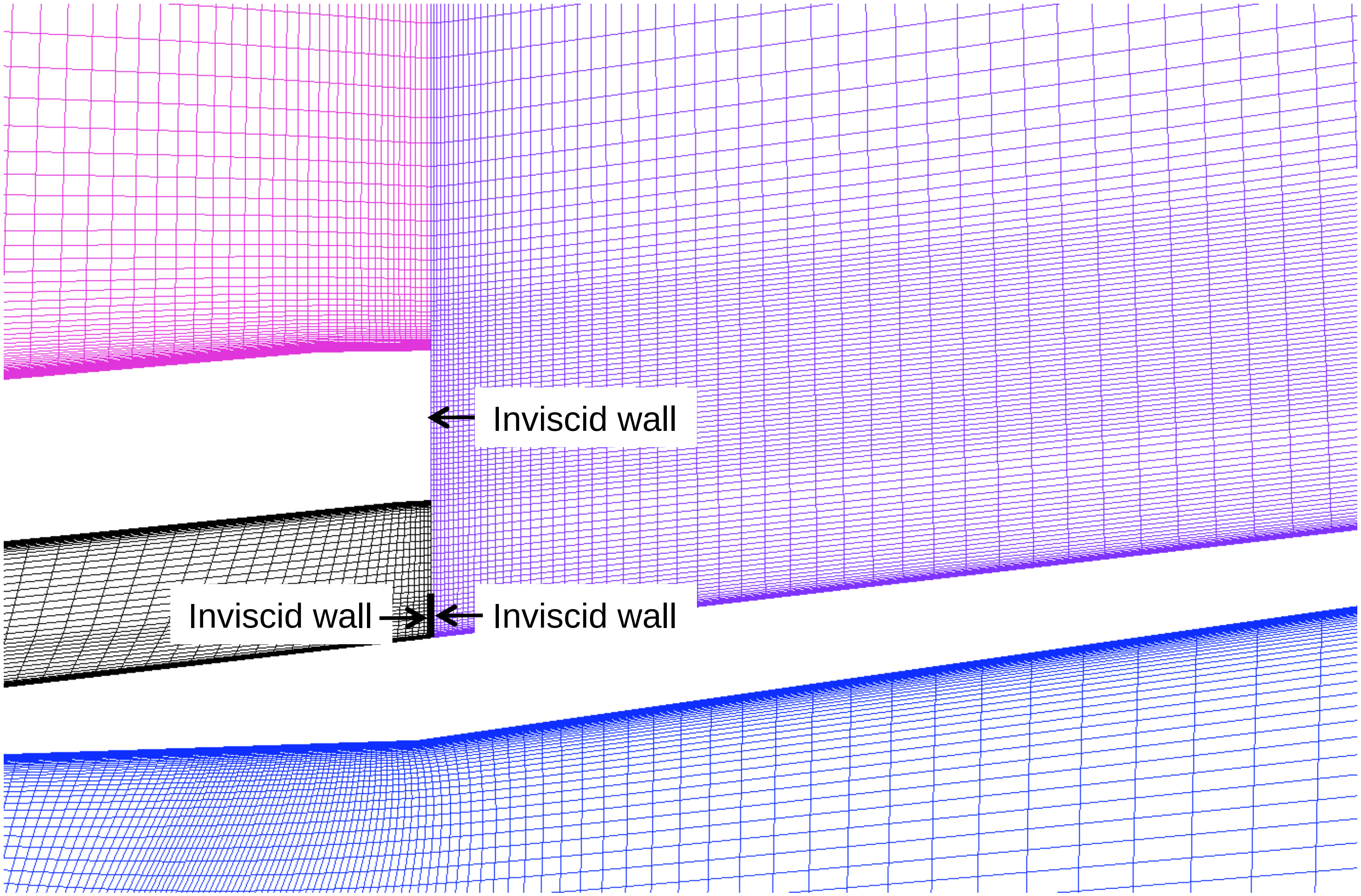
Side view of reflected shocks should be nearly correct.

# Computational Grid



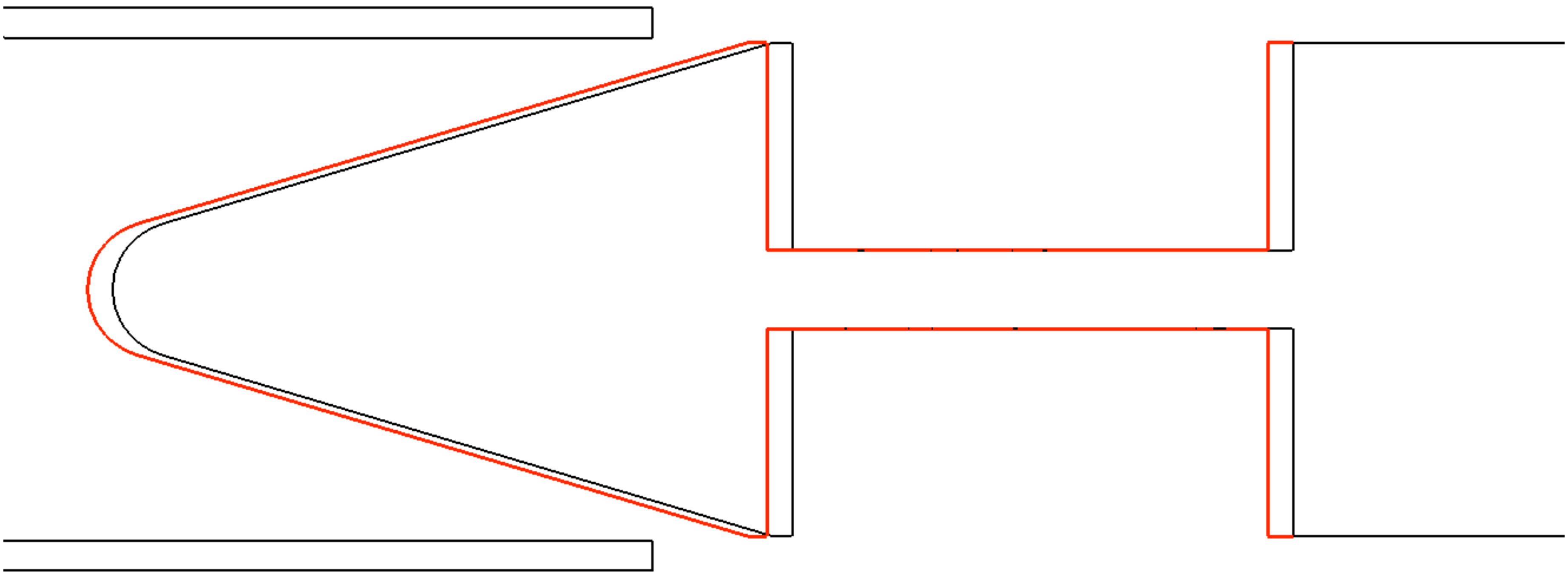

- Grid generated using Pointwise.
- Boundary conditions added using Gridgen and GMAN.
- 144,525 points in 7 zones

# Bypass Exit Plate Model



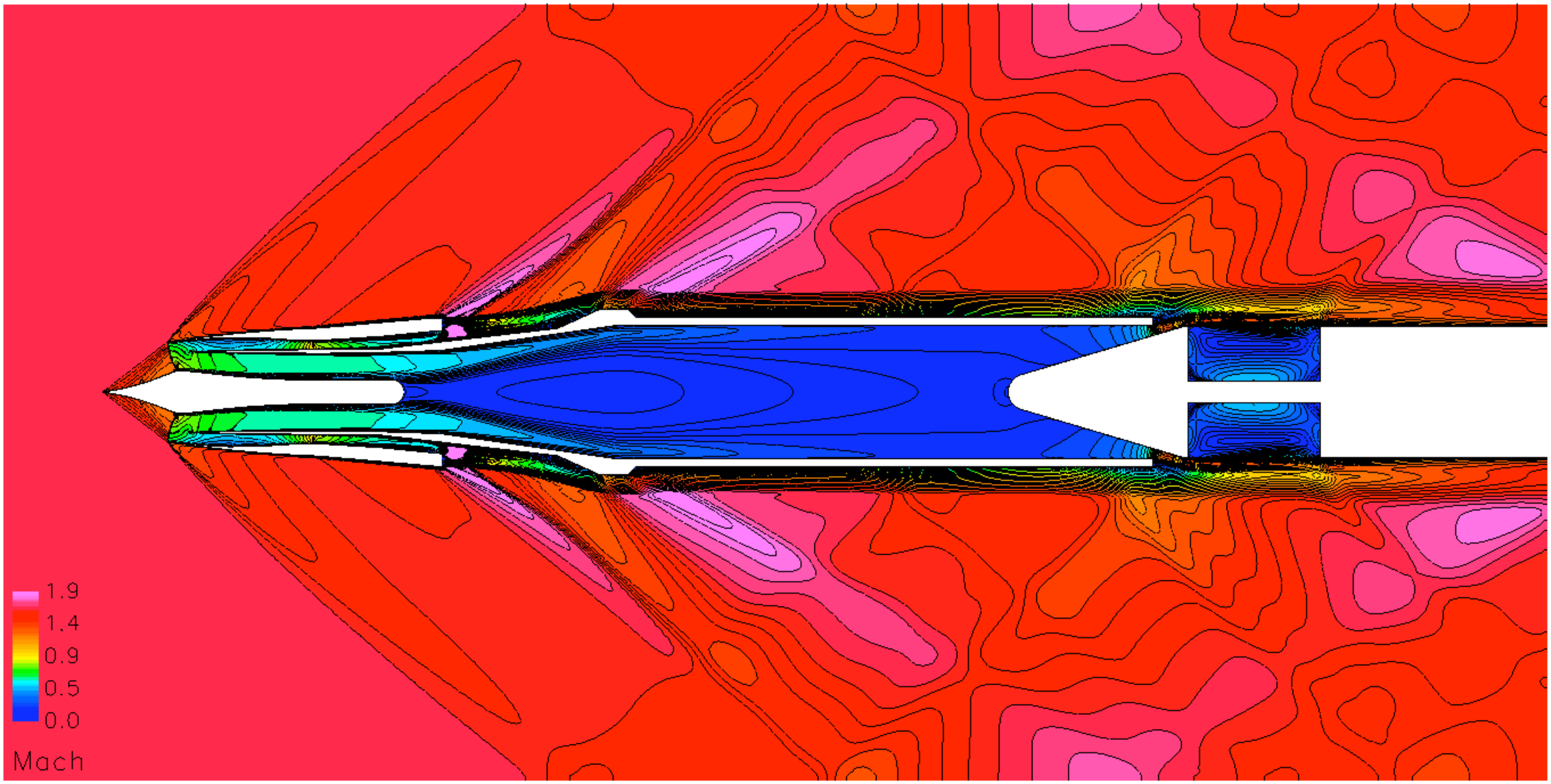

- Bypass IML reduced to model gearbox and strut blockage (like Kim and Liou.)
- Zero thickness inviscid wall used to model bypass exit plate
- Axisymmetric exit area = total plate exit area
- 4 exit plate areas were tested. Normalized exit areas Aex = 1.0, 1.1, 1.2, and 1.3

# Mass Flow Plug Translation



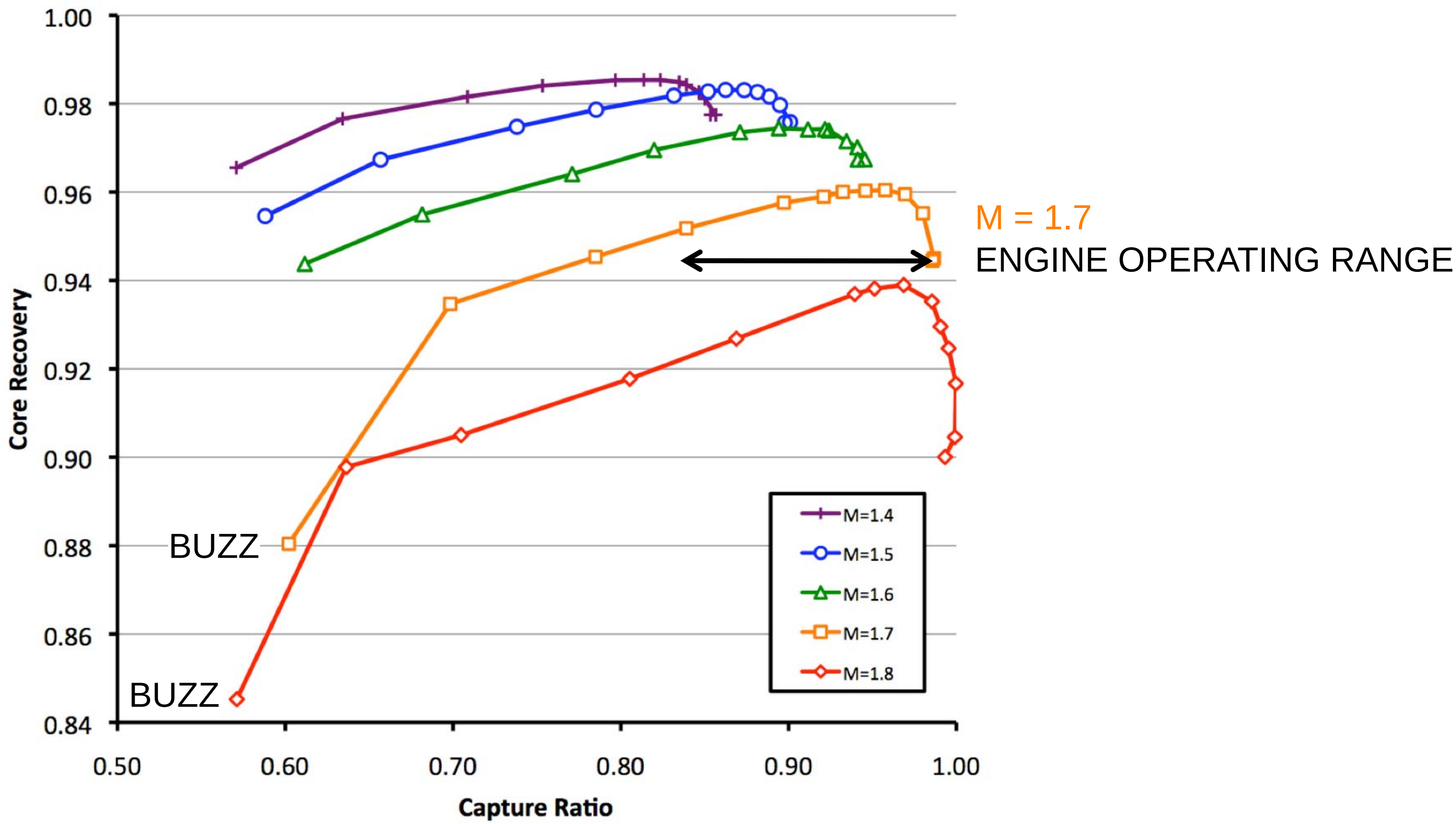
- Calculations throttled by translating MFP.
- Surface database translated in Pointwise, attached grids morph automatically.
- BC reset using scripts in Gridgen and GMAN.
- Total translation of 1.0 inches covers the entire engine operating range.
- Much larger range tested experimentally.

# Computed Results - Mach Contours



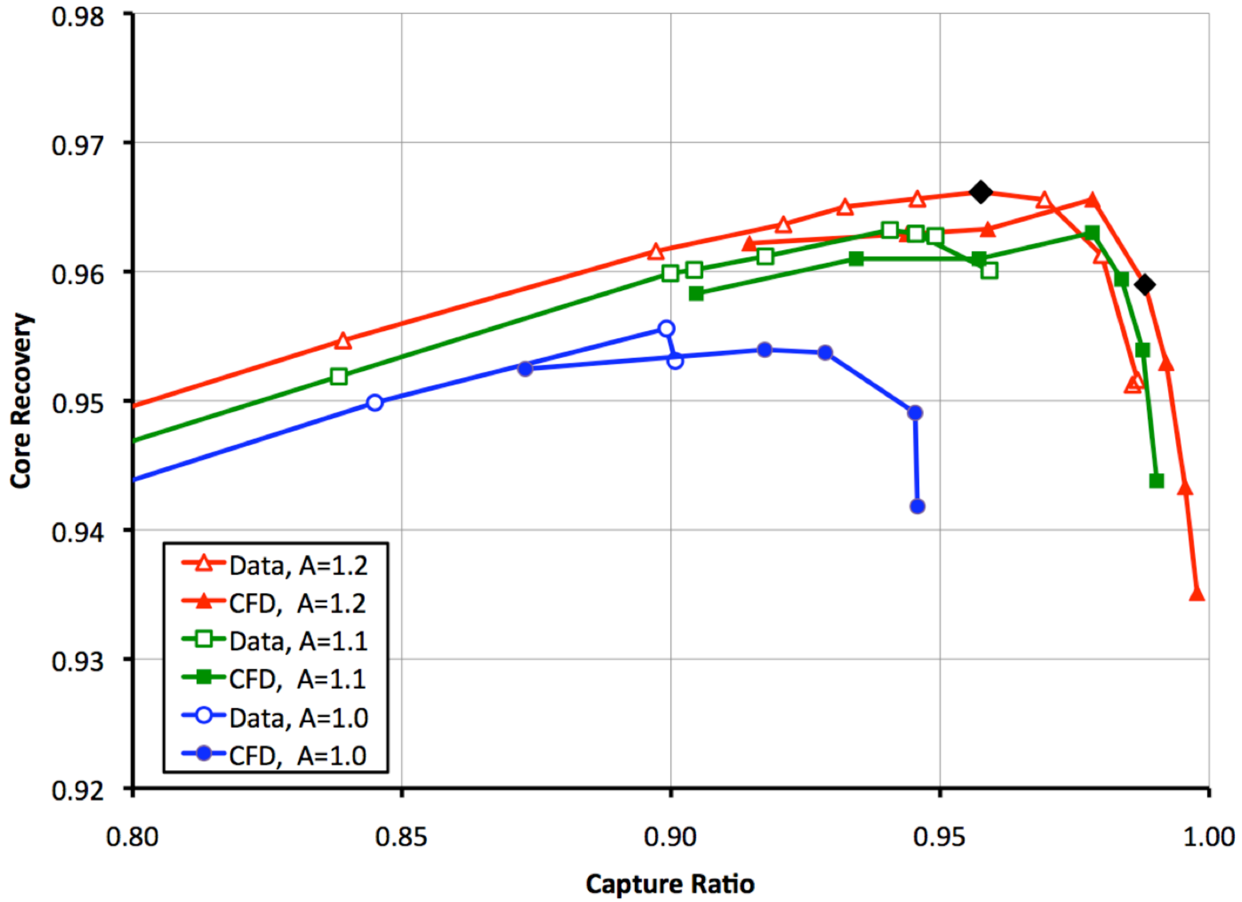

- WIND-US CFD code, Roe upwind scheme, SST turbulence model
- ~ 1.5 hr per case on 6 CPUs

# Measured Inlet Performance (Core)



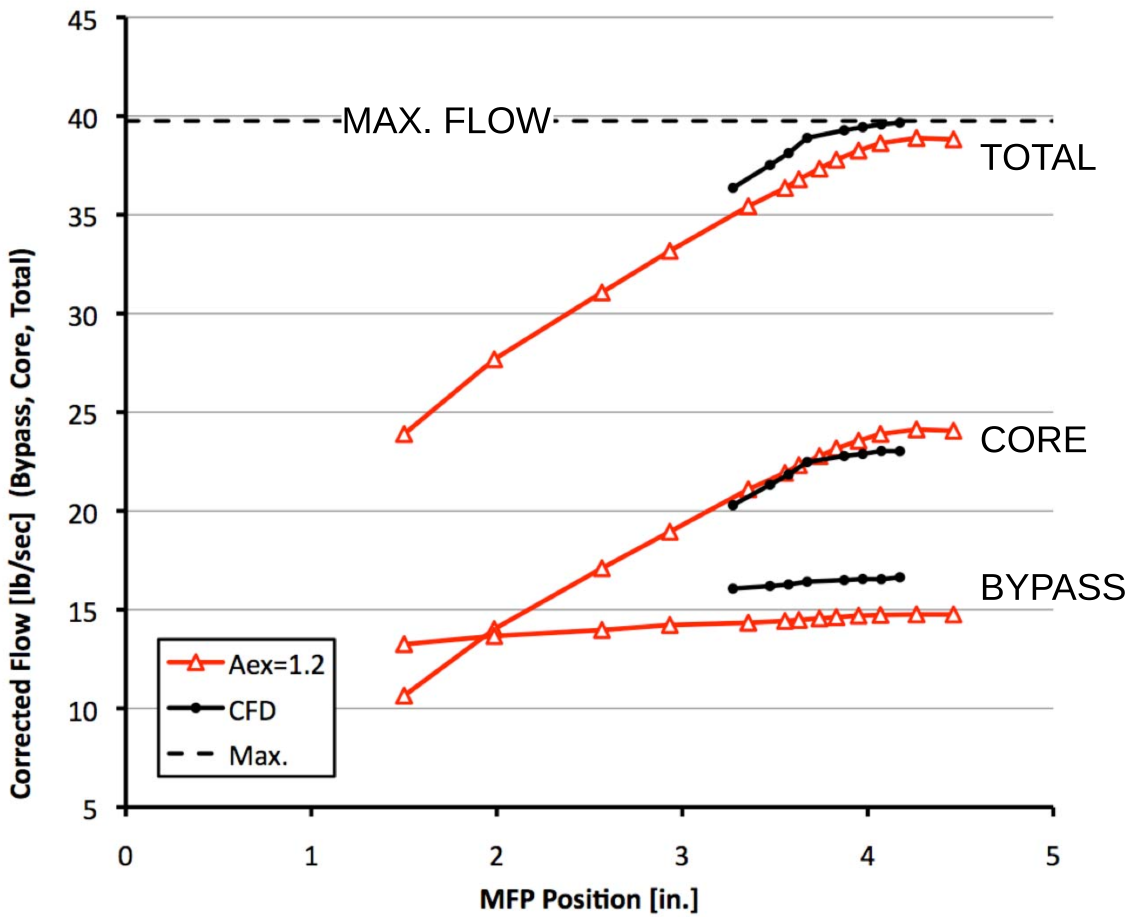

- Excellent recovery: 96% at M = 1.7 design point.
- Buzz boundary well below engine operating range.
- CFD was only performed for the engine operating range.
- The inlet operating range was increased greatly during the experiment.

# Core Recovery Neglecting Rake Behind Strut



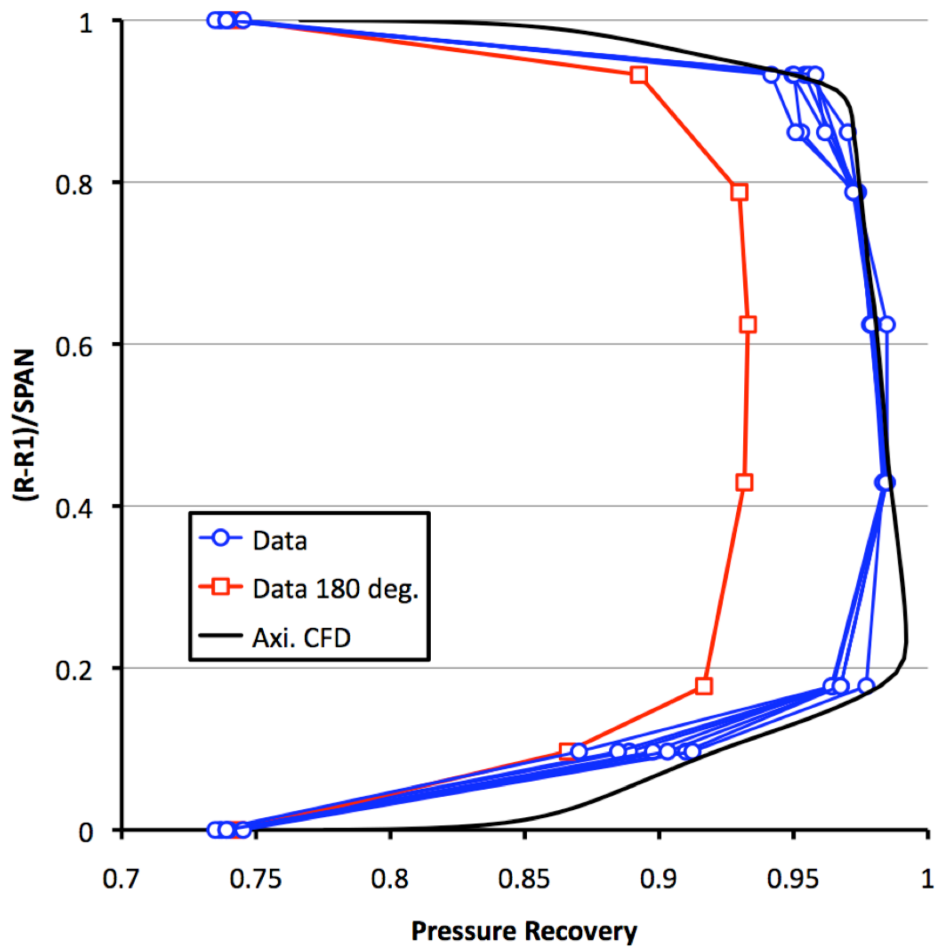

- Axisymmetric CFD agrees with measured recovery when bottom rake behind strut is neglected.
- Black diamonds show points at same MFP position used for centerline pressure comparison later.

# Flow Rate vs. Mass Flow Plug Position



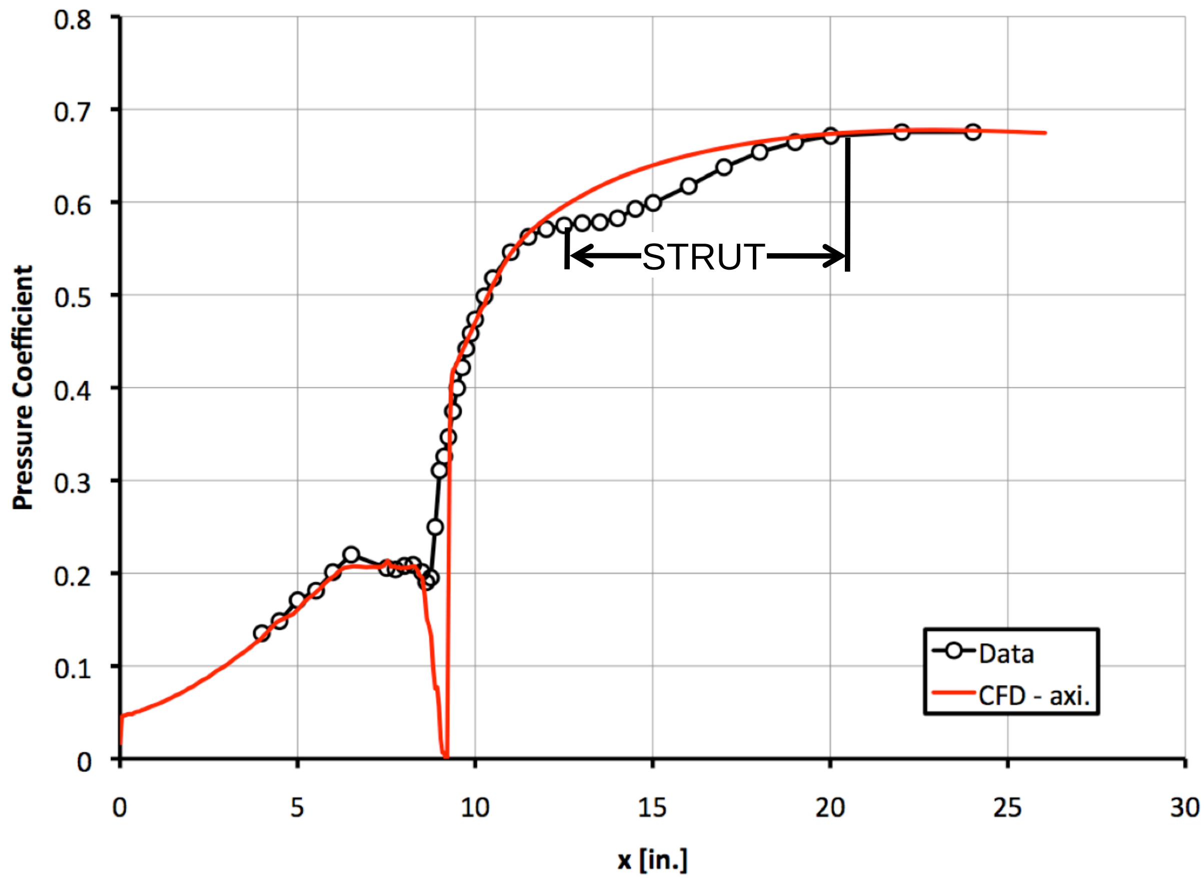

- CFD was used to set the initial MFP travel to cover a nominal engine operating range. The range was increased greatly during the experiment.
- Axisymmetric CFD over predicts bypass flow by 11 percent.
- CFD under predicts max. core flow.
- Good prediction of mass flow variation with MFP position (slopes.)

# Radial P0 Profiles at Fan Face



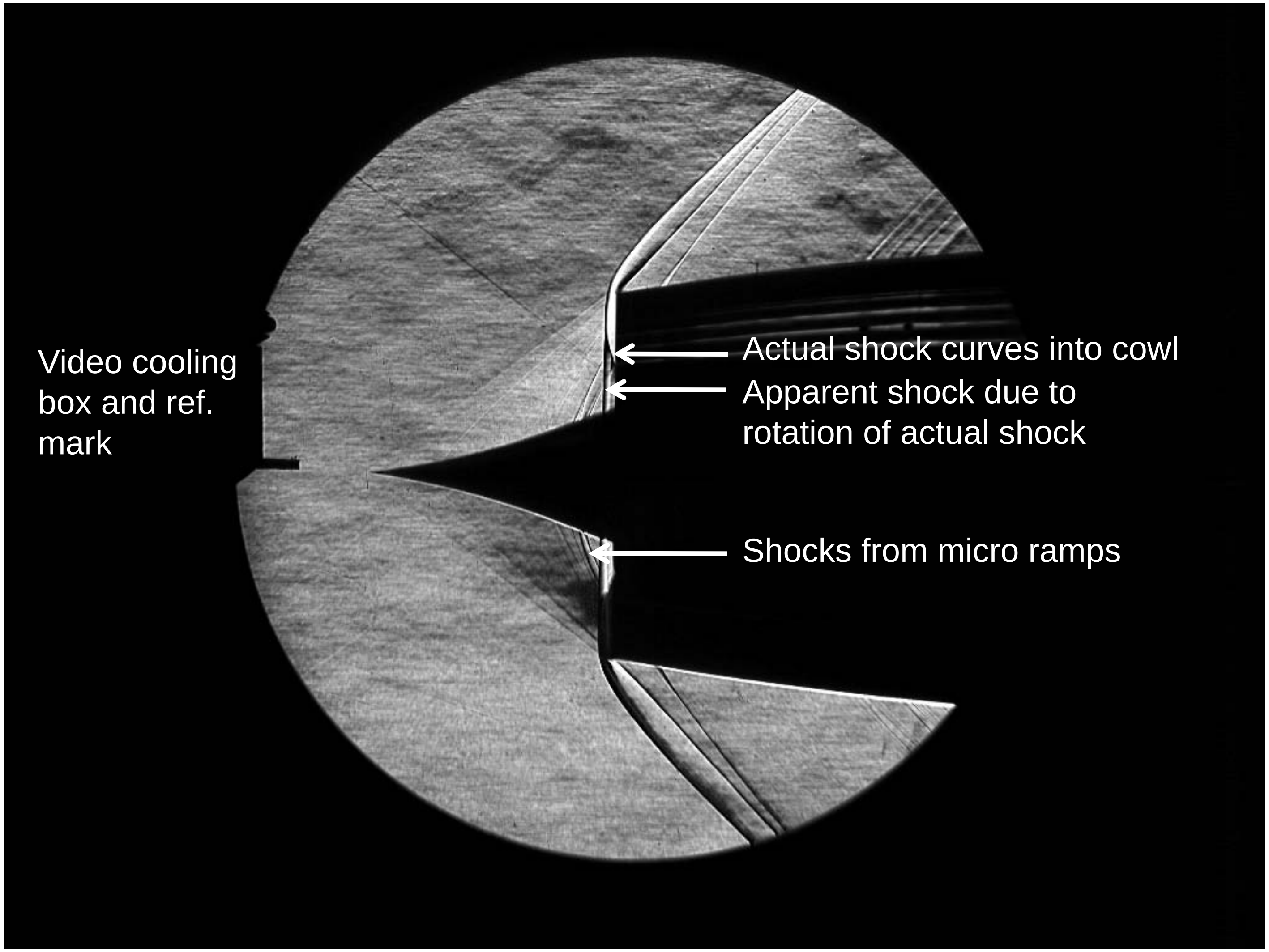

- Aex = 1.2, points at same MFP position.
- Good agreement between CFD and 7/8 rakes.
- 180 deg. rake is immediately behind a strut and measures lower P0. Not captured by axisymmetric solution.

# Centerline Pressures



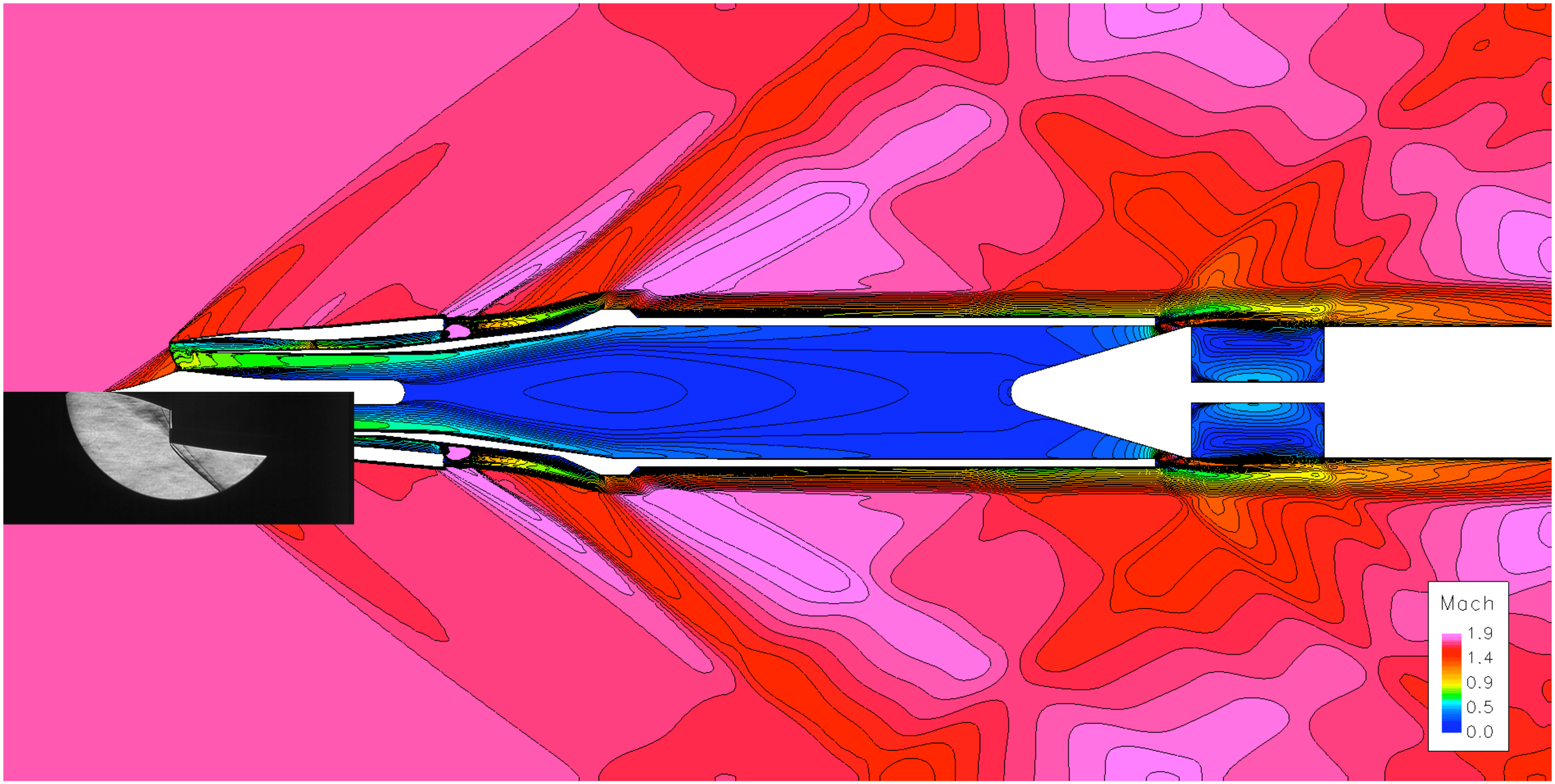

- Aex = 1.2, peak recovery
- Slight discrepancy in shock position
- Axisymmetric solution does not include strut blockage

# Schlieren Comparisons



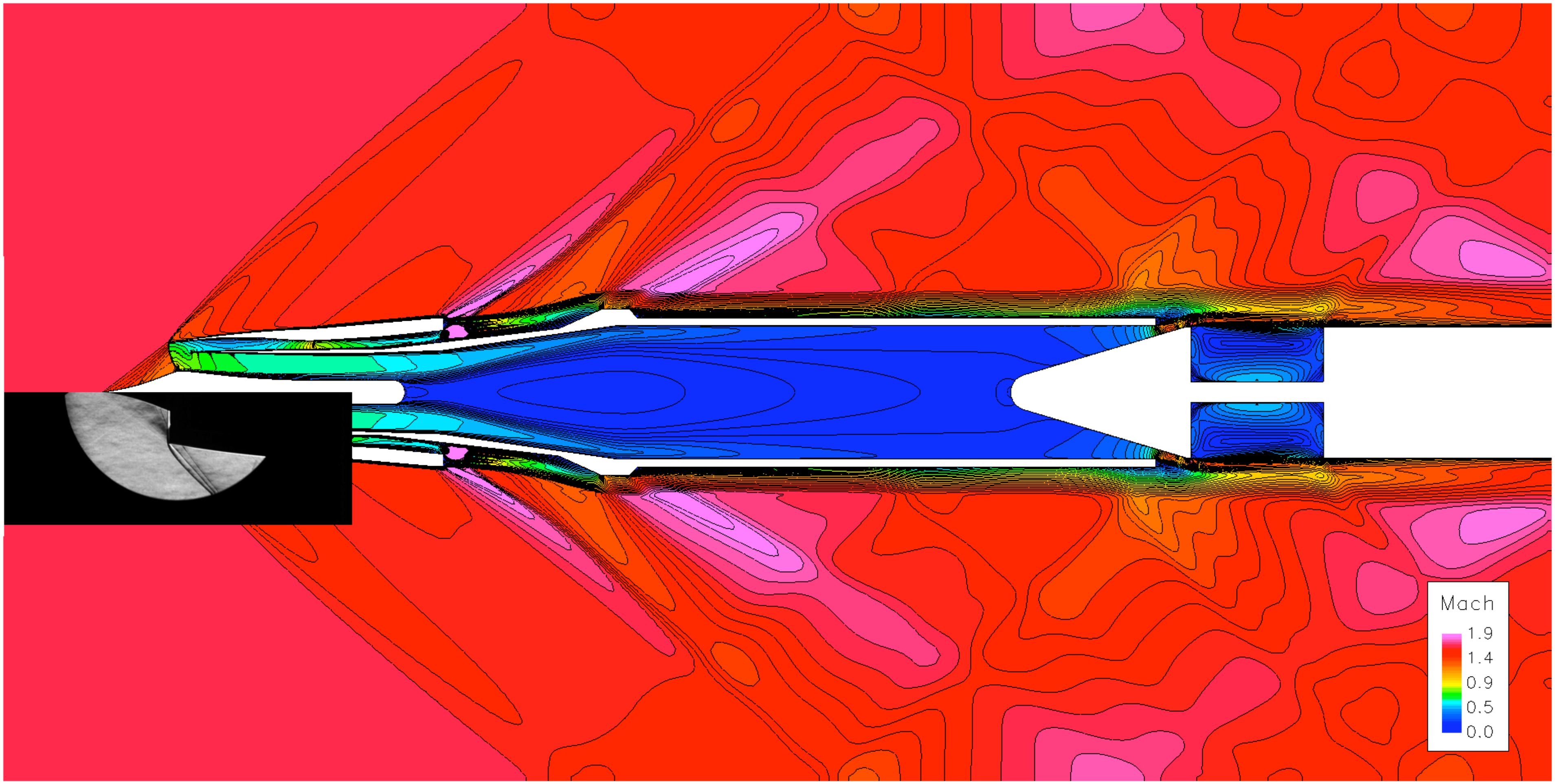

- Schlieren images taken with high-speed Phantom camera at 2000 fps
- Images include shocks from micro ramps not included in CFD

# Schlieren Comparison, M = 1.779

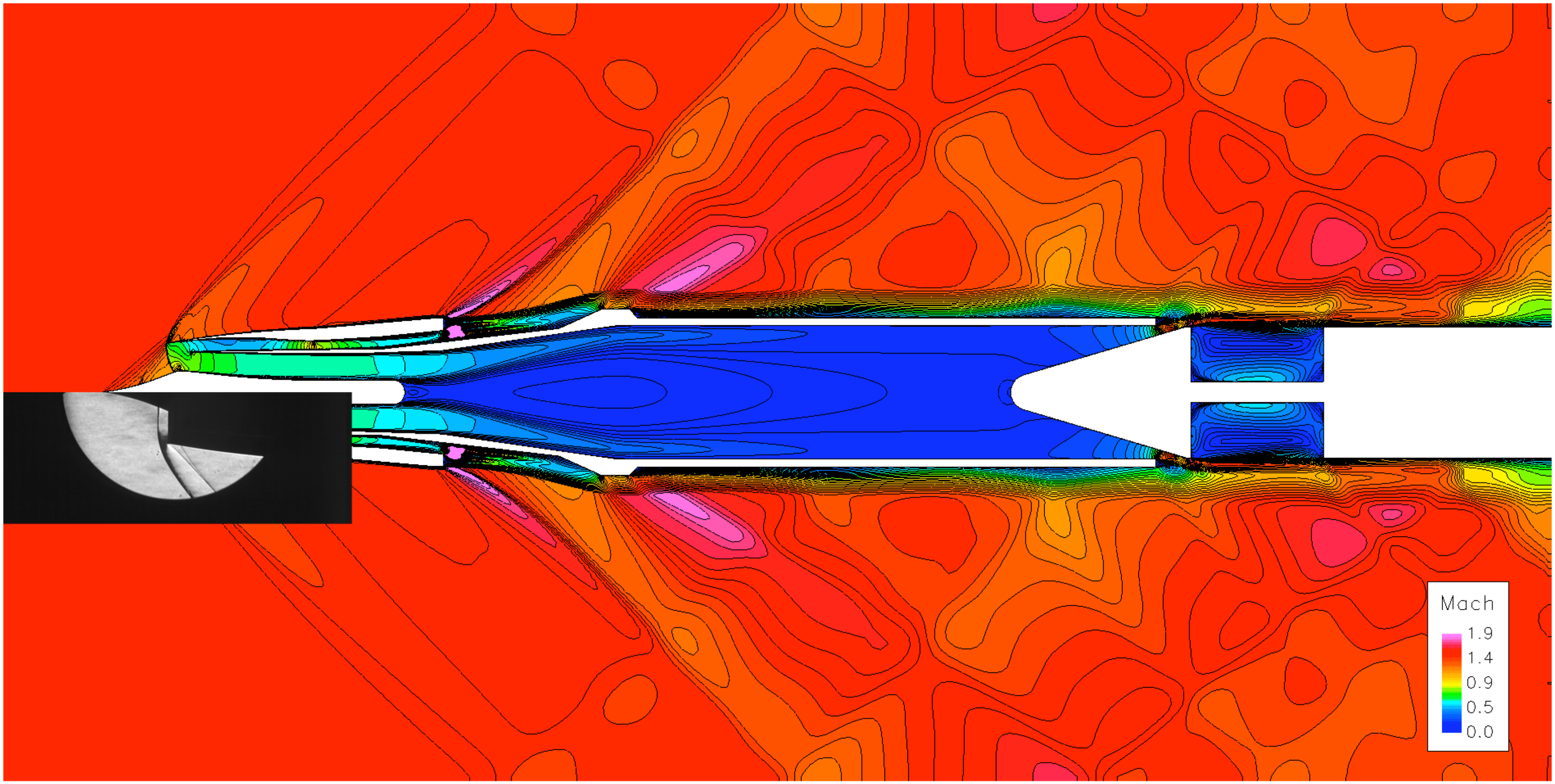



- Mach number reduced in 0.1 increments (using 8x6 operating points)
- MFP held fixed
- Schlieren images acquired at fixed MFP location

# Schlieren Comparison, M = 1.664

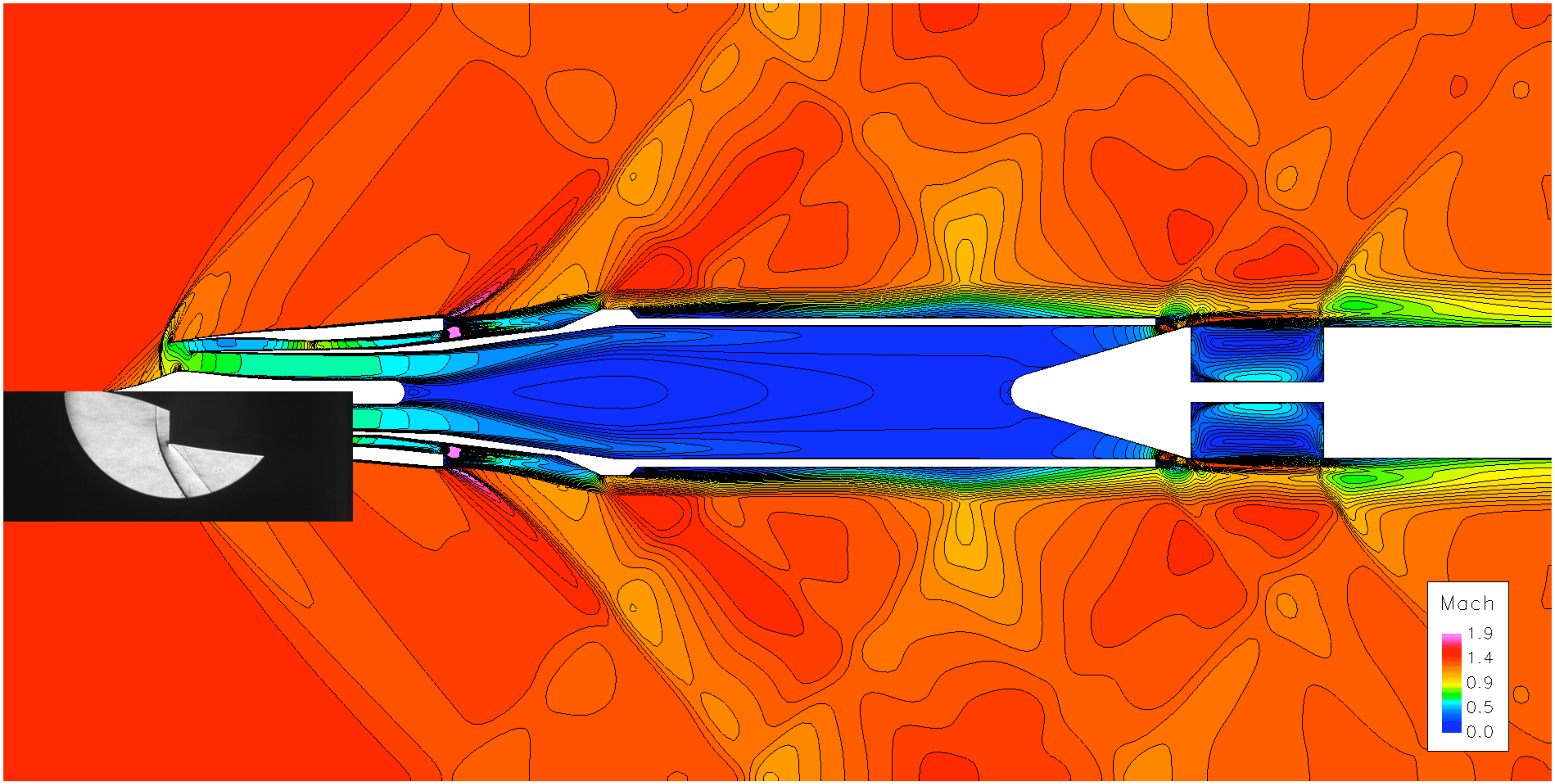


# Schlieren Comparison, M = 1.555

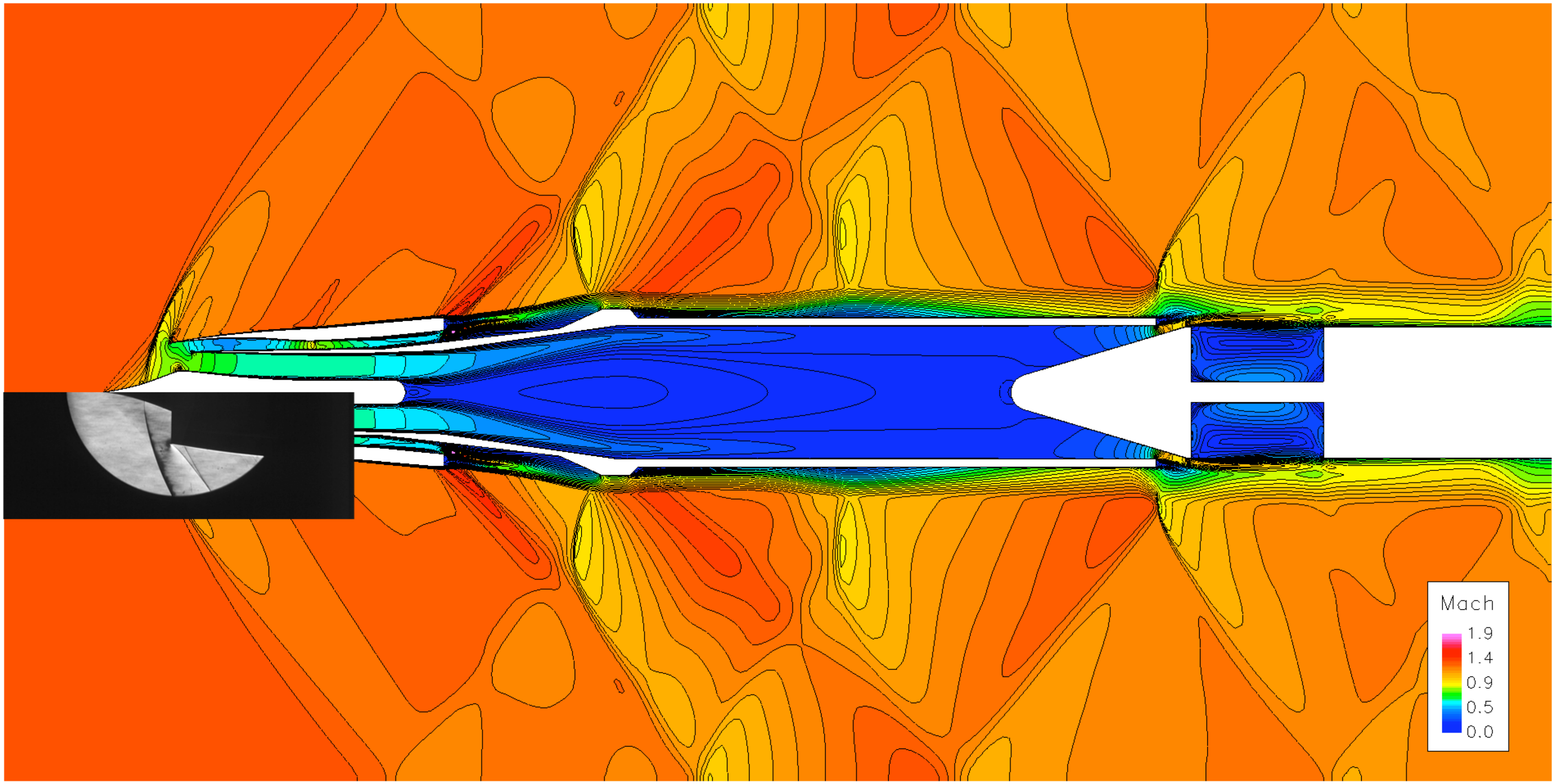



• No schlieren image available at correct MPF position for this Mach number

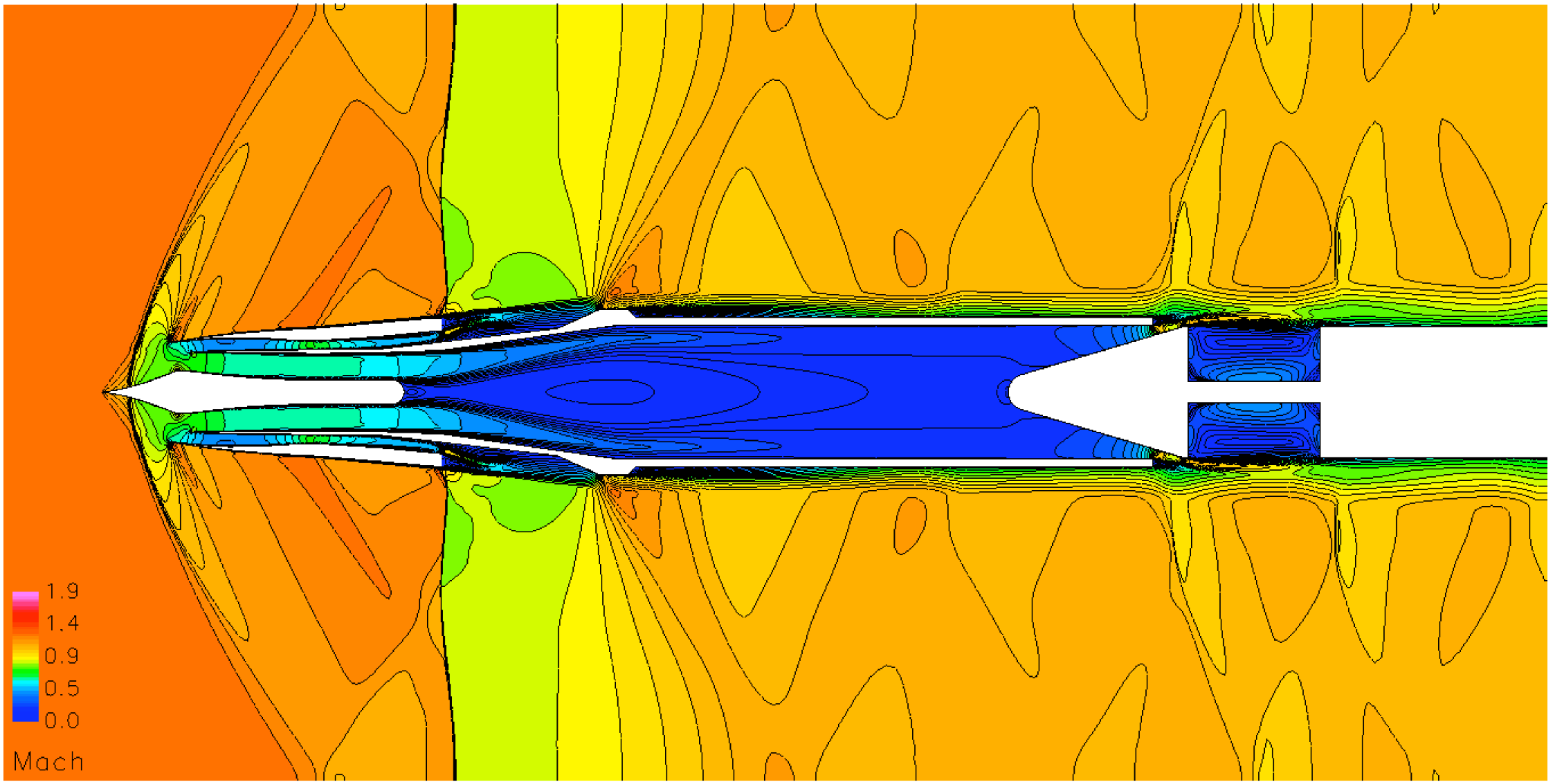
# Schlieren Comparison, M = 1.452



# Schlieren Comparison, M = 1.352



# Schlieren Comparisons, M = 1.253




- Tunnel passed through this point during start up and shut down, but no data taken.

# 3-D Analysis - Computational Grid

| Region | Blocks | i | j | k | Points |
|---|---|---|---|---|---|
| Core | 2 | 279 | 121 | 65 | 4,388,670 |
| Bypass | 2 | 274 | 121 | 45 | 2,983,860 |
| External | 4 | 314 | 121 | 65 | 9,878,440 |
| Struts | 5 | 181 | 45 | 65 | 2,647,125 |
| Core Exit | 1 | 17 | 441 | 65 | 487,305 |
| Bypass Channels | 10 | 193 | 33 | 45 | 2,866,050 |
| Bypass Exit | 1 | 51 | 321 | 45 | 736,695 |
| **Totals** | 25 | | | | 23,988,145 |

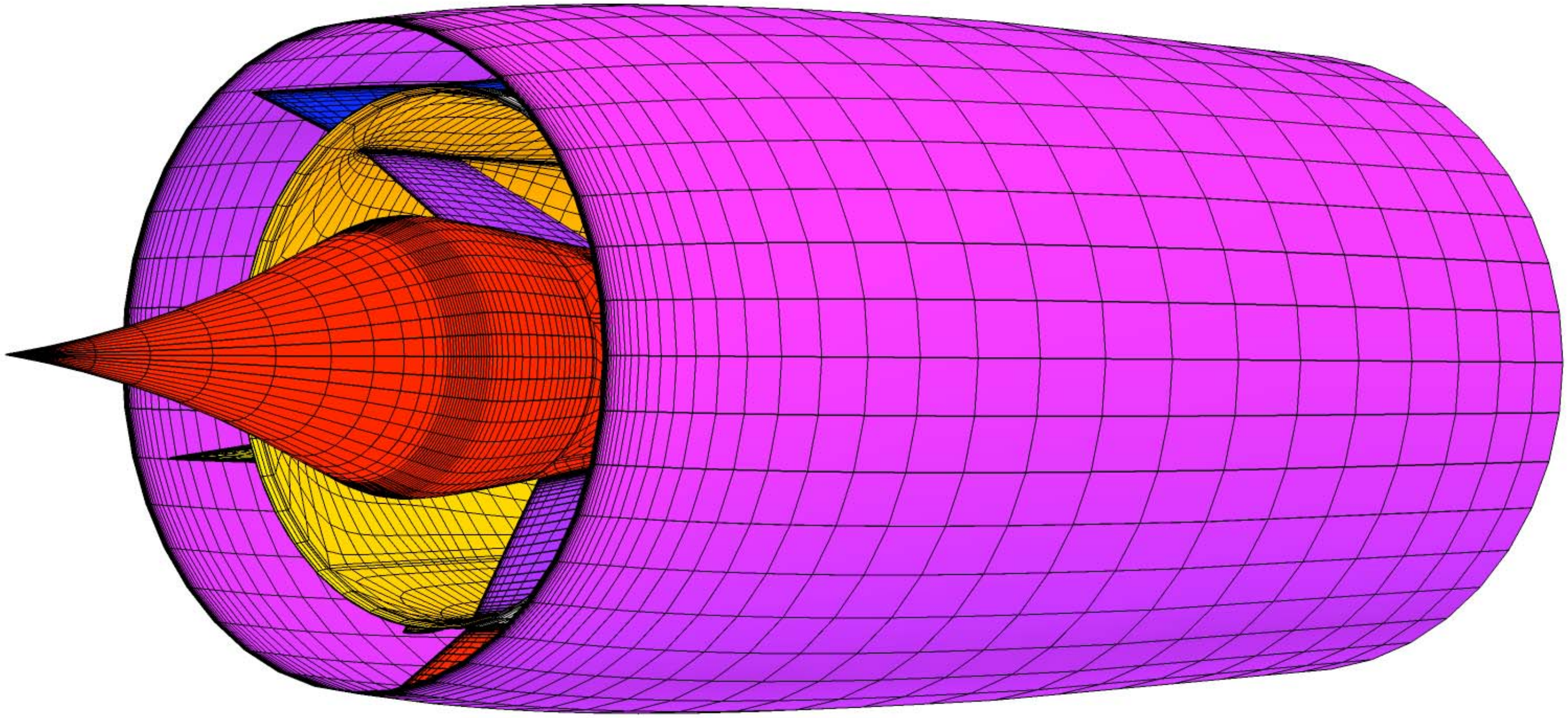
**Grid details**

- 25 blocks, 24 M points
- Wall spacing 1.e-5 in. gives $y^+ \approx 2$.
- Full 360°, allows for yaw

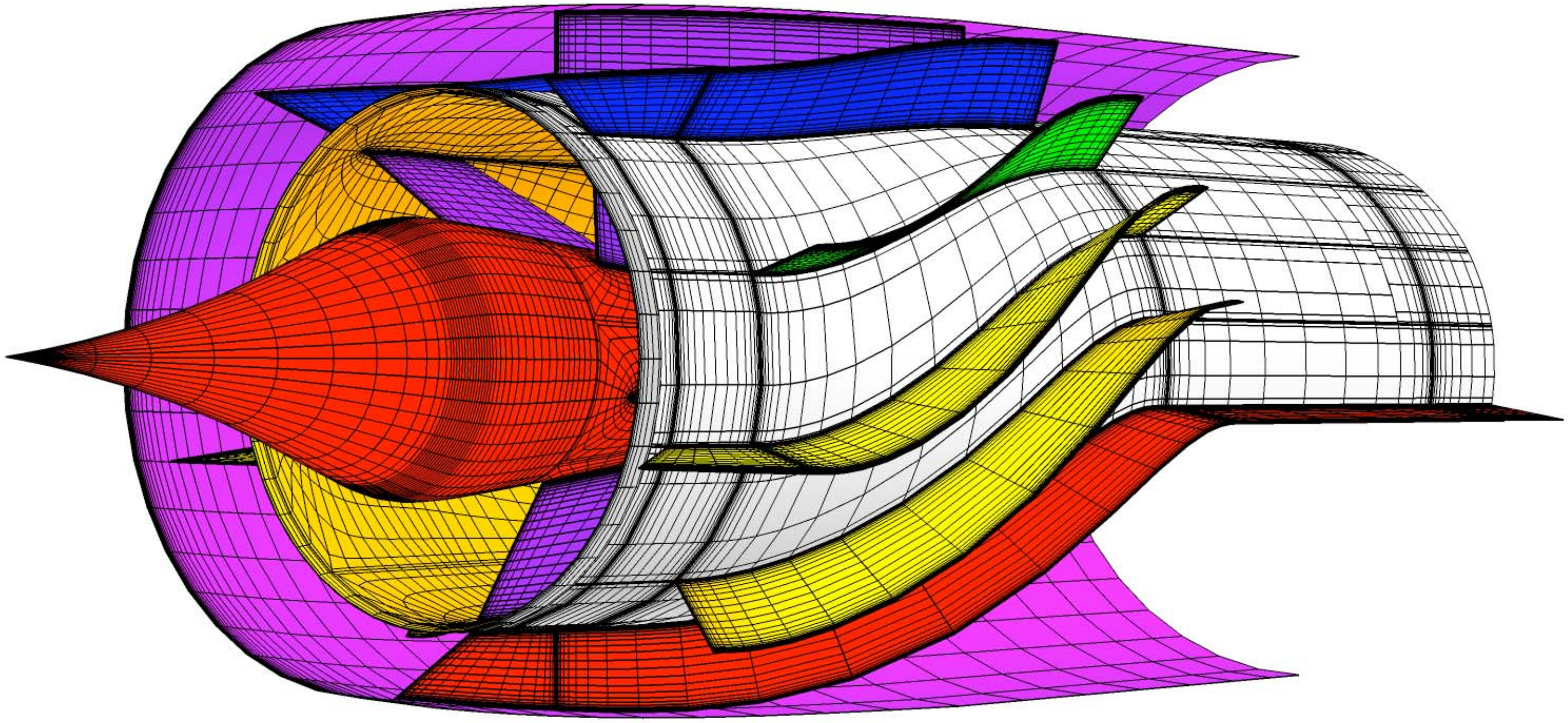
**Grid Codes**

- Main blocks - Pointwise
- Struts - turbomachinery grid code TCGRID (Chima)
- Bypass channel grids sheared tangentially with custom code
- Boundary conditions - Gridgen and GMAN (WIND-US utility)

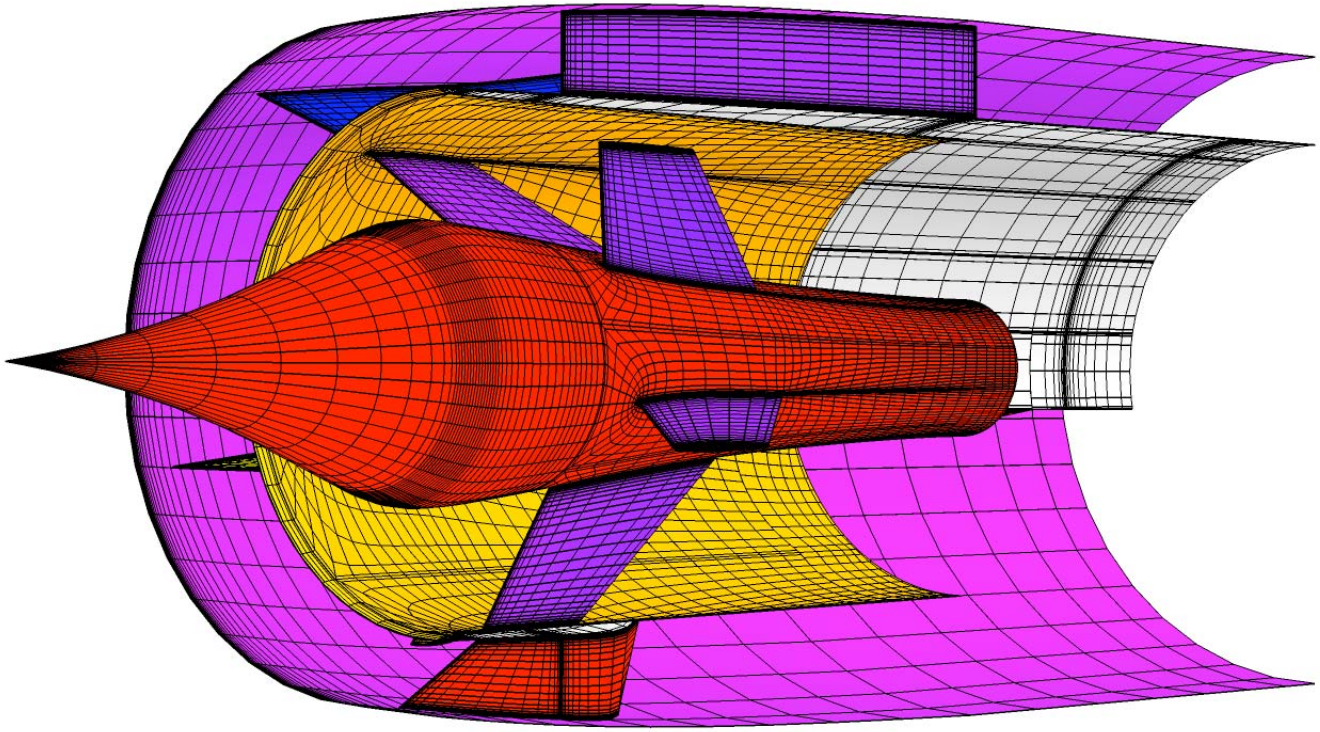
# Cowl



# Bypass Channels



# Centerbody and Struts



# WIND-US Code

**Solution scheme**

- HLLC (Harten, Lax, van Leer, Contact) upwind scheme
- minmod limiter
- SST turbulence model

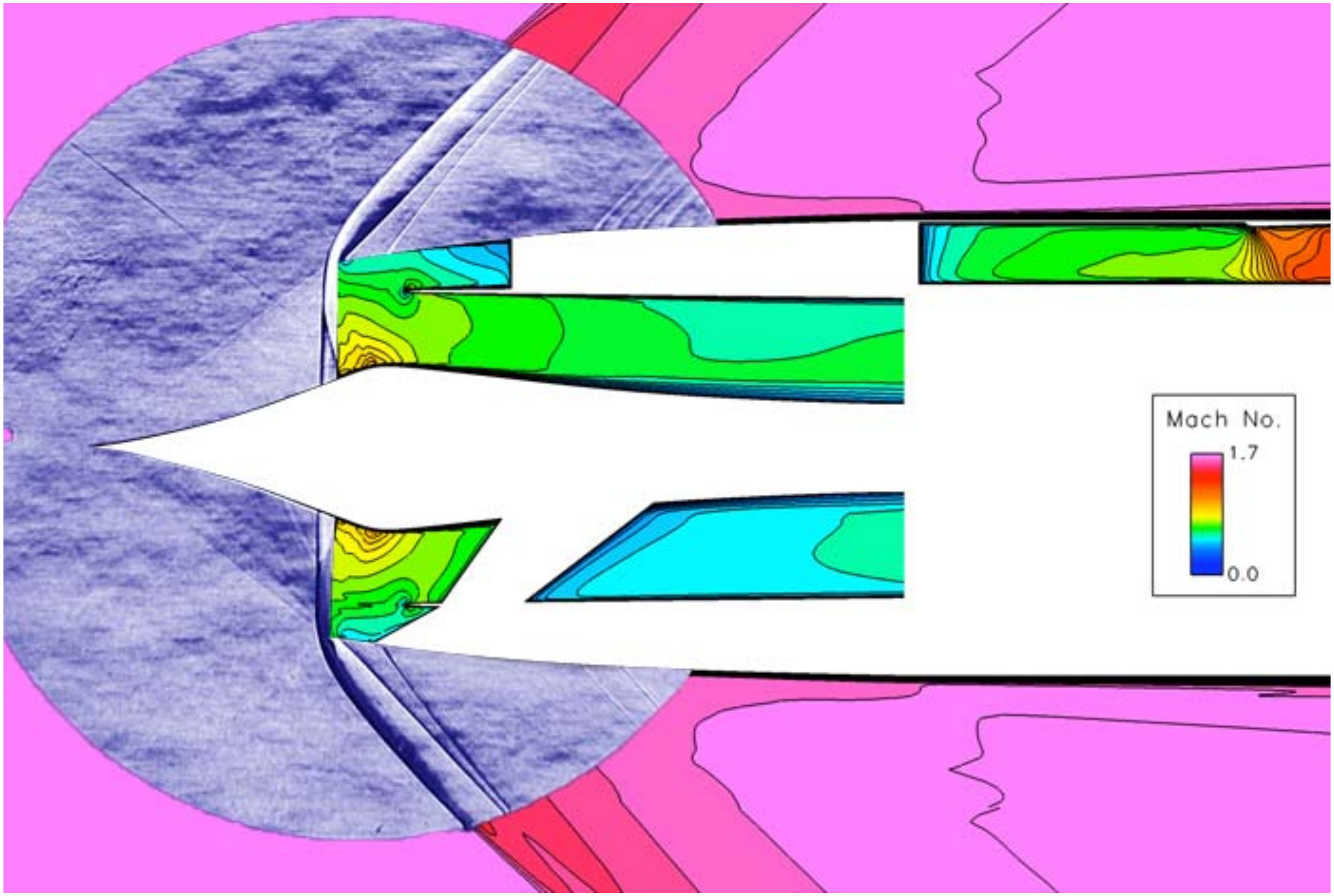
**Boundary conditions**

- Supersonic inflow with M = 1.7
- Bypass exit choked to freestream pressure
- Core exit pressure varied to change capture ratio

**Solution details**

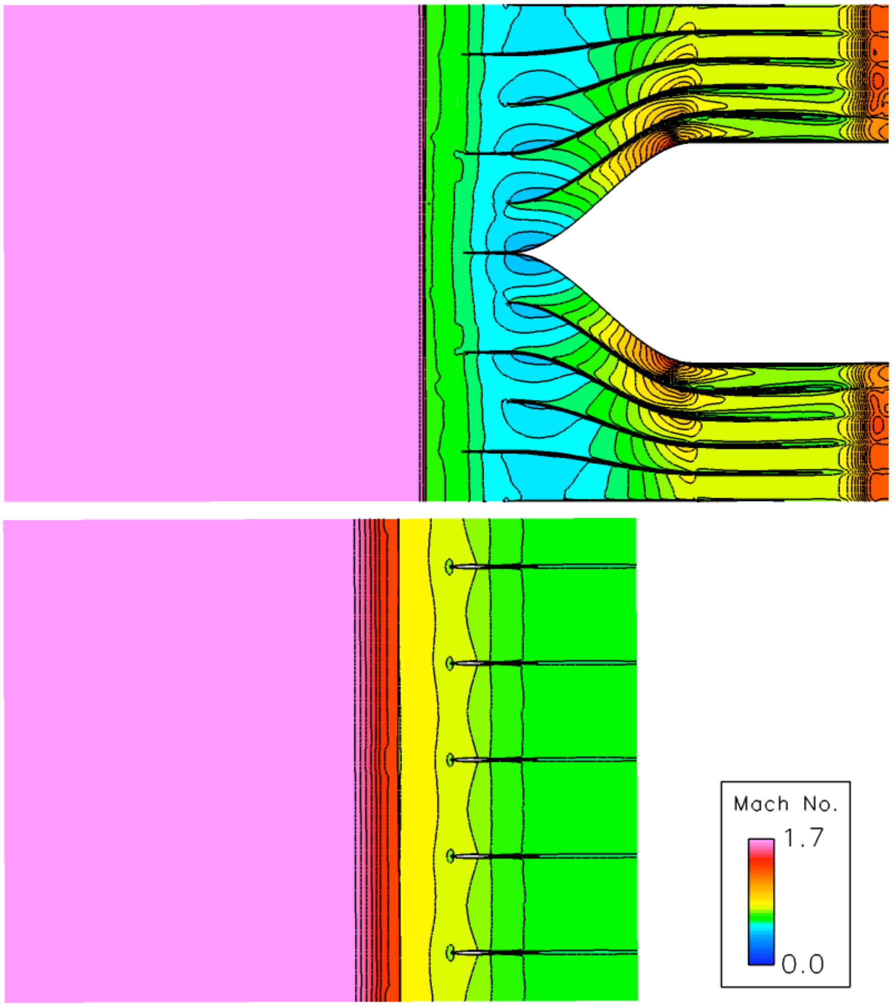
- Cases run 7,500 – 10,000 iterations with CFL = 2.0
- Core and bypass mass flow and recovery monitored for convergence
- 25 block grid run on 11 CPUs at 3.2 GHz
- 24 – 33 hours per case

# Mach Contours, M = 1.7, $\alpha = 0°$




• Capture ratio ~ 0.94

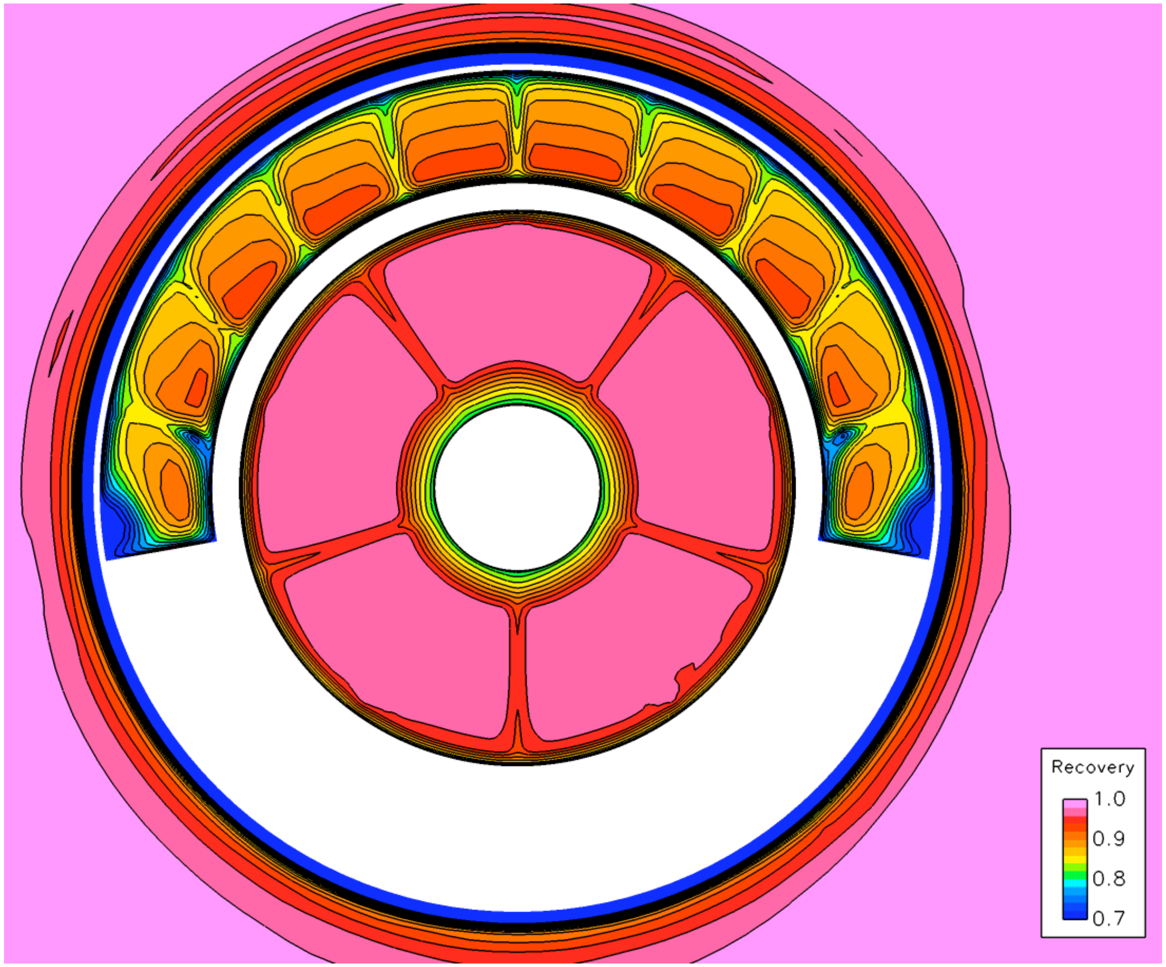
# Mach Contours, Unrolled Surfaces at Mid Span, $\alpha = 0°$




**Bypass**
- Straight shock
- Inner channels nearly choked
- Thin wakes from vanes

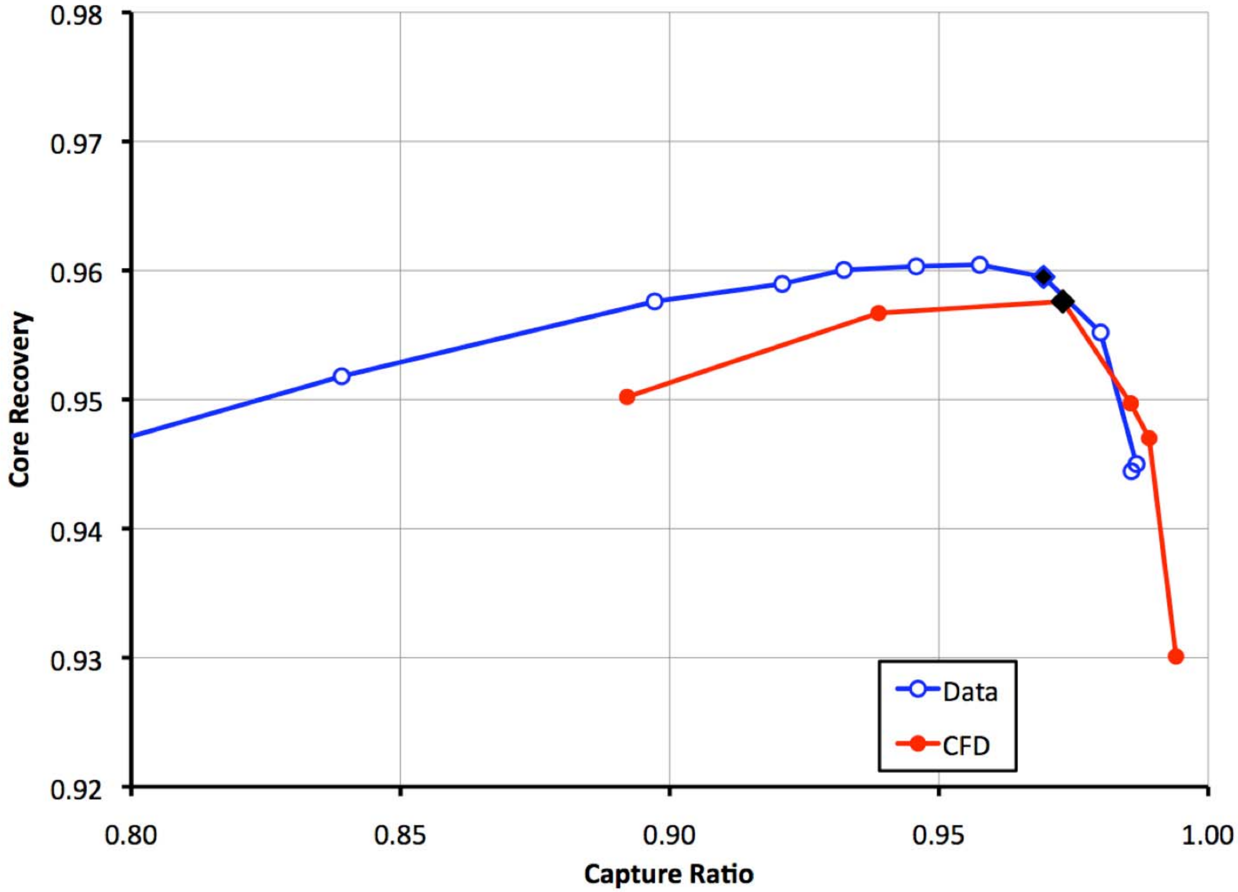
**Core**
- Straight shock
- Very thin wakes from struts

# P0 Contours at Rake Face, $\alpha = 0°$



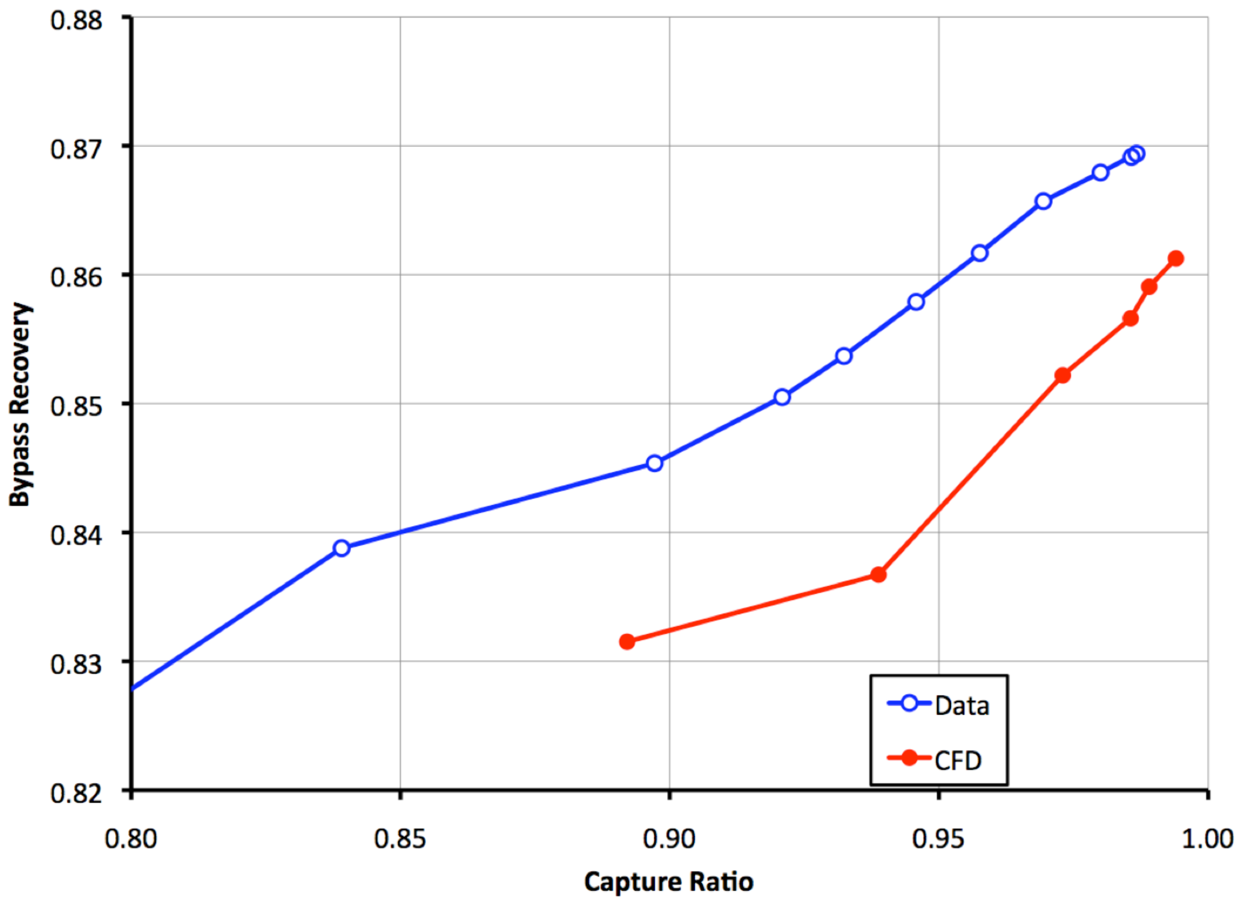

- Core – thick hub boundary layer, little $\theta$-distortion
- Bypass – mostly radial distortion except outer channels

# Core Recovery vs. Capture Ratio




- Computed max. capture ratio > measured, but experimental bypass flow rate is not known accurately
- Computed recovery 0.3 – 0.5 points low, evaluated at rake locations
- Black diamonds show operating points compared later

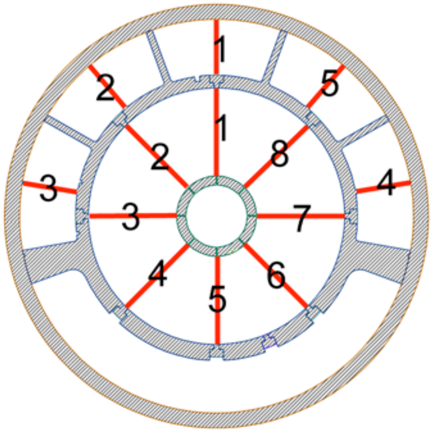
# Bypass Recovery

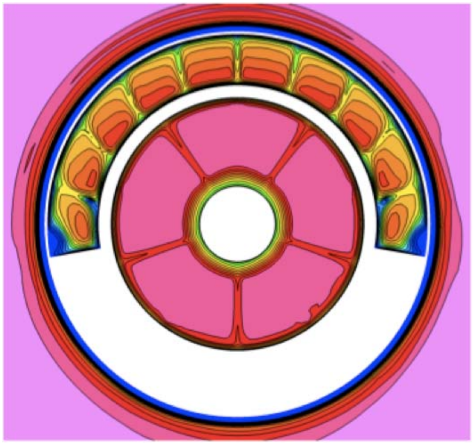


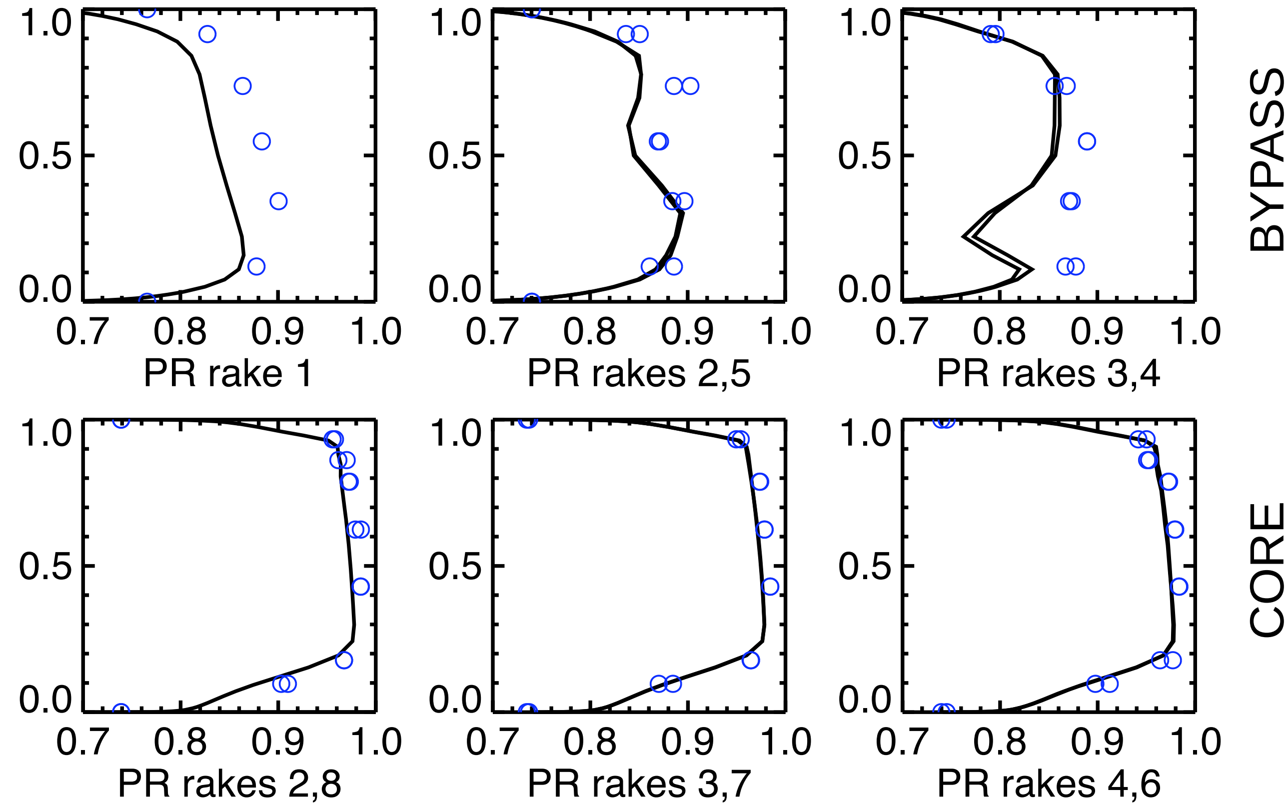

- Computed bypass recovery 1 – 1.5 points low, evaluated at rake locations
- Differences probably because rakes are centered in bypass vane wakes which do not mix out sufficiently
- Differences possibly due to differences between test and flight / CFD geometries

# Rake P0 Profiles, $\alpha = 0°$

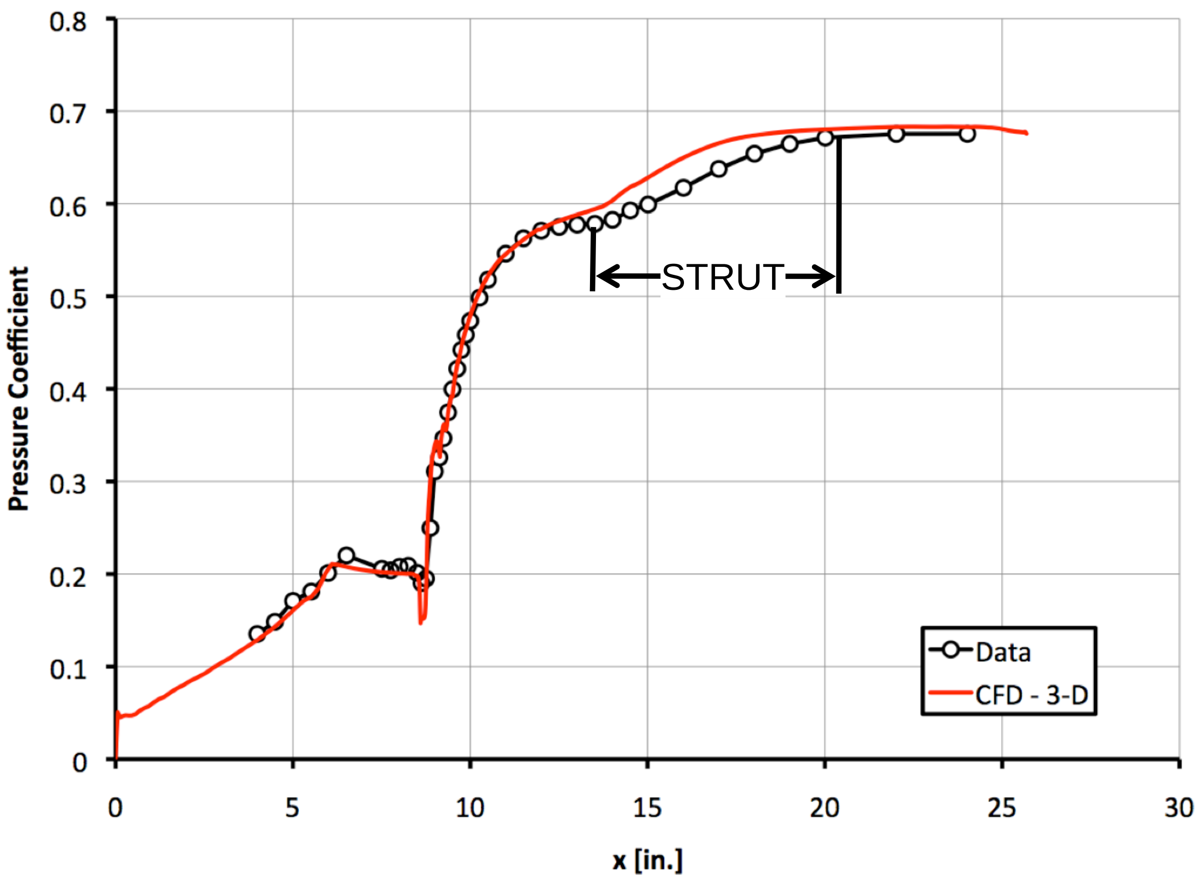
- Data and CFD show good L-R symmetry
- Bypass: CFD generally low. Rakes are in bypass vane wakes.
- Core: Excellent agreement between CFD and experiment



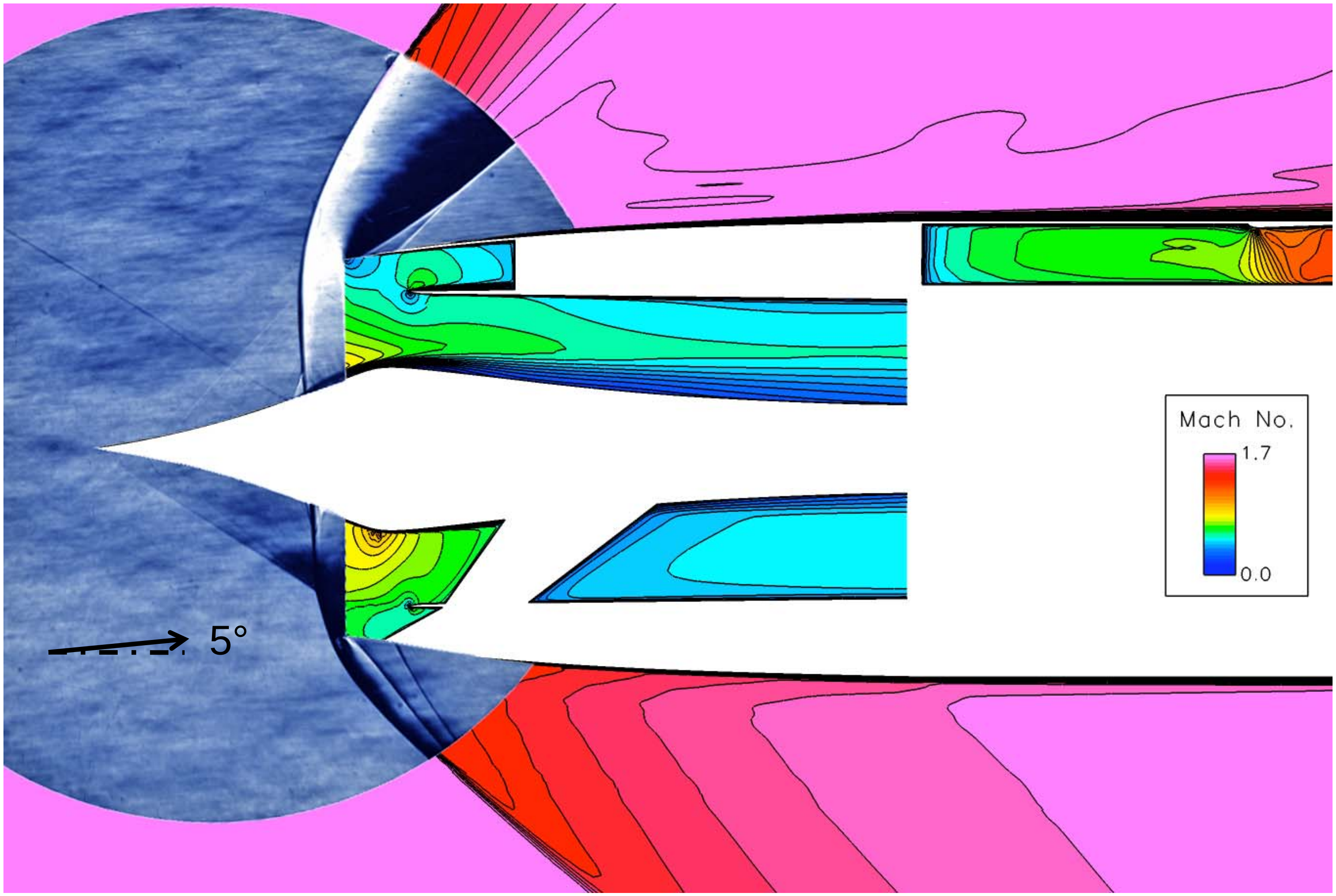


# Centerline Pressures



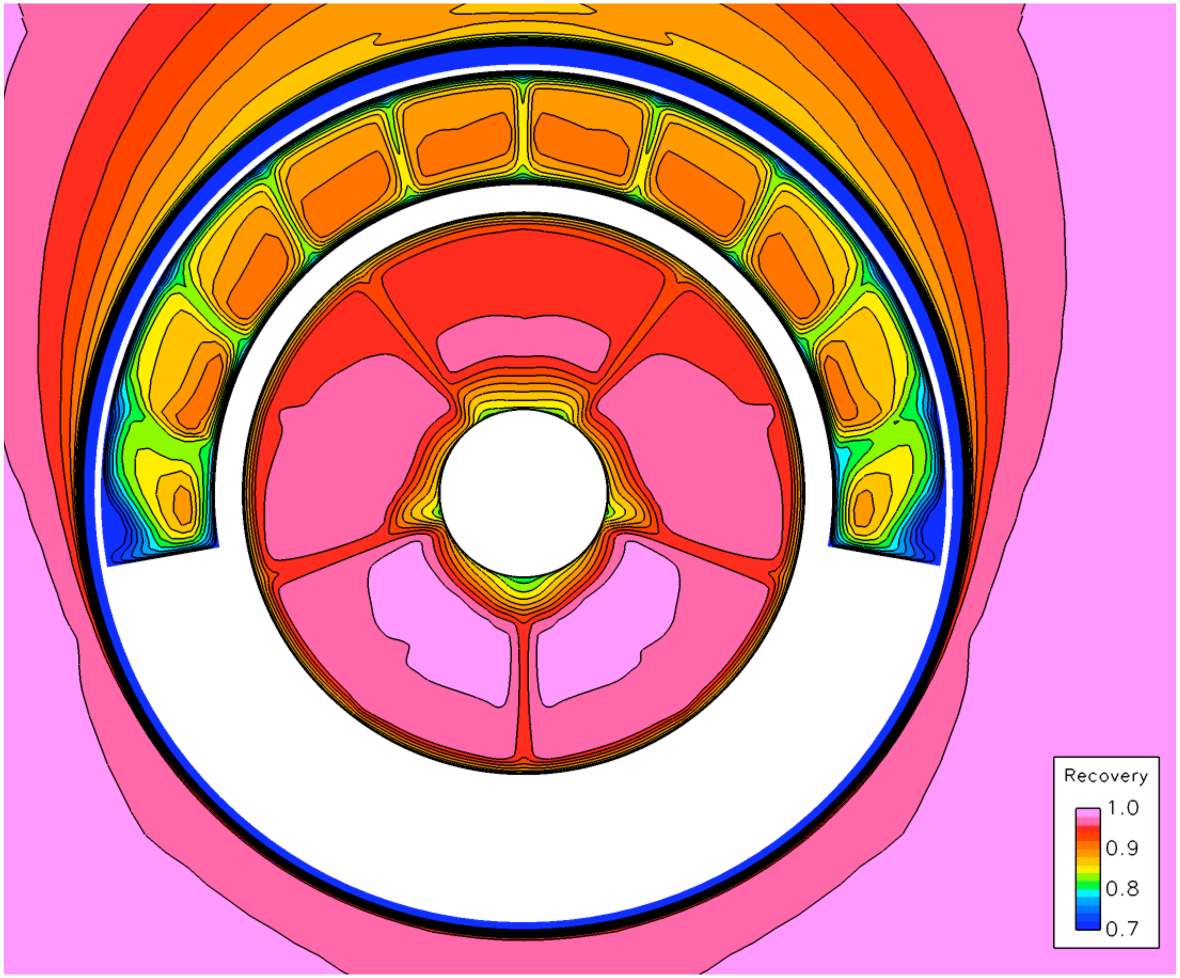

• Excellent agreement between CFD and experiment except between struts

# Mach Contours, $\alpha = 5°$



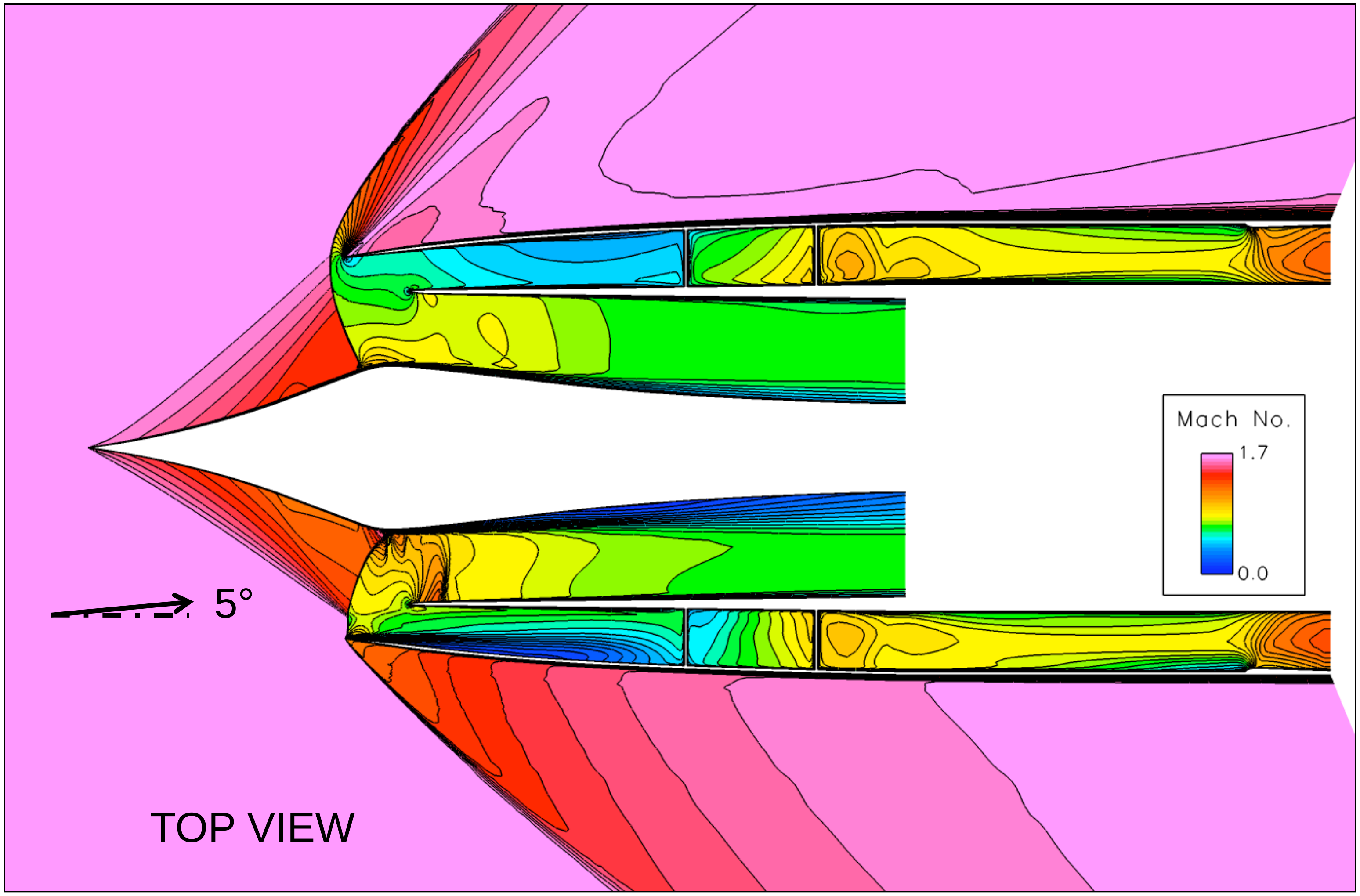

- Capture ratio ~ 0.89

# P0 Contours at Rake Face, $\alpha = 5°$



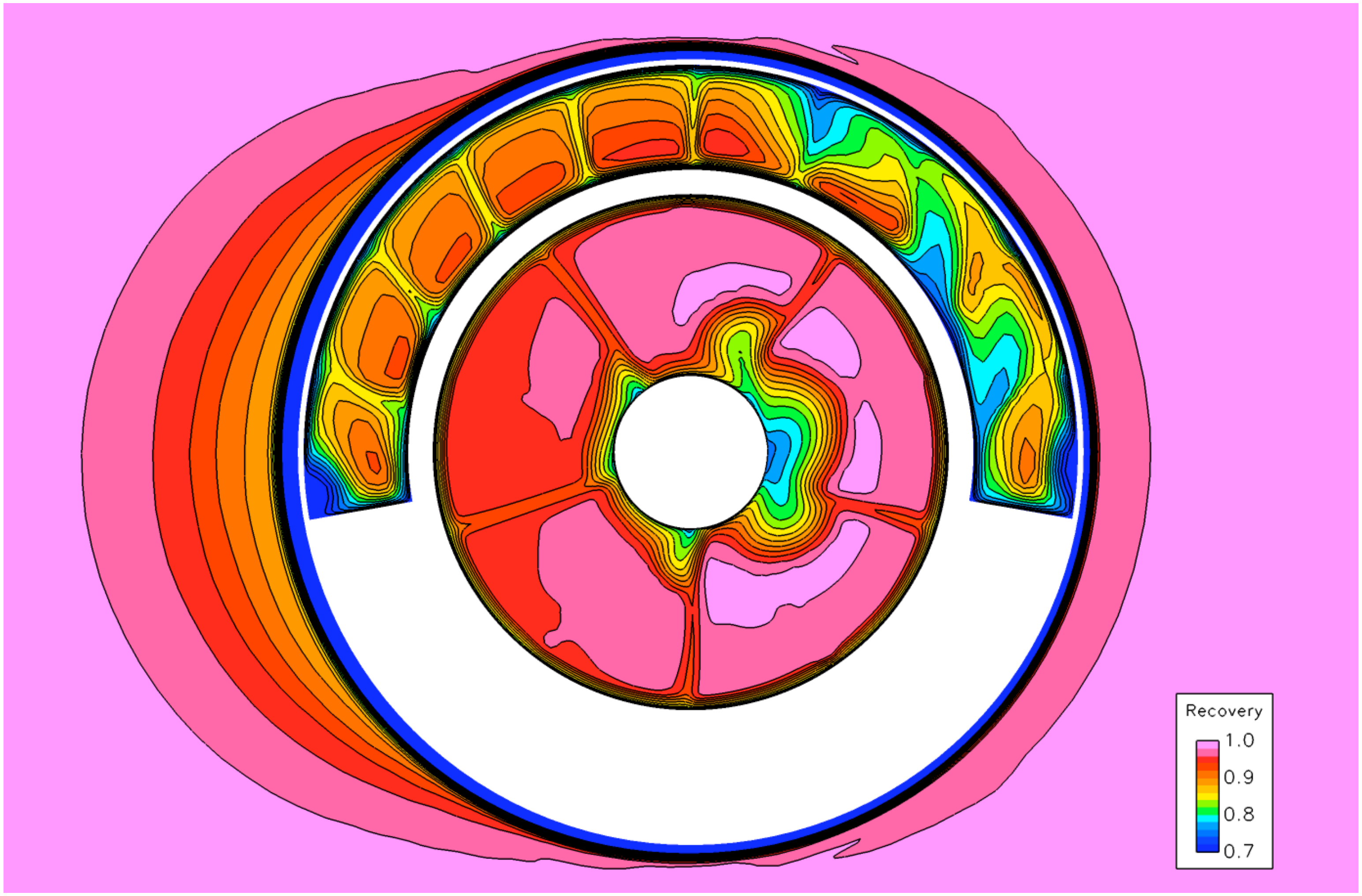

- Core – thick hub boundary layer, $\theta$-distortion constrained by struts
- Bypass – mostly radial distortion except outer channels

# Effect of Yaw, $\beta = 5°$




- Yaw not studied experimentally
- Effects of yaw similar to angle of attack

# P0 Contours at Rake Face, $\beta = 5°$




- Bypass channels highly asymmetric
- Unusual circumferential distortion in core stream could affect engine operability

# Conclusions (1/2)

Axisymmetric and 3-D calculations were made of the Gulfstream dual stream low boom inlet before the test, and results were compared to experimental data. The following results were noted:

## Experiment

- The dual stream inlet had excellent core recovery and buzz margin.

## Axisymmetric CFD Results

- Predicted core recoveries were about 0.4 points high. When strut losses were omitted from the experimental data the agreement was excellent.
- AIP profiles agreed very well with measurements, except behind the strut.
- Predicted bypass recoveries were about a point high, probably because channel walls and 3-D effects were missing in the axisymmetric calculation.
- CFD predictions were used to determine the optimal bypass exit plate size and to set the initial range of the MFP.

# Conclusions (2/2)

## 3-D CFD Results

- Computed shock positions compared well with schlieren images.
- Computed centerline pressures agreed very well with experimental data.
- CFD predicted a slightly higher max. capture ratio than was measured. However, the bypass mass flow is not known accurately.
- Predicted core recoveries were 0.3 – 0.5 points low, but AIP profiles agreed very well with measurements.
- Predicted bypass recoveries were 1 – 1.5 points low, probably due to insufficient mixing of the bypass vane wakes, and bypass rake pressure profiles tended to be low.

Additional results to be presented in two papers at the 29th AIAA Applied Aerodynamics Conference, June 27-30, 2011, Honolulu, Hawaii.

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