Ongoing Study of Supersonic Retro-Propulsion Using Structured Overset Grids and OVERFLOW

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The interest in supersonic retro-propulsion (SRP) as a means of deceleration during planetary entry increases with the desire to land high mass vehicles on Mars. Since it is difficult to obtain flight data or properly simulate this type of flow field in a wind tunnel, the use of computational fluid dynamics (CFD) becomes increasingly important, as does the need to verify the current CFD methods. This presentation will show results from structured overset grids and OVERFLOW, a Reynolds Averaged Navier-Stokes solver, obtained during the continuing CFD verification process. Flow structure, surface pressure, forces, and moments are compared to historic and modern wind tunnel data as well as to other Navier-Stokes solvers, DPLR and FUN3D. Cases include single and multiple nozzle cases from the Jarvinen and Adams experiment,[i] the Daso et al experiment,[ii] and a recent test in the NASA Langley Unitary Wind Tunnel (scheduled for June 2010).

[i] Jarvinen, P.O. and Adams, R.H., "The Aerodynamic Characteristics of Large Angled Cones with Retrorockets," NASA Contract No. NAS7-576, Cambridge, MA, Feb. 1970.
[ii] Daso, E. et al, "Dynamics of Shock Dispersion and Interactions in Supersonic Freestreams with Counterflowing Jets," AIAA Journal Vol. 47, No. 6, June 2009.

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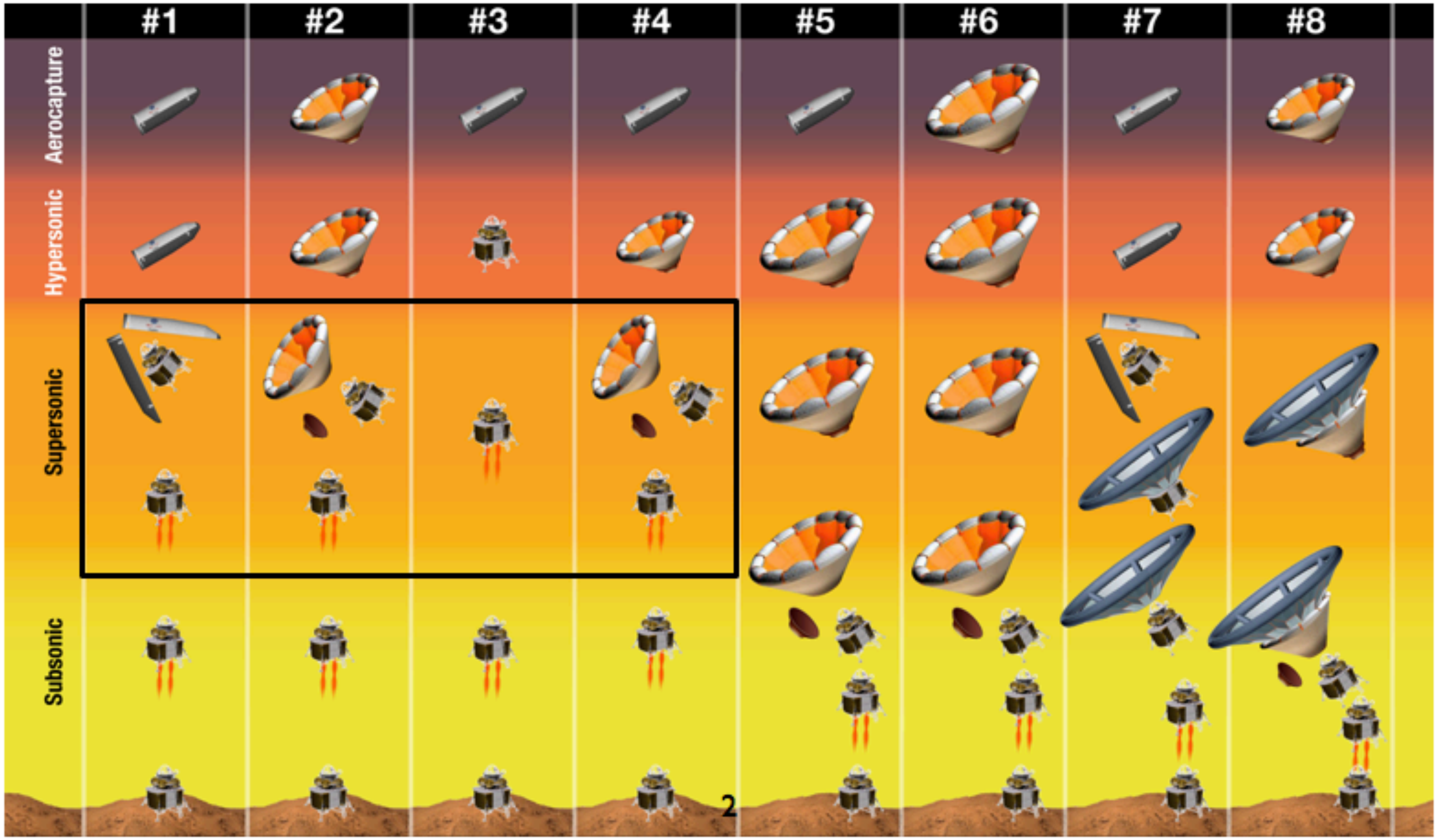
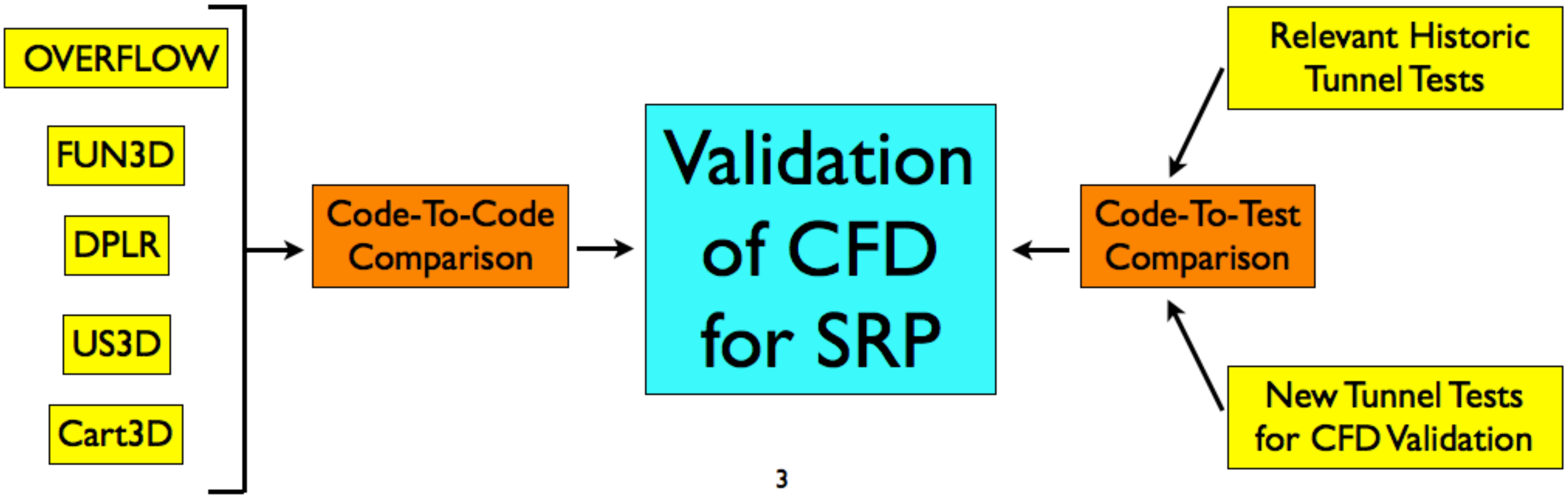
Introduction

- The goal is to softly land high mass vehicles (10s of metric tons) on Mars
- Supersonic Retro-Propulsion (SRP) is a viable means of deceleration
- CFD is of increasing importance since flight and experimental data at these conditions is difficult to obtain
- CFD must be validated at these conditions



CFD Validation Approach

- Employ multiple CFD codes (OVERFLOW, FUN3D, and DPLR) to solve the same SRP problems
    - New additions of US3D and Cart3D
- Compare results between codes and with historic data
    - Shock structure/ shock standoff distance
    - Surface pressures and forces
- Run new wind tunnel tests for CFD validation
    - Complete run conditions
    - Higher thrust coefficients than in existing data

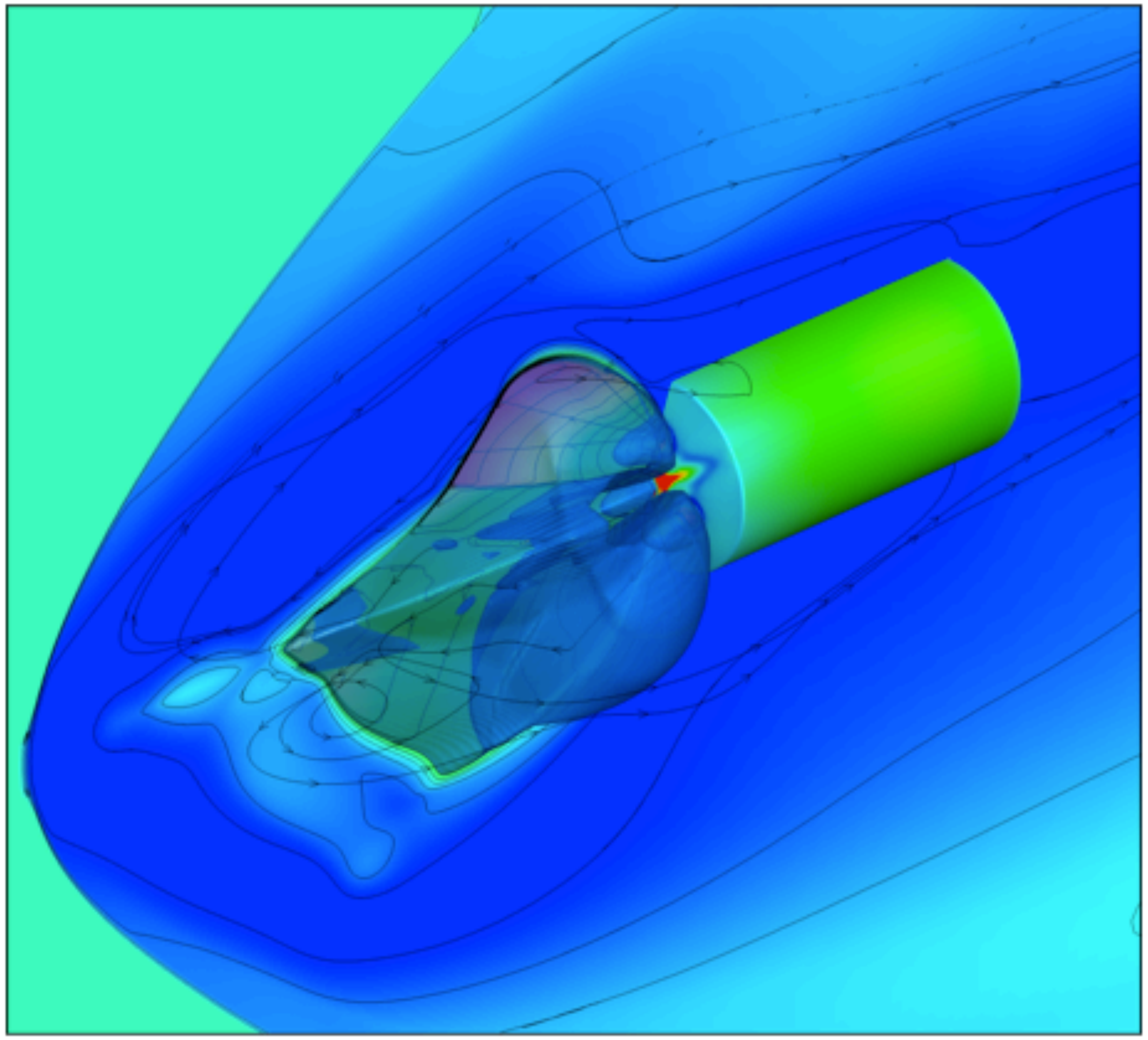


Presentation Preface

- Focus on OVERFLOW results
- Results from Kerry Trumble (NASA ARC, DPLR) and Bil Kleb (NASA LaRC, FUN3D) will also be shown
- This is a work in progress

Outline

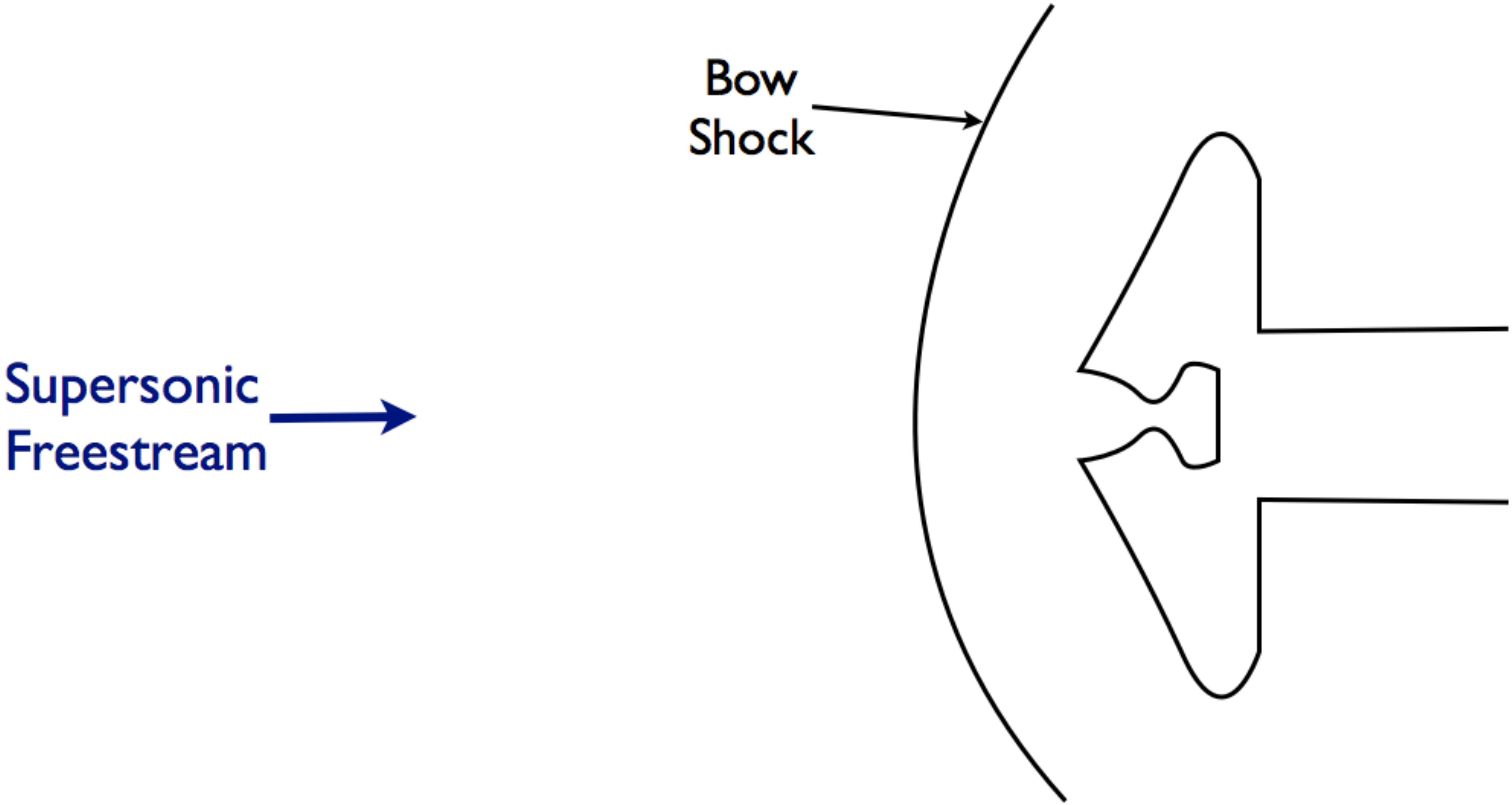
1. Jarvinen and Adams Single Nozzle
2. Daso et al Single Nozzle
3. Jarvinen and Adams Triple Nozzle
4. Langley UPWT 4x4 Pre-Test
   - Single, triple, and quad nozzle cases
5. Current Work
6. Future Work



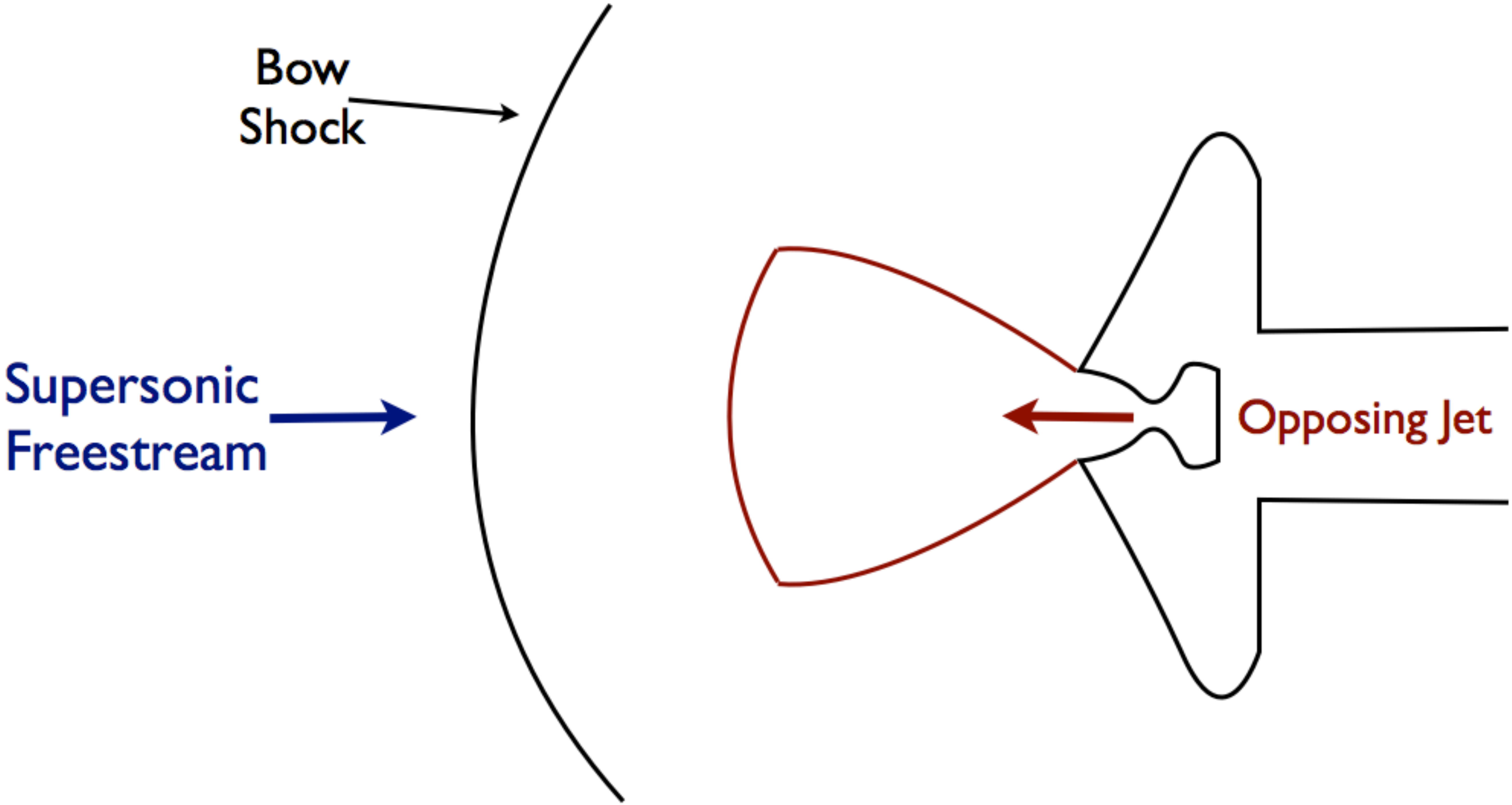
Langley UPWT pre-test, 4 nozzle, Mach 4.6, C_T 5

Single Jet SRP Flow Field Structure

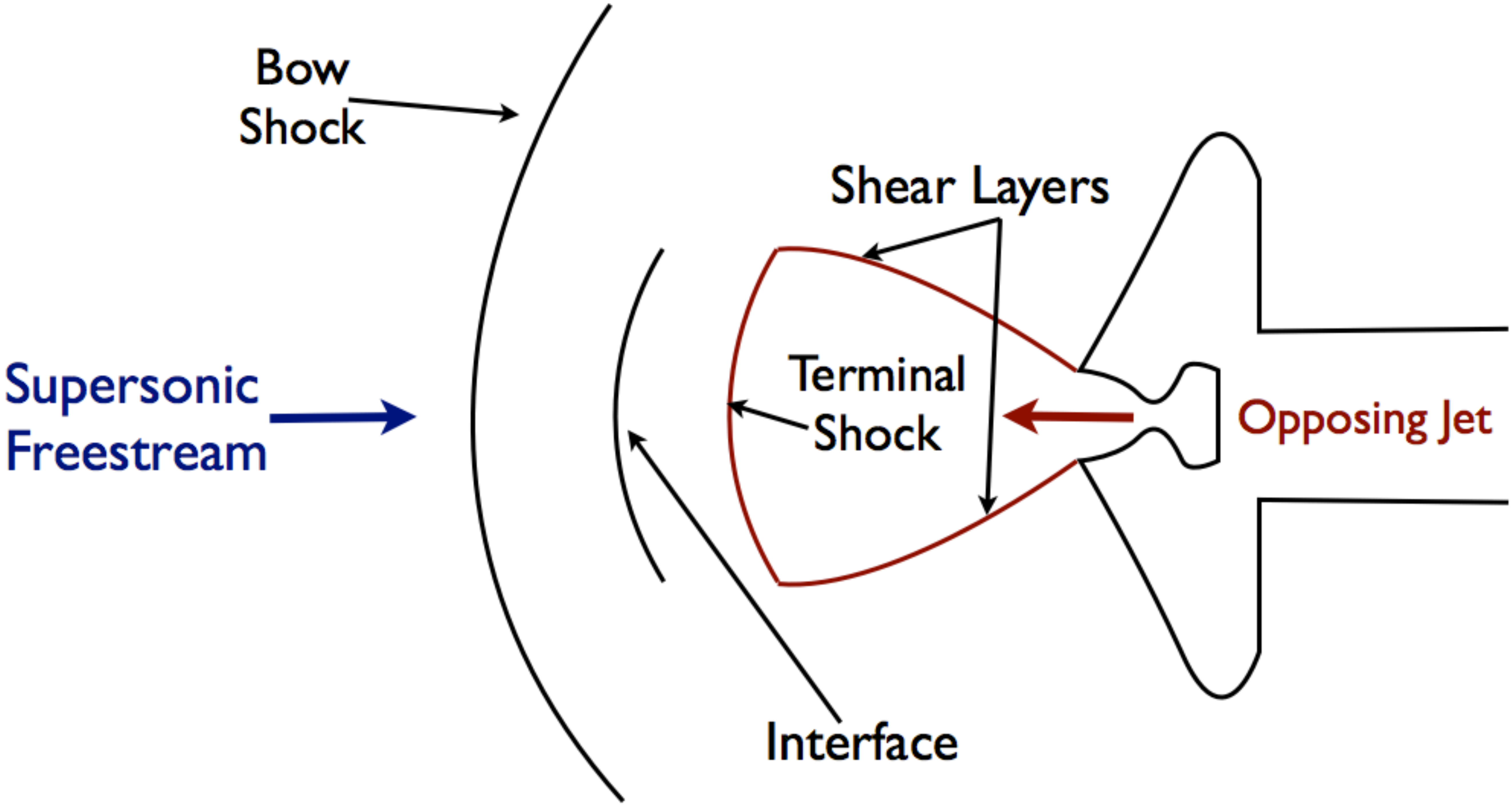
Single Jet SRP Flow Field Structure



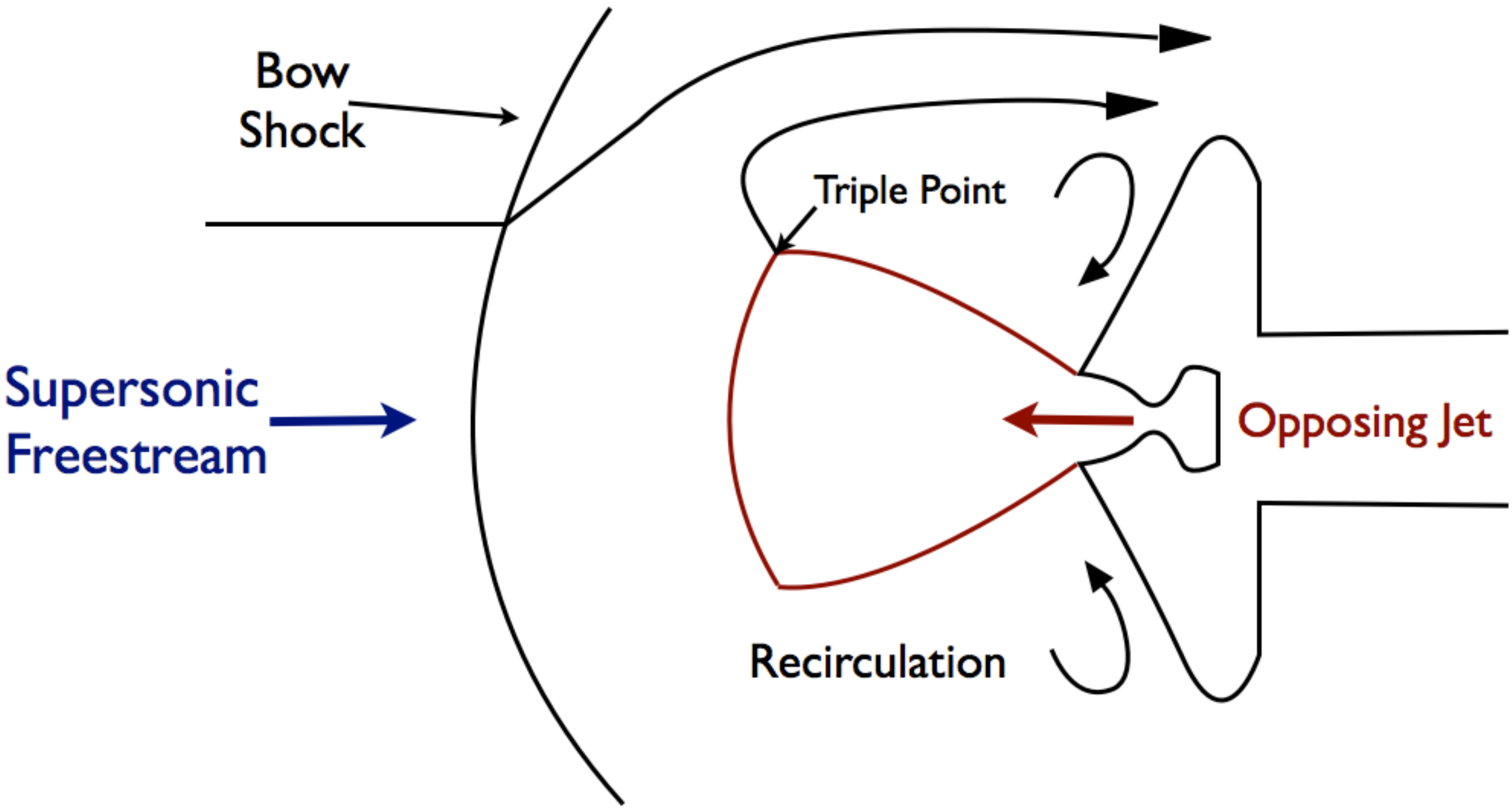
Single Jet SRP Flow Field Structure



Single Jet SRP Flow Field Structure



Single Jet SRP Flow Field Structure



Jarvinen and Adams Single Nozzle

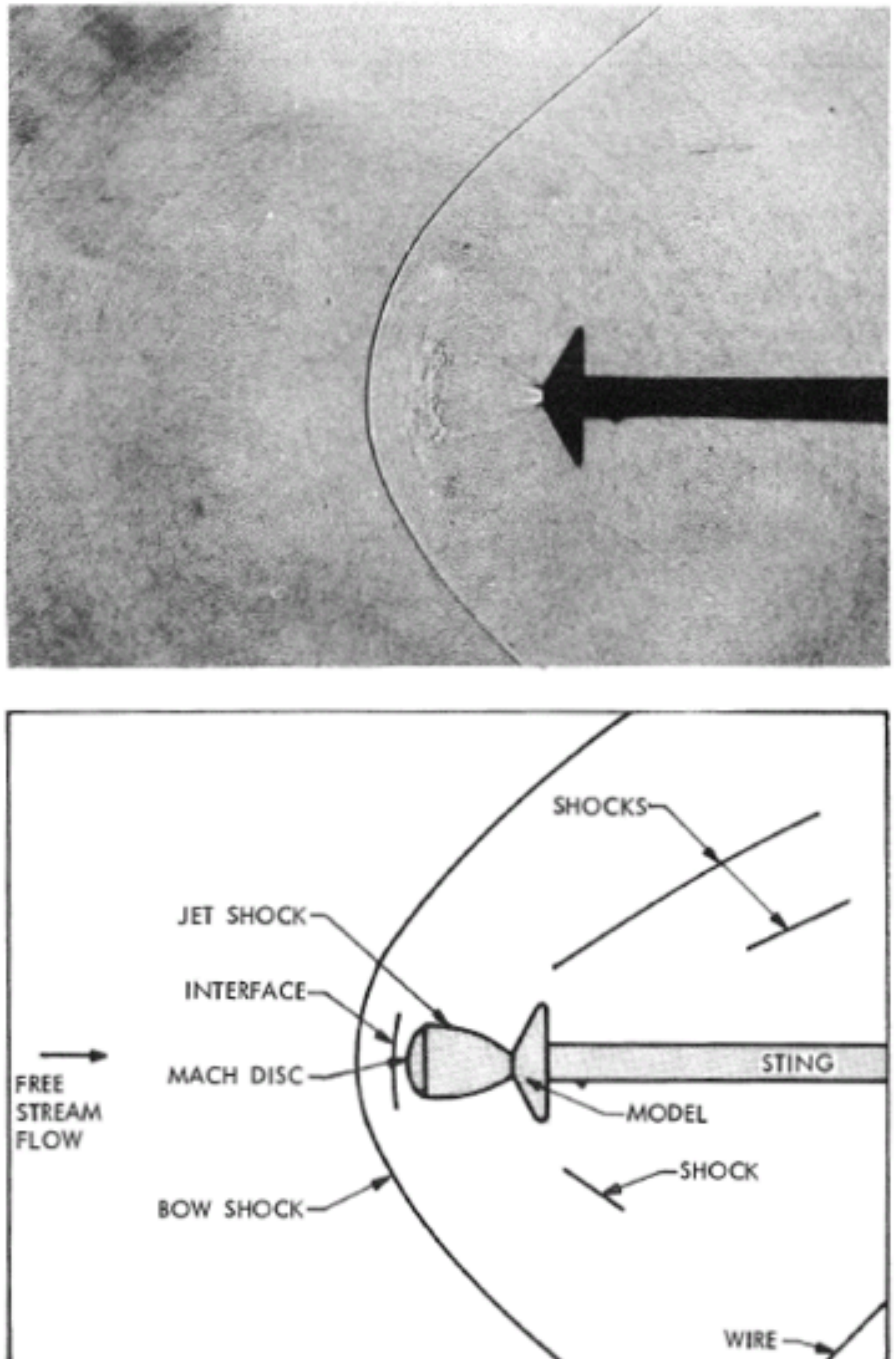
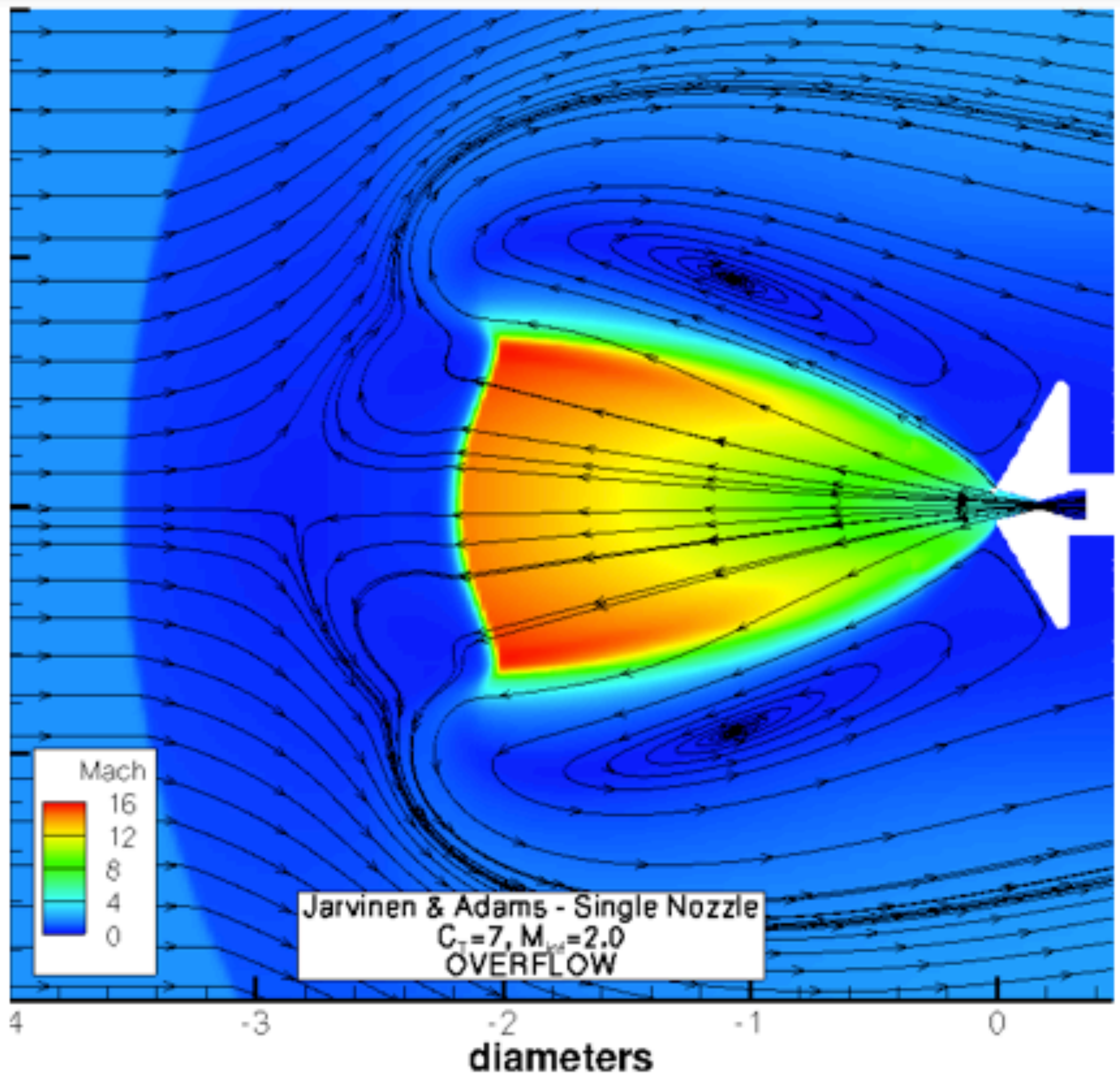
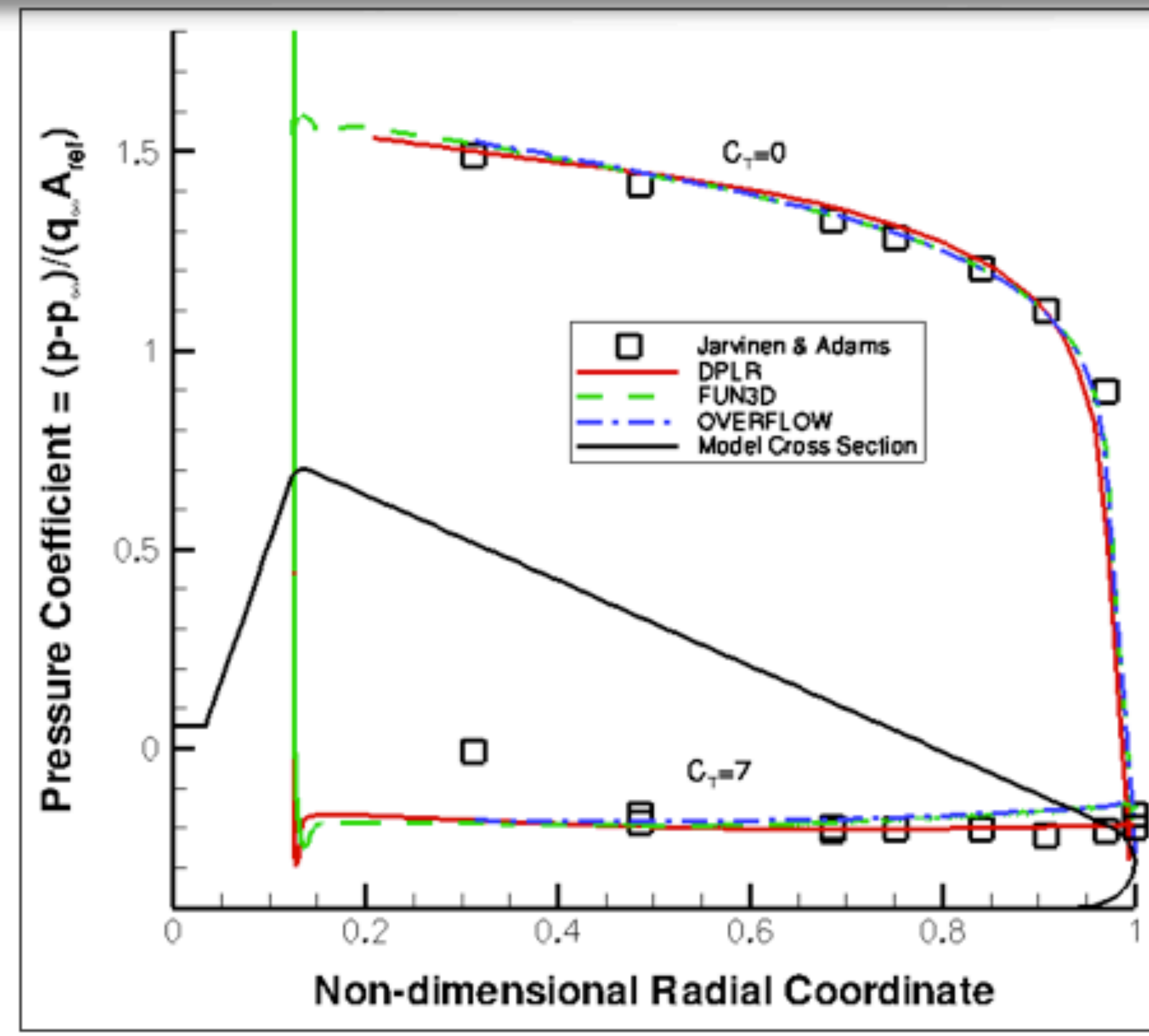


Figure 14 Single Nozzle 60° Aeroshell Model with Blunt Flow Interaction, $M_{\infty} = 2.0$, $C_T = 1.1$.

- 60 degree sphere cone
- Ames 6'x6' supersonic wind tunnel in 1970
- Inconsistencies in the report
  - Geometric dimensions
  - Freestream total temperature and pressure
  - No uncertainties reported
- For this test, code-to-code comparison was relied on heavily
- Run conditions
  - Mach = 2.0, Re/in = 40604.3
  - C_T = 0, 7

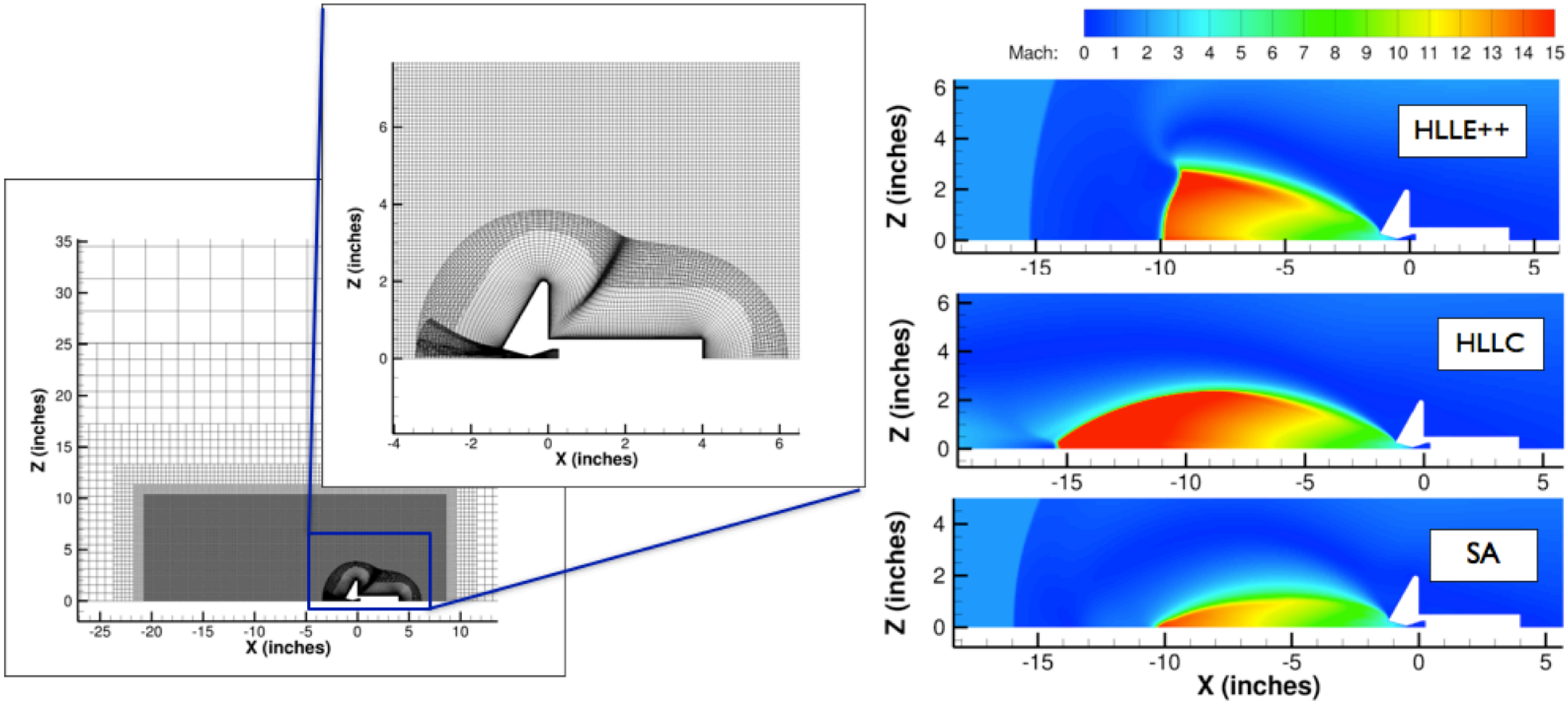
Jarvinen and Adams Single Nozzle Results





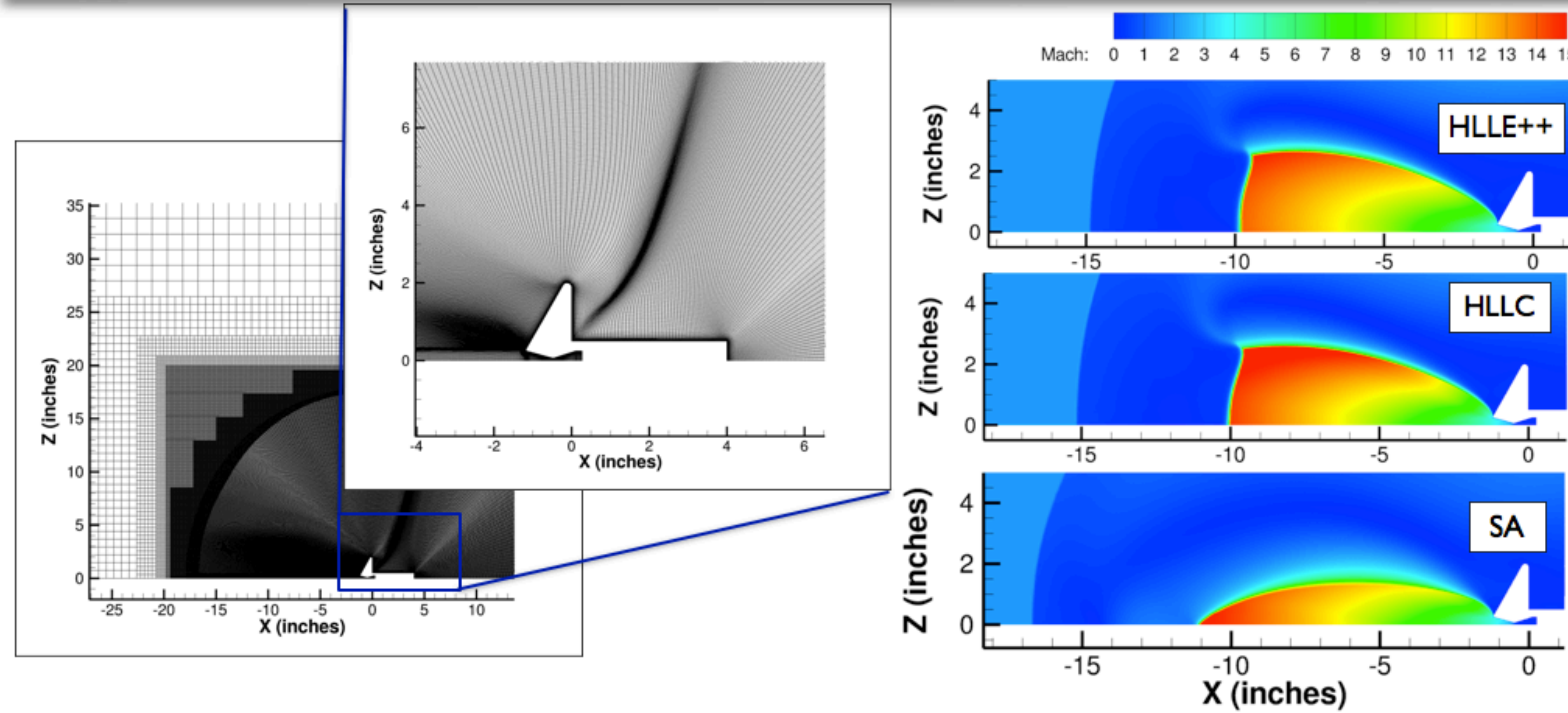
- HLLE++, SSOR, and SST without compressibility correction
- Literature says this is a steady flow, OVERFLOW results are unsteady
- Overpredict shock standoff distances by ~20% (used average distance)
- Pressure comparison good for no jet case
- For C_T =7, pressure is under-predicted at first data point and over-predicted at shoulder

Grid and Numerical Method Sensitivity



- HLLE++ with SST can predict the proper plume structure on this coarse Cartesian mesh
- HLLC with SST and HLLE++ with SA incorrectly predict plume structure

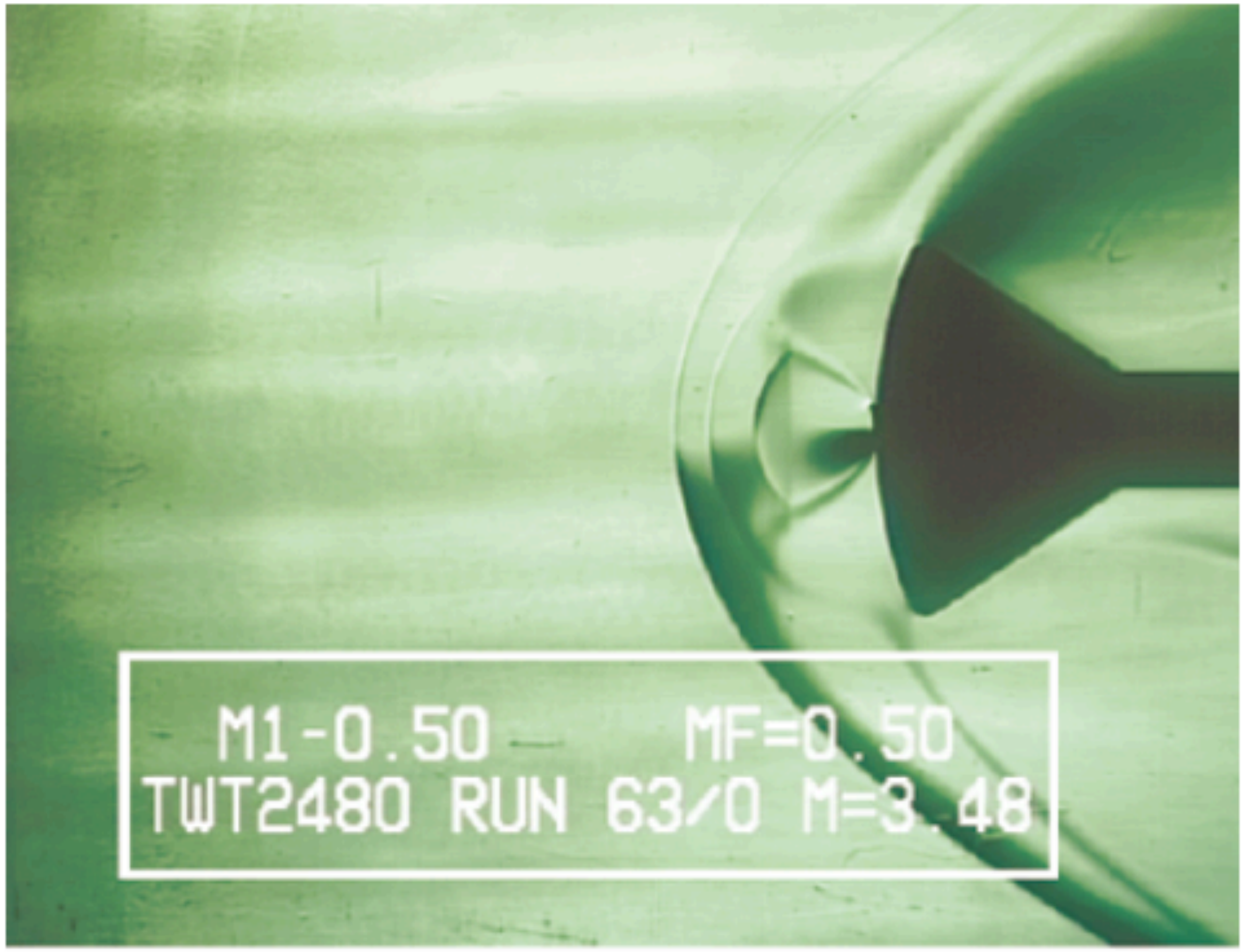
Grid and Numerical Method Sensitivity (cont.)



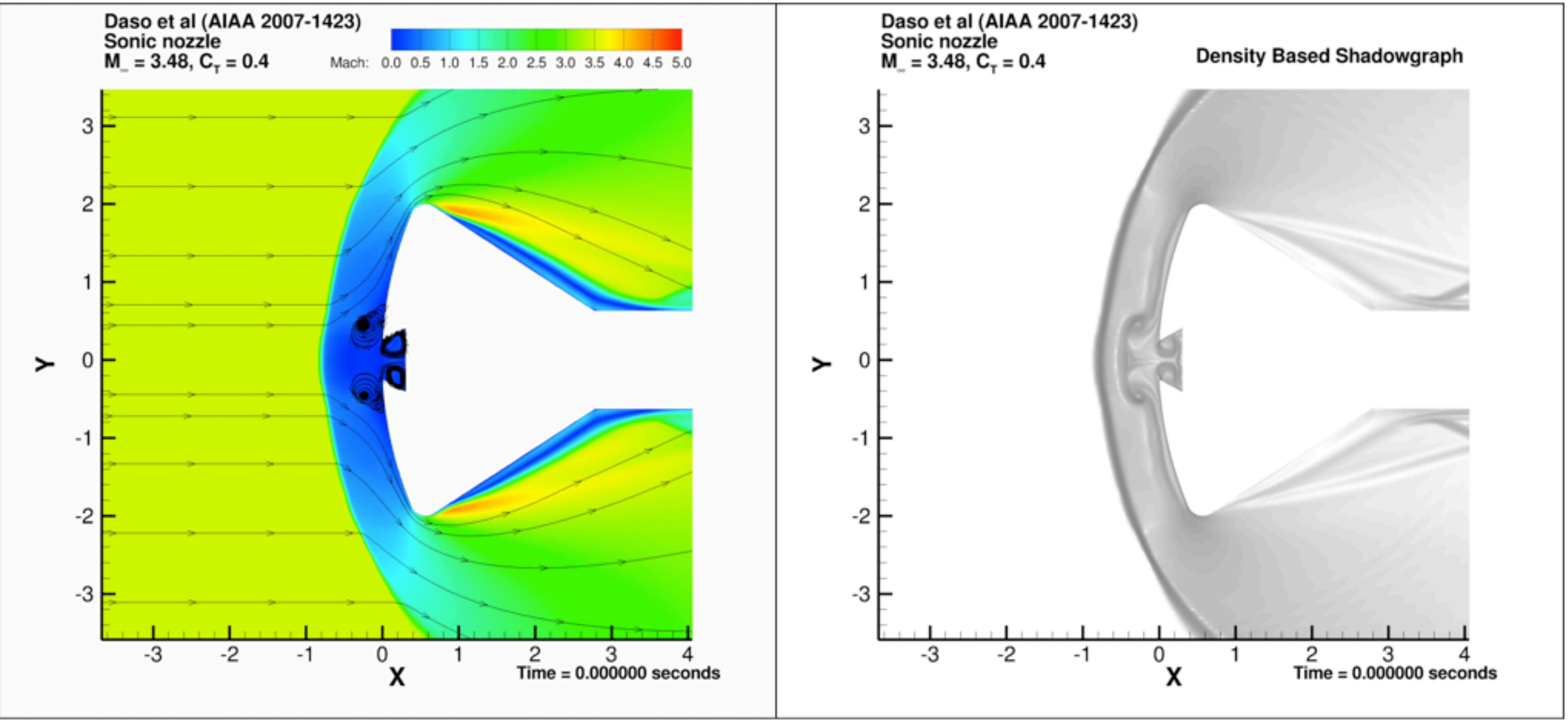
- With a finer curvilinear mesh, HLLC with SST correctly predicts plume structure
- HLLE++ with Spalart-Allmaras still predicts a steady "candle flame" behavior.
- SST solutions unsteady
  - Shown above are instantaneous solutions in time and probably not at the same time
- Running with SST compressibility correction or laminar makes solution more unsteady

Daso et al Single Nozzle Case

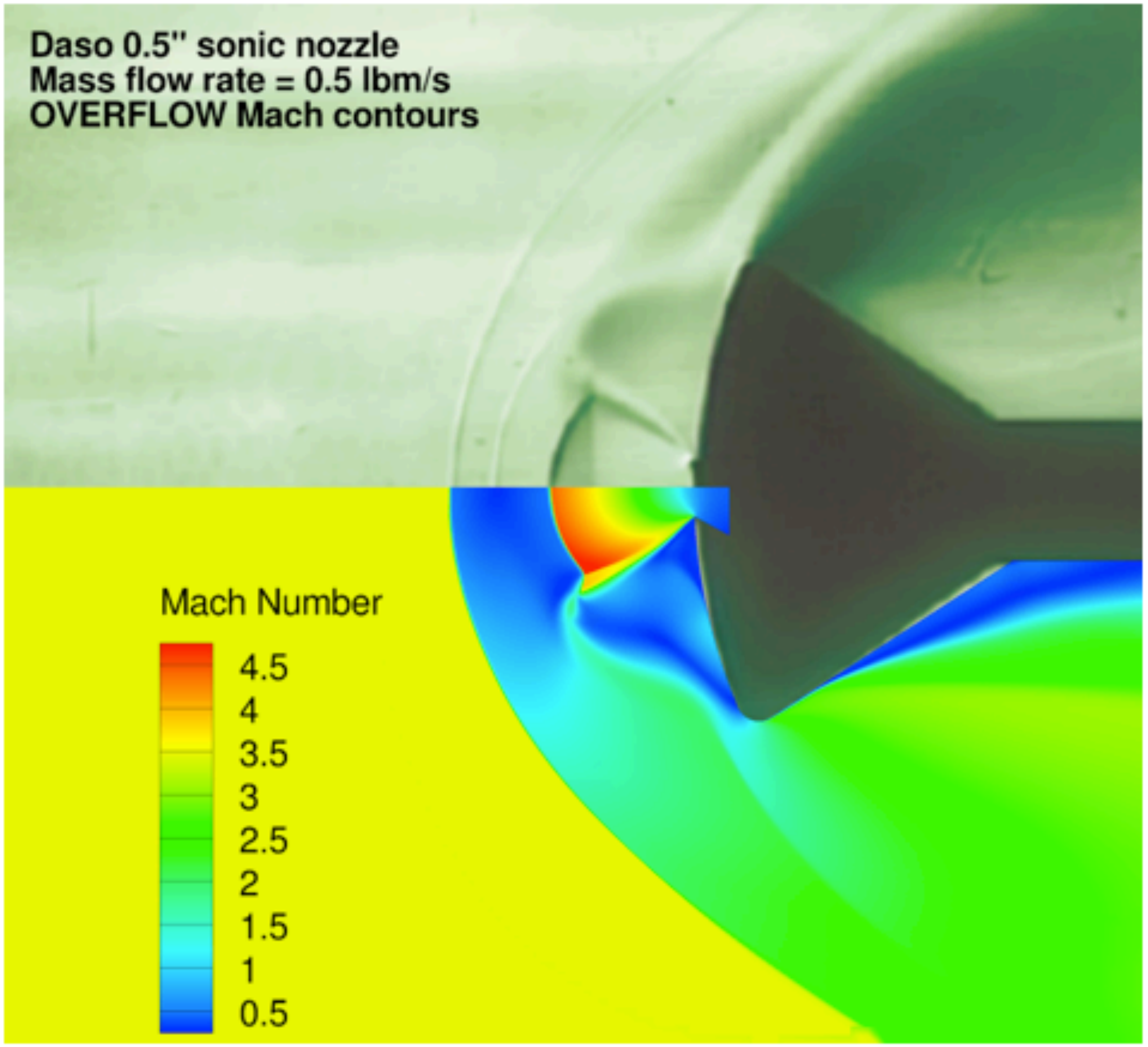
- NASA Marshall Trisonic Blowdown Wind Tunnel, 2007
- Apollo capsule with sonic nozzle
- Good Schlieren images
- No pressure data reported
- Freestream Conditions
  - Mach=3.48, Re=4.88E6/ft
- Low thrust coefficient of 0.4

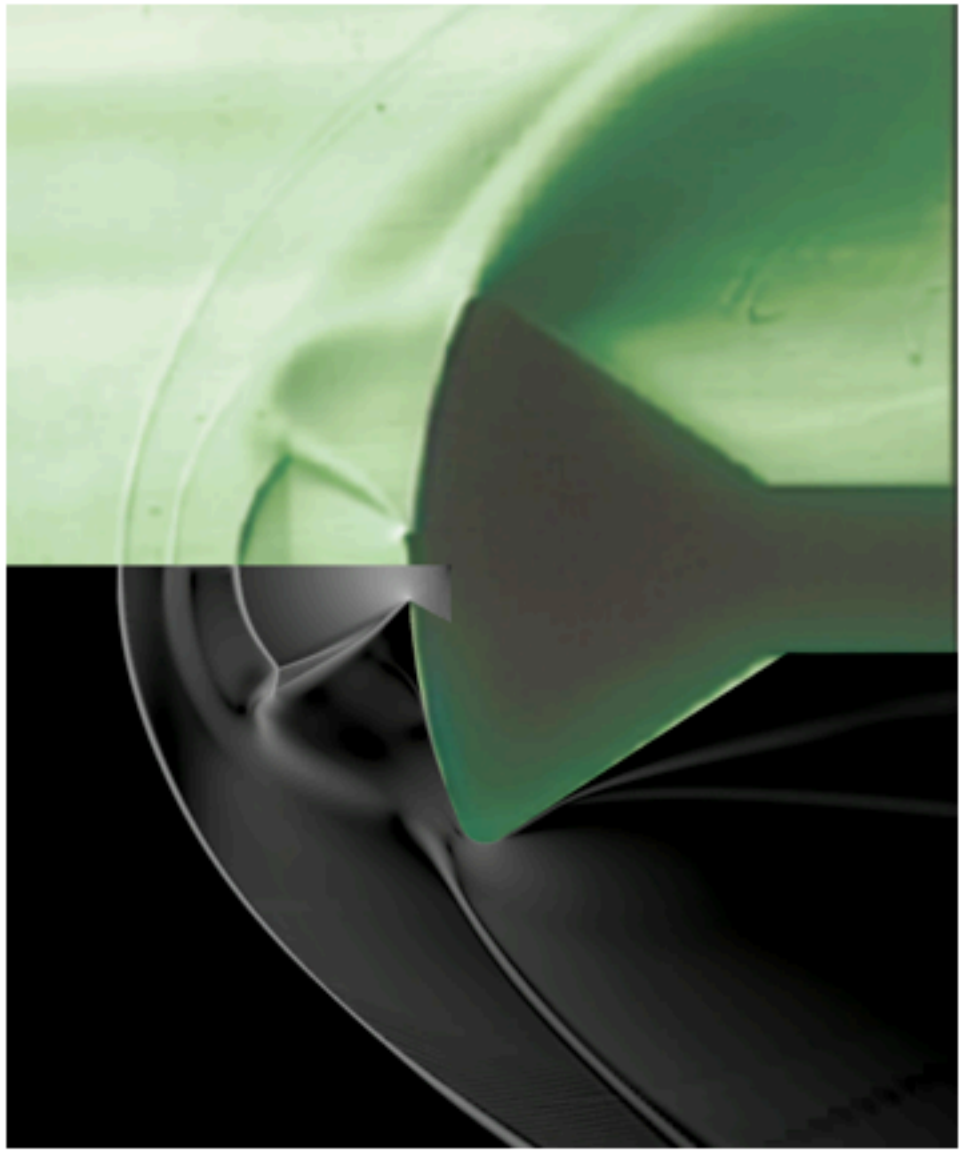


Daso Results



Daso Results



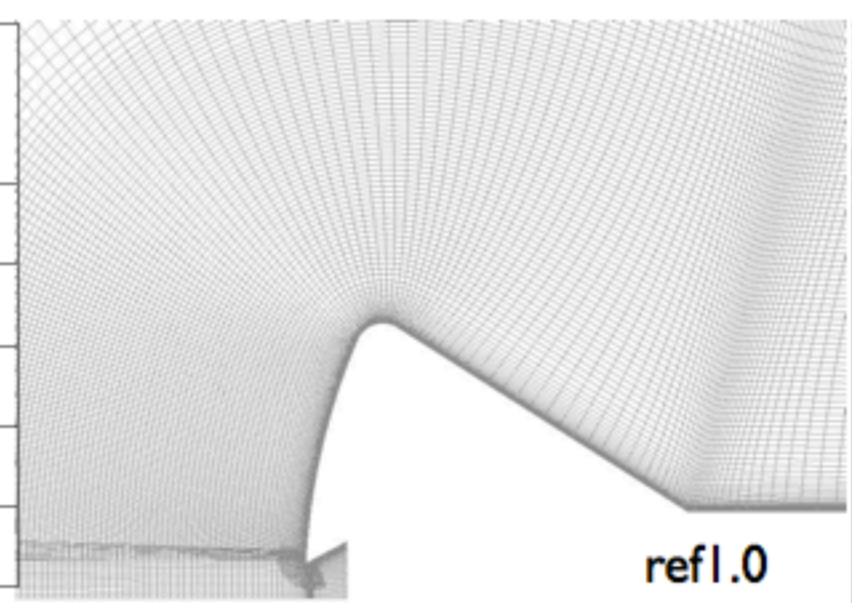


- HLLE++, SSOR, and SST without compressibility correction
- Great shock standoff distance comparison
- Solution reaches a steady state
  - Makes this case good for grid refinement and numerical method sensitivity studies

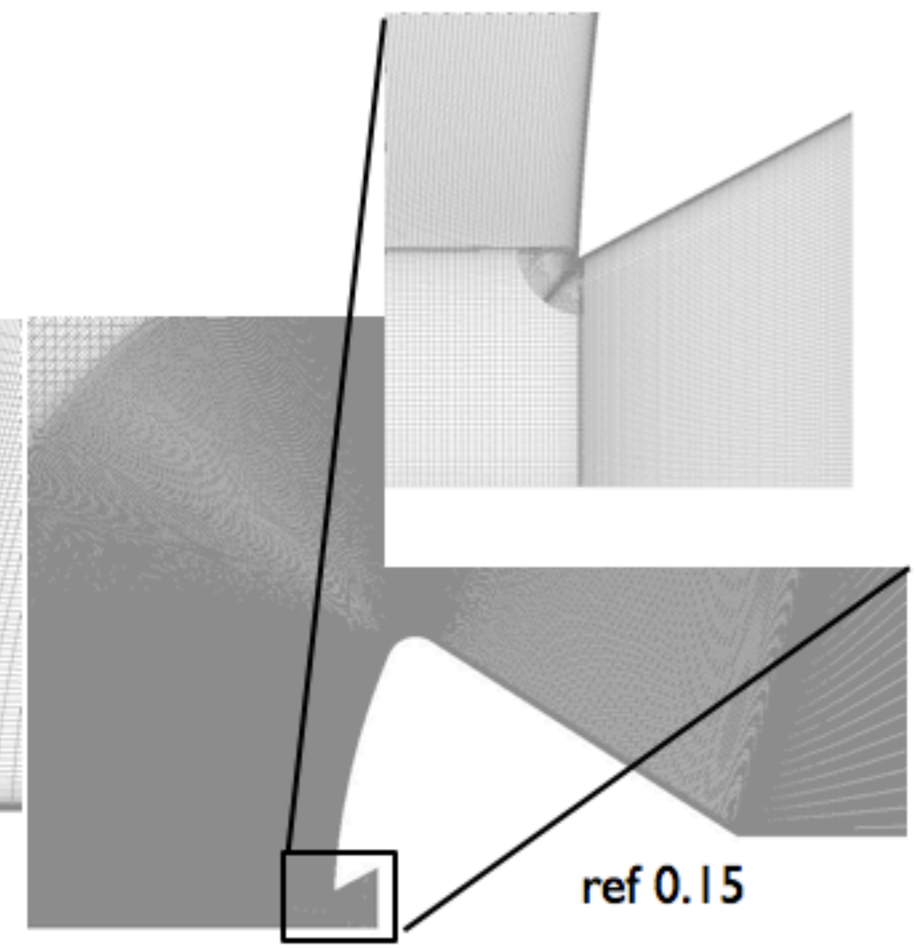
Grid Refinement Study

- Axisymmetric
- Created script to generate mesh based on a global scaling parameter
  - Mesh spacing = value * scale factor
  - The smaller the scale factor, the smaller the grid spacing, which means the greater the refinement
- Created 5 refinement levels

Refinement Level	Number of Points	Increase per Direction
1.25	67581	1
1	93051	1.17
0.5	237867	1.88
0.25	739590	3.31
0.15	1767999	5.11



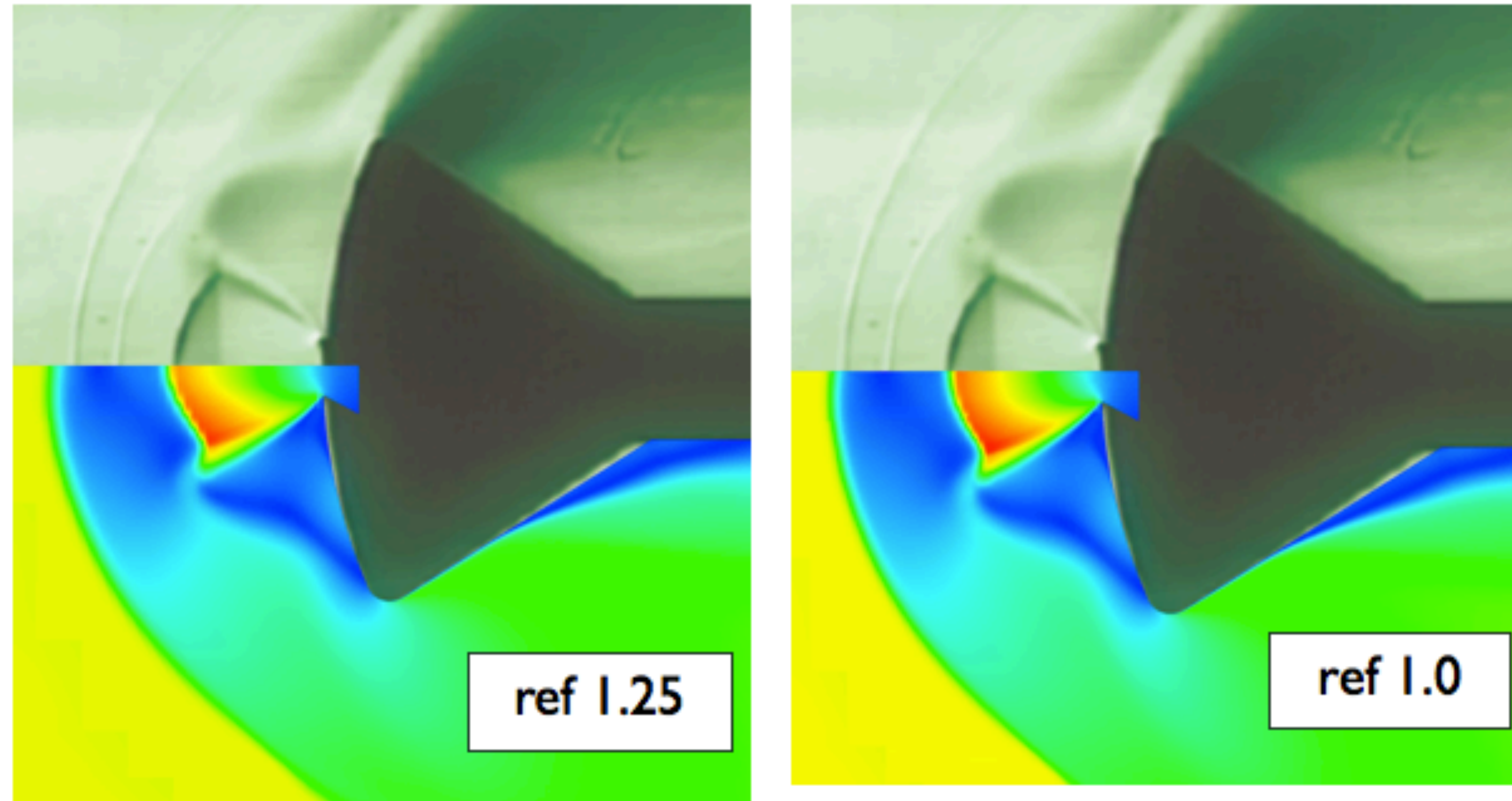
ref1.0

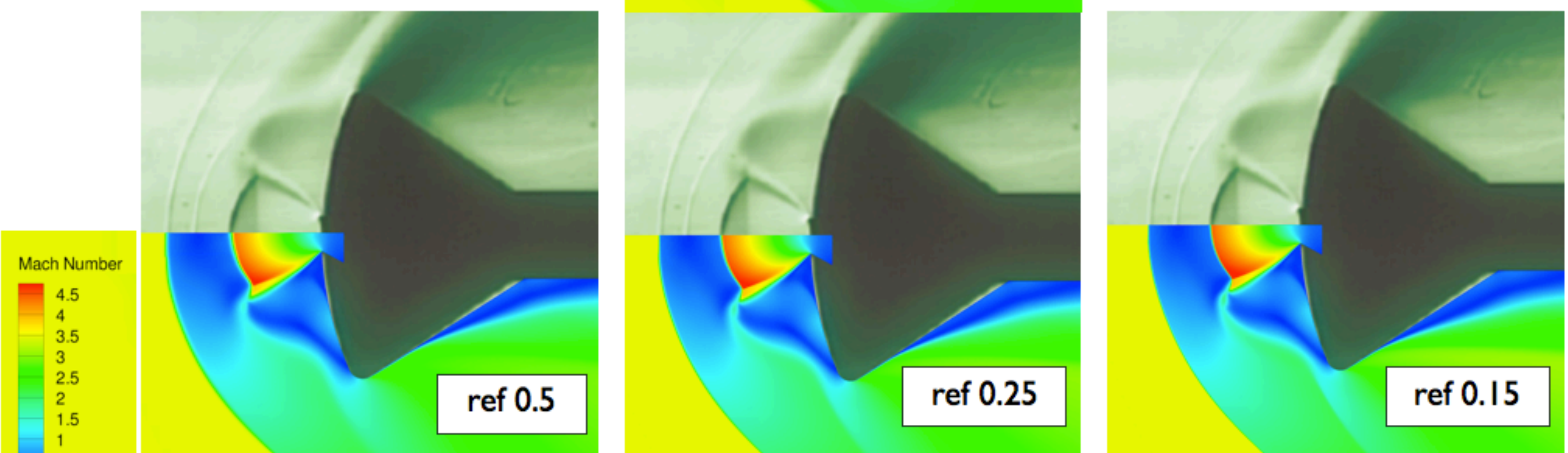


ref 0.15

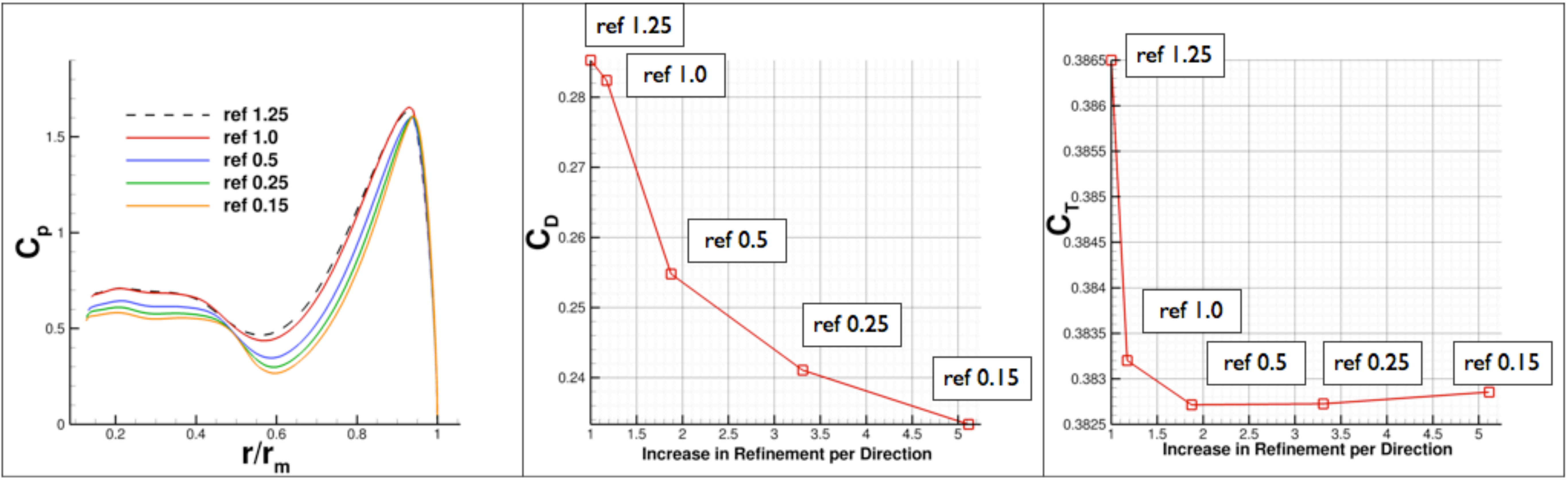
Qualitative Comparison to Schlieren

- Features sharpen as refinement increases
- Shock distance comparisons are more accurate with increased refinement
- Feature position does not change much with last three refinements
- Qualitatively, refinement level 0.5 is good enough



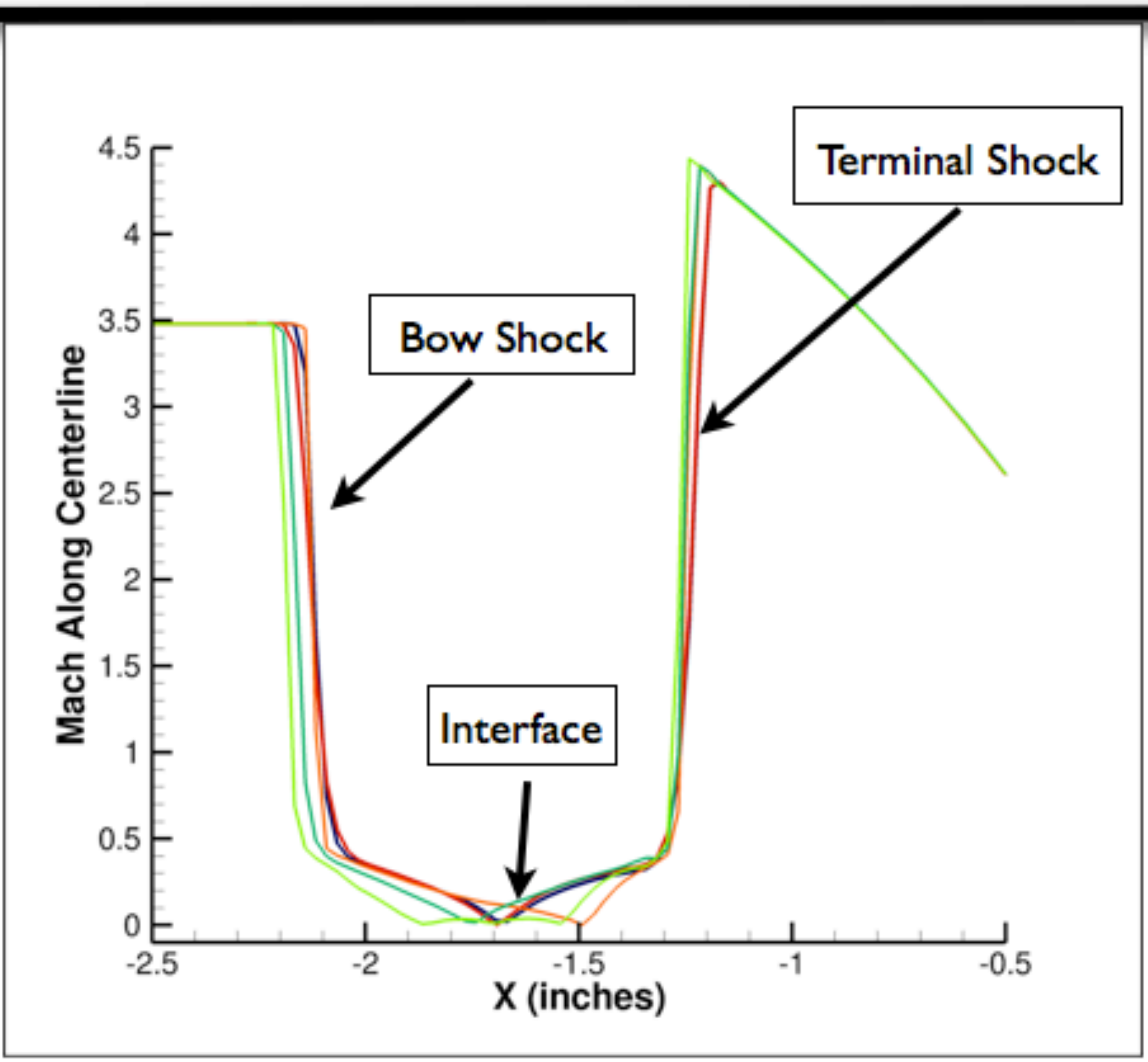


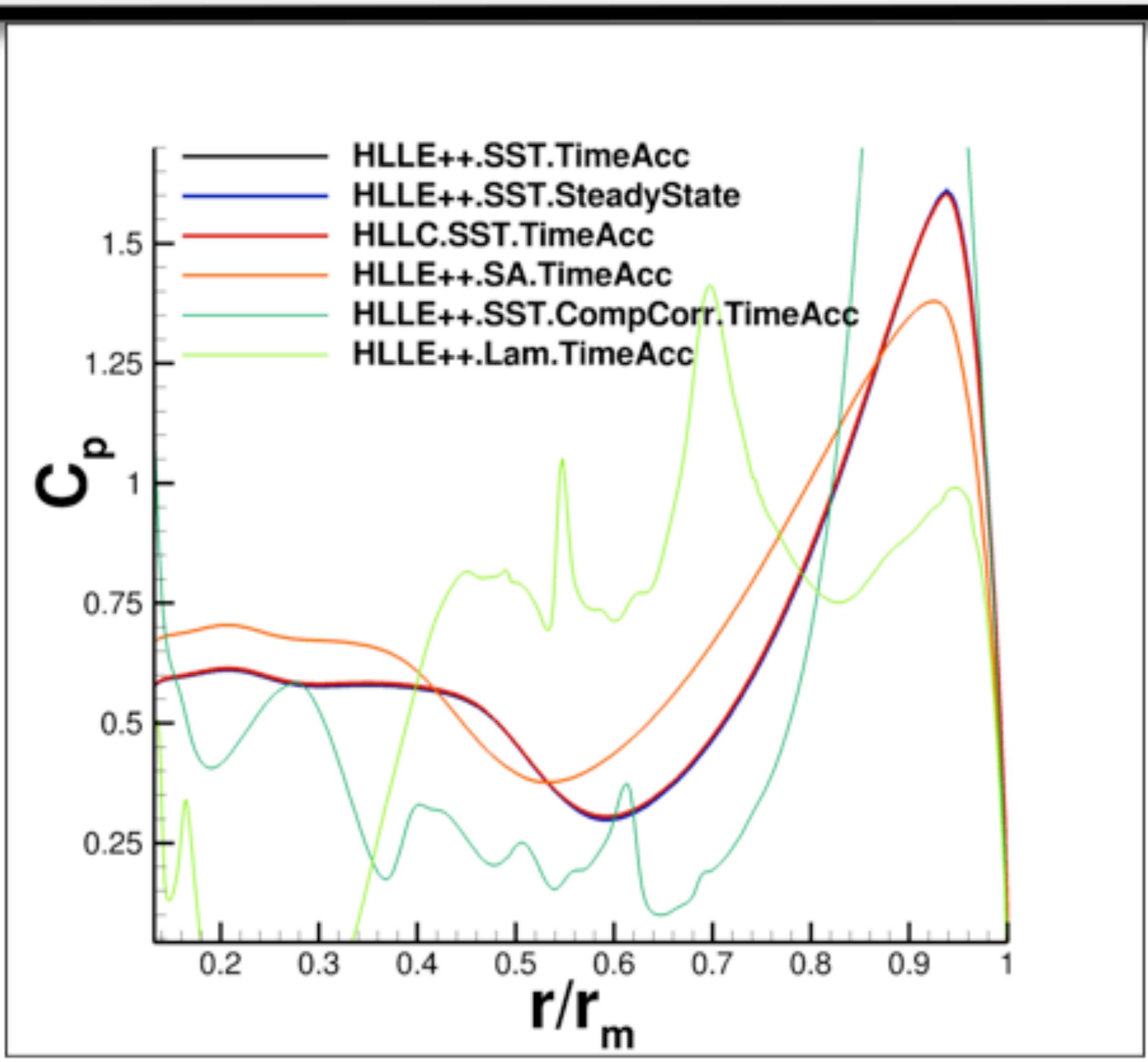
Quantitative Comparisons



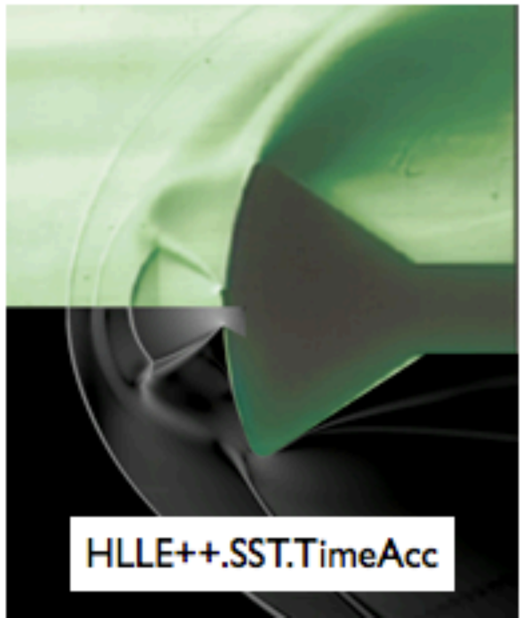
- Surface pressure coefficient on the capsule frontal area
  - Large gap between refinement levels 1.0 and 0.5
  - Gap decreases with finer levels
  - Locations of local min/max appear to be converging
- 3% change in drag coefficient between refinement levels 0.25 and 0.15
- Negligible change in thrust coefficient after refinement level 0.5
- Quantitatively, refinement level 0.15 is best, 0.25 is probably good enough

Daso Numerical Method Sensitivity (ref 0.25)

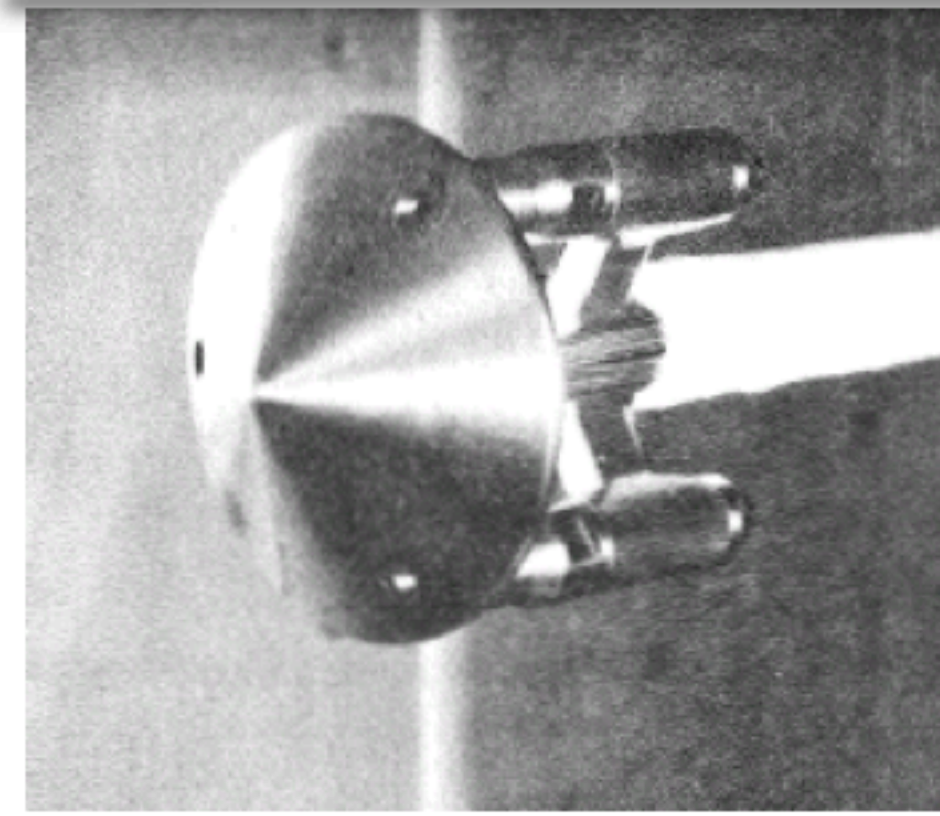




- All SST results (not using compressibility correction) are very similar
  - Correctly predict locations of the terminal shock, interface, and bow shock
- Spalart-Allmaras results differ from SST results
  - Interface standoff distance
  - Pressure coefficient in recirculation area and near shoulder
- SST with compressibility correction and laminar cases are both unsteady
- SST without compressibility correction best choice



Jarvinen and Adams Triple Nozzle



- Three radially aligned nozzles 120 degrees apart
- Modeled geometry behind the aeroshell as a solid piece
- Thrust coefficients of 0, 1, 4, and 7
- Freestream Mach number of 2.0

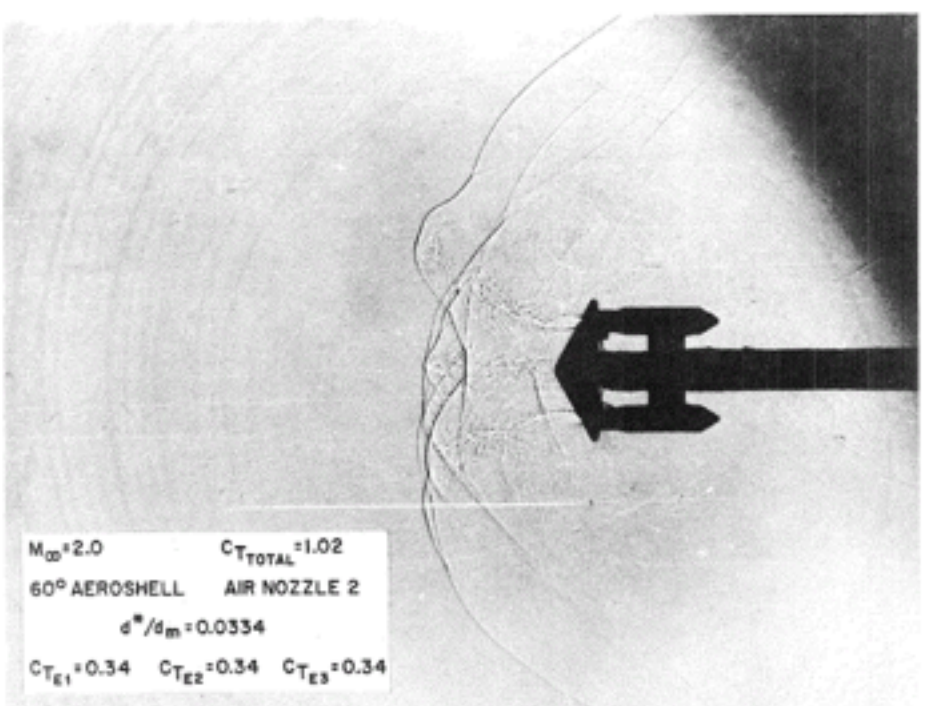
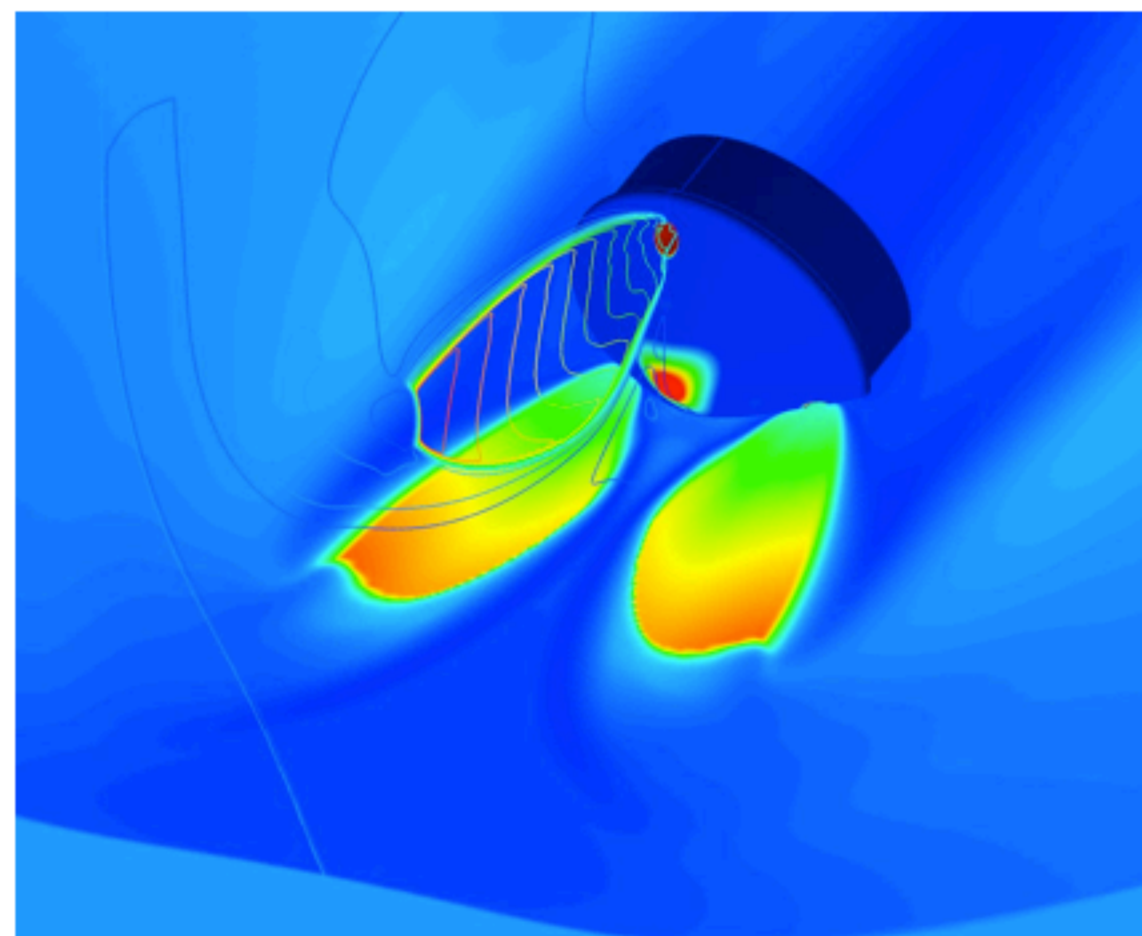
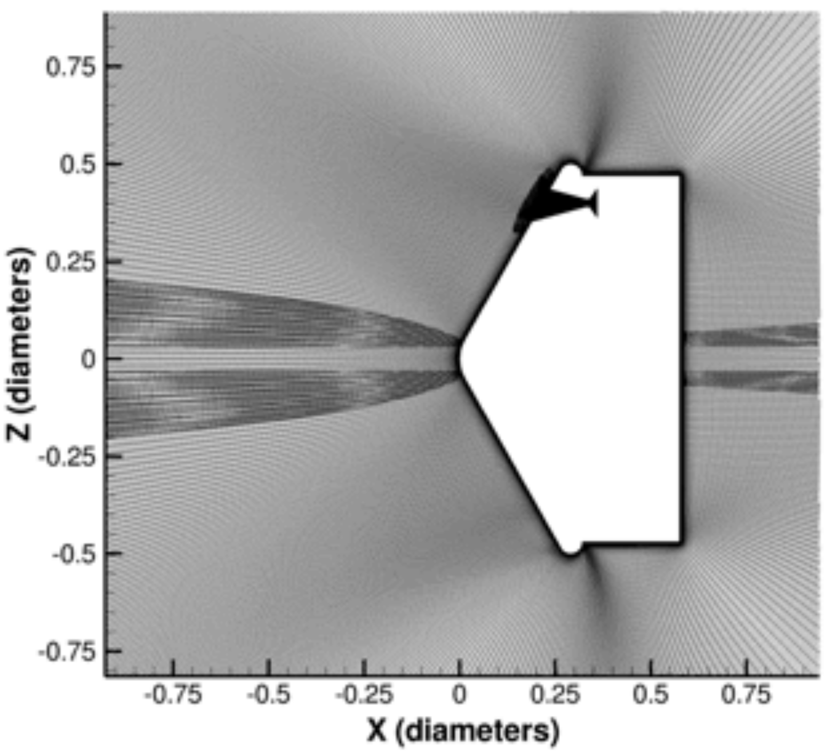


Figure 49 Three Engine 60° Aeroshell Flow Field $M_{\infty} = 2.0$, $C_{T_{TOTAL}} = 1.02$, $\phi = 30°$.

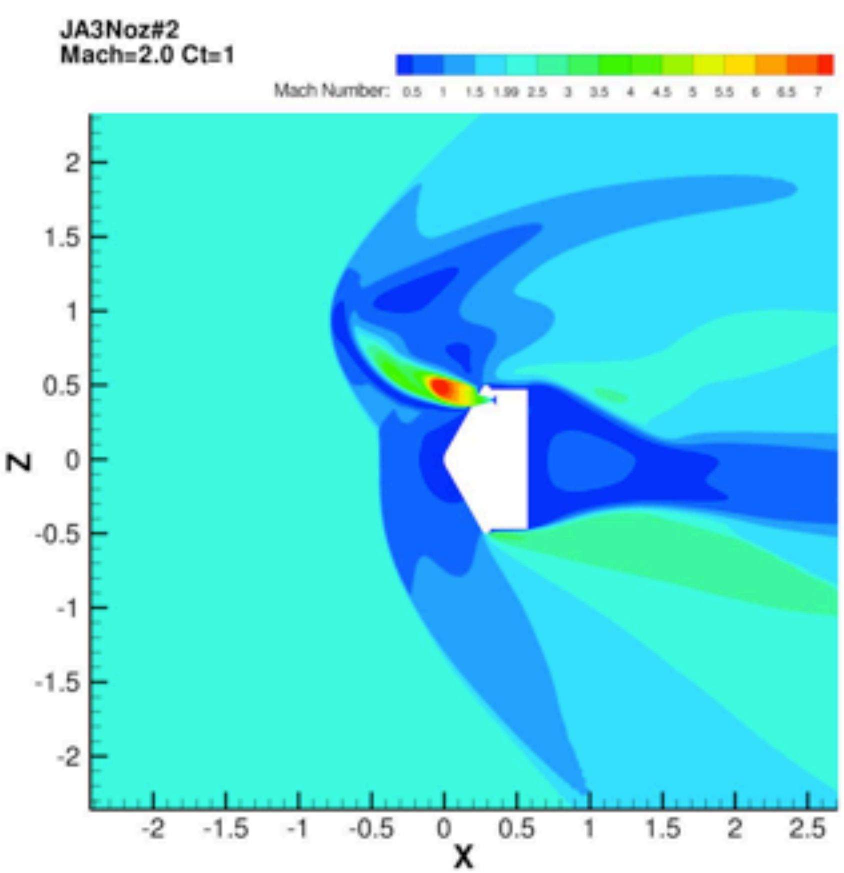


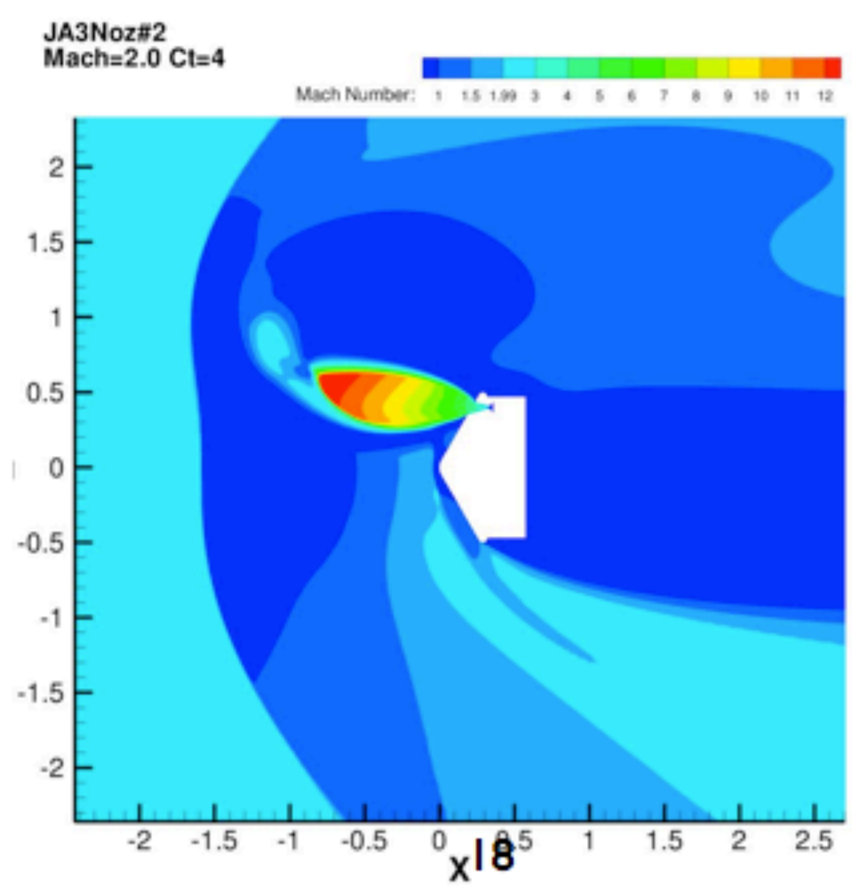
Jarvinen and Adams Triple Nozzle, Mach 2.0, C_T 7

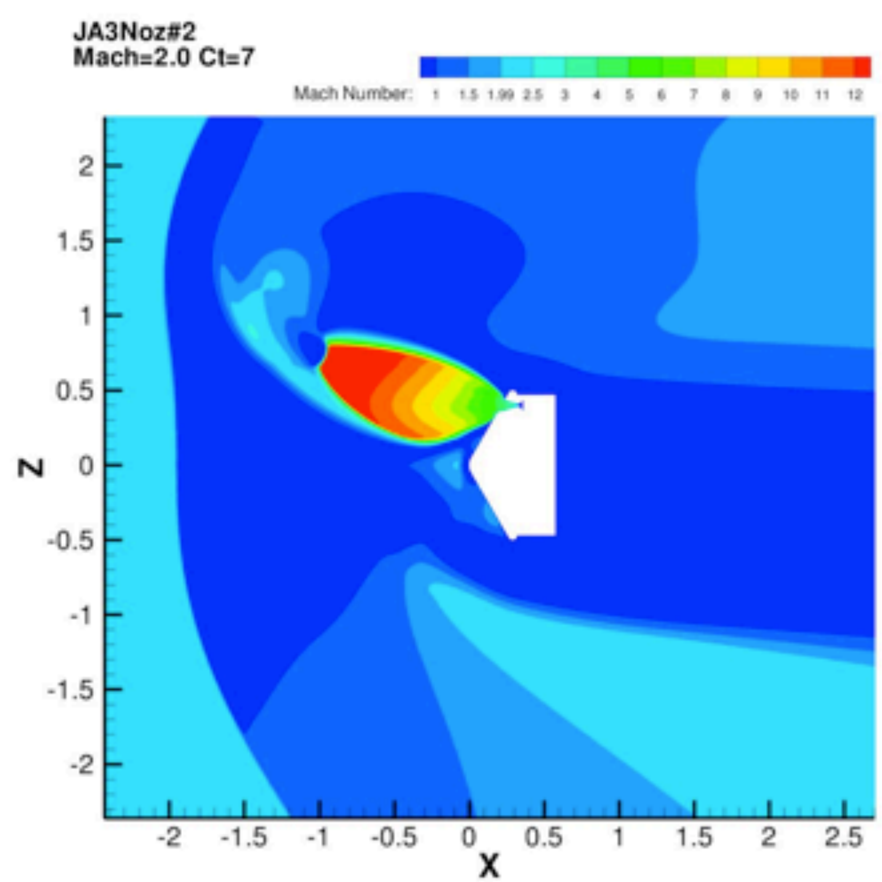
Problem Setup



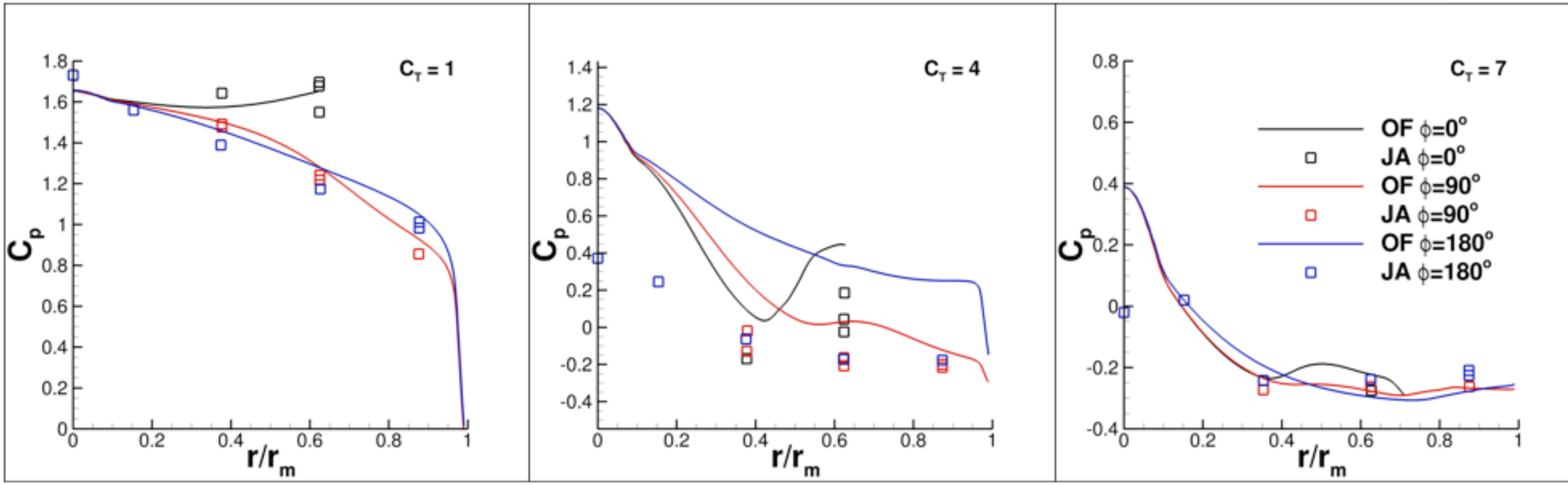
- Used a curvilinear refined mesh for plume region
- Plenum Boundary Condition
  - BC41- specify total pressure and temperature was unstable for this configuration
  - Adopted use of BC43 and BC31- prescribed Q variables coupled with characteristic condition based on Reimann invariants
  - Started subsonic plenum region at the converging section of nozzle to encourage acceleration towards the nozzle exit



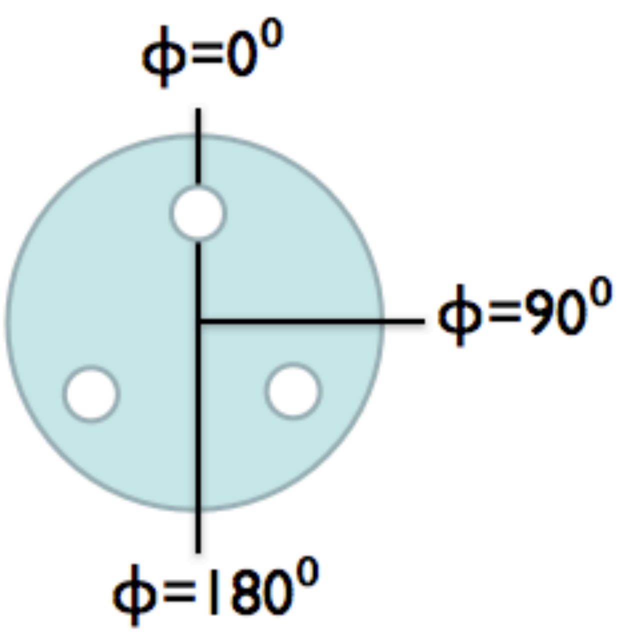




Jarvinen and Adams Triple Nozzle Results



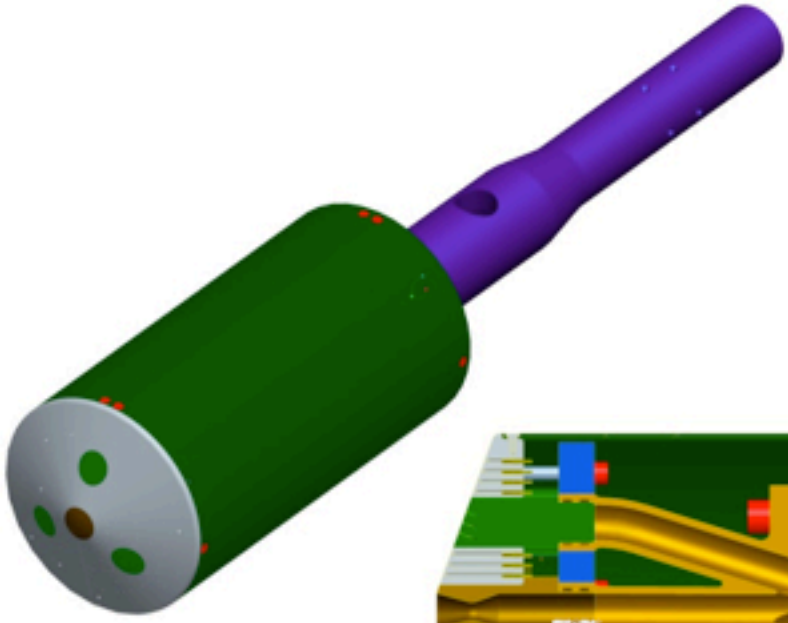
Model Front Face

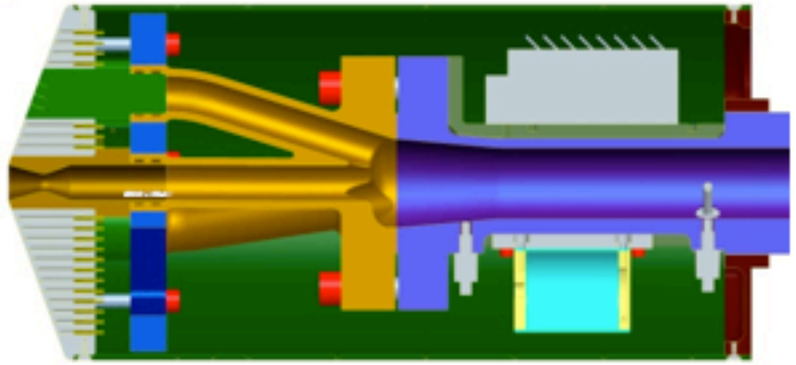


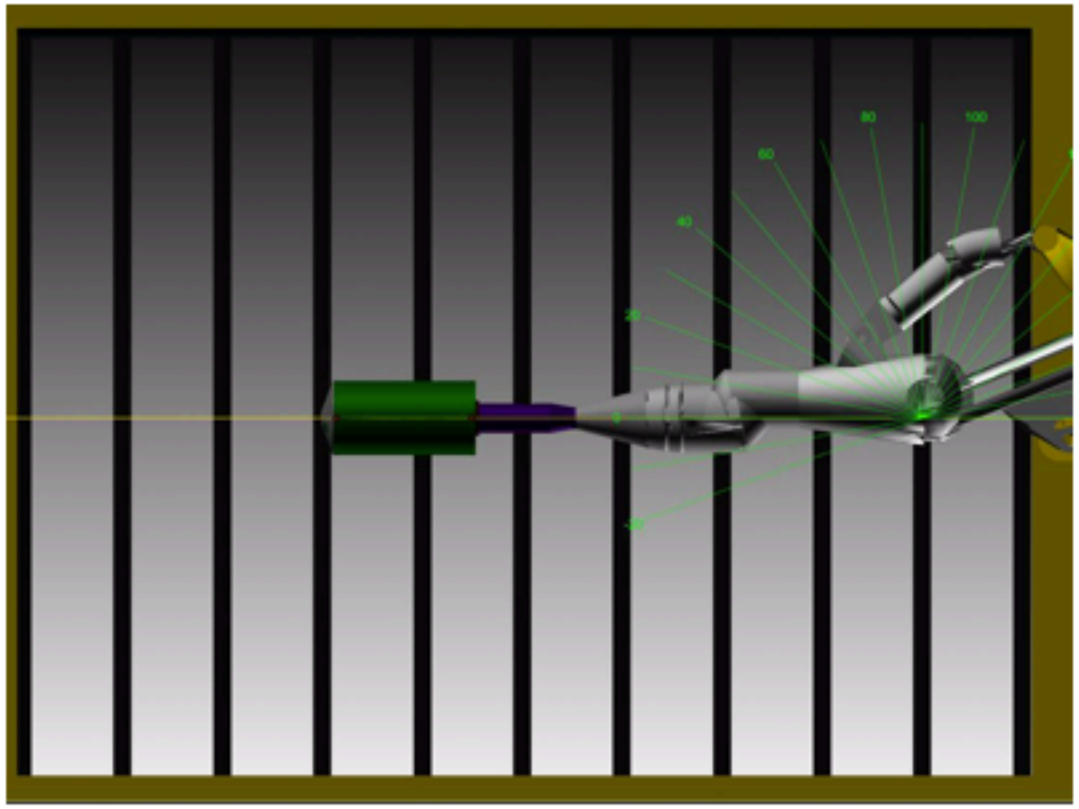
- Reasonable agreement for Ct=1
- Not very good agreement for Ct=4
- Okay agreement except at the nose for Ct=7
- For all three thrust coefficients, code-to-code comparison was much better than code-to-test comparison

Langley UPWT Pre-Test

- Tunnel test designed for CFD validation
- Used CFD to predict effects of model diameter
  - Wall effects
  - Possible blockage
  - Tunnel un-starts
- CFD Run conditions
  - Mach numbers of 2.4, 3.5, and 4.6
  - Thrust coefficient range up to 10
  - Angle of attack sweeps up to10 degrees
  - 0, 1, 3, and 4 nozzles
- Experiment completed July 31, 2010



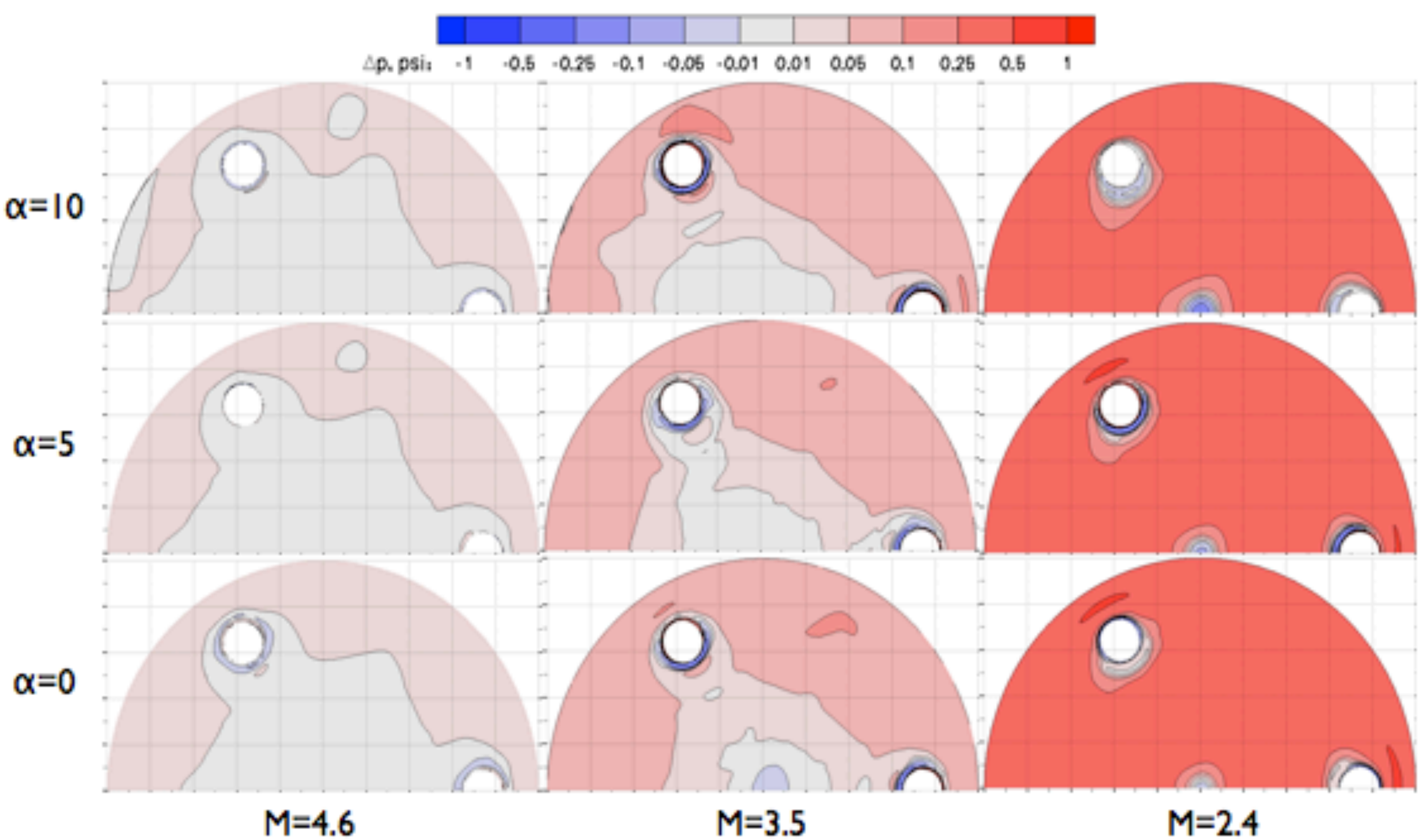


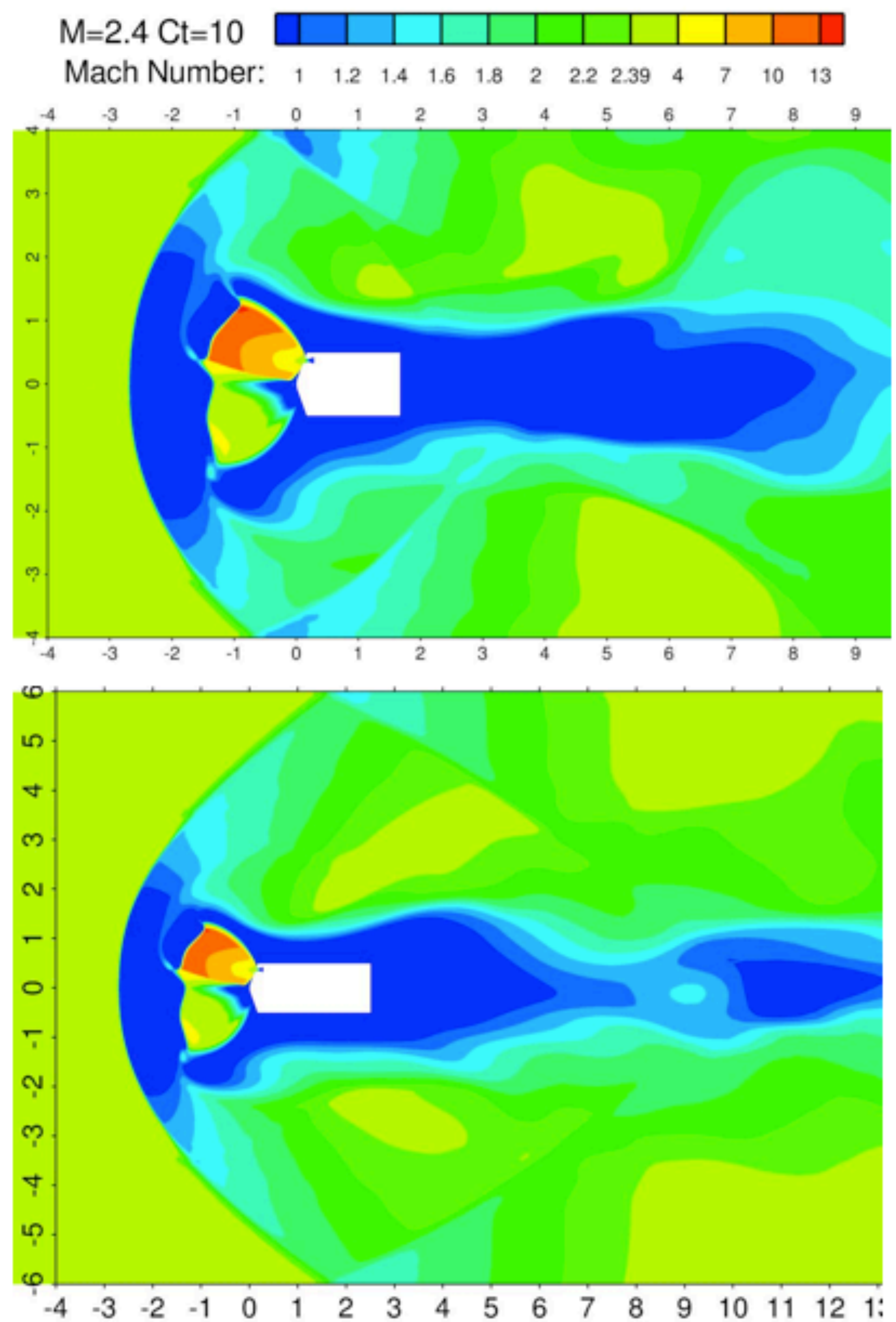


Pre-Test Results on Model Diameter

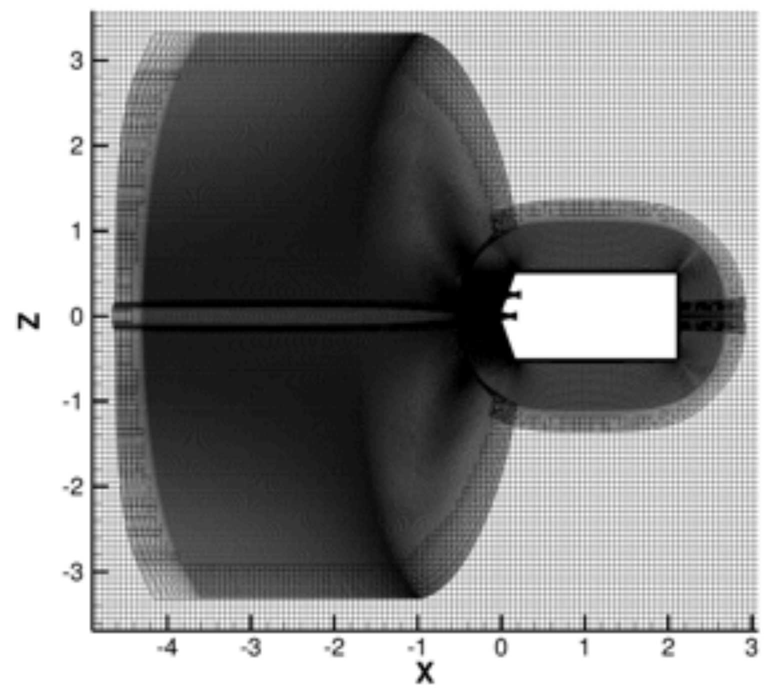
- Modeling Assumptions
  - No attach hardware
  - Inviscid tunnel walls
  - Symmetric test section
- Ran simulations of 4 and 6 inch model diameters
  - Saw notable wall effects for 6 inch diameter
  - 4 inch diameter too small for instrumentation
  - Selected 5 inch model diameter

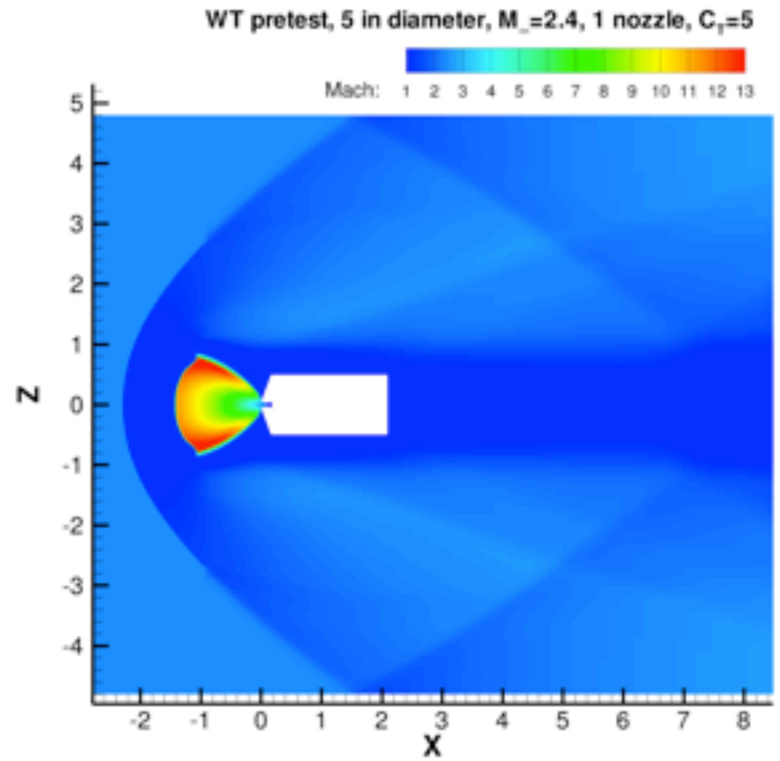
FUN3D (Bil Kleb, NASA LaRC) simulations for 6-inch diameter for C_T=10.

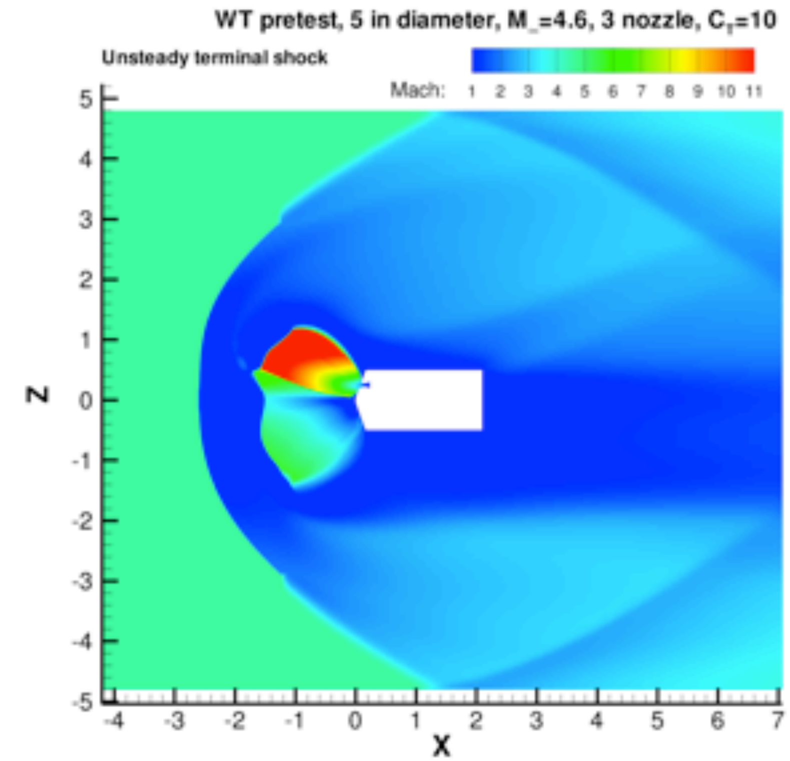


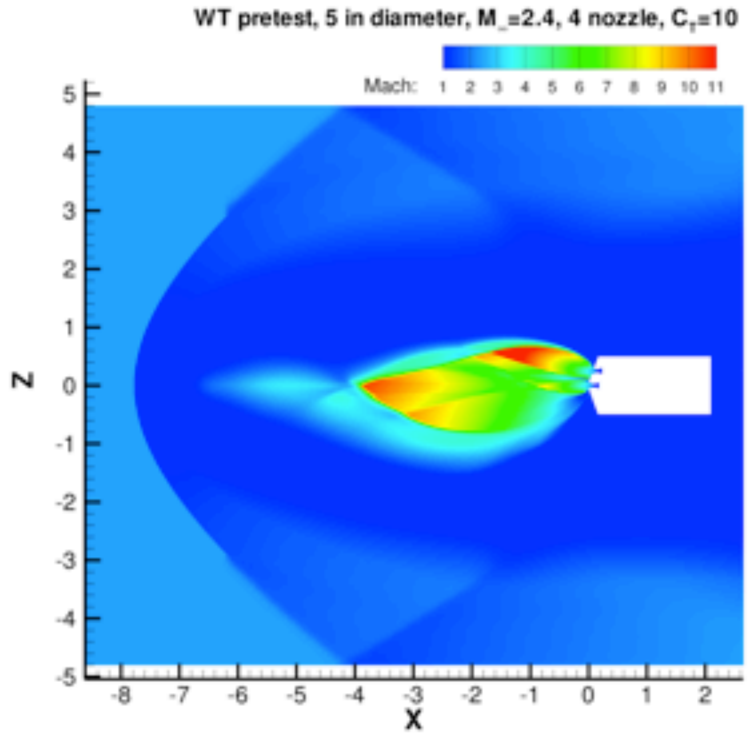


5 inch Pre-test Results



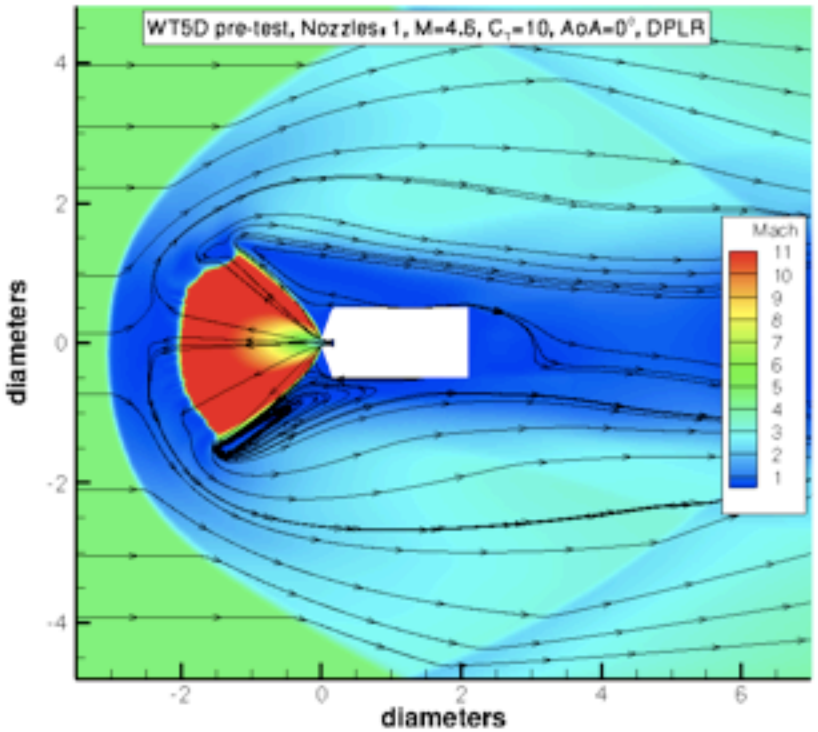


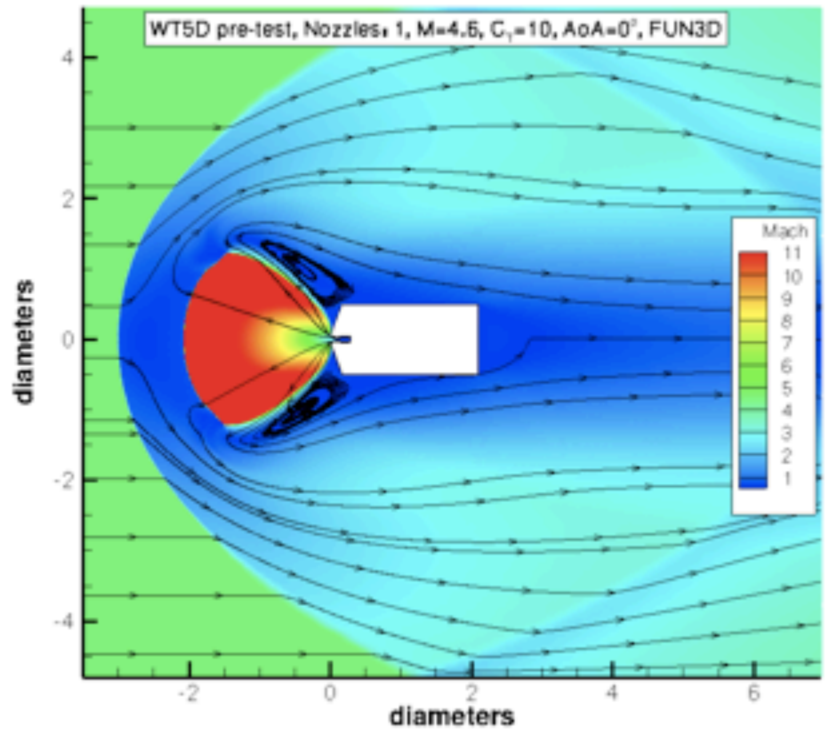


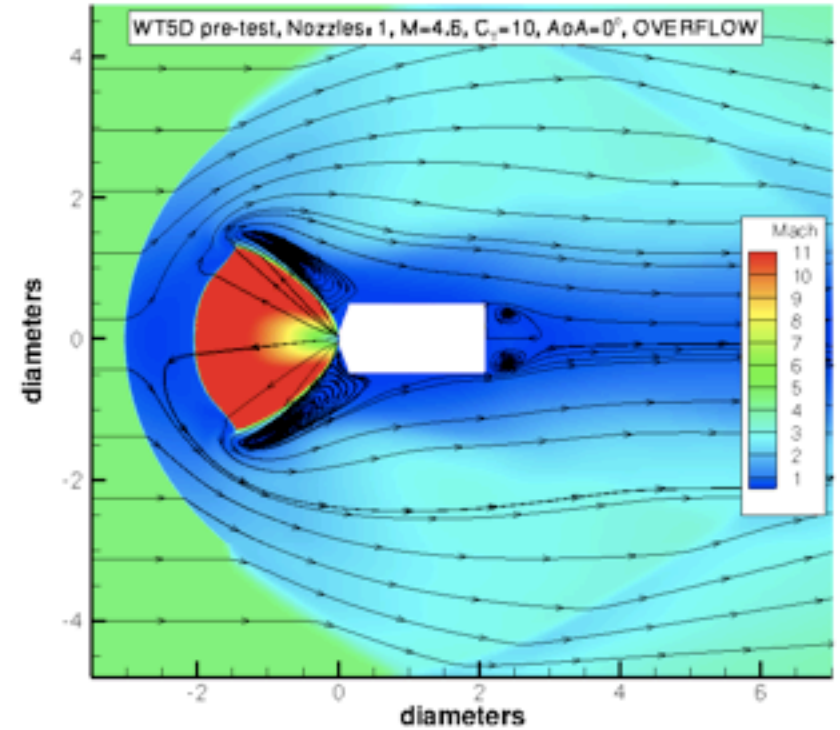


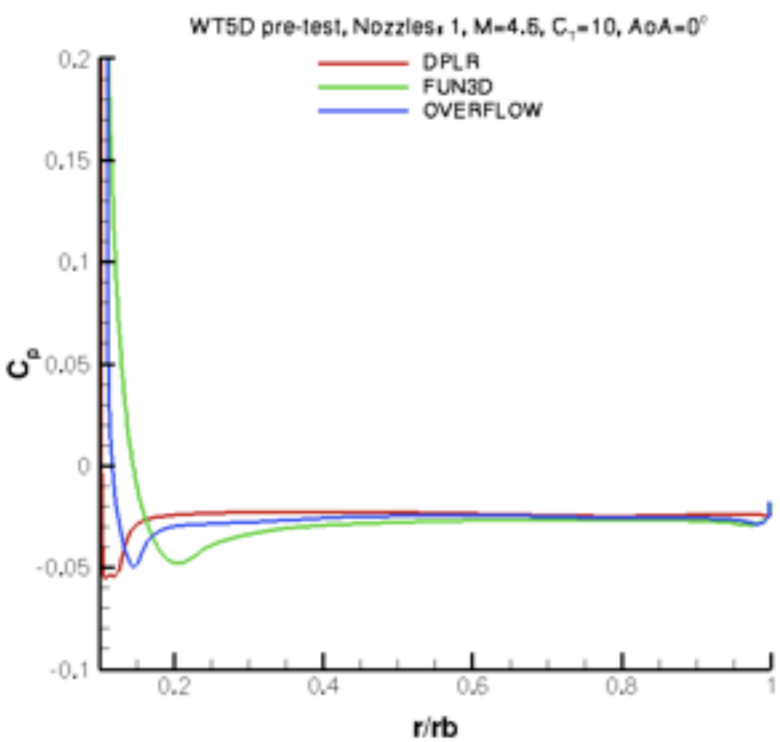
- Grid
  - One focused plume grid for all nozzle configurations
  - Overlap between plume and background grids cause blip in the bow shock
    - Ran a refined background case and saw minimal change in bow shock reflection location and model surface pressure
- Solutions
  - Ran a series of cases representative of the test run matrix
  - Results used for real-time test-to-code comparisons
  - Preliminary comparisons to tunnel test results are promising

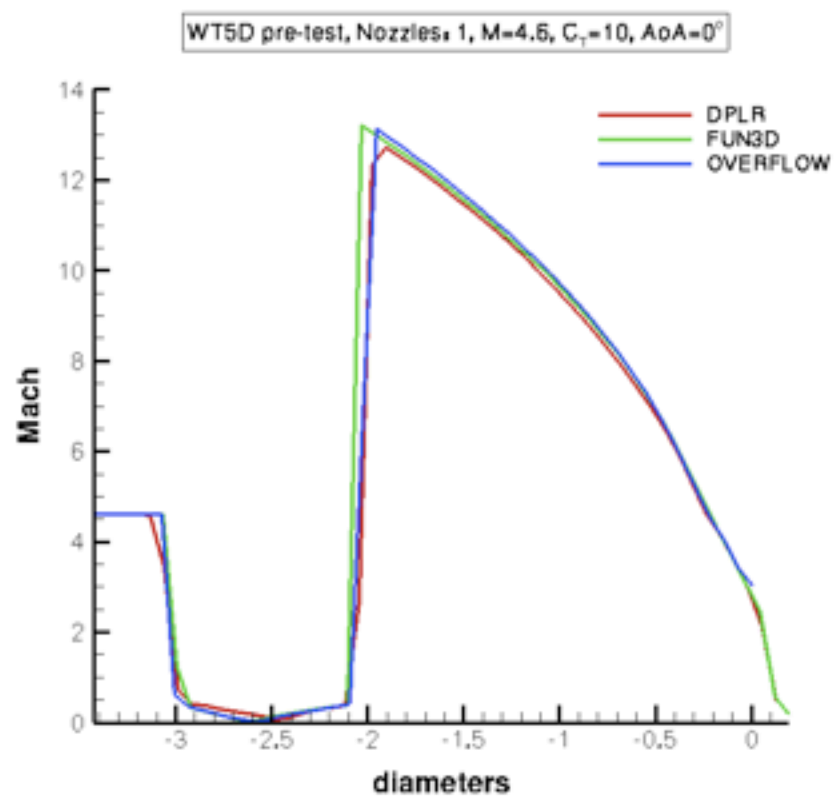
Pre-test Code-to-Code Comparison







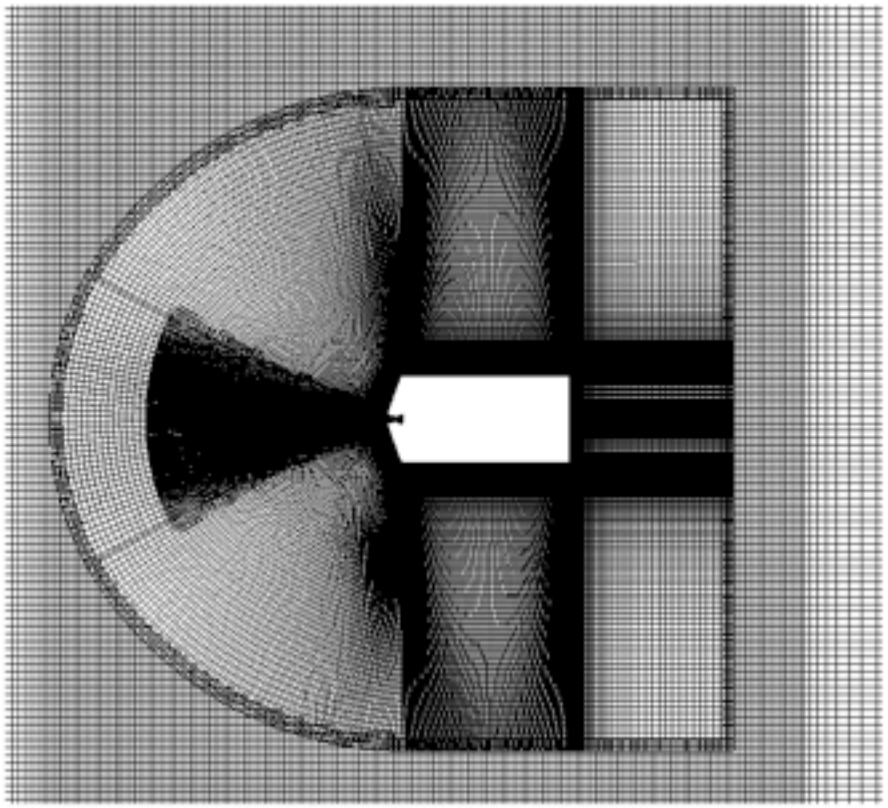


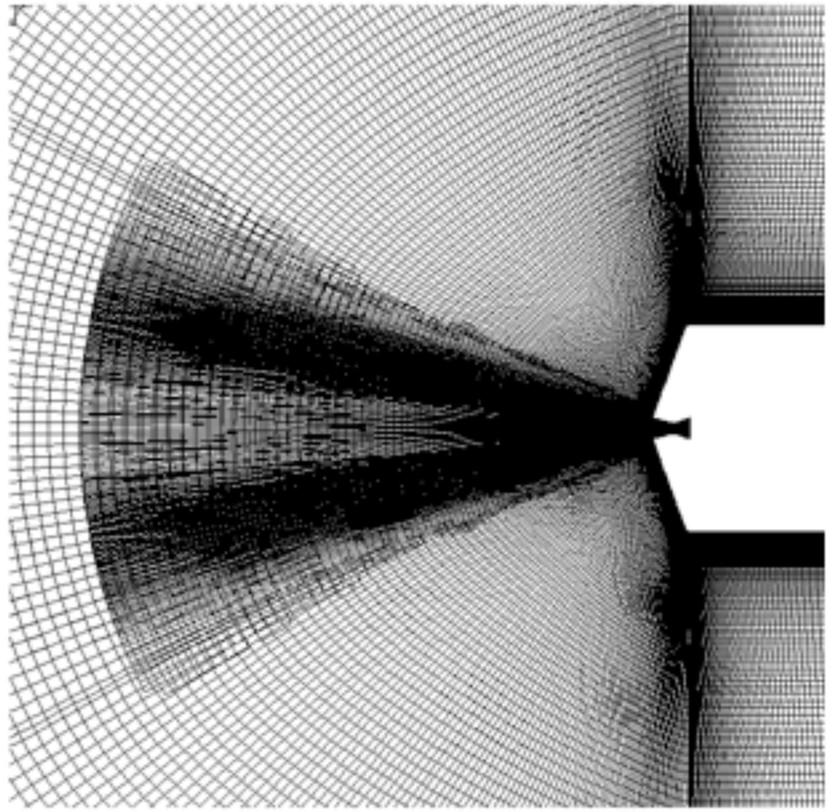


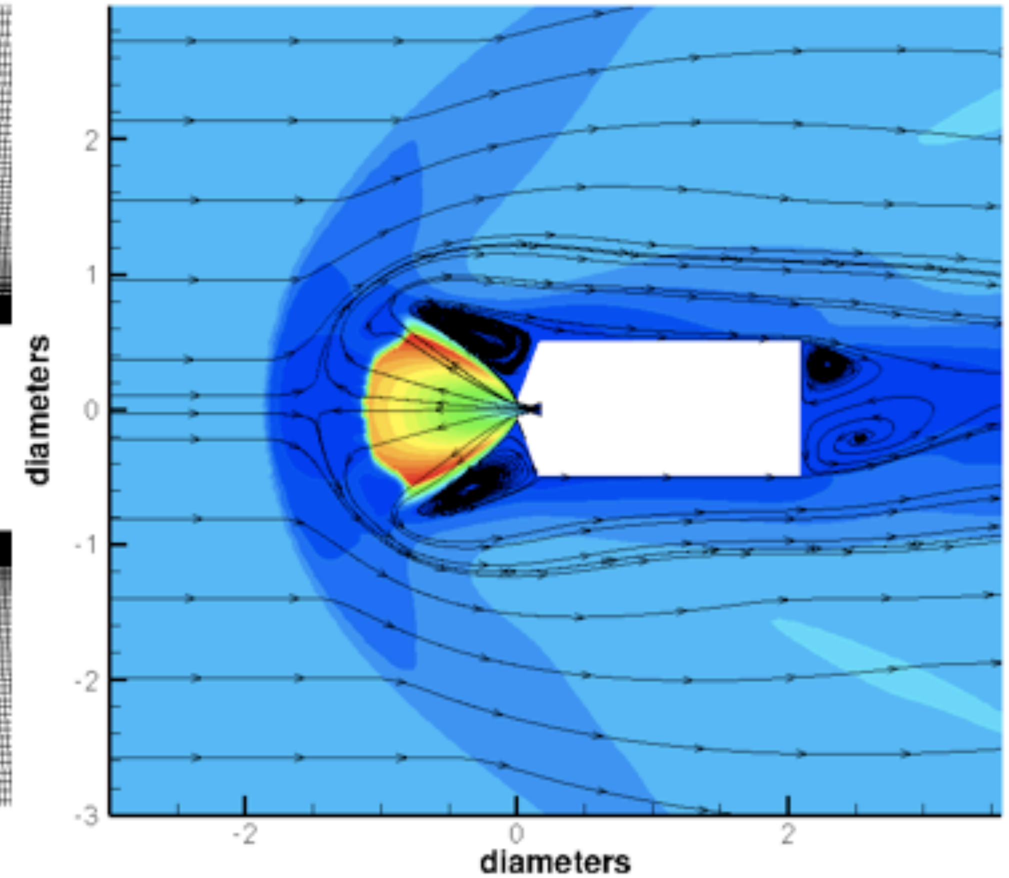
- Good agreement for this case
- Not all cases agree this well

- Overset DPLR used for this case (see next slide)

Overset DPLR



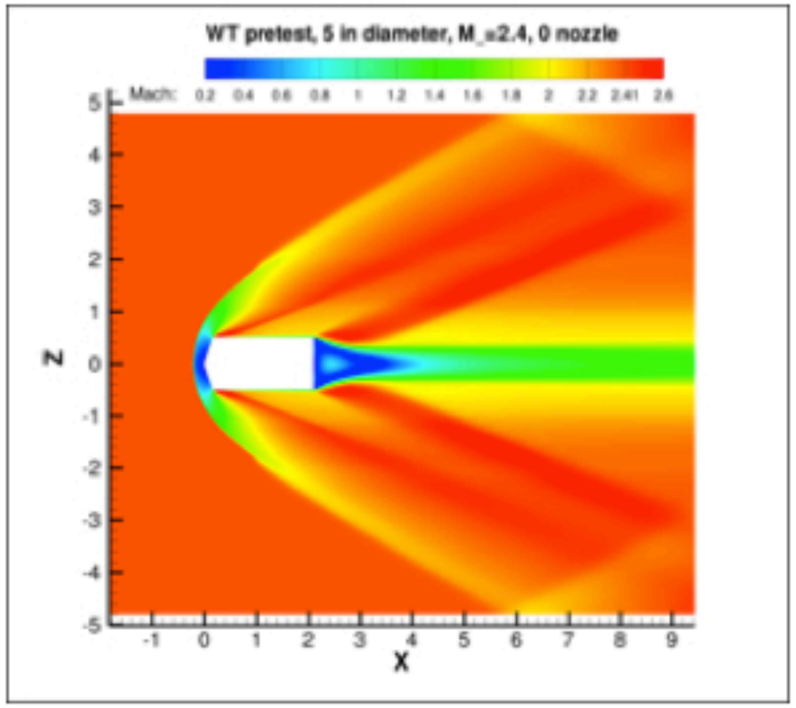


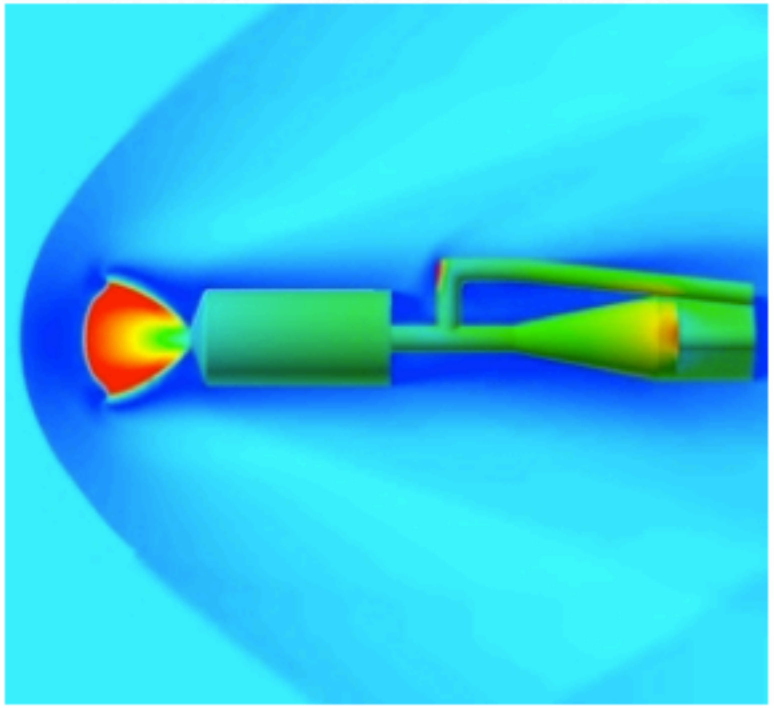
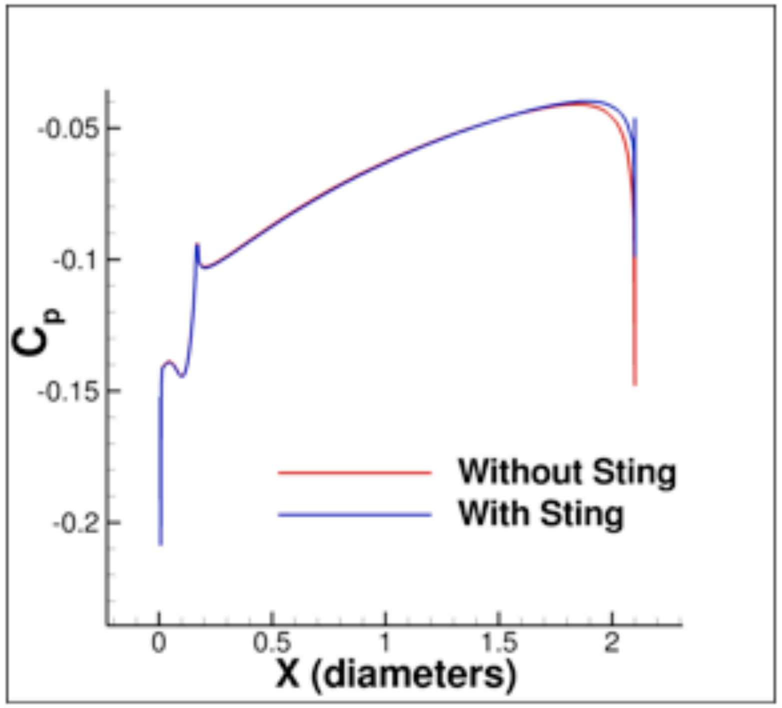


- This work is from Kerry Trumble (NASA ARC)
- Point-matched grids are limiting for these geometries
- Made overset grid with Gridgen
- Domain connectivity with Suggar
- Will be using Usurp for force and moment calculations

Current Work: Post-Test Analysis

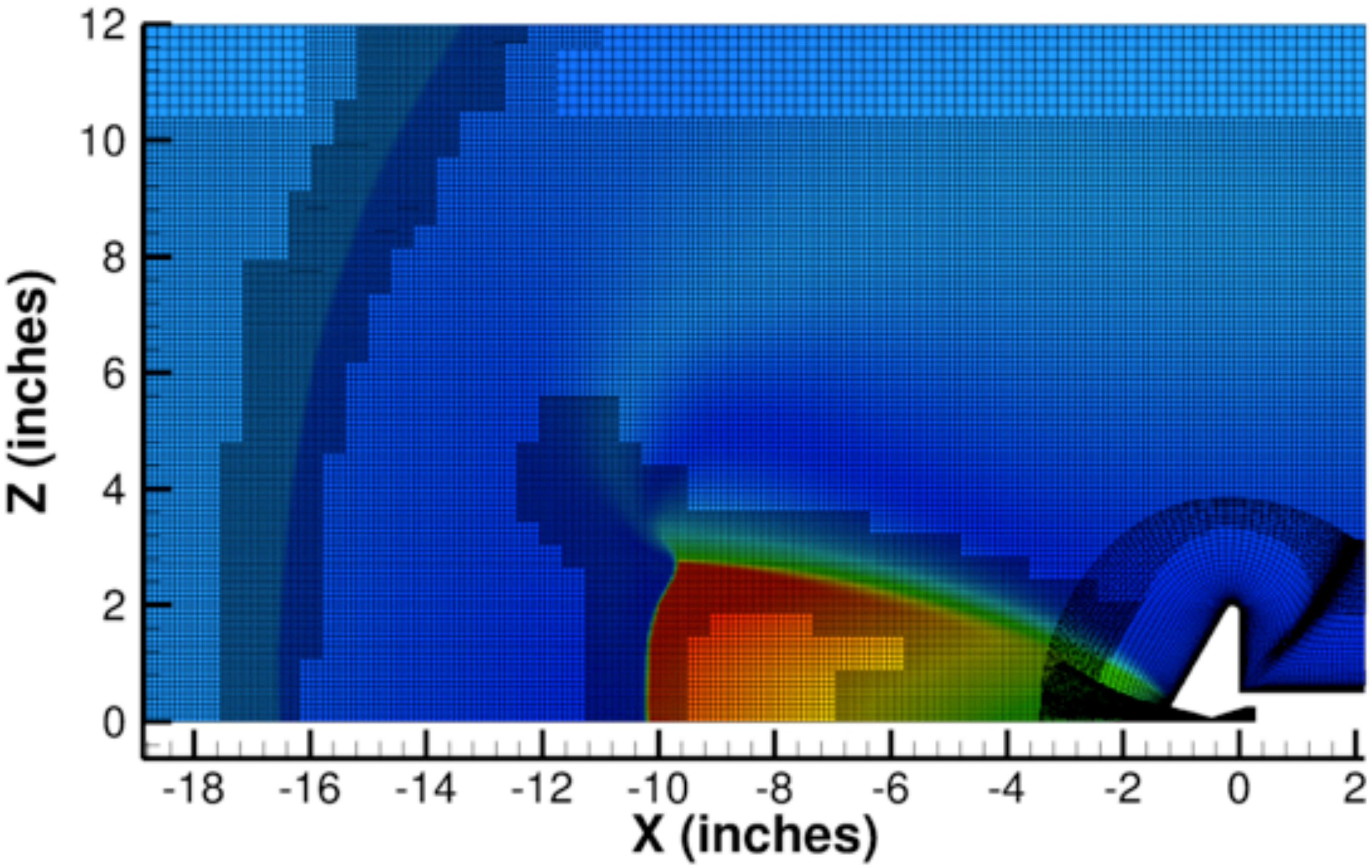


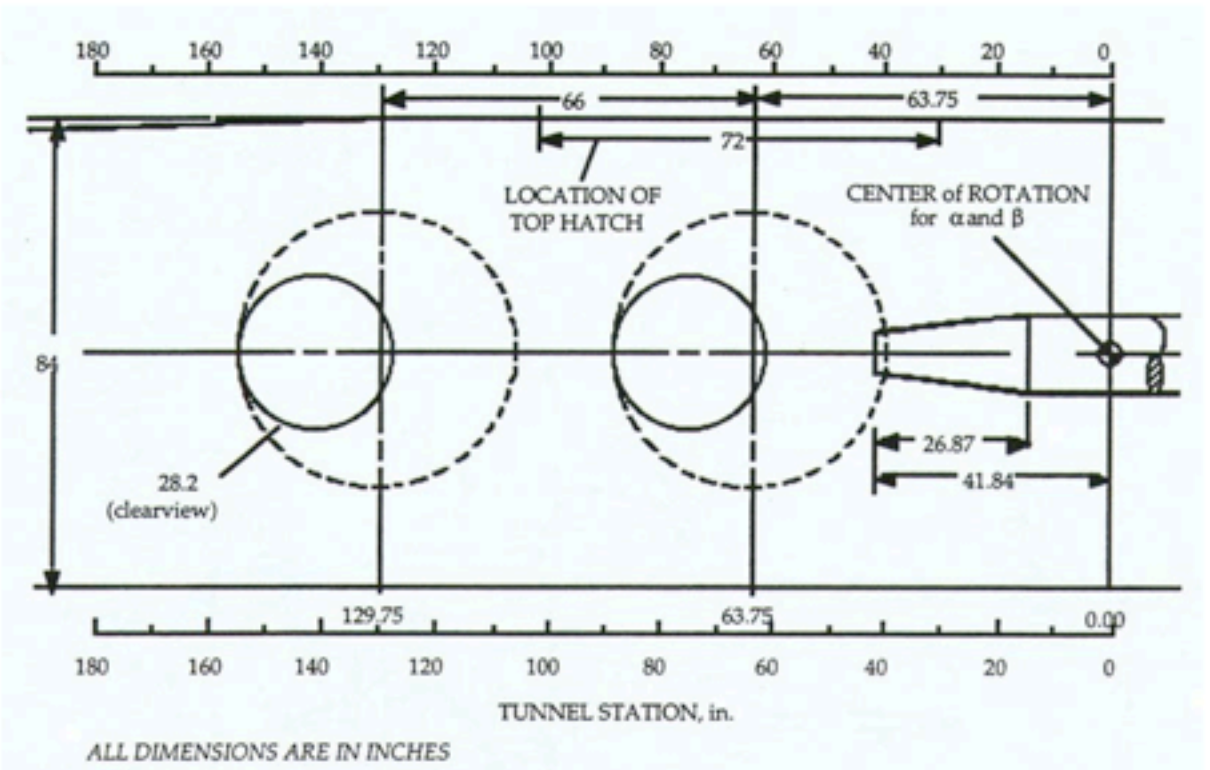



- The recent Langley UPWT test provided a lot of well defined data
- Current work for CFD team
  - Match the tunnel data
  - Explore effects of tunnel artifacts such as attach hardware and viscous tunnel walls

Future Work





9x7 Supersonic Wind Tunnel Model Installation

- OVERFLOW future work
  - More grid sensitivity study
    - Refinement, alignment
    - OVERFLOW grid adaption capabilities
  - Effects of turbulence modeling
  - Thermally vs. calorically perfect simulations
- SRP team future work
  - Use the same model from the Langley UPWT 4'x4' in the Ames 9'x7' tunnel
    - Hopefully obtain higher thrust coefficients
    - Less tunnel artifacts

Acknowledgements

ETDP EDL Project

SRP CFD and Wind Tunnel Teams

JSC Applied Aeroscience and CFD Branch

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