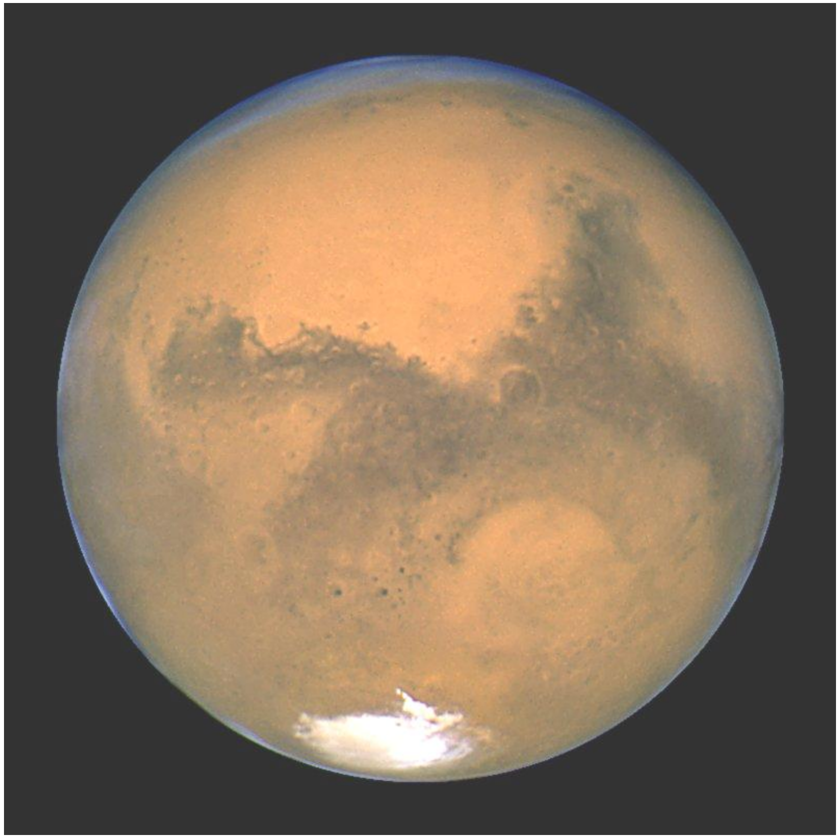
Validation of OVERFLOW for Supersonic Retropropulsion



Guy Schauerhamer
Jacobs/NASA JSC
10/2012

SRP CFD Team
Karl Edquist, Kerry Zarchi, Bil Kleb

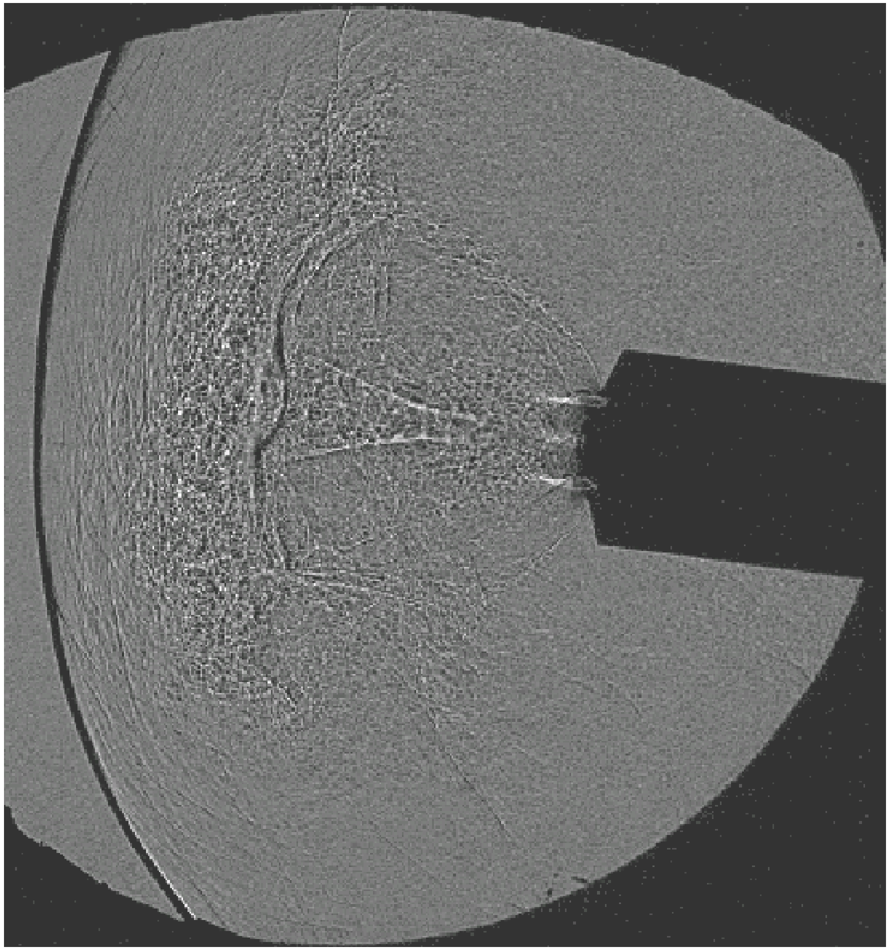
Outline

- Project Introduction
- Explanation of SRP Flow Structure
- Validation Approach
- LRC UPWT Test
- Ames UPWT Test
- Conclusions/Future Work

Introduction

The goal is to softly land high mass vehicles (10s of metric tons) on Mars

- Supersonic Retropropulsion (SRP) is a potential method of deceleration
- Current method of supersonic parachutes does not scale well past ~1 metric ton
- CFD is of increasing importance since flight and experimental data at these conditions is difficult to obtain
- CFD must first be validated at these conditions



Introduction

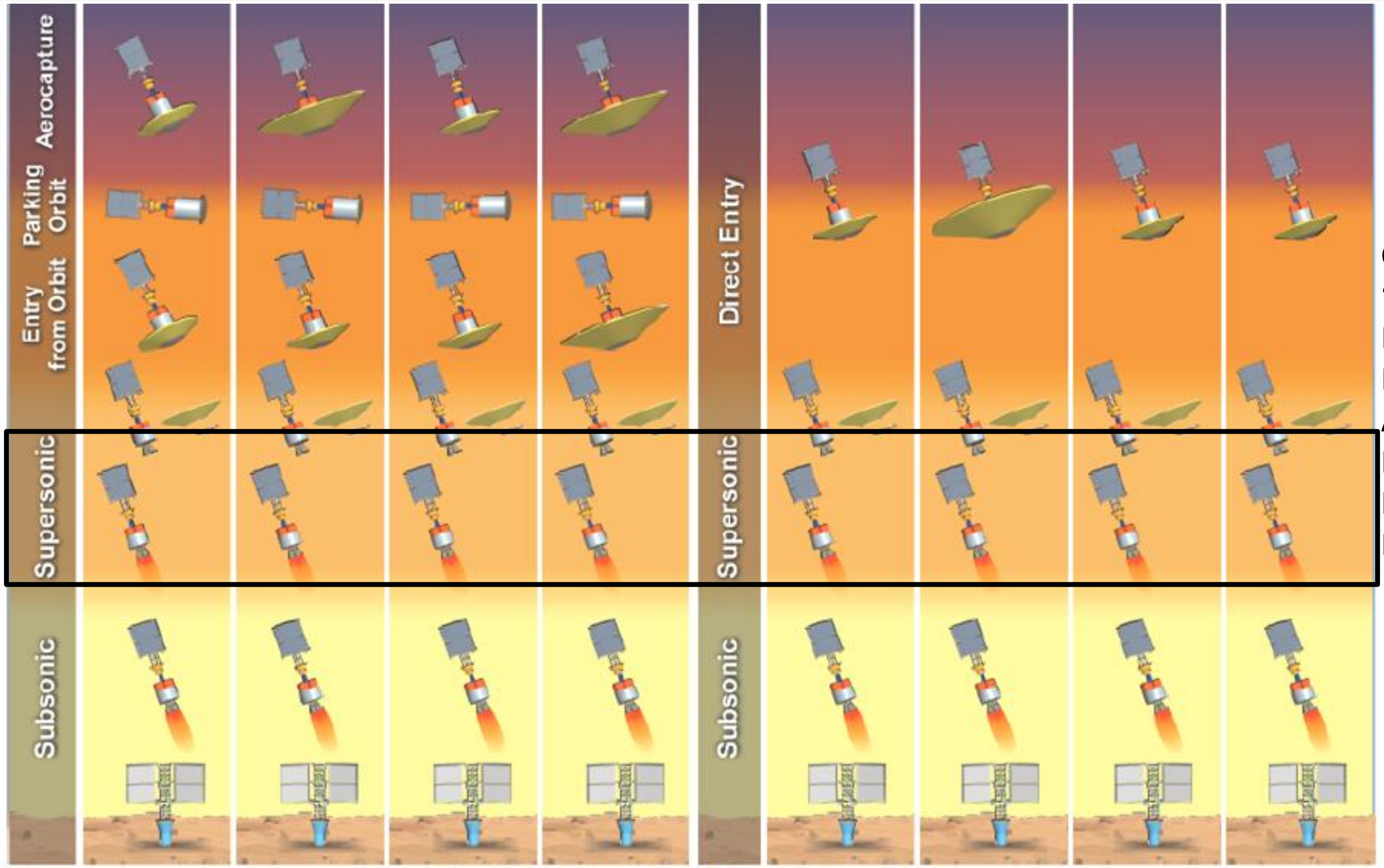
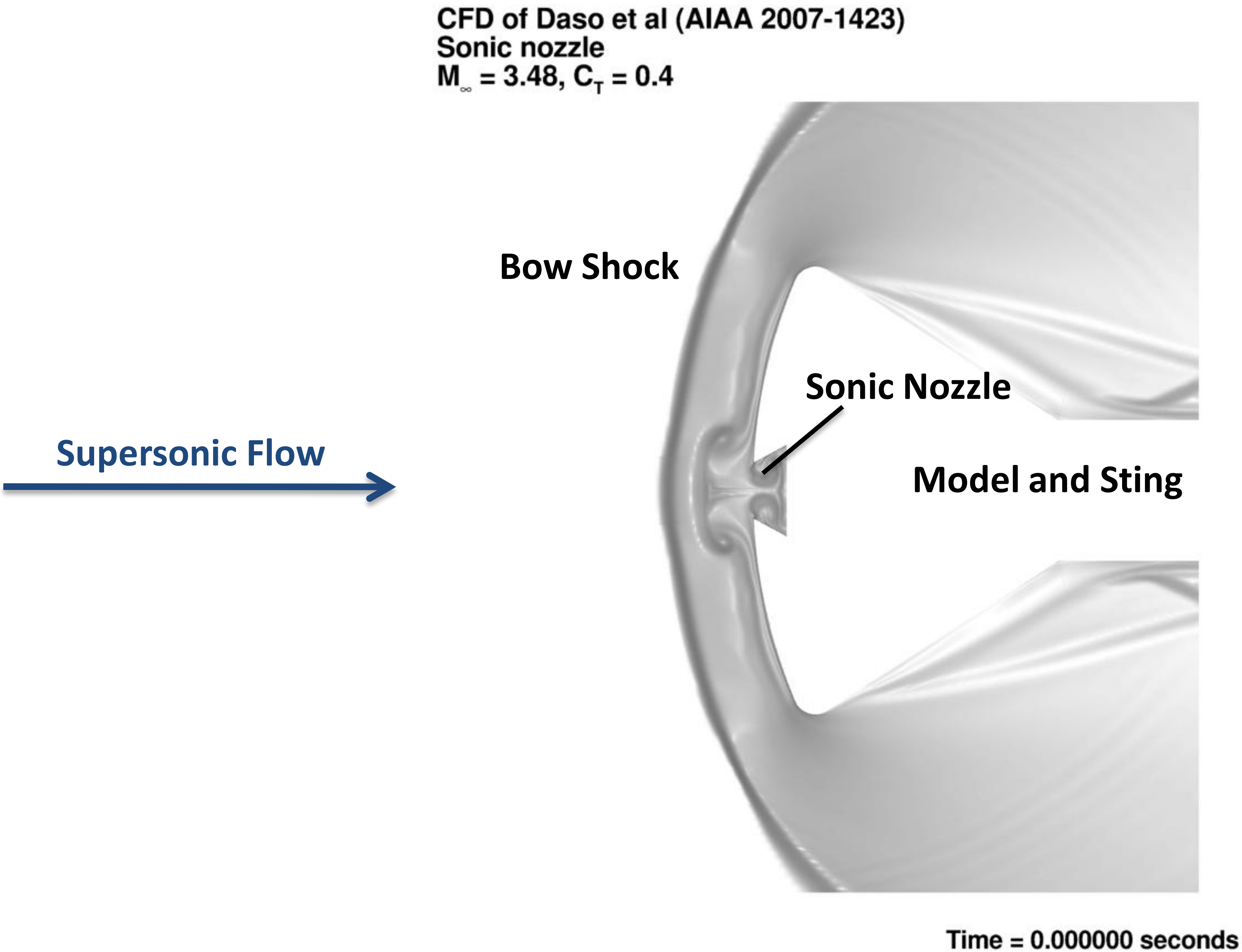


Fig. 3. Exploration Feed Forward Concepts

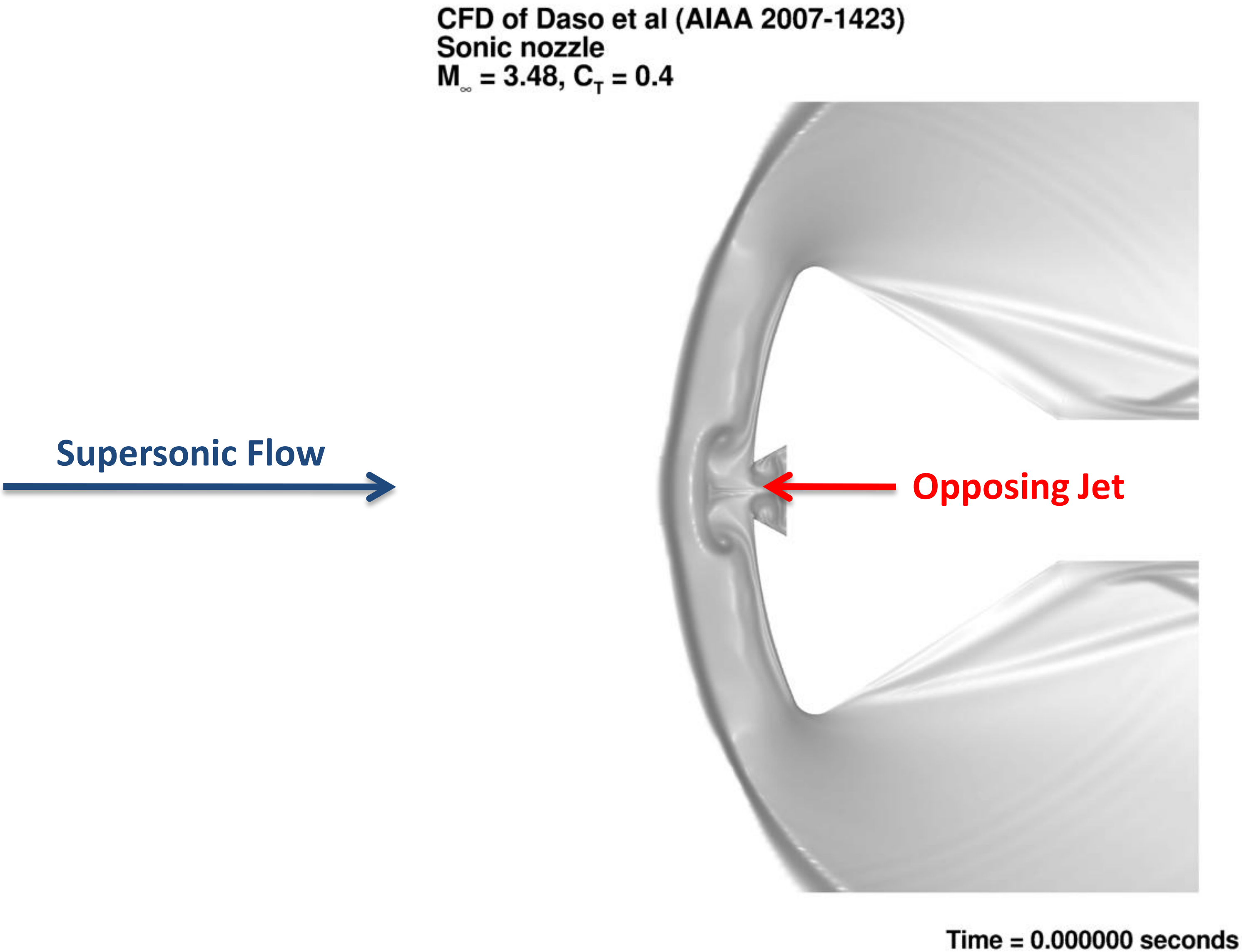
Cianciolo, A. D., et al, "Overview Of The NASA Entry, Descent and Landing Systems Analysis Exploration Feed-Forward Study," International Planetary Probe Workshop, 2011.

- The EDL SA Team identified SRP as the only credible method of supersonic deceleration for Exploration Class (100 metric tons) vehicles entering Mars

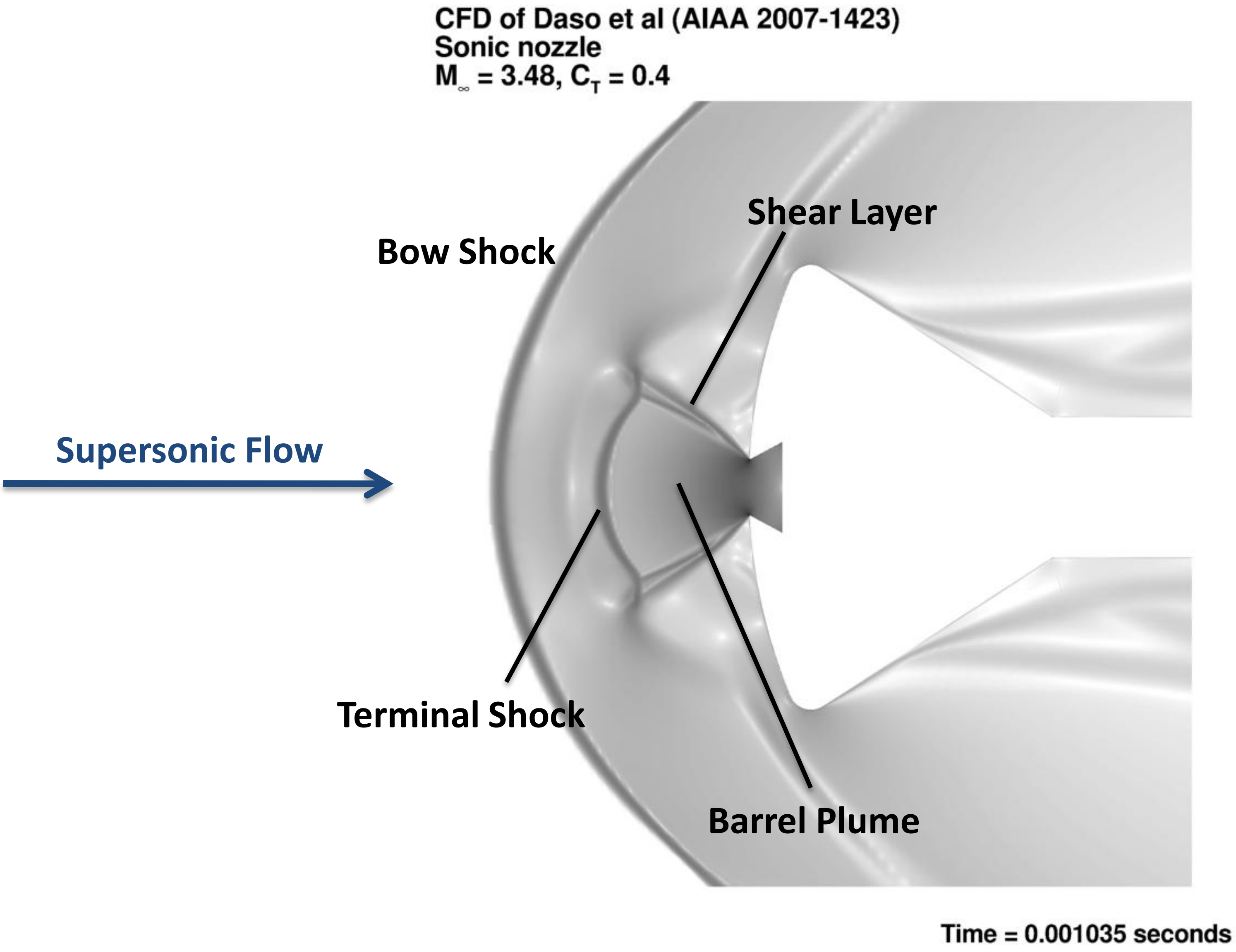
SRP Flow Structure



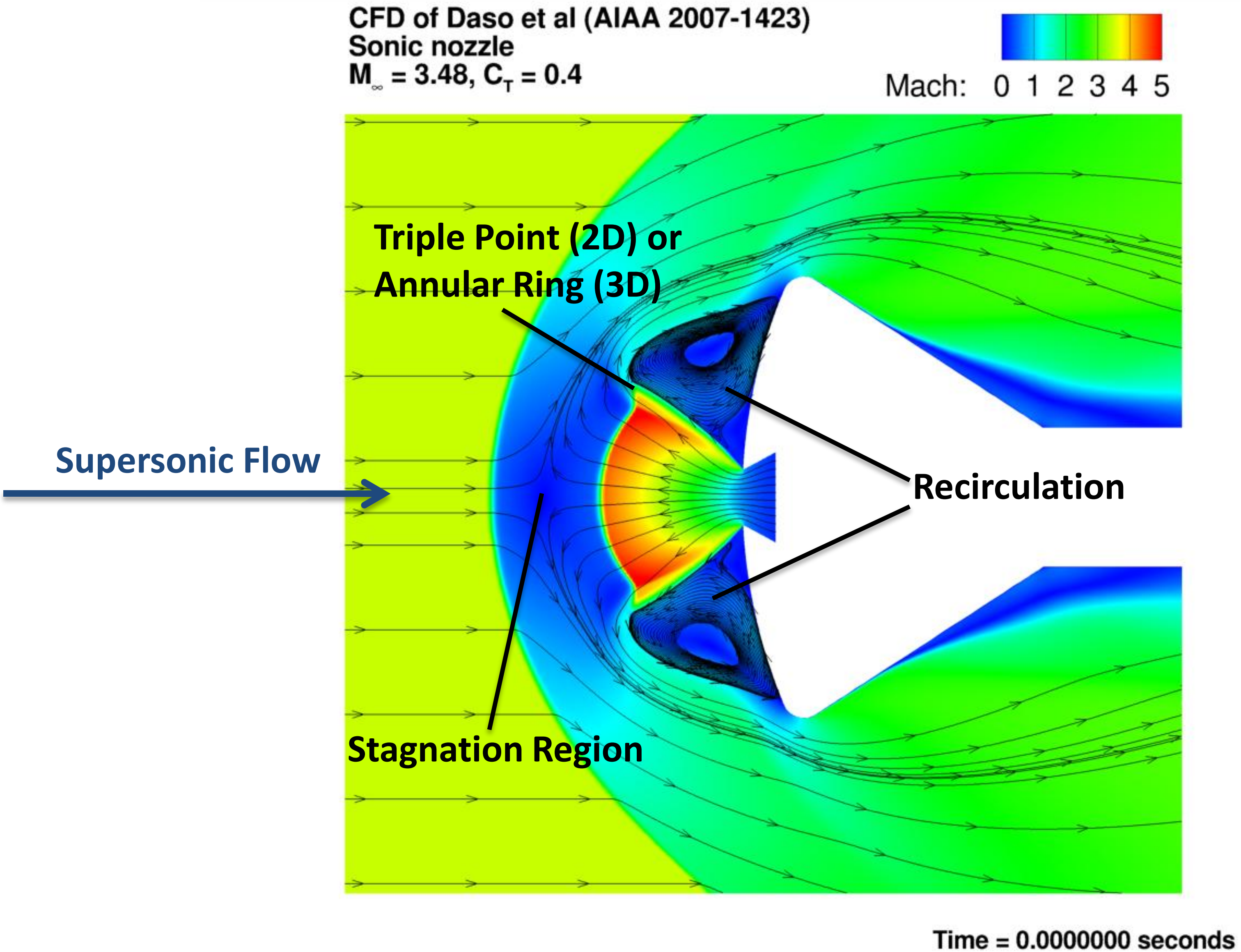
SRP Flow Structure



SRP Flow Structure



SRP Flow Structure



CFD Validation Approach

Employ multiple solvers to the same SRP problems

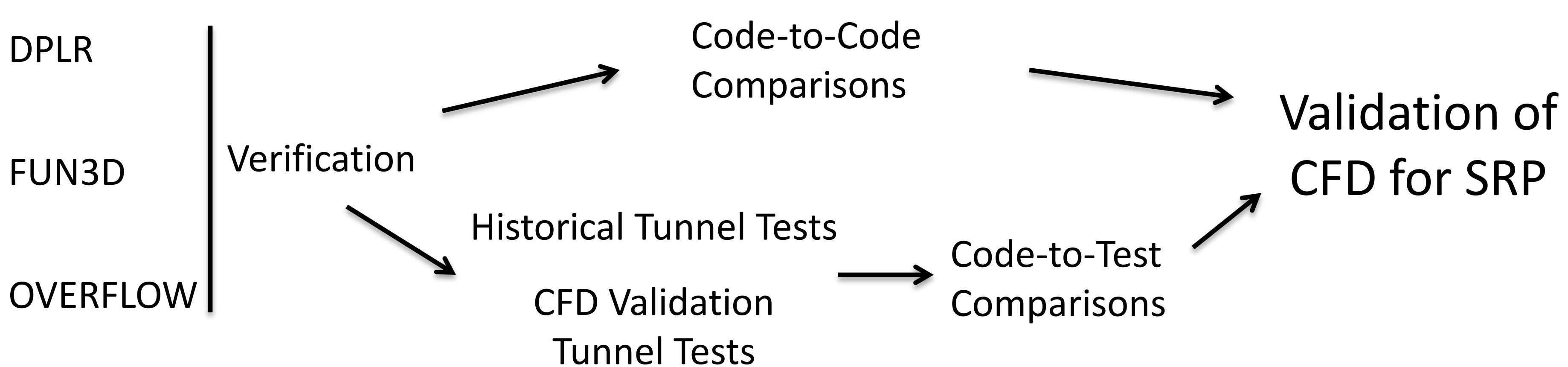
- DPLR (Kerry Zarchi, ARC)
- FUN3D (Bil Kleb, LRC)
- OVERFLOW (Guy Schauerhamer, Jacobs/JSC)

Compare results between codes and with historical tunnel data

- Qualitative: Shock structure and standoff distance, unsteady behavior
- Quantitative: Surface pressure, forces and moments

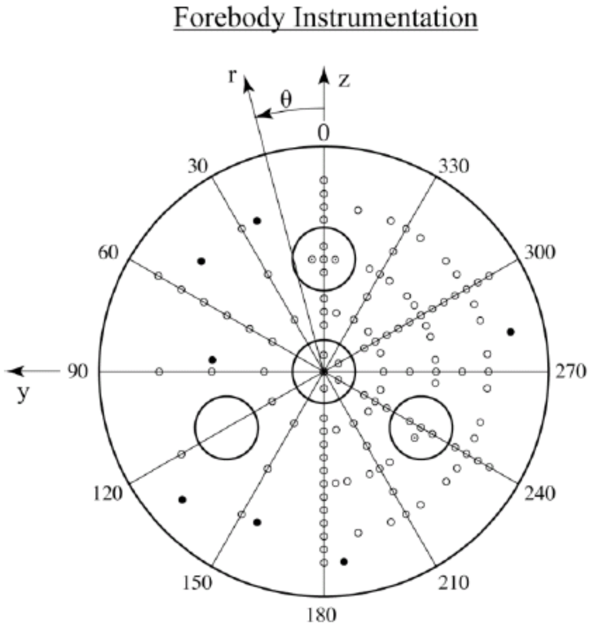
Perform CFD-validation wind tunnel tests of SRP

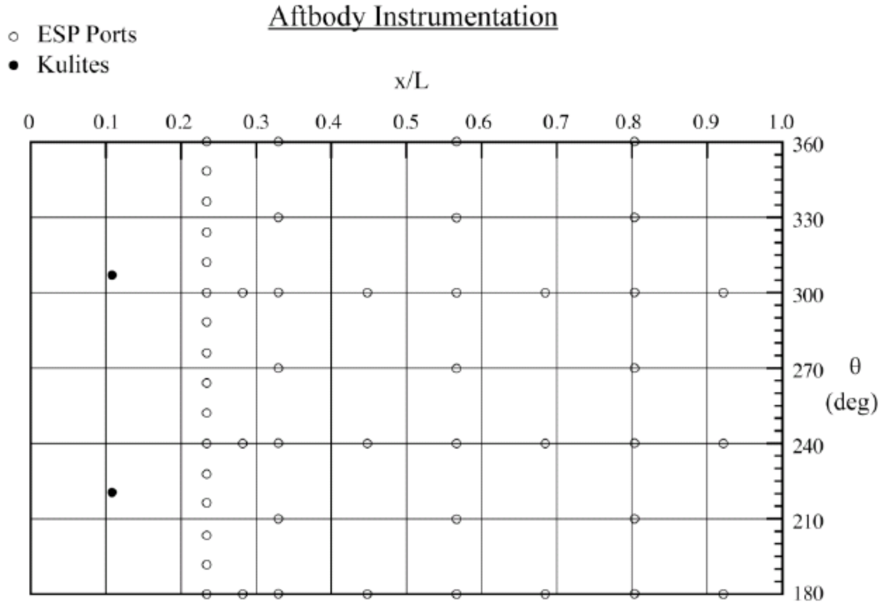
- Complete run conditions, quantified tunnel uncertainties
- Higher thrust coefficients to better match flight requirements



Wind Tunnel Model

- Air as freestream and jet gas.
- 4 removable nozzle plugs.
- 167 pressure taps including 7 high frequency pressure transducers.
- High speed Schlieren video (5-10 kfps).
- Same model used in both tests.





Wind Tunnel Tests

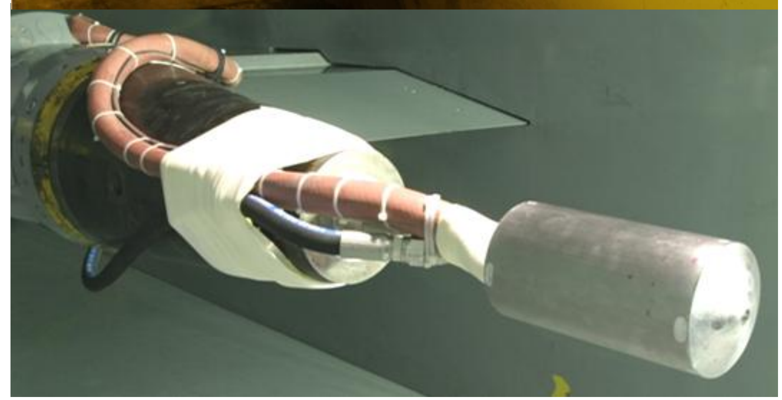
Langley 4’x4’ Test

- Mach 2.4, 3.5, 4.6
- C_Ts up to 3, a couple at 6

Ames 9’x7’ Test

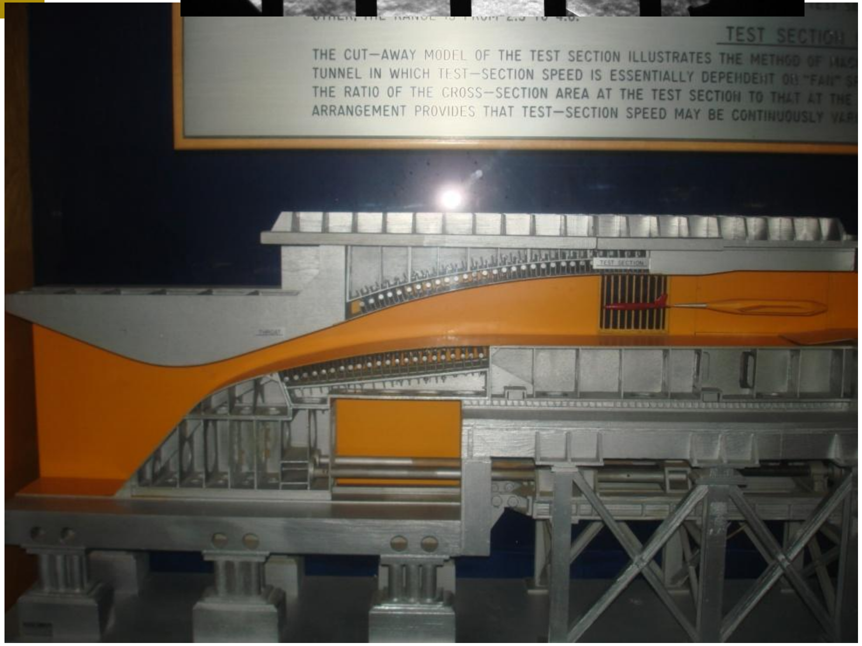
- Mach 1.8, 2.4
- C_Ts up to 10
- Liquefaction in plumes

LRC



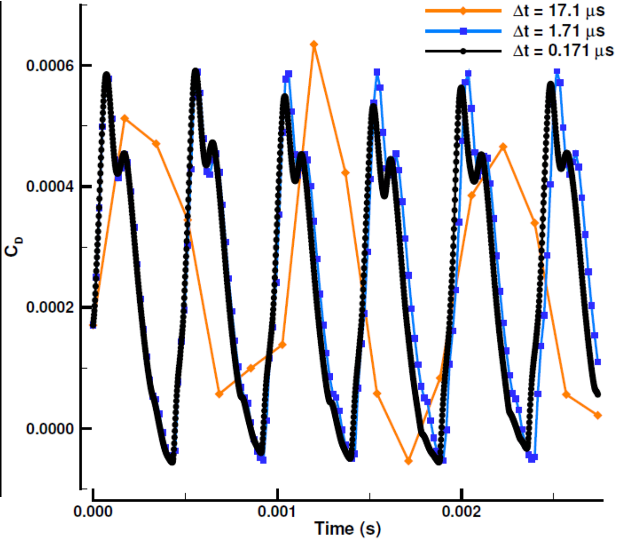
ARC

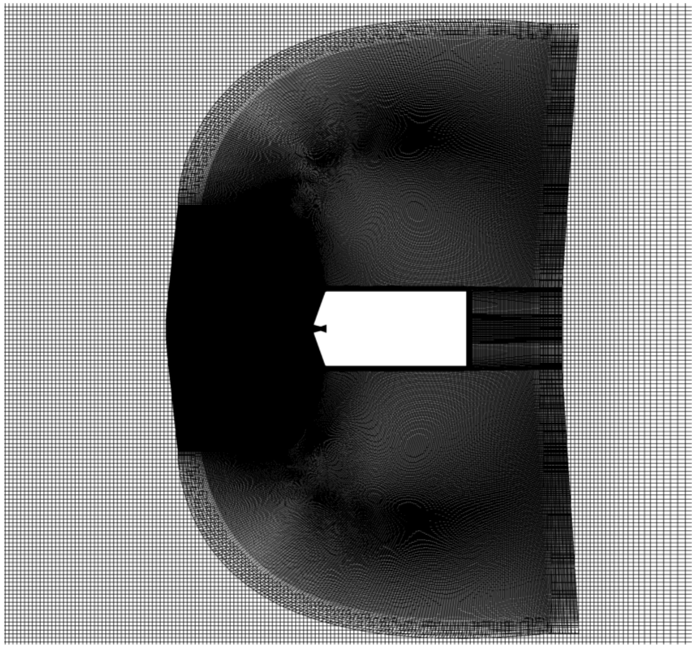
Langley Test



OVERFLOW Best Practices for SRP

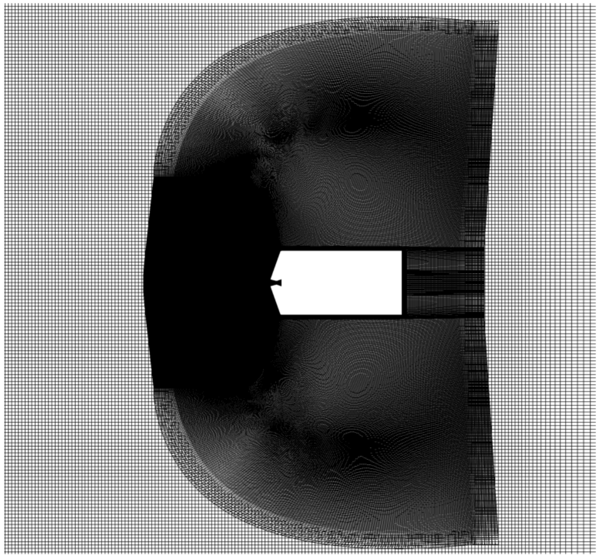
- Best practices based from LRC UPWT Run 165: 1-nozzle, Mach 4.6, C_T 2
- Grid refinement and time step sensitivity studies
  - Grids between 80 and 90 million points
  - Time steps <= 1.71e-06 seconds
  - 5 Newton subiterations
- HLLE++ numerical flux function with Van Albada limiter for spatial terms
- Symmetric Successive Over Relaxation (SSOR) algorithm with Newton dual time stepping for temporal terms.
- Used Direct Eddy Simulation (DES) turbulence modeling with Menter's Shear-Stress Transport (SST) as the Reynolds Averaged Navier-Stokes (RANS) submodel.
  - For SST, used strain-based production term employing Wilcox's realizability constraint
- All jet-on cases were solved time-accurately.

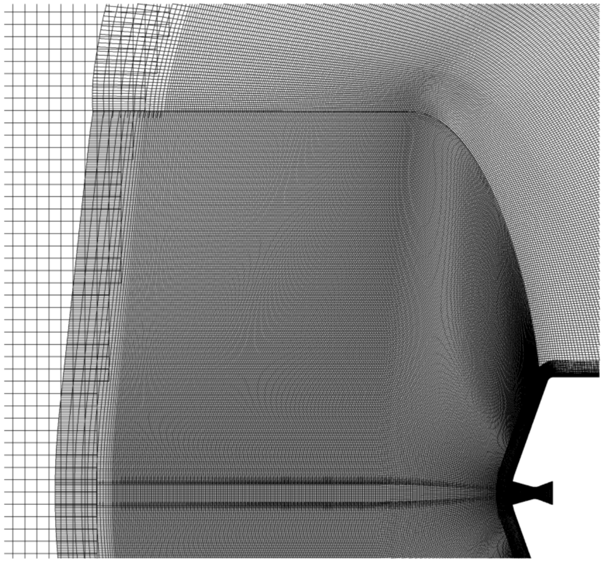


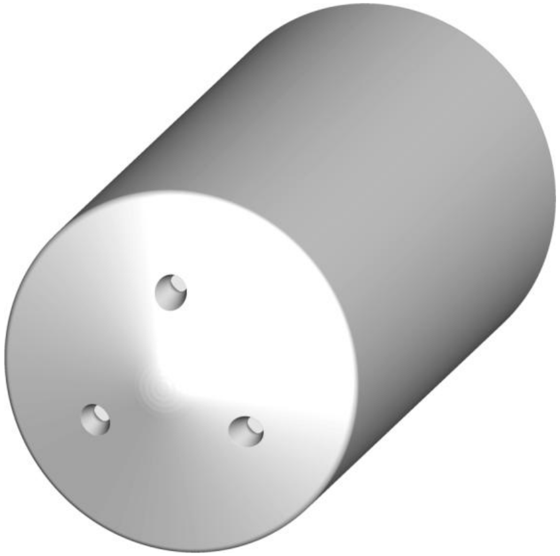


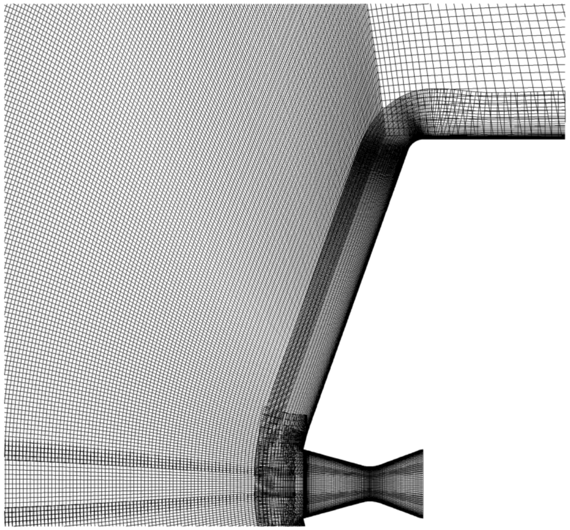
Structured Overset Grid System

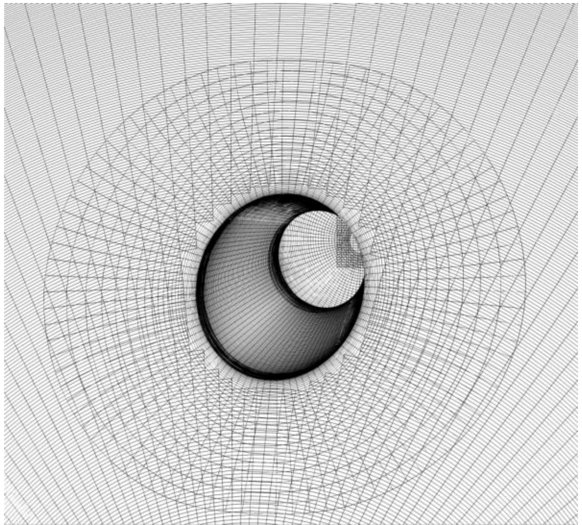
- Chimera Grid Tools script library- all configurations in single script
- X-rays and DCF for domain connectivity



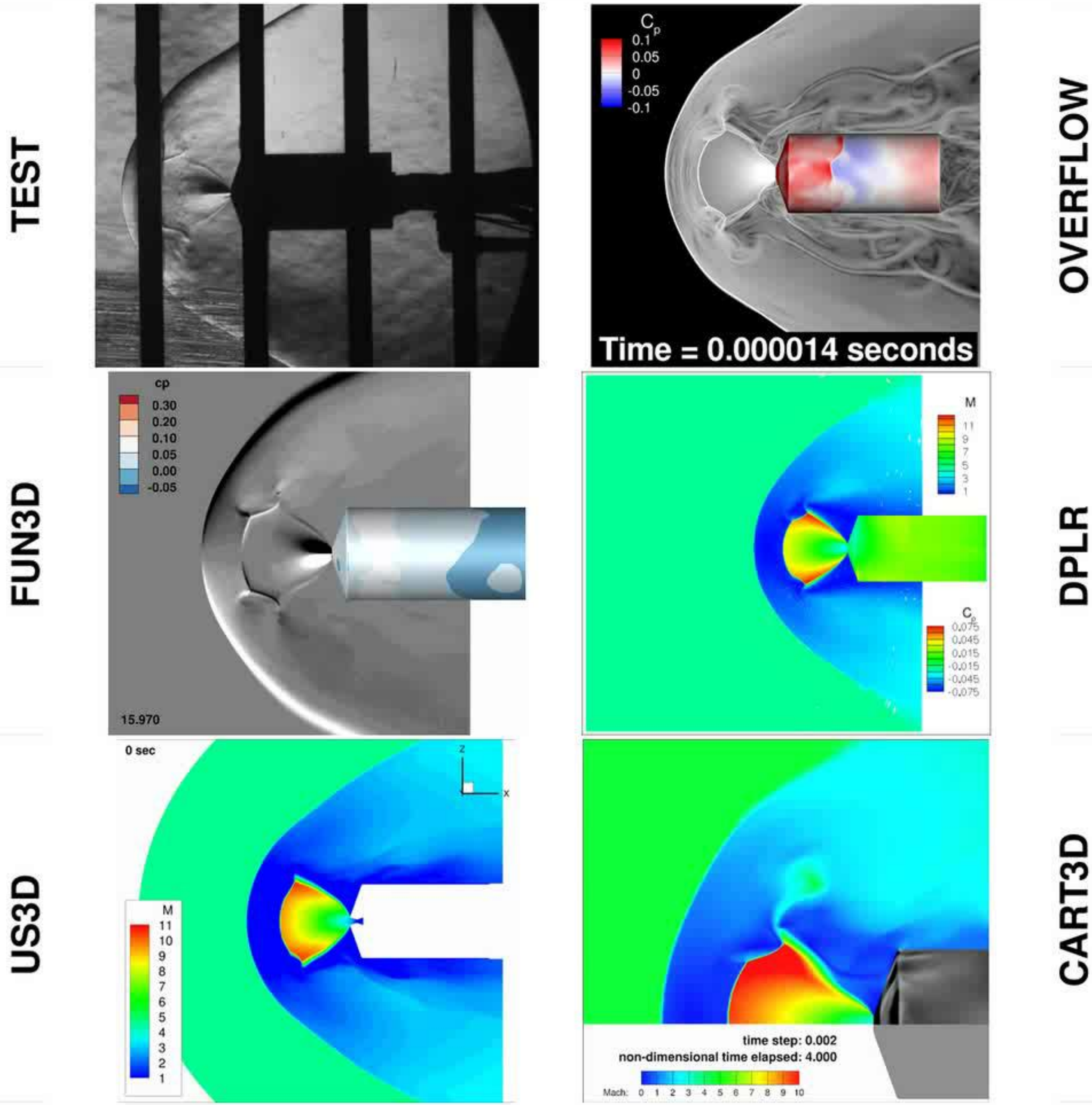








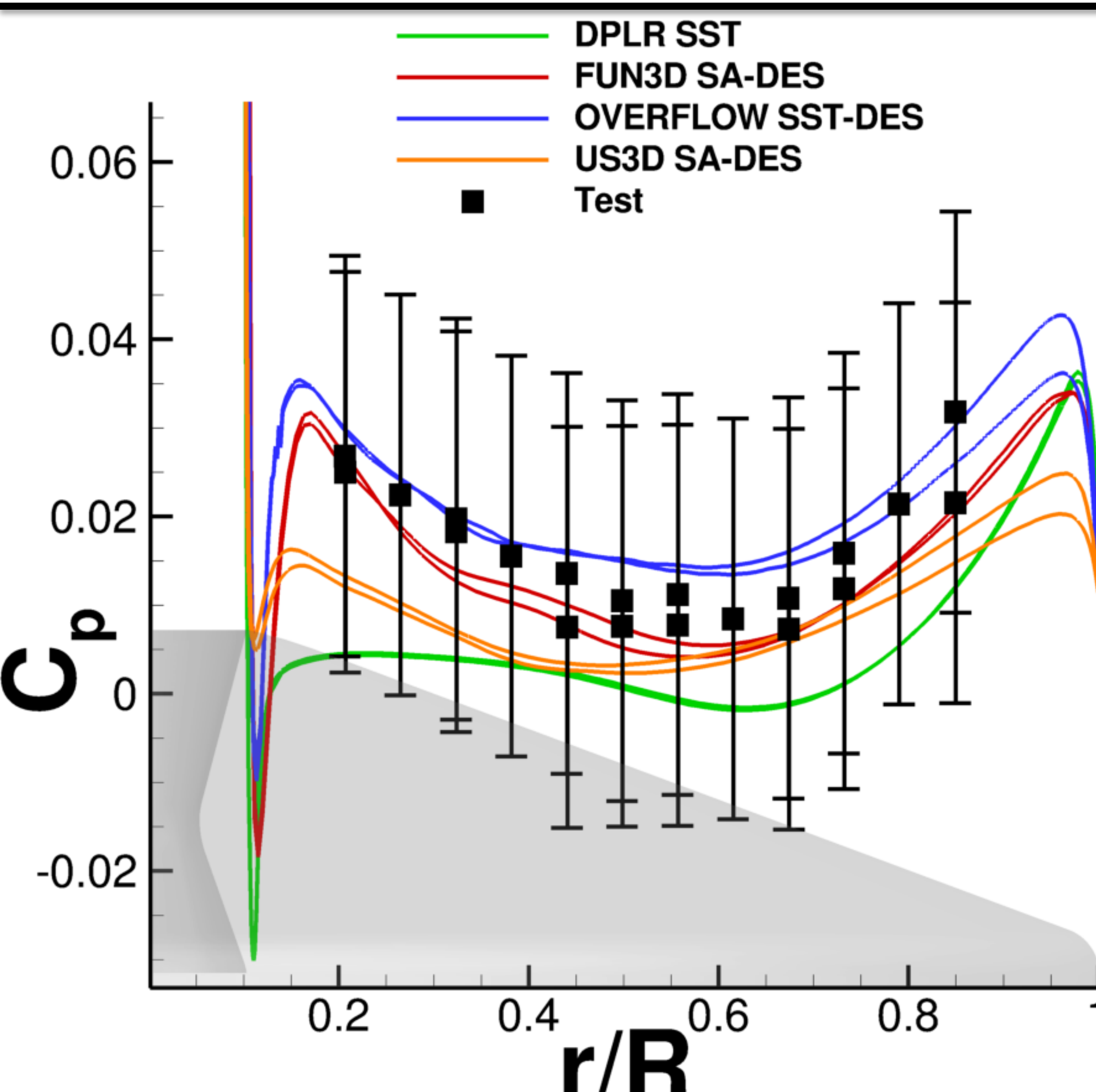
LRC Run 165 Qualitative Comparison



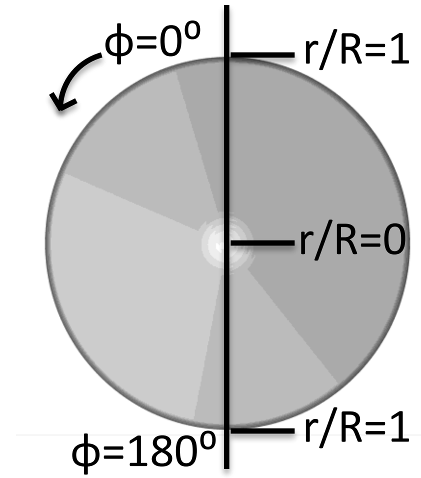
- 1-nozzle, Mach 4.6, C_T 2.
- Periodic unsteadiness.
- Oscillating pressure wave increases average pressure on model face.
- Movies not synced in time.

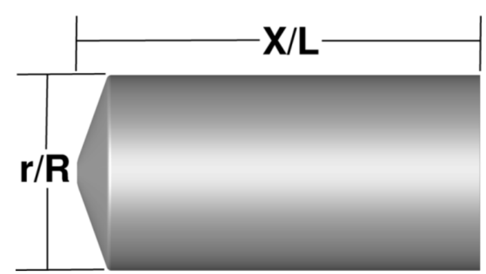
- US3D solution by Emre Sozer (ARC)
- Cart3D solution by Noel Bahktian (Stanford) and Michael Aftosmis (ARC)

LRC Run 165 Comparisons



- Capturing periodic oscillation in the triple point increased average pressure on the face.
- All codes fall within tunnel uncertainty.

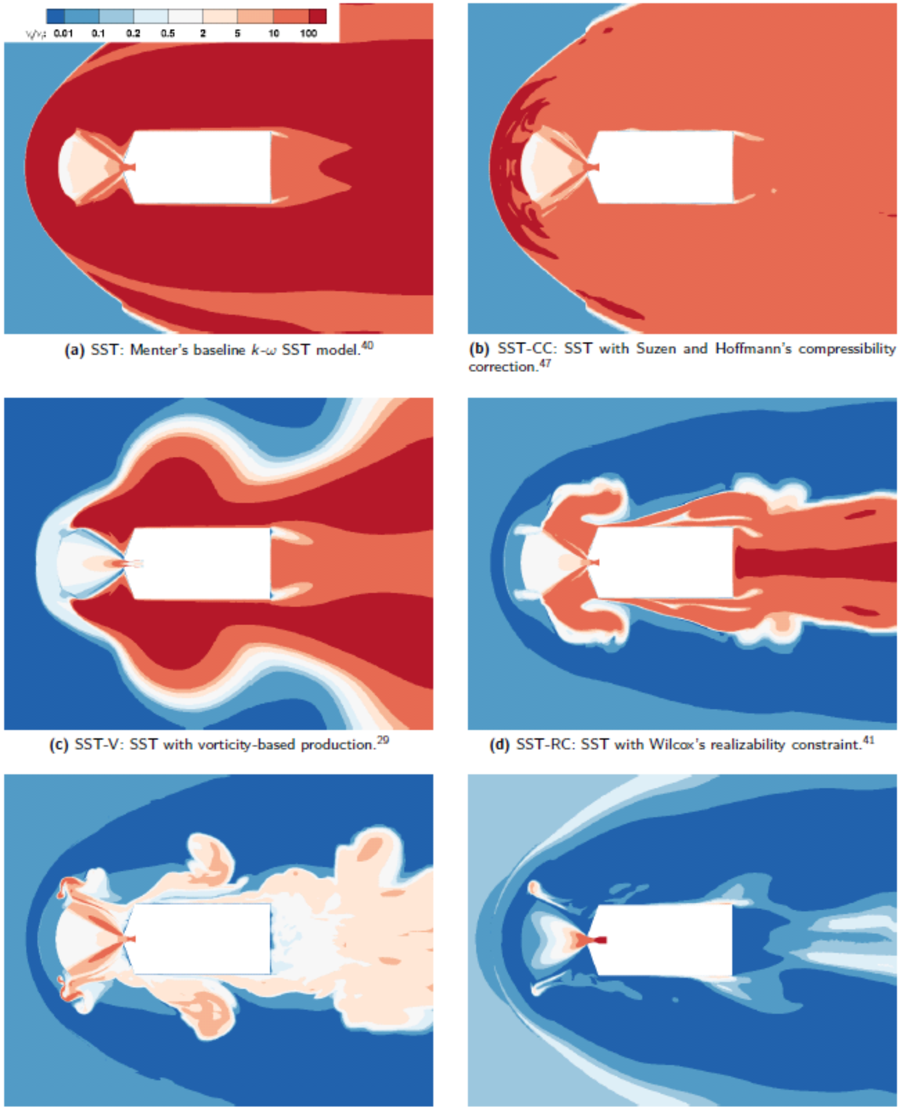




Turbulence Modeling

Unsteady behavior was influenced by turbulence modeling.

- For SRP, limiting eddy viscosity produced more realistic behavior
    - Cart3D is inviscid
- Figure is ratio of eddy to laminar viscosity for different turbulence models, simulated with OVERFLOW and FUN3D.
- For SRP simulations:
    - DPLR used SST-V.
    - FUN3D used SA-DES
    - OVERFLOW used SST-DES and SST-RC



(a) SST: Menter's baseline k-ω SST model.[40]

(b) SST-CC: SST with Suzen and Hoffmann's compressibility correction.[47]

(c) SST-V: SST with vorticity-based production.[29]

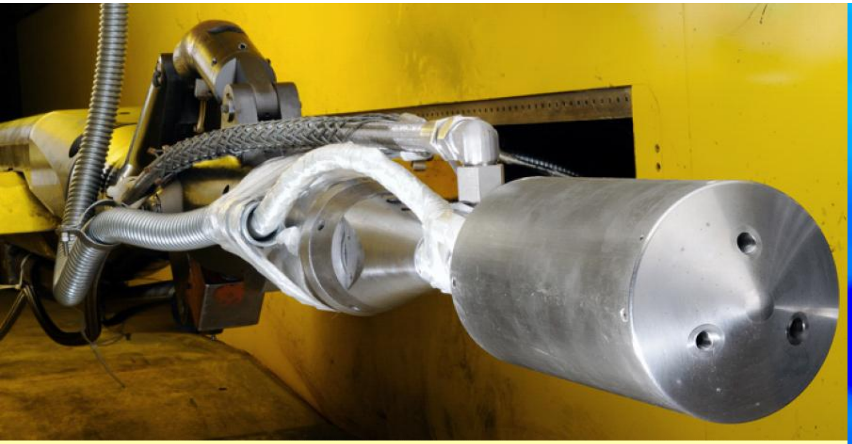
(d) SST-RC: SST with Wilcox's realizability constraint.[41]

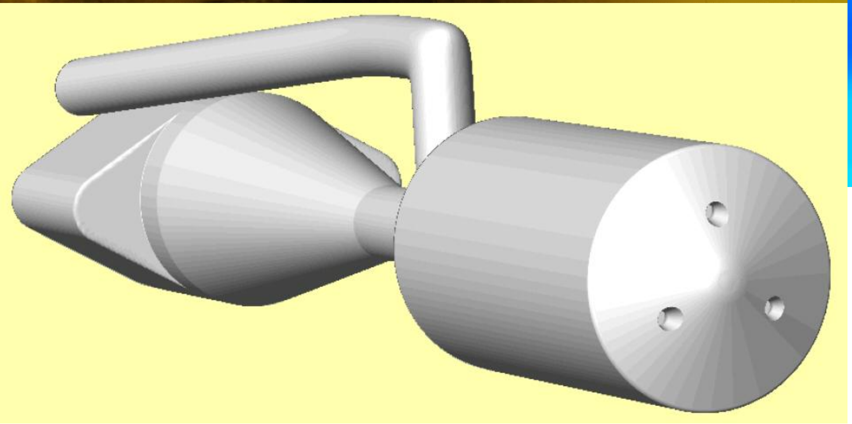
(e) SST-DES: SST-based DES.[42]

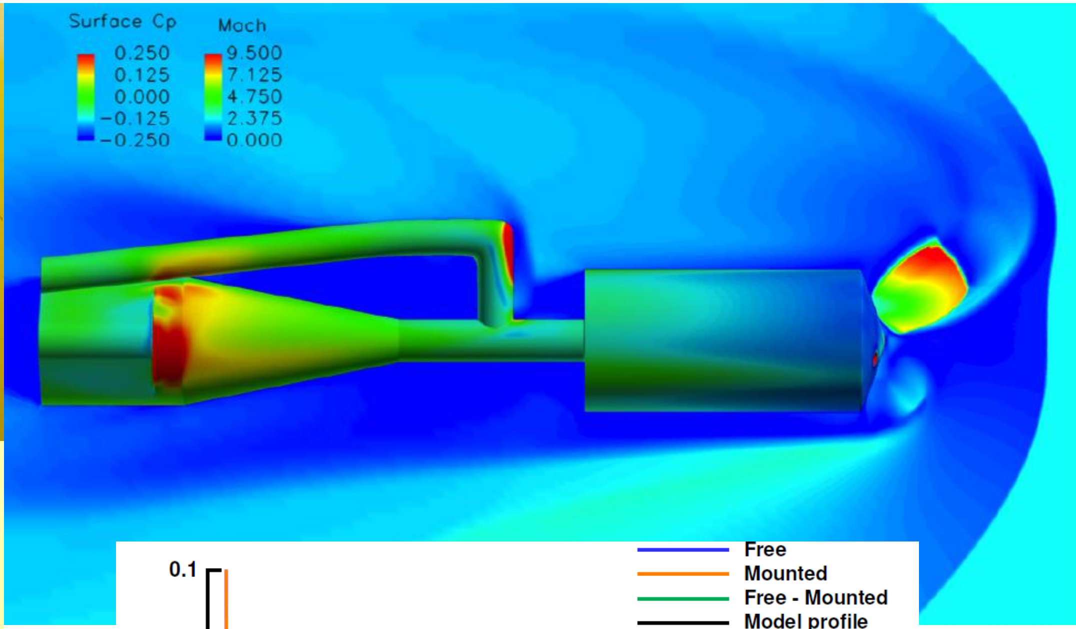
(f) SA-DES: SA-based DES.[34]

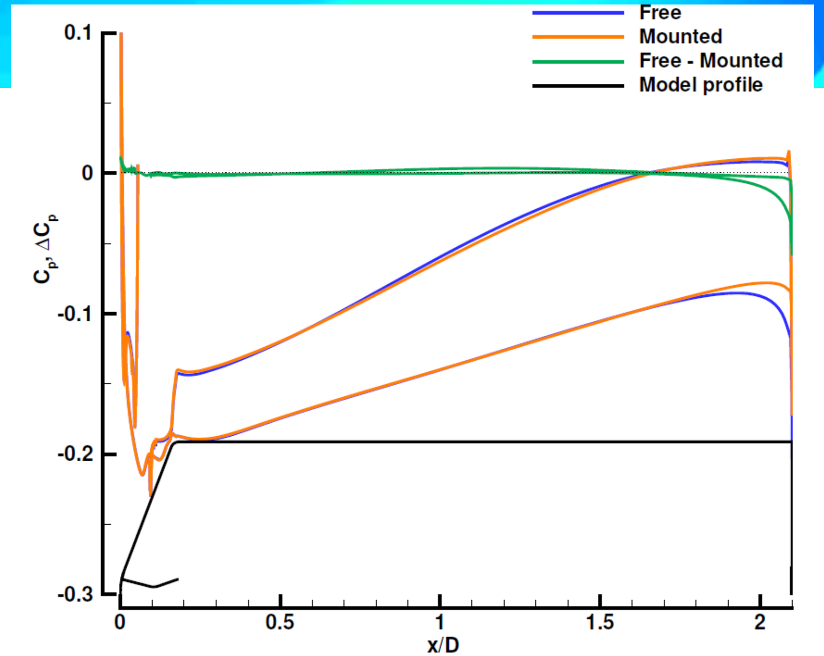
Figure 20: The ratio of turbulent eddy viscosity to laminar (bulk) viscosity for various turbulence models. Note: No attempt was made to capture these instantaneous snapshots near the same point of the quasi-periodic cycle.

LRC Sting Sensitivity Study, 3-nozzle

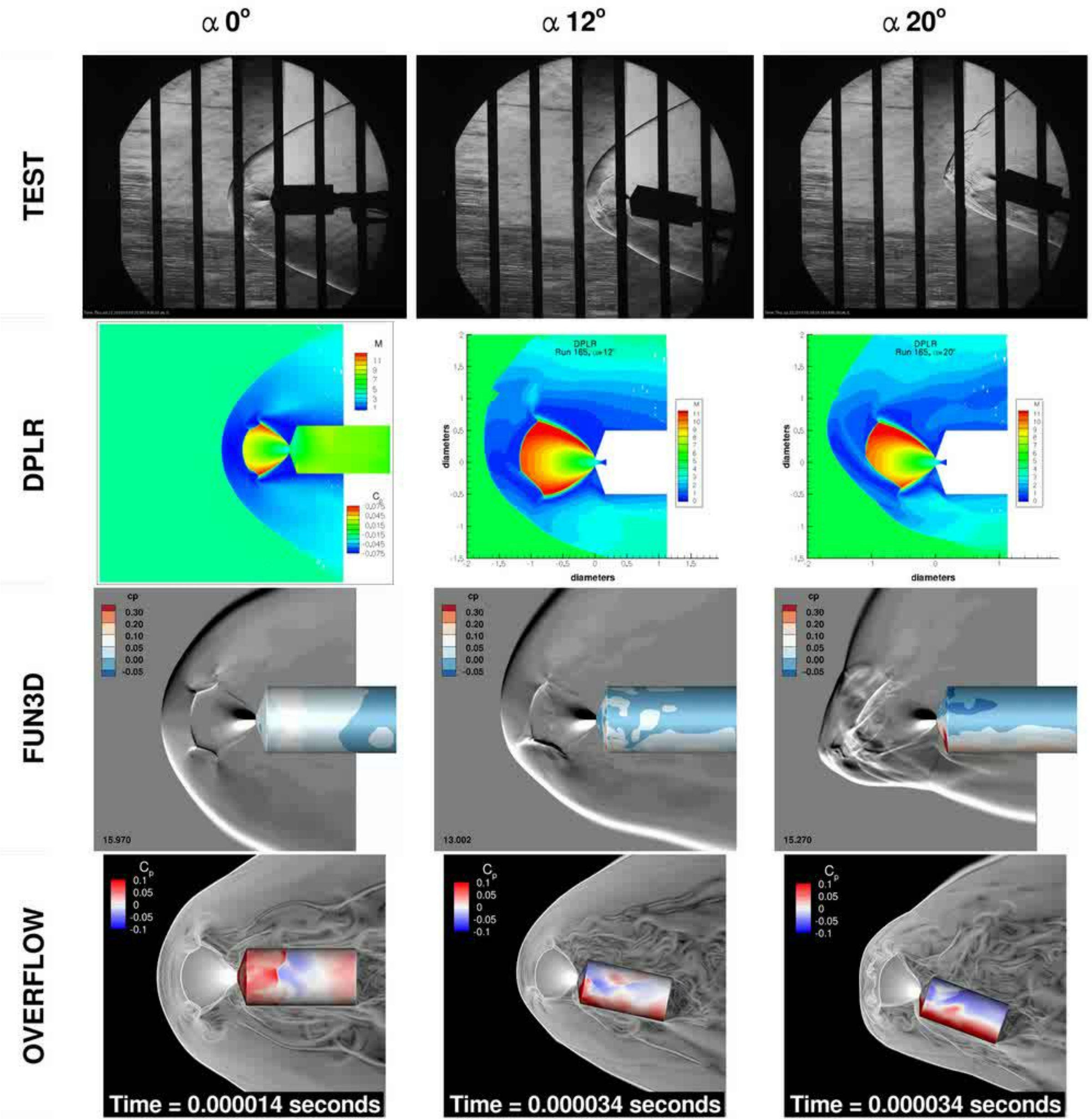




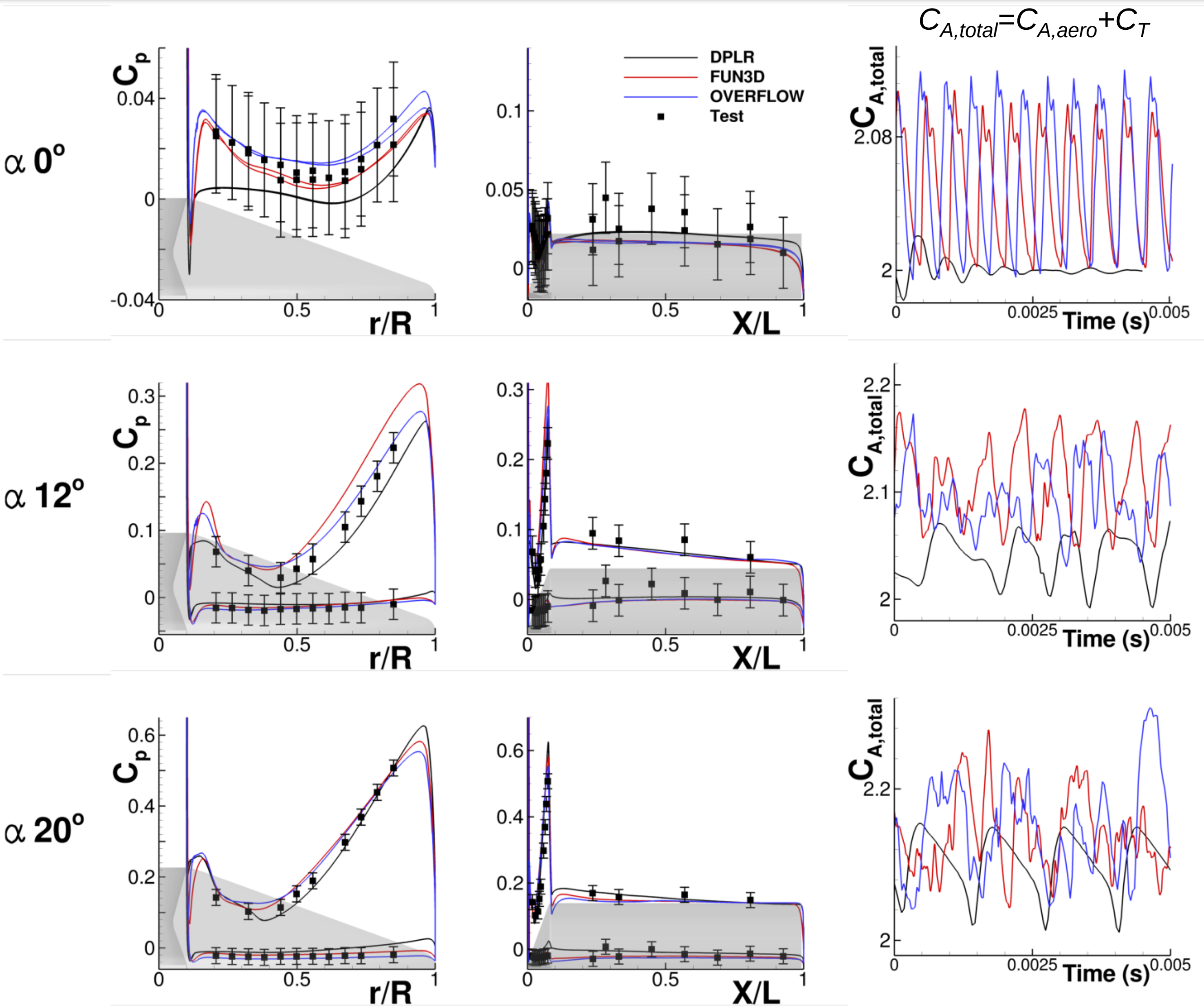




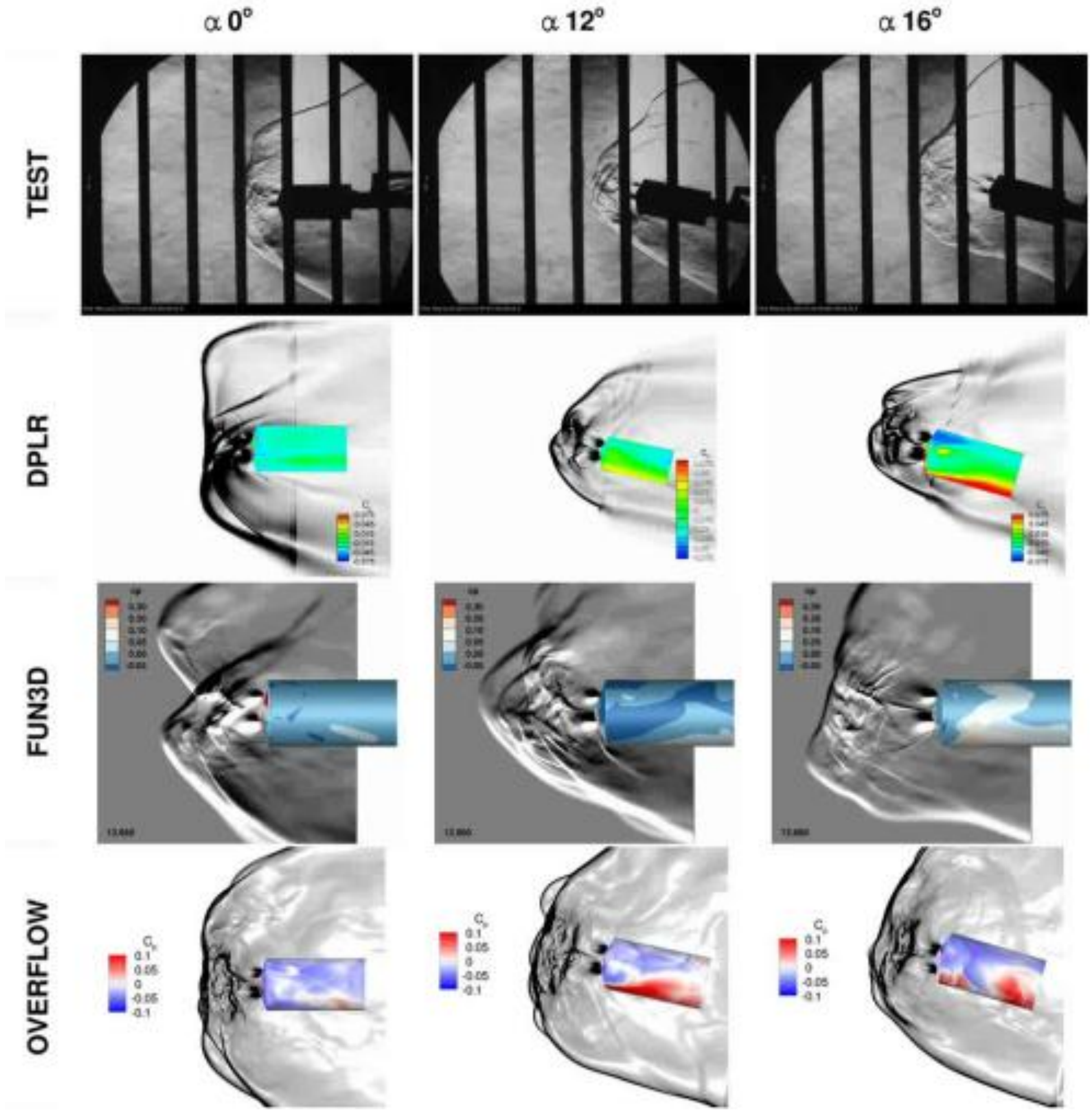
LRC Run 165 Comparisons



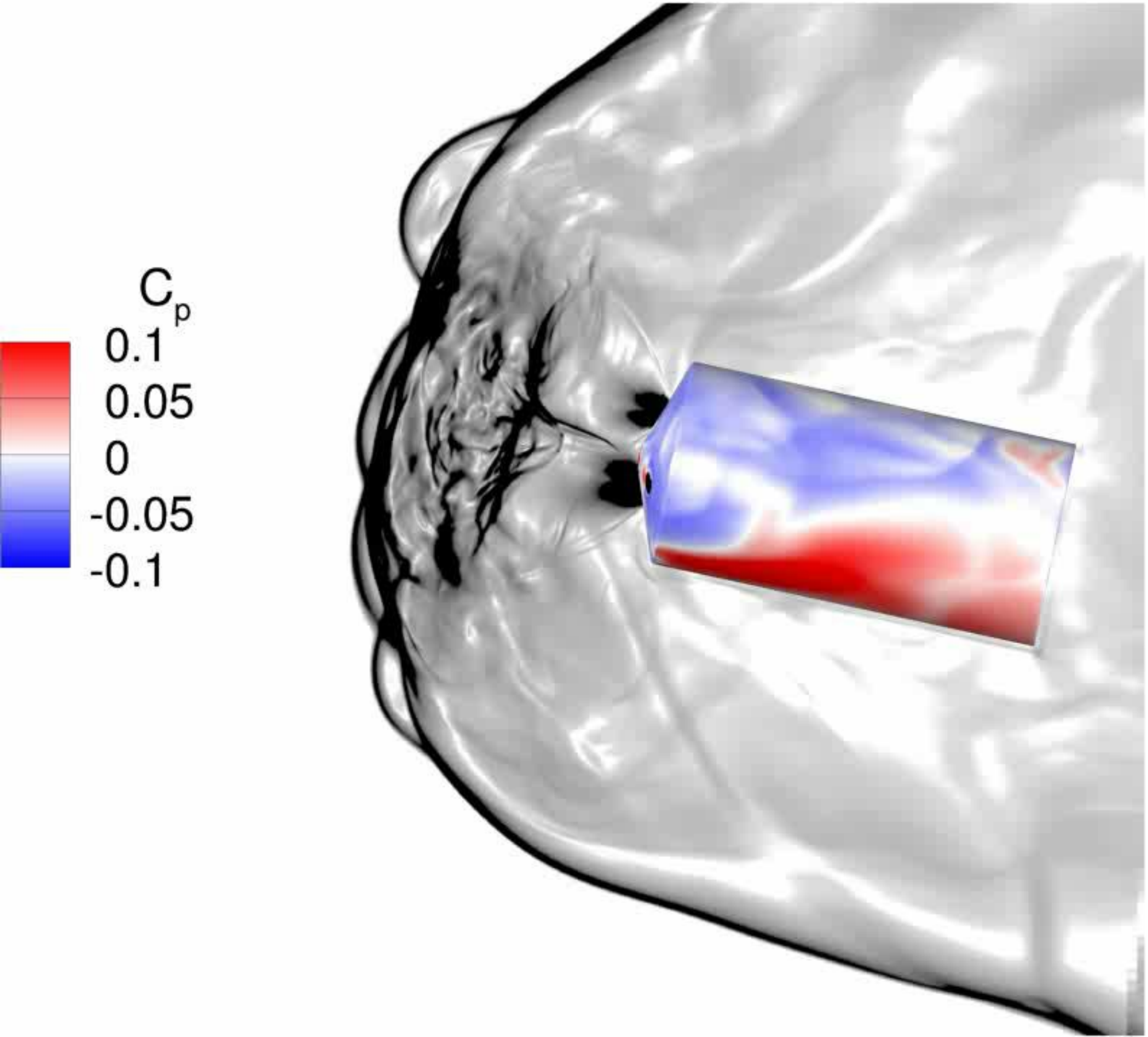
LRC Run 165 Comparisons



LRC Run 262: 3-nozzle, Mach 4.6, C_T=3



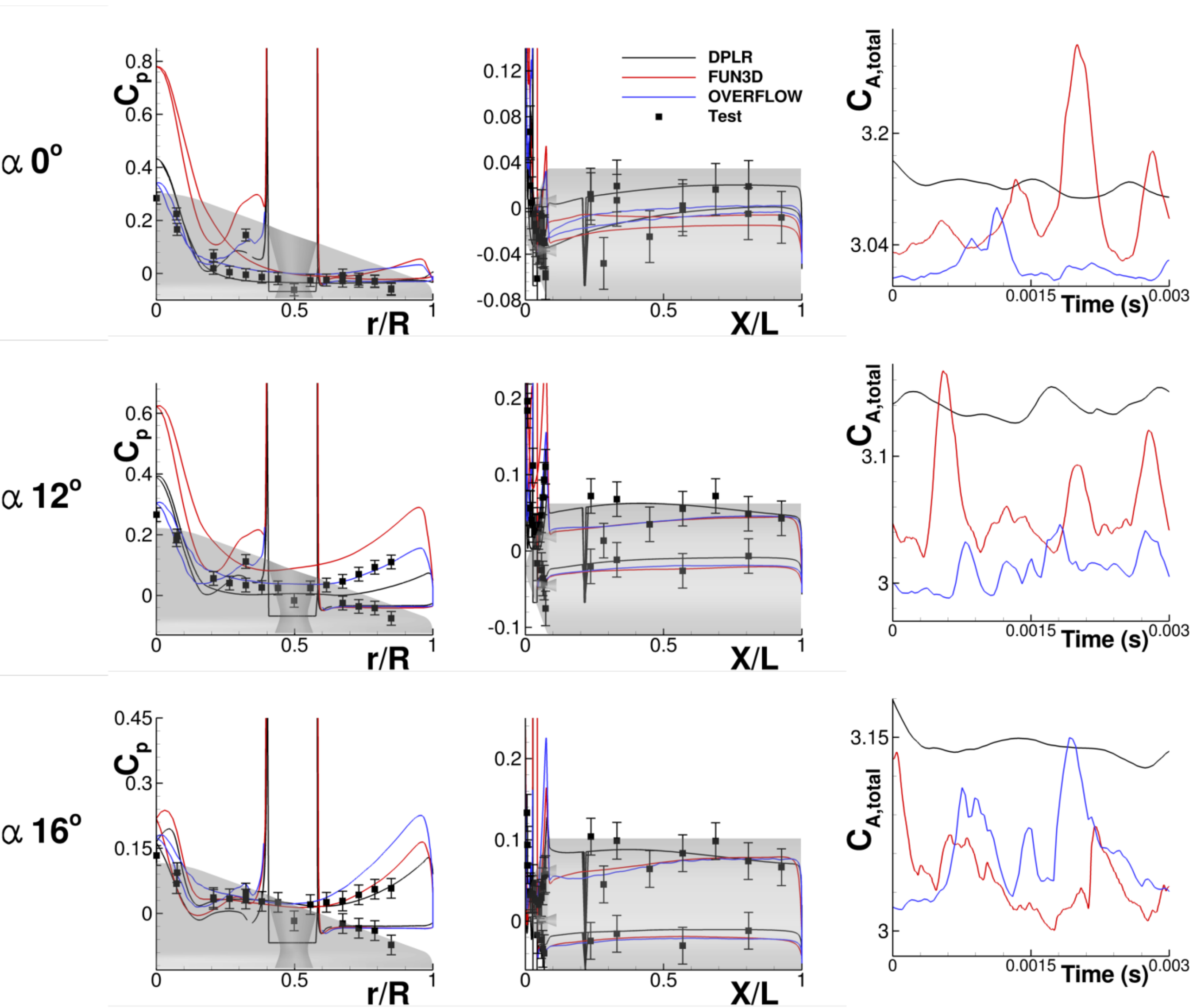
LRC Run 262: 3-Nozzle, C_T=3, α=12^o



Bow shock shedding impacts model face and side shell

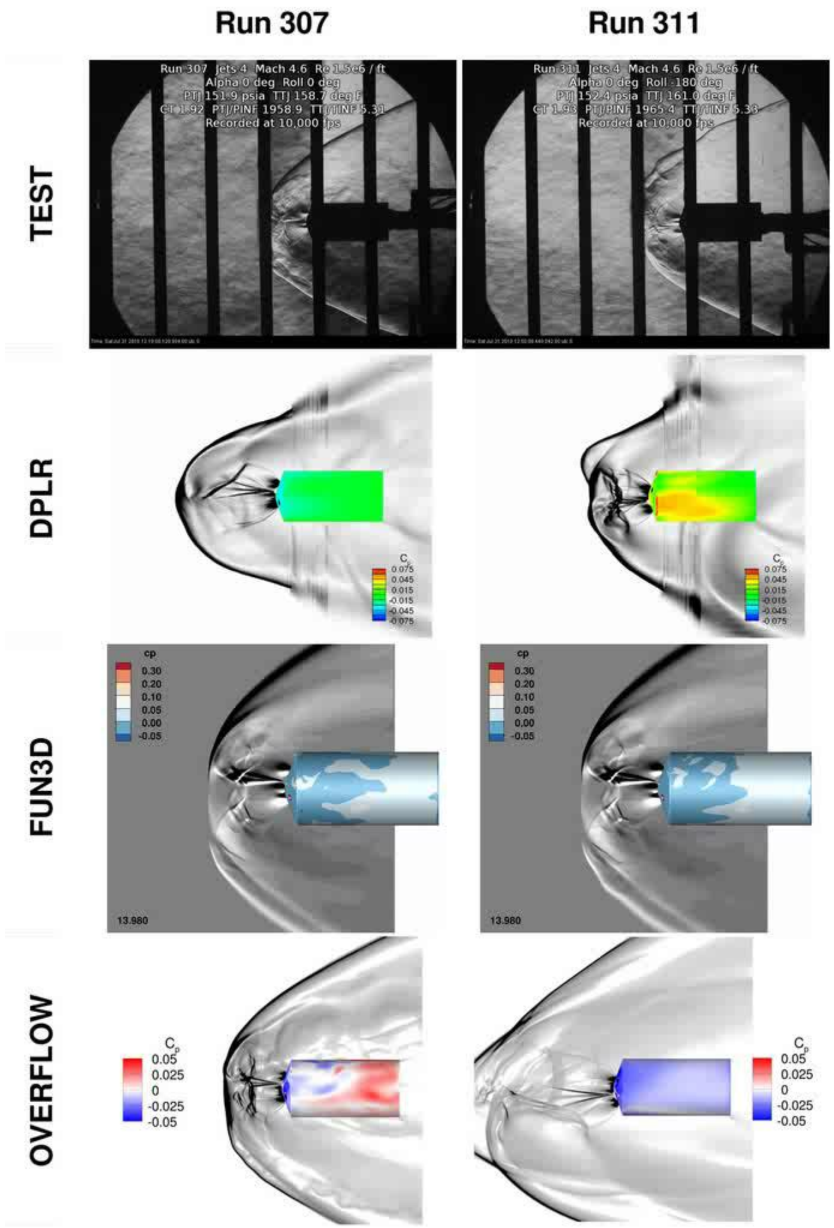
Constructed shadowgraph of CFD solution

Run 262: 3-Nozzle, $C_T=3$, $\phi=0^o$



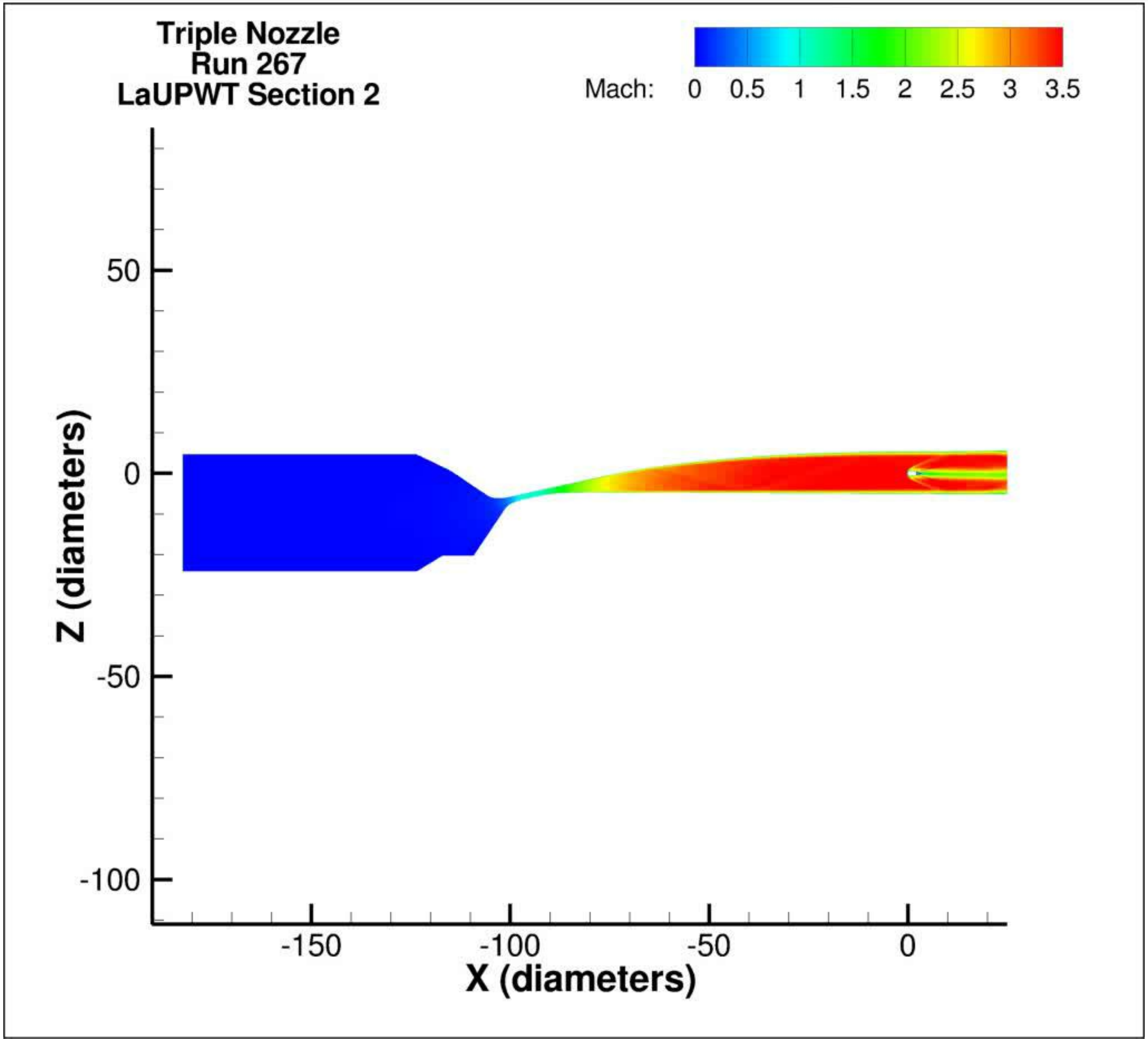
- DPLR steadier than FUN3D and OVERFLOW (SST-V vs DES)
- Large scatter in neighboring pressure ports on the model windward side shell
- FUN3D overpredicts C_P on model face for $\alpha=0^0$ and $\alpha=12^0$
- Deviation at nose implies jet-to-jet interactions predicted differently between codes
- Deviation at shoulder implies differences in shock shedding impacting the model face

Run 307 and 311: 4-Nozzle, C_T=2, ϕ=0°, 180°

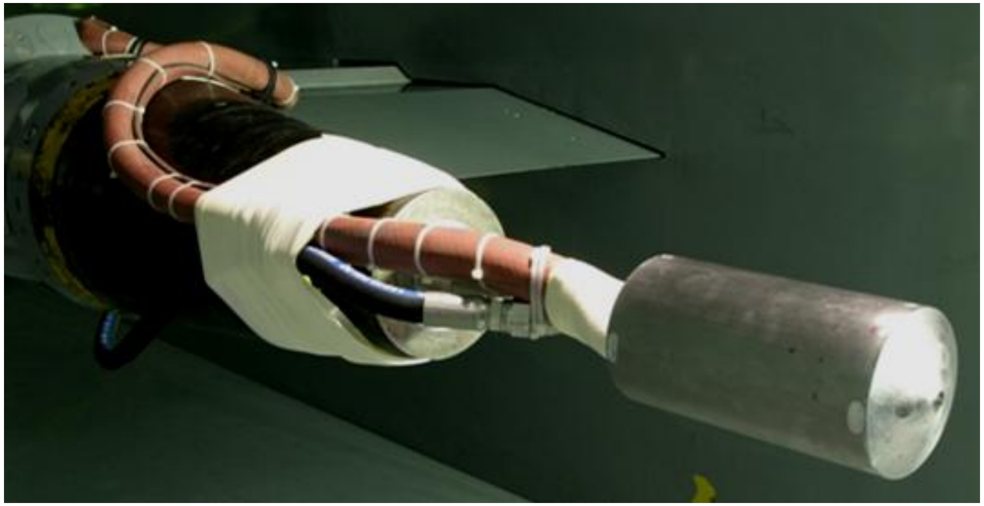


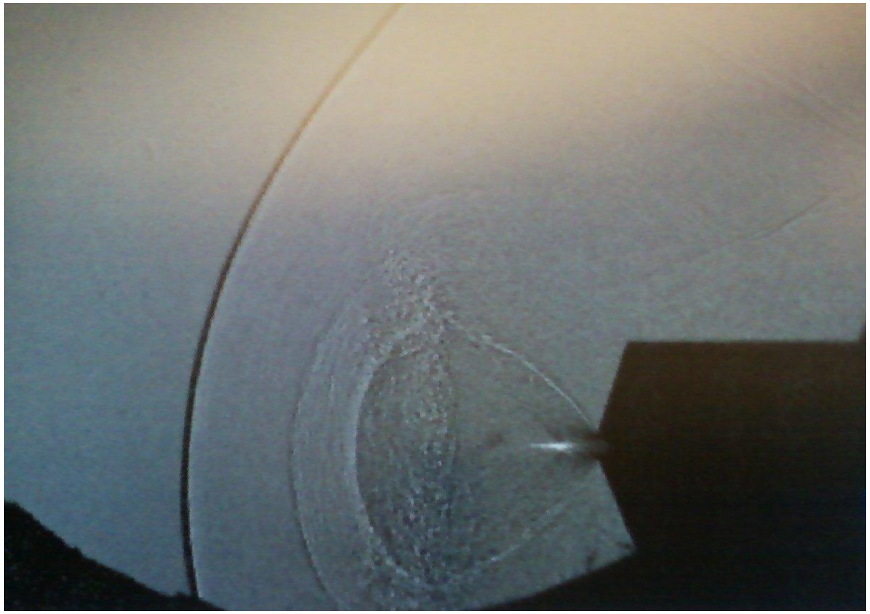
- Runs only differ in roll angle.
- Short blunt behavior vs. large shock standoff.

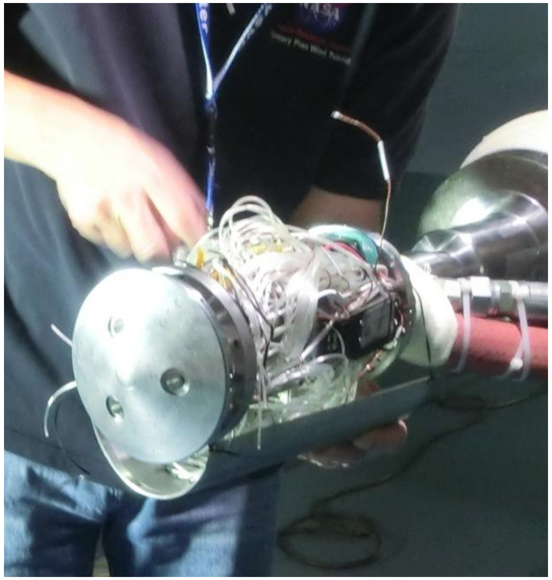
Viscous Full Tunnel

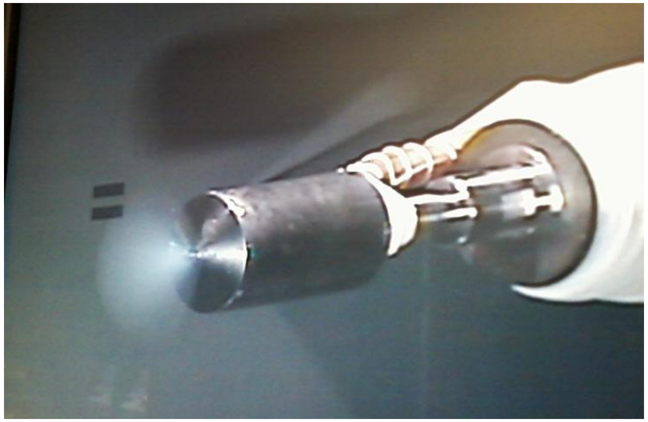


Ames Test

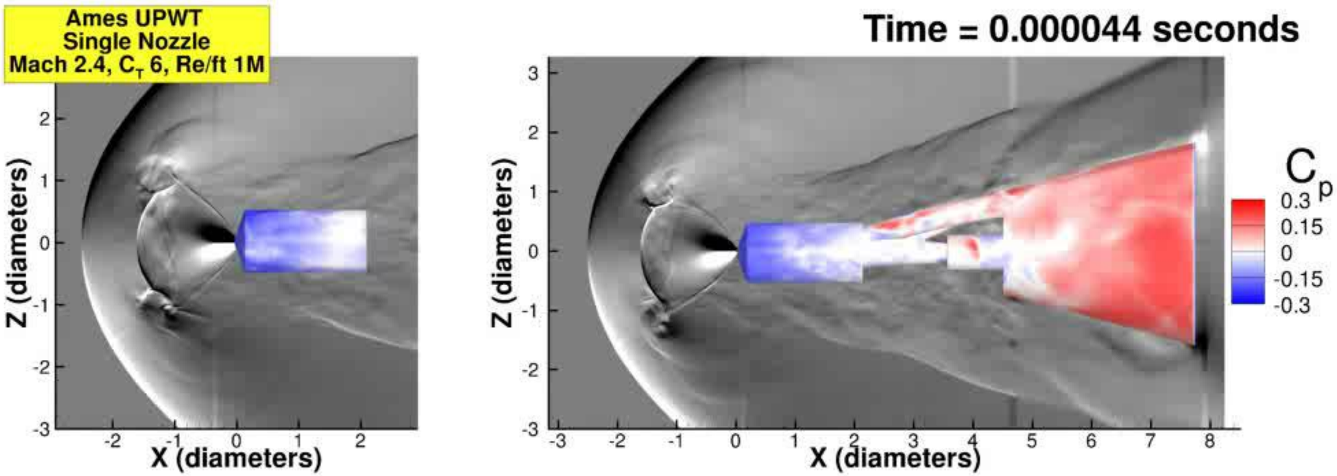


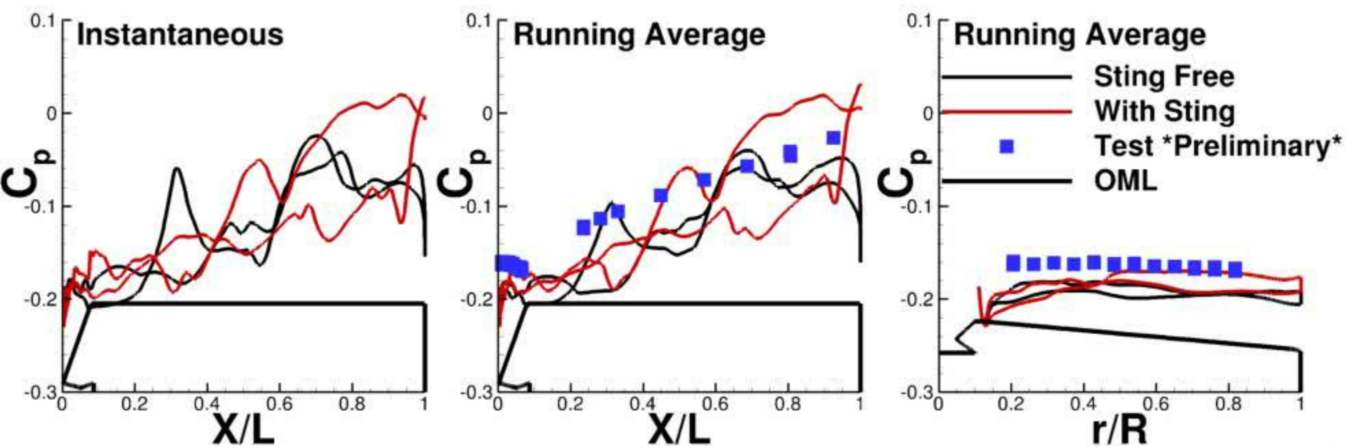


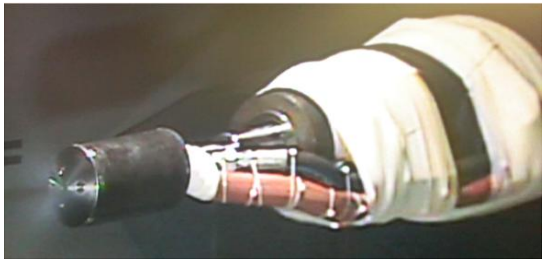


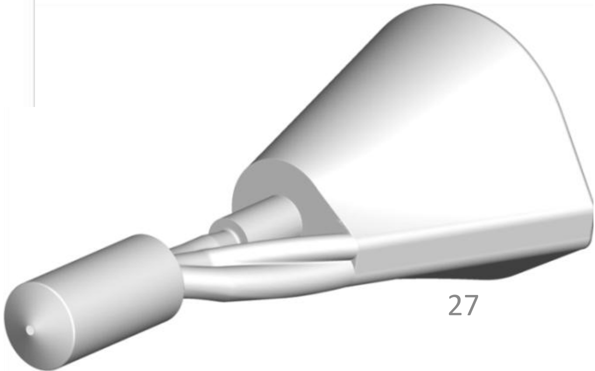


Ames Sting Sensitivity Study, 1-nozzle









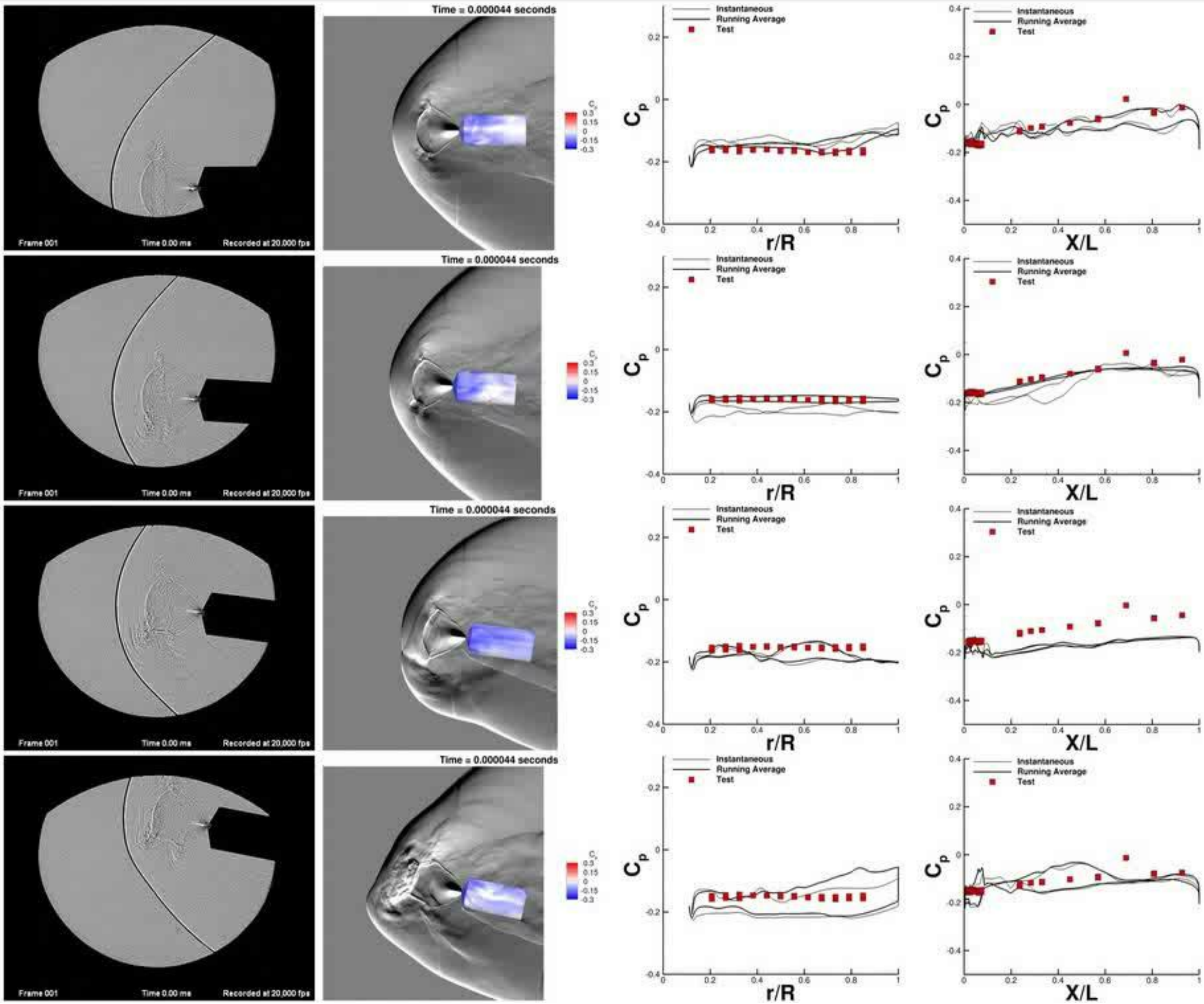
Run 223, β = 0º, 4º, 8º, and 12º

Run 223
1-nozzle
Mach 2.4, C_T 4

Run 223
1-nozzle
Mach 2.4, C_T 4
β 4º

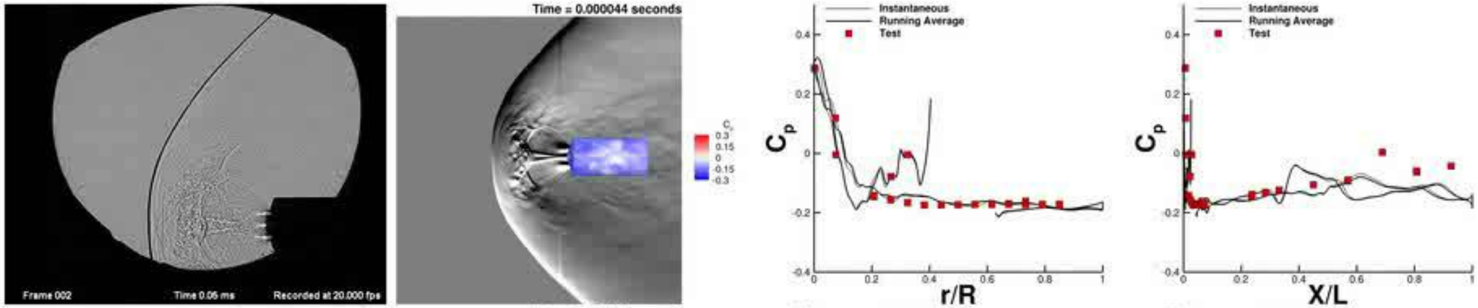
Run 223
1-nozzle
Mach 2.4, C_T 4
β 8º

Run 223
1-nozzle
Mach 2.4, C_T 4
β 12º

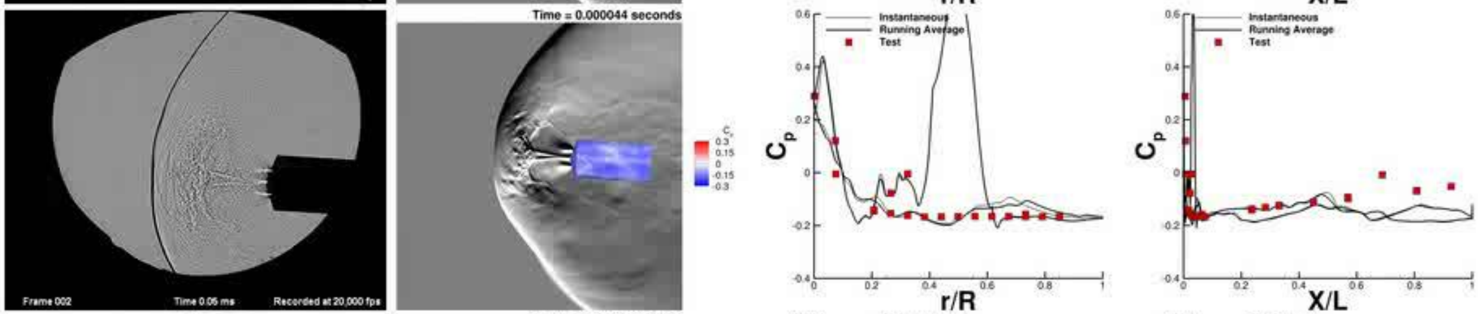


Run 141, β = 0º, 4º, 8º, and 12º

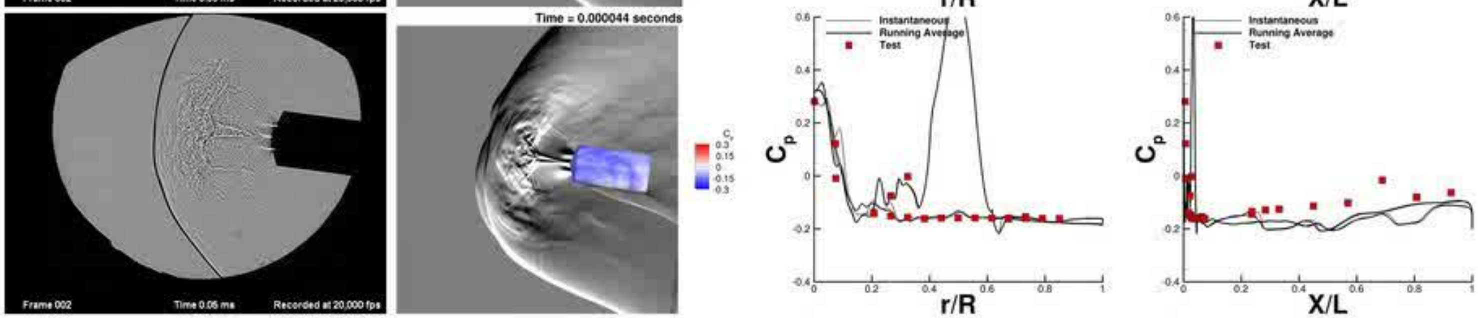
Run 141
3-nozzle
Mach 2.4, C_T 6



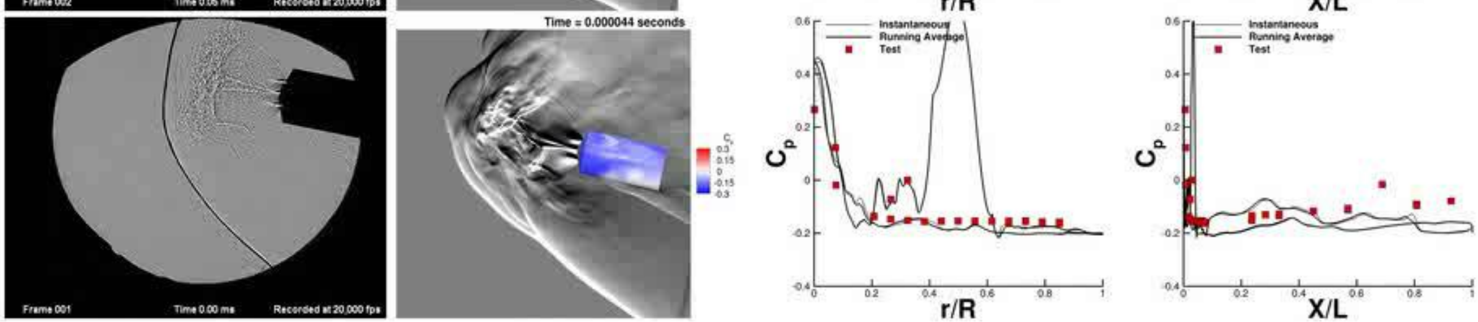
Run 141
3-nozzle
Mach 2.4, C_T 6
β 4°



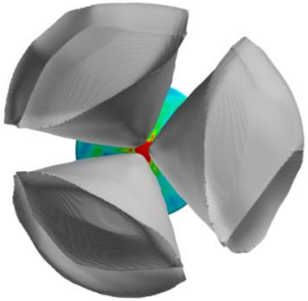
Run 141
3-nozzle
Mach 2.4, C_T 6
β 8°

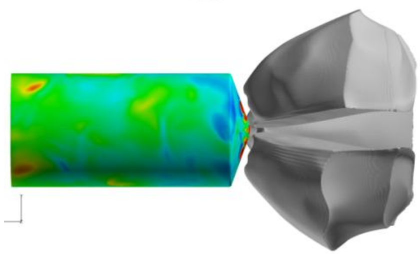


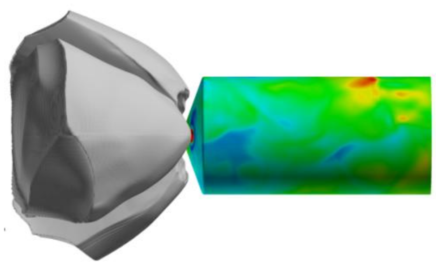
Run 141
3-nozzle
Mach 2.4, C_T 6
β 12°

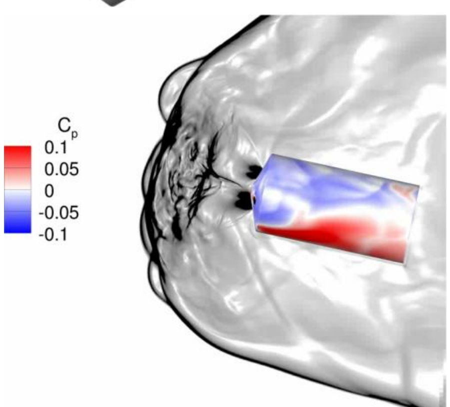


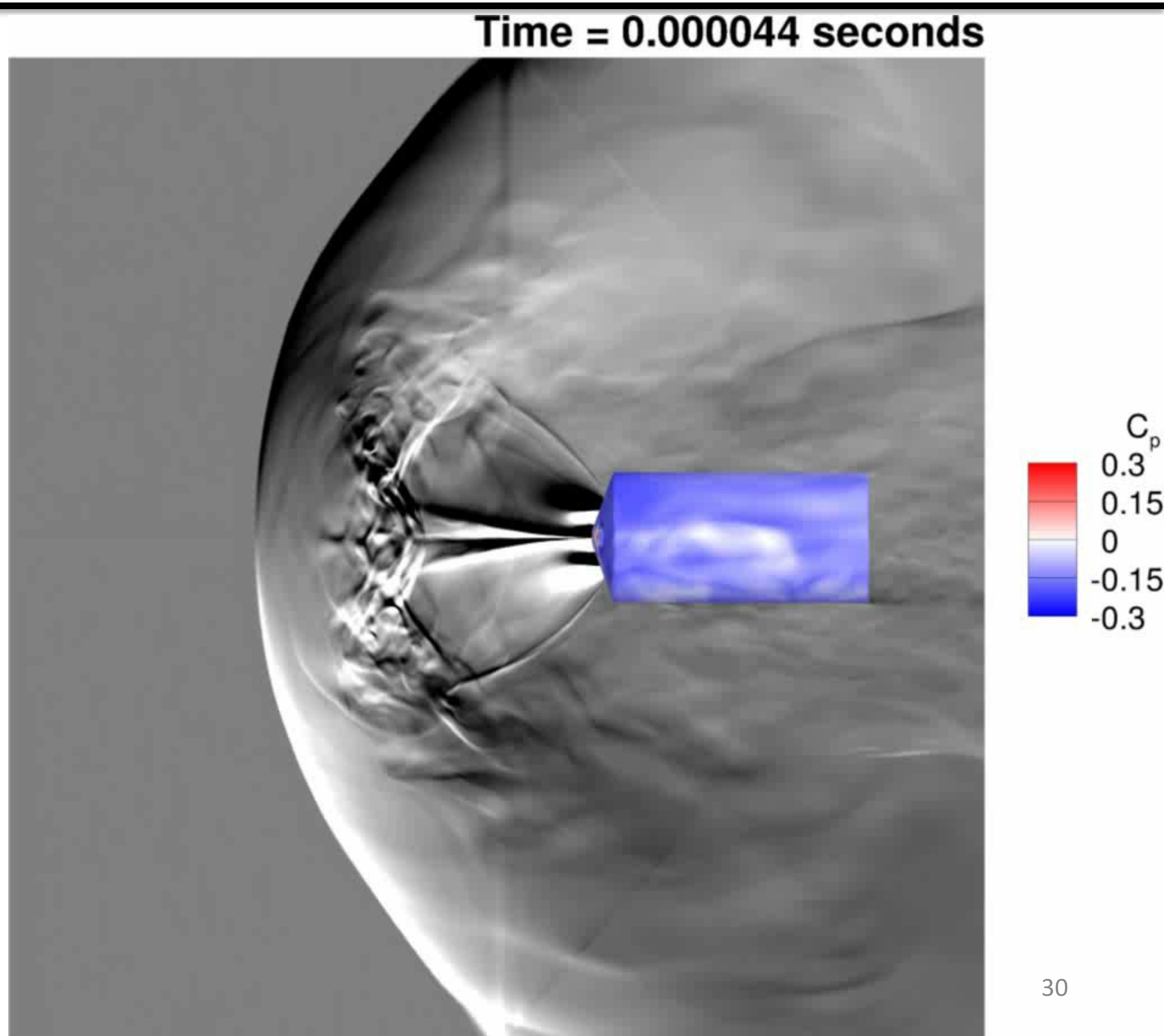
3-Nozzle, Mach 2.4, C_T 10, Run 145





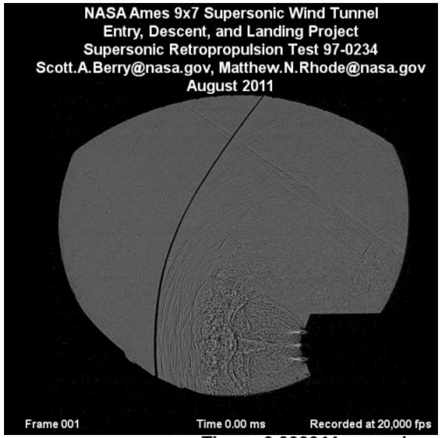


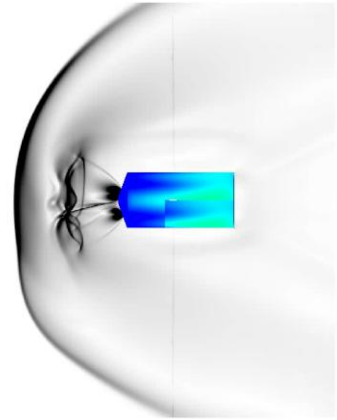




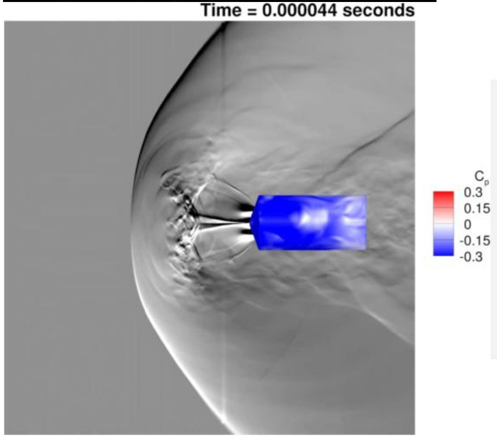
Run 130, C_T 6, $\beta = 0^o$

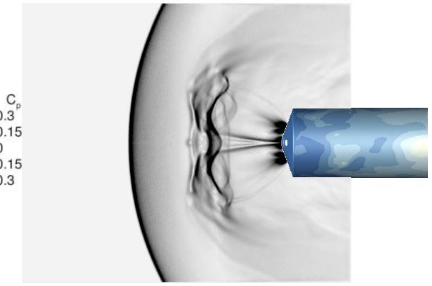
- Comparisons with other codes
- DPLR reached steady state, captures side shell C_p well.
- FUN3D and OVERFLOW simulations are similar
- OVERFLOW captures C_p and nose and near nozzle

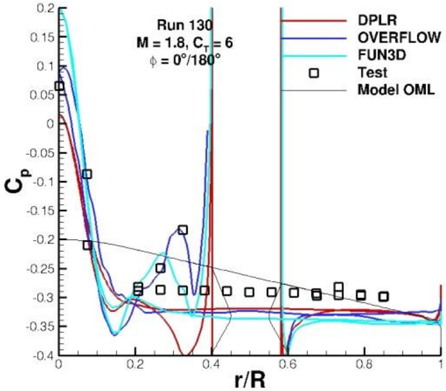


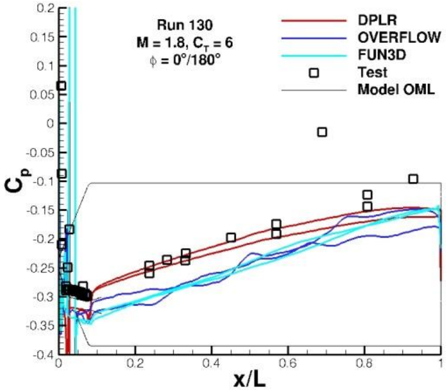


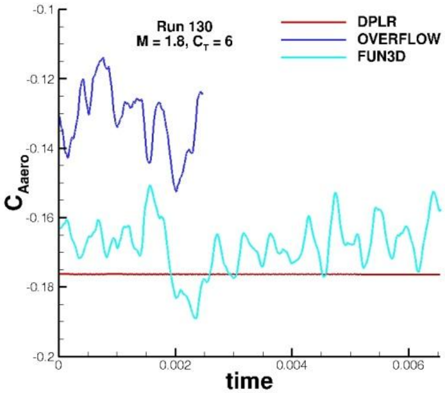
Time = 0.000044 seconds



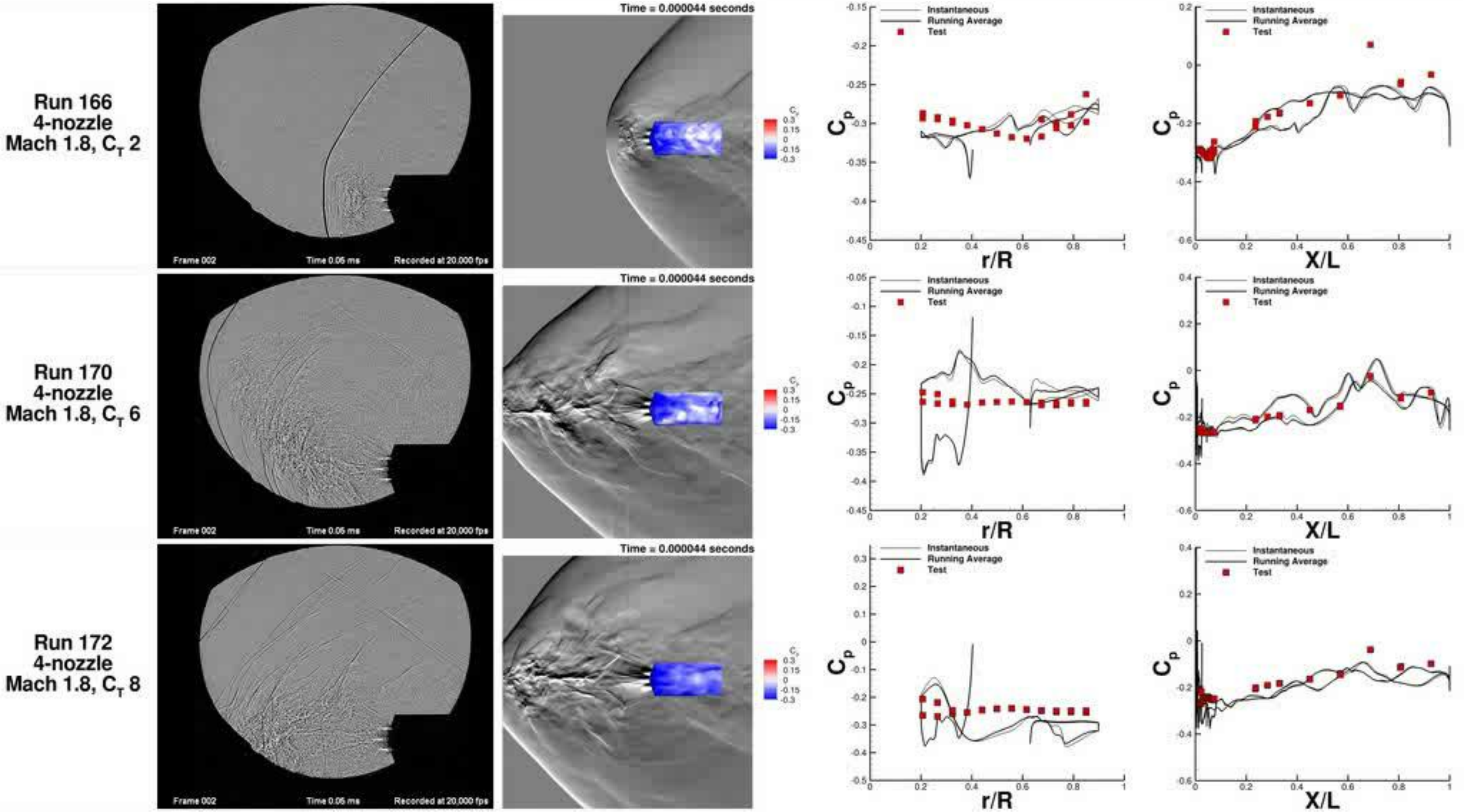








4-Nozzle, Mach 1.8



Large difference exists in data acquisition rates between the CFD and WTT.

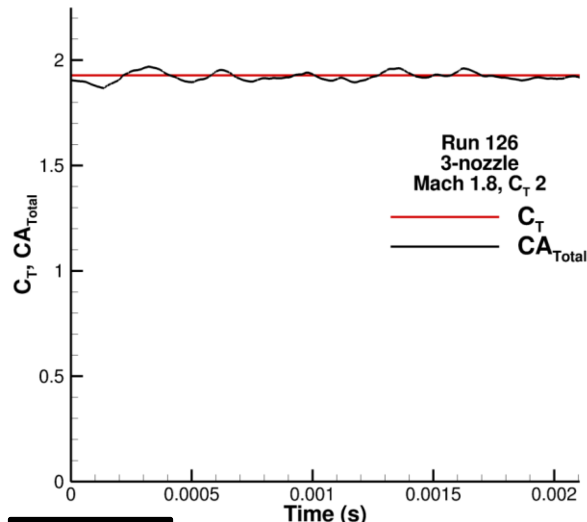
- Average surface pressure is not comparable for this chaotic of a flowfield.

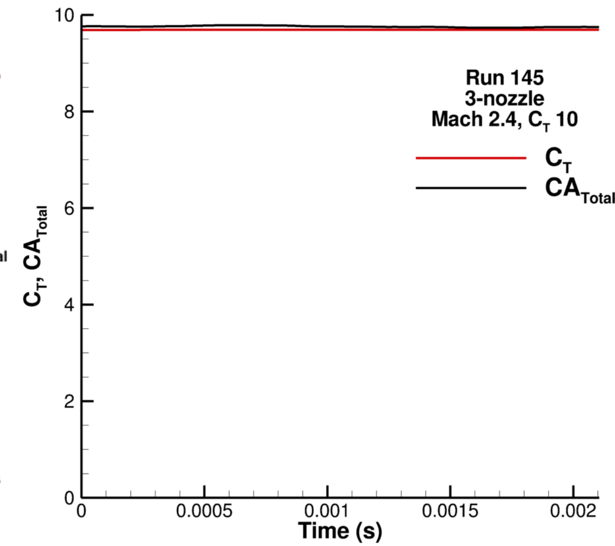
Thrust Dominance

Aerodynamic forces are small when compared to thrust.

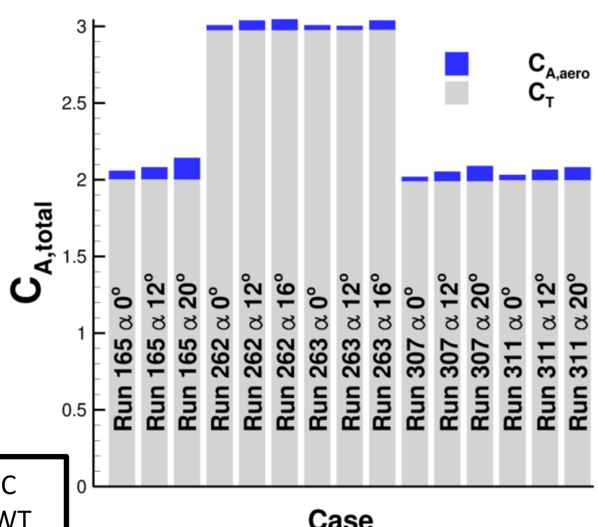
Are aerodynamic forces negligible?

- Need to know entry angles and vehicle design
- Scalability

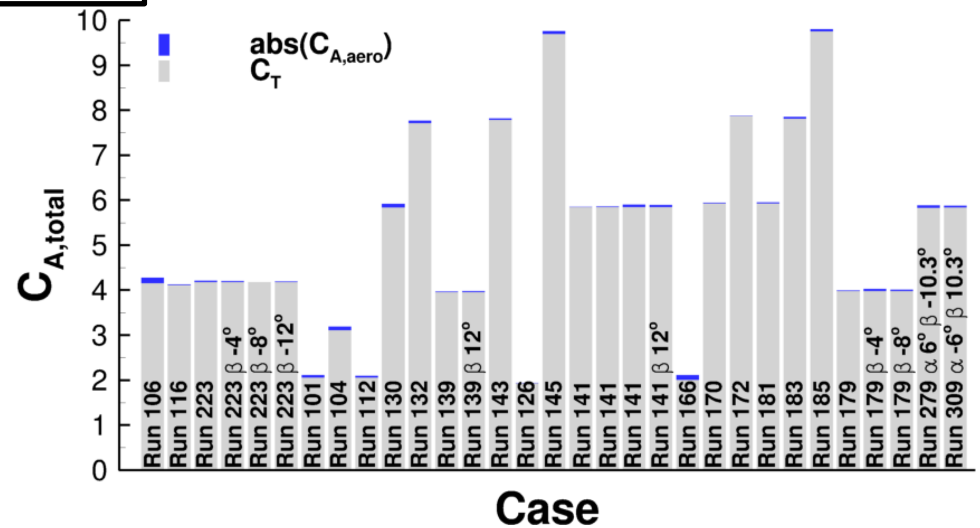




ARC UPWT



LRC UPWT



Computational Costs

- From the Ames post-test runs
- All cases run on Pleiades, either Nehalem or Westmere nodes
- This is not a perfect comparison
  - DPLR is an average of three estimates
  - FUN3D is from a single case (not an average)
  - OVERFLOW is an average of six runs
- Need time accurate runs for predictions
- Would need to cut down computational costs for parametric studies or database generation.

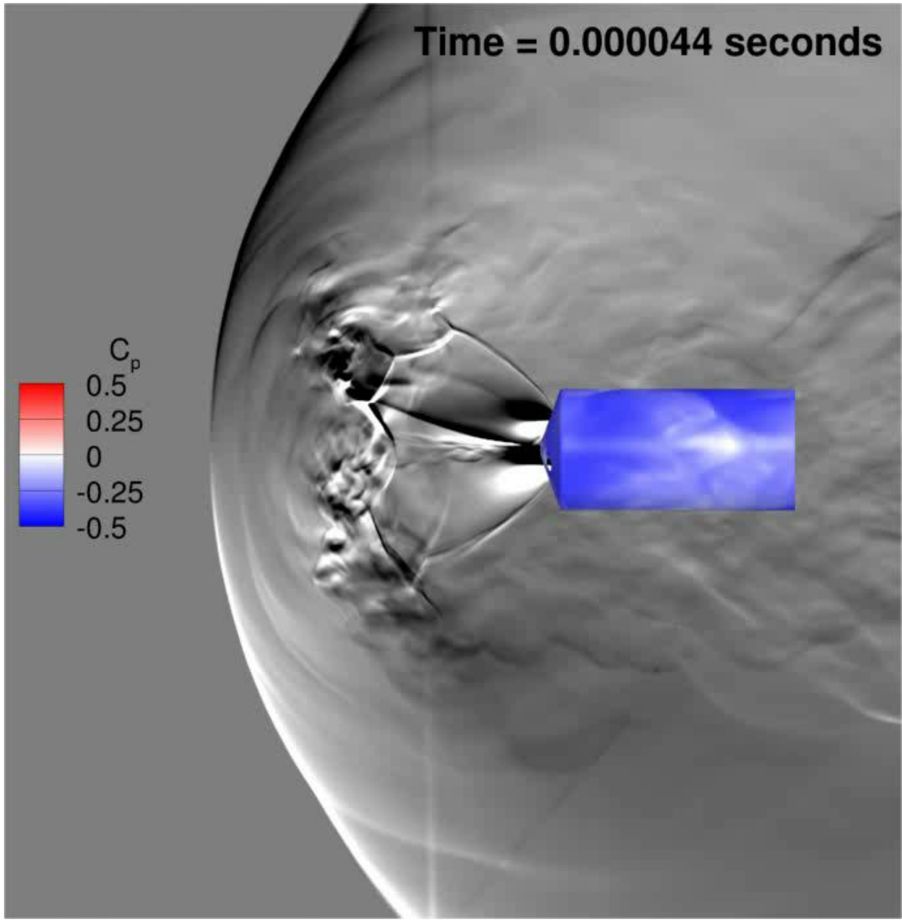
Solver	CPU Hours per Case	Iterations per Case	Grid Points	CPU seconds/ iteration/ grid point
FUN3D	28000	39500	42M	6.1e-05
DPLR	44500	106000	53M	2.9e-05
OVERFLOW	35039	73500	85M	2.0e-05

Conclusions

- Best agreement between WTT and CFD is for 1-nozzle cases and high thrust 3-nozzle cases.
- Worst agreement was for low thrust 3-nozzle cases and high thrust 4-nozzle cases.
- 3-nozzle cases more steady at C_Ts > 4.
- 4-nozzle cases highly unsteady and chaotic at C_Ts >≈ 4.
    - WTT averages spanning 2.5 seconds are probably not converged.
    - CFD averages spanning < 0.01 seconds are not too comparable to WTT data.
- Large difference in data acquisition rates exists between codes and test.
    - Test rate was 10 or 30 Hz (0.1 or 0.033 seconds per reading) for 2.5 seconds for 25 or 75 points per average.
    - CFD rate was between 190 and 400 points over a maximum of 0.017 seconds.
    - Frequencies captured by CFD not captured by test, and vice versa.
    - A “converged” average for CFD may be a completely different than the average that was obtained by the test data acquisition system.
- Aero effects are small when compared to thrust.
- Computational costs high for validation, could be much less for production.

Future Work

- More steps need to be taken to better simulate Mars EDL SRP
  - NASA funding for SRP was discontinued in Fiscal Year 2012
  - Live rocket engine test including startup in SRP conditions
  - Sounding rocket test
  - CFD of flight conditions
    - Atmospheric and rocket
- SRP is an enabling technology which still needs development
  - Large-scale propulsion
  - Aero/aerothermal analysis
  - Vehicle design
  - GN&C
- Additional funding avenues are being pursued
  - SpaceX and the USAF are researching SRP for Return To Launch Site capabilities
  - Masten Space is interested in returning rockets using SRP



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