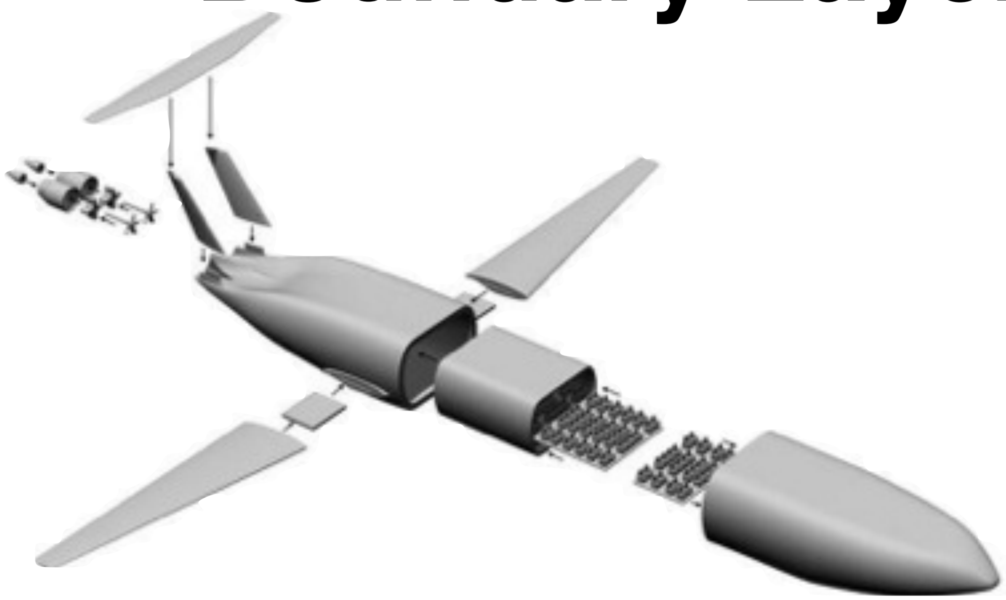
The D8 Aircraft: An Aerodynamics Study of Boundary Layer and Wake Ingestion Benefit



Shishir A. Pandya

Applied Modeling and Simulation Branch

NASA Ames Research Center

AA294: Case Studies in Aircraft Design

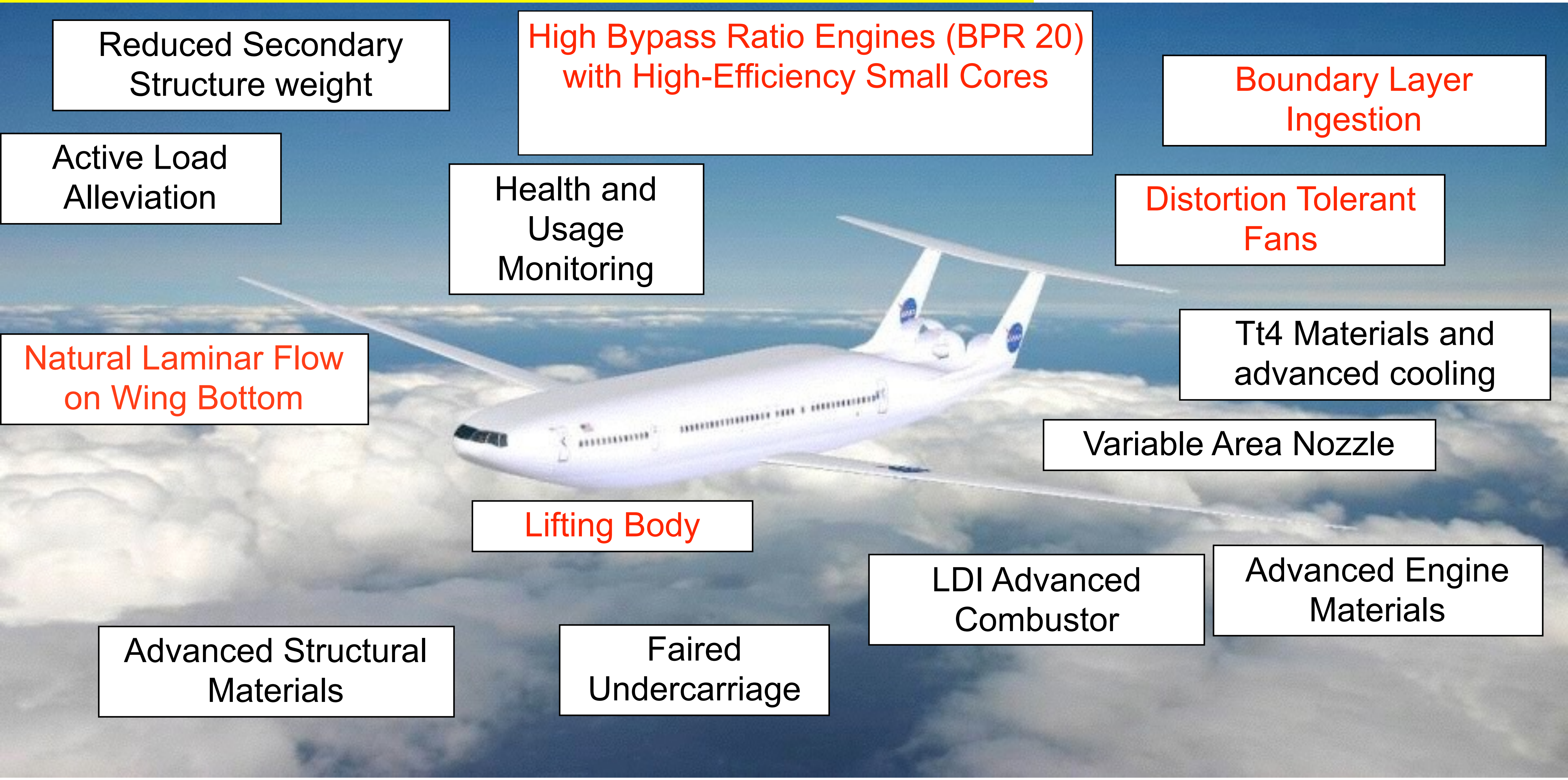
Stanford University, CA, Apr.22, 2015

With contributions from:Arthur Huang, and Alejandra Uranga at MIT, and
H. Dogus Akaydin and Shayan Moini-Yekta, Science and Technology Corporation

MIT/Pratt & Whitney/Aurora D Series

Airframe & Propulsion Technology Overview

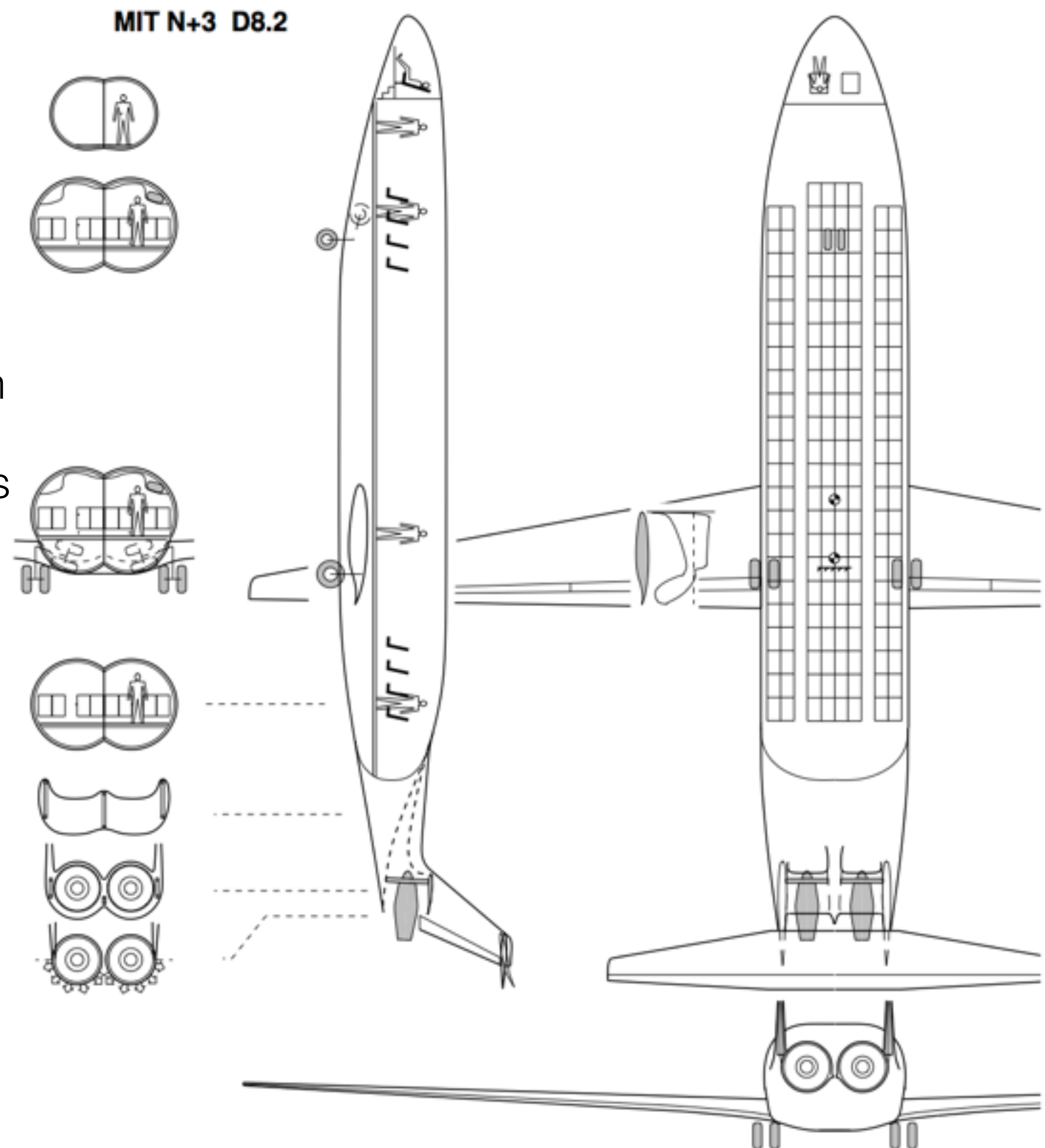
Novel configuration plus suite of airframe and propulsion technologies, and operations modifications



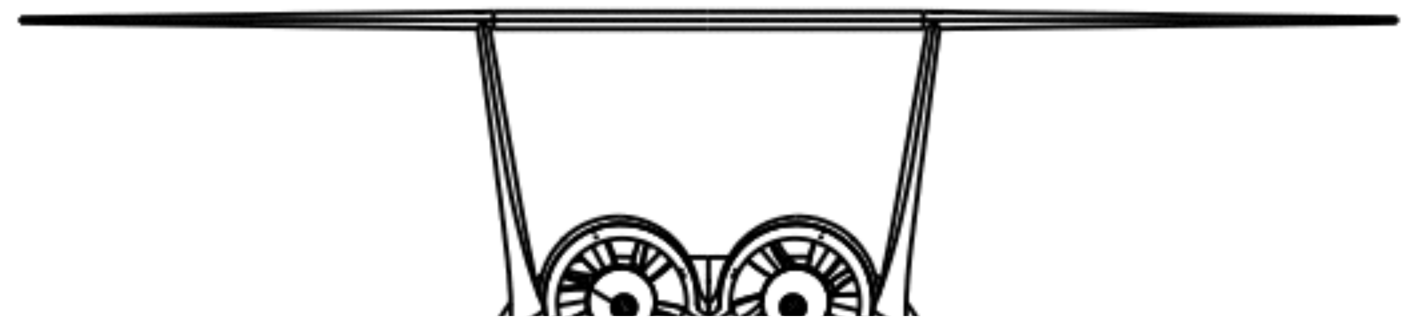
Massachusetts Institute of Technology Aurora Pratt & Whitney

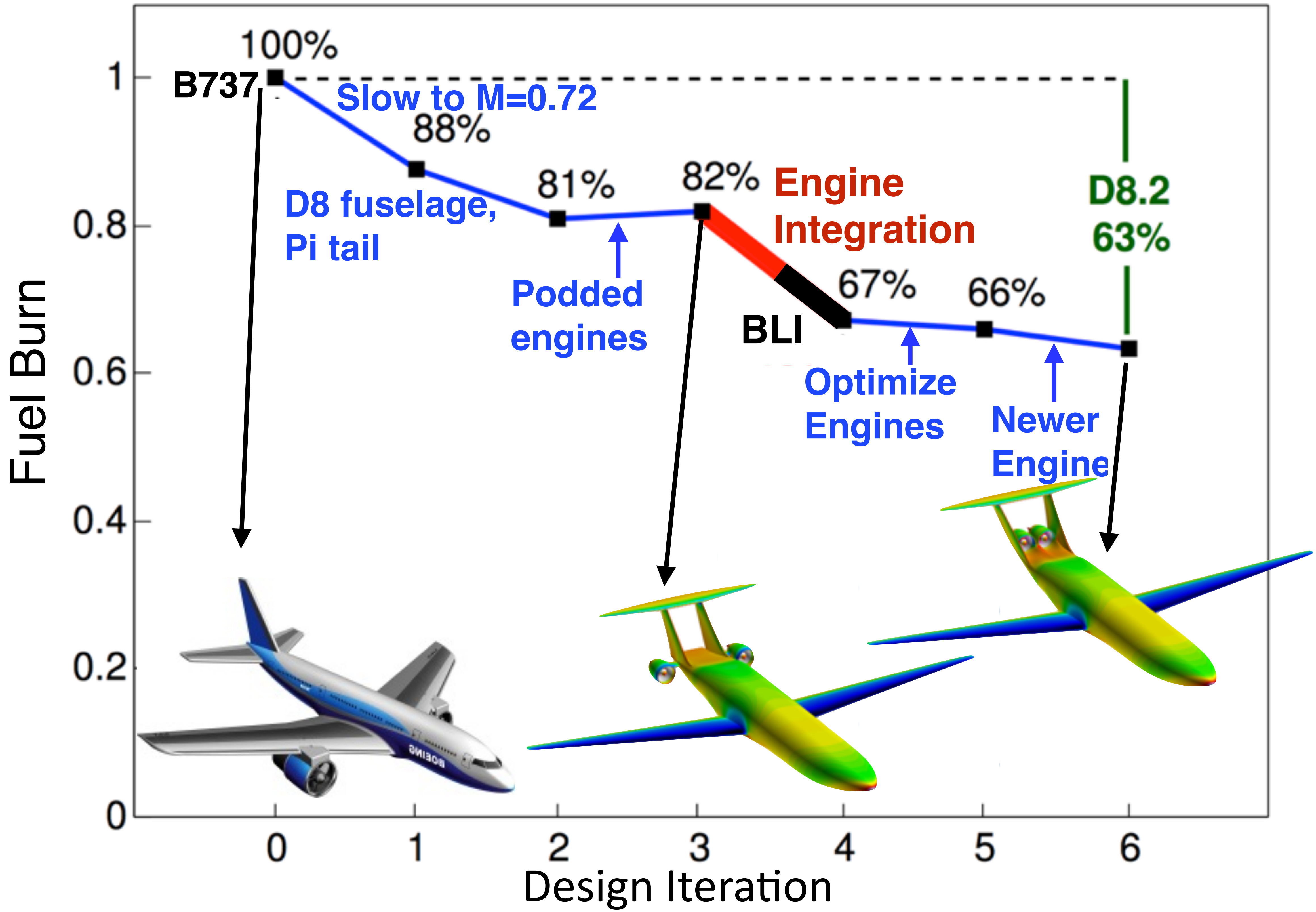
The D8 Aircraft Concept

- “Double-Bubble”
- Advanced Air Transportation Technologies (AATT) project
    - –Fixed-wing
    - –N+3 advanced vehicle configuration
        - Lower fuel burn, noise, emissions
- 180 passengers
- 3000 nmi range
- 118 ft span
- Boeing 737/A320 class
- Lifting fuselage, pi-tail
- Flush-mounted engines

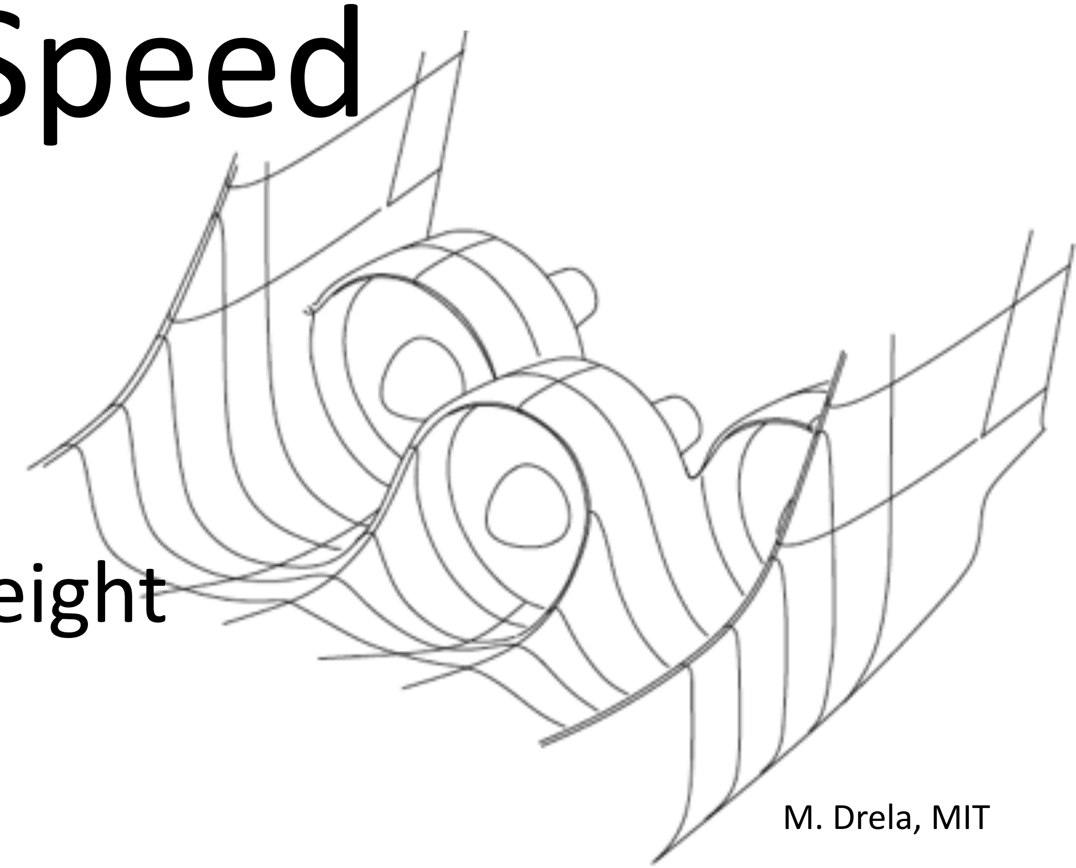


B737—>D8
Our Focus: BLI





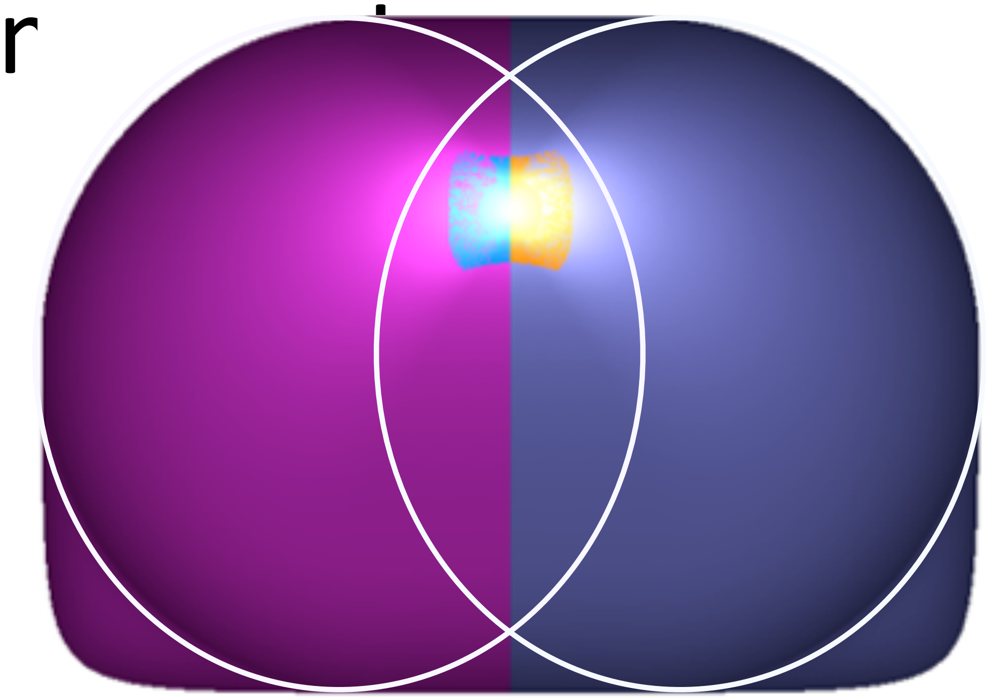
Lower Cruise Speed



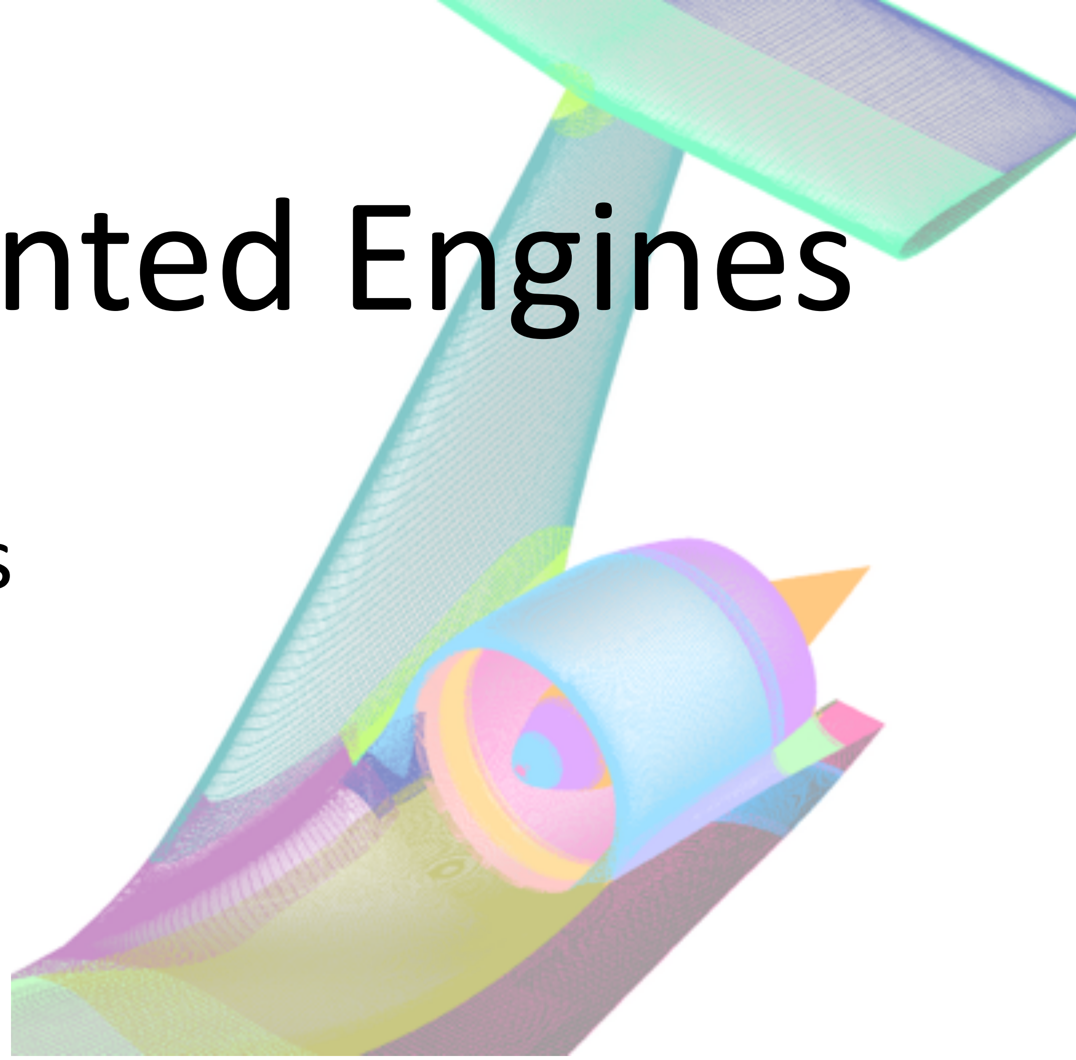
- M=0.72
  - –Lower wing sweep
    - Reduced structural load => lower weight
    - Increased CL
    - Can eliminate high-lift devices
  - –Proper speed at engine fan face (M=0.6)
    - Reduces nacelle, inlet size
- Reduced nacelle drag
  - –Nacelles embedded in the π-tail and fuselage
  - –Reduced size, weight

Fuselage Advantages

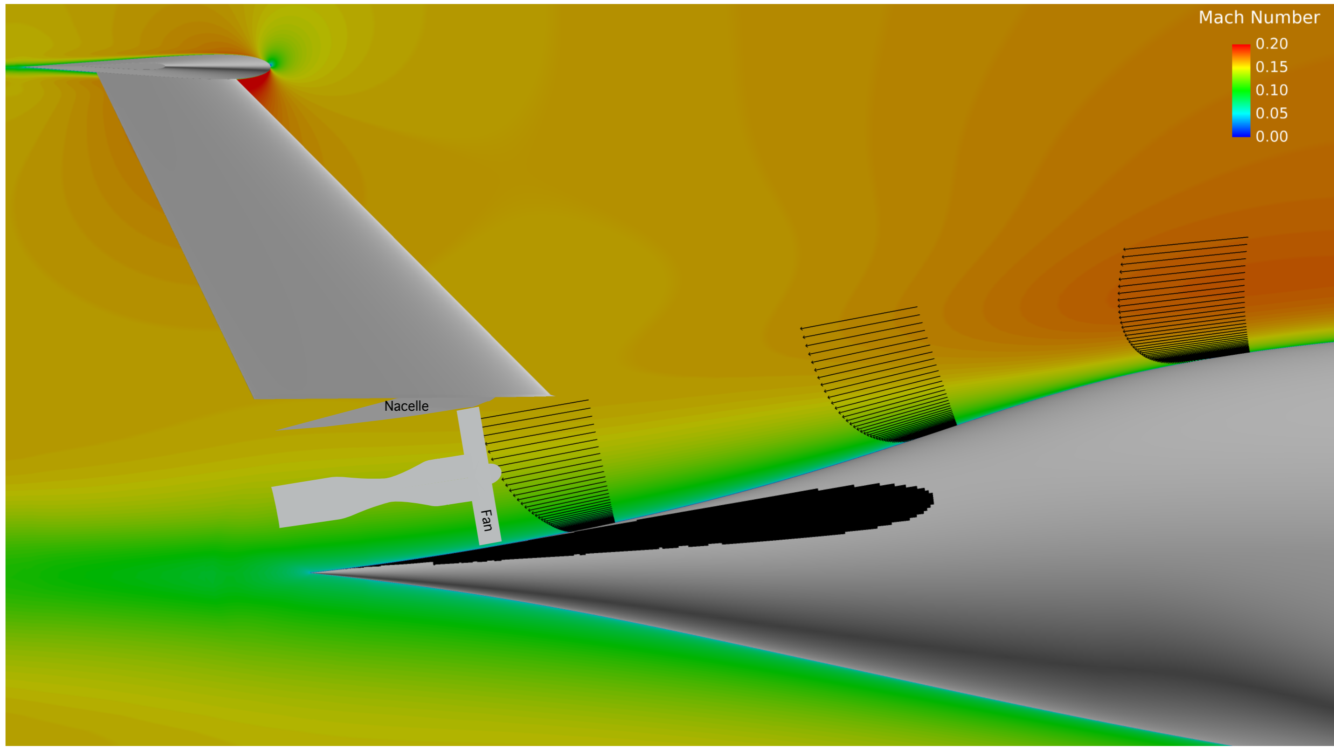
- "Double-bubble" fuselage provides more lift
  - –Gives partial span-wise loading / smaller wing
- Shorter cabin (wider body, two isles)
  - –Results in lighter landing gear support structure
  - –Faster passenger loading with two isles
- Provides a nose-up pitching r
  - –Shrinks horizontal tail
  - –Lighter horizontal tail



Embedded Rear-Mounted Engines

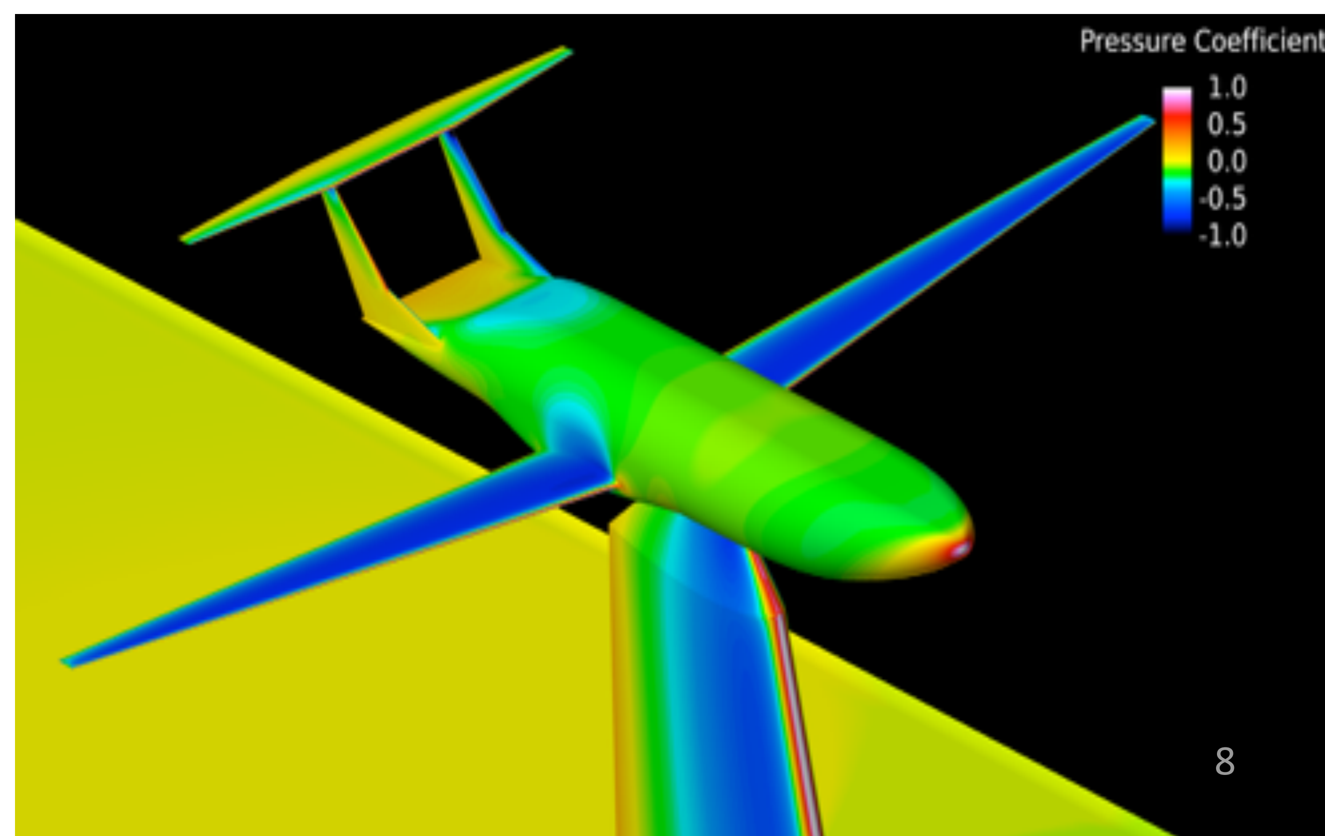


- Boundary Layer Ingesting (BLI) engines for propulsive efficiency
  - –Thicker boundary layer in the rear
  - –Designed for M=0.6 flow around engine inlet area
  - –Distortion tolerant fan
  - –High bypass ratio (~20)
- Lower engine-out yaw
  - –Reduced vertical tail size
- Noise shielded by fuselage



Previous Computational Work

- "Double-bubble" fuselage provides more lift
  - Gives partial span-wise loading / smaller wing
- Thicker boundary layer in the rear
  - Designed for M=0.6 flow around engine inlet area
- Provides a nose-up pitching moment
  - Shrinks horizontal tail
  - Lighter horizontal tail
- Validation of CFD
  - Mesh sensitivity
  - Comparison to Experiment



Goals and Approach

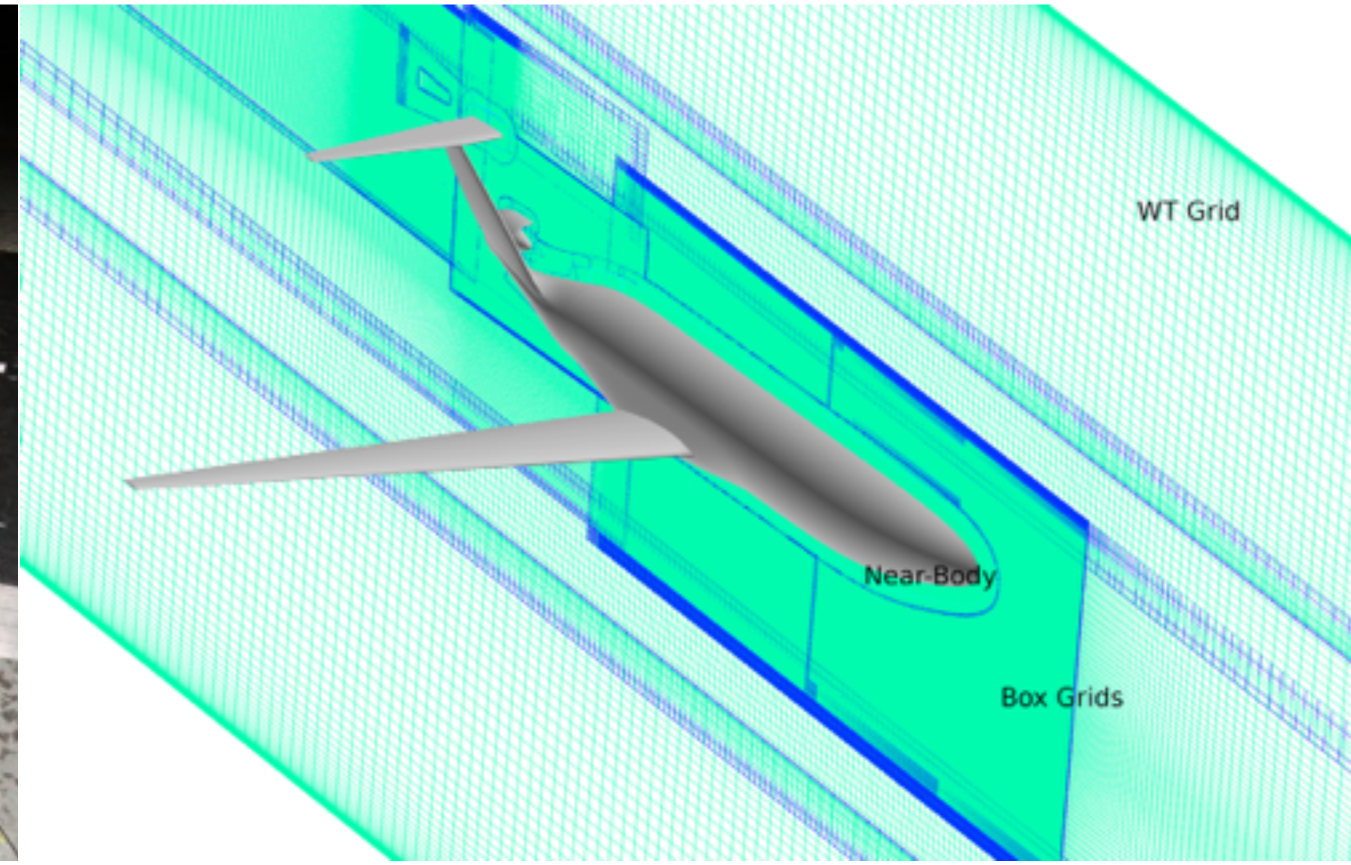
- Goal: Quantify benefits of boundary layer and wake ingestion for the D8
- Overset CFD using CGT and Overflow-2:
  - –CFD validation
    - NASA LaRC 14x22 WT data for a 1:11 scale model
  - –Quantifying the BLI and wake ingestion benefit:
    - Direct Comparison between:
      - –Efficient conventional (podded nacelle) configuration
      - –BLI (integrated nacelle) configuration

Wind Tunnel Configurations

Configuration Details

- WT runs at 70 mph, Re_c = 570,000
  - lower-speed and Re compared to full-size at M=0.72
- 1:11 Scale powered model
- Wing designed for low Mach, low Re
- Same wings
- Most of fuselage is the same
- Same propulsors plug into both podded and integrated configuration empennage sections

D8 Model

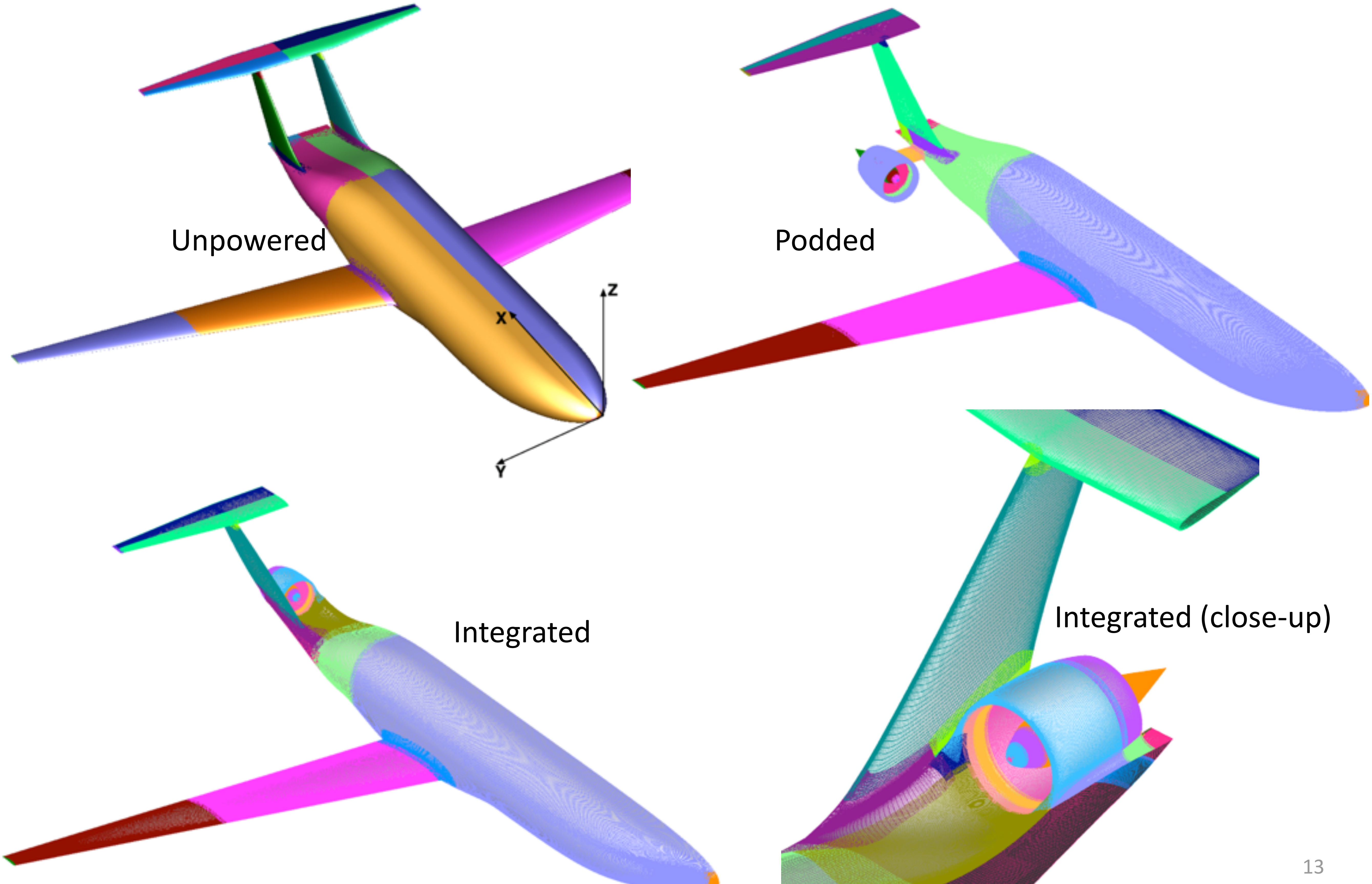


Blue indicates regions of overlap

- Larc 14x22 WT model
  - 1:11 scale, Full body
  - Mounting hardware controls AoA

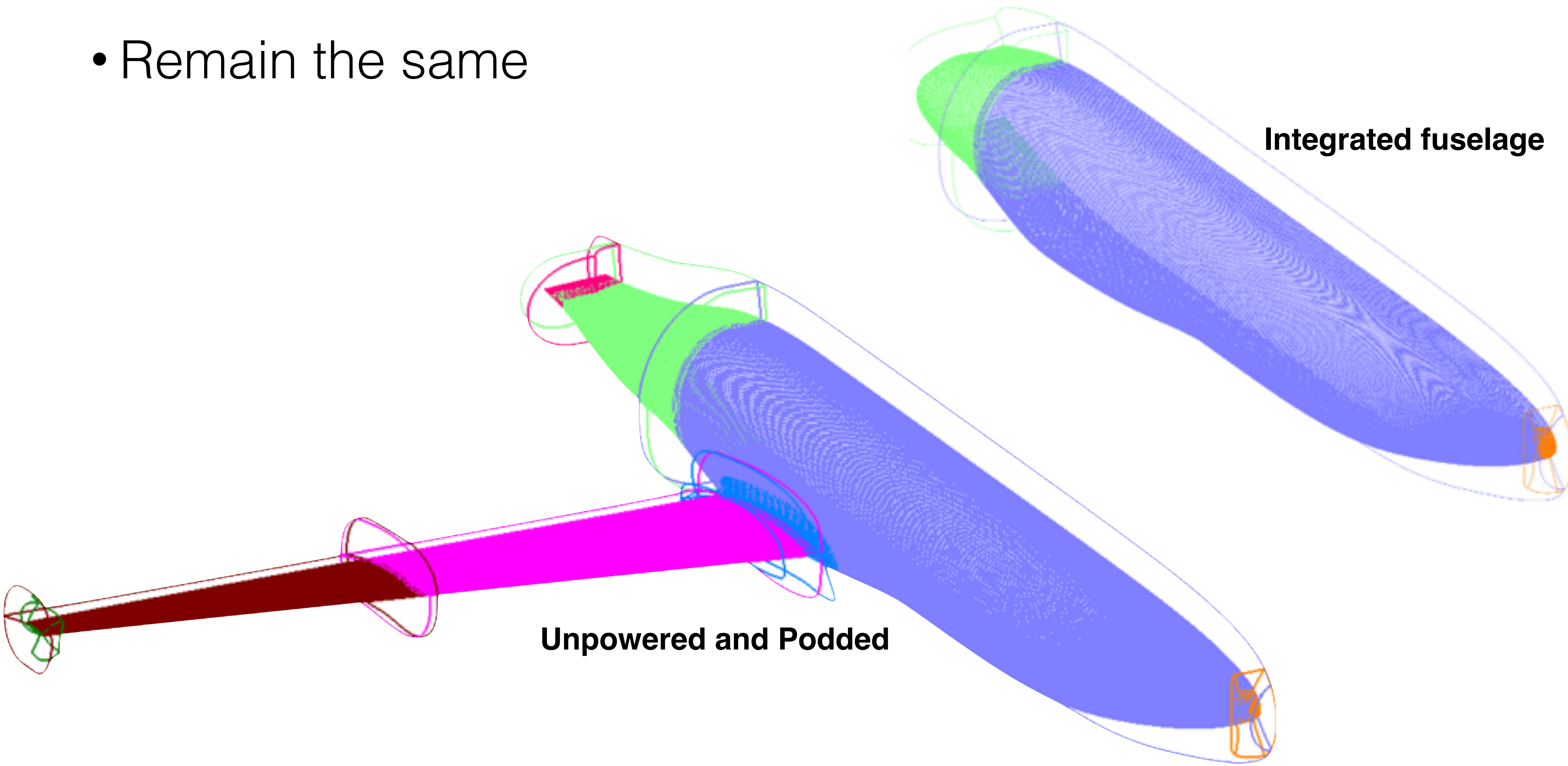
- Computational model
  - 1:11 scale, Half body
  - No mounting hardware
  - Inviscid wind tunnel walls

Computational Configurations

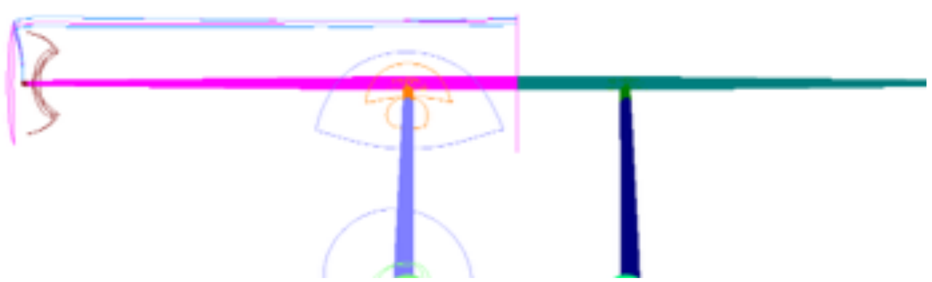


Fuselage and Wing Grids

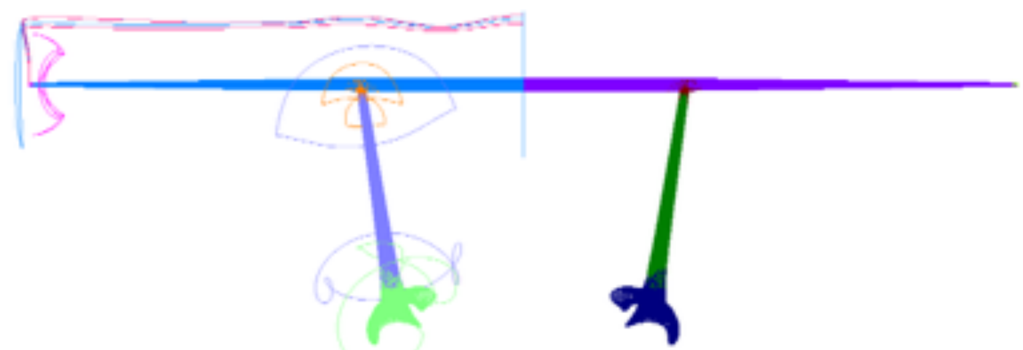
- Remain the same



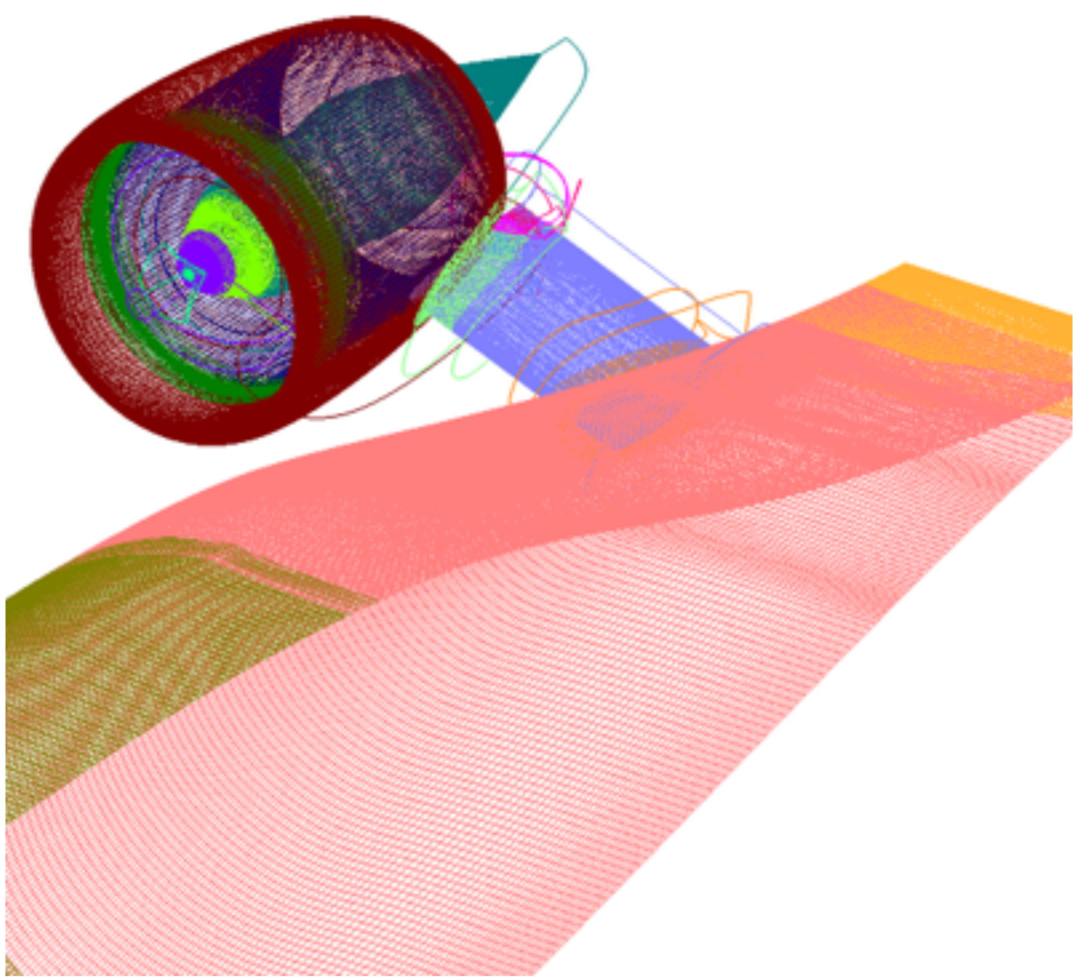
π-tail, Nacelle, Pylon

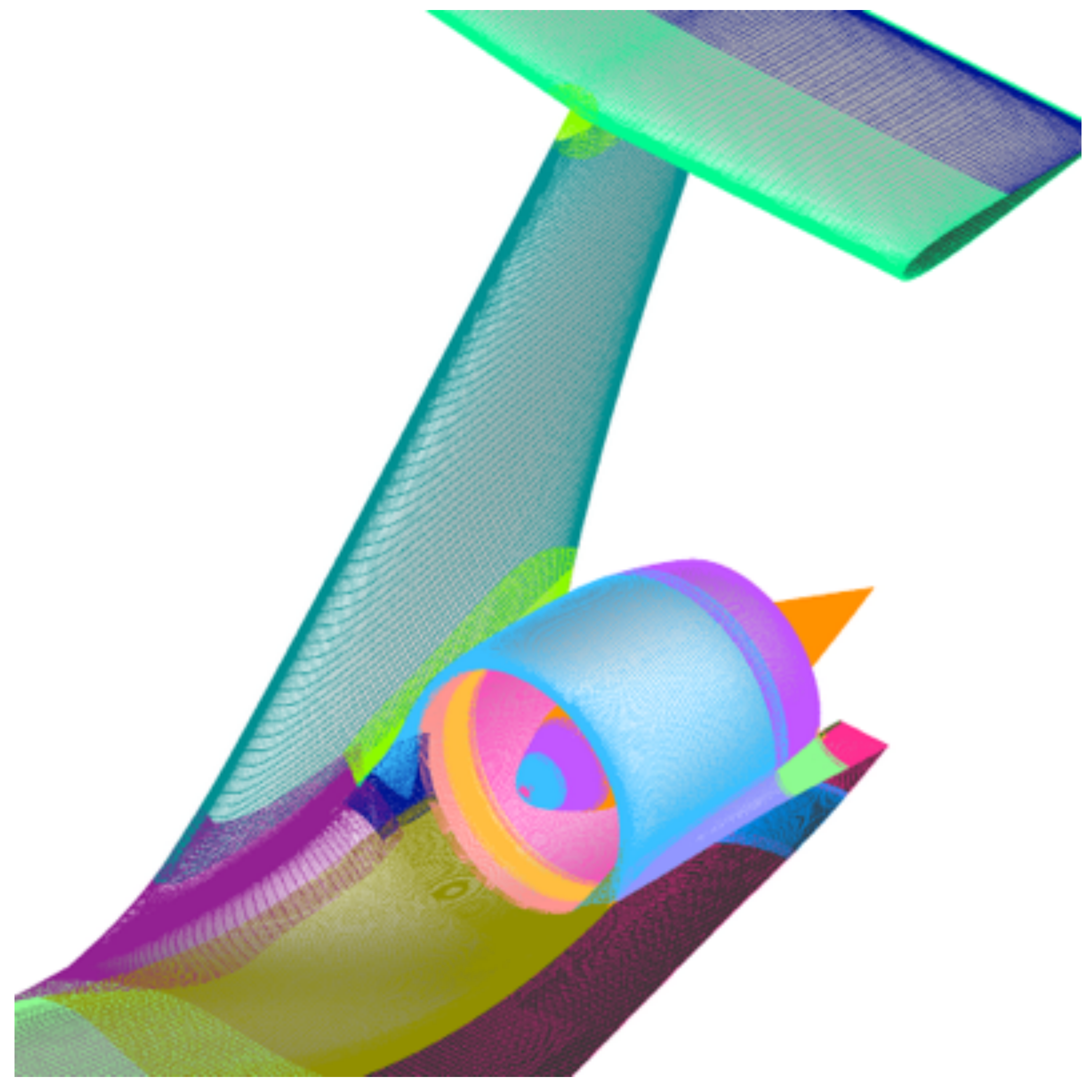


Unpowered and Podded



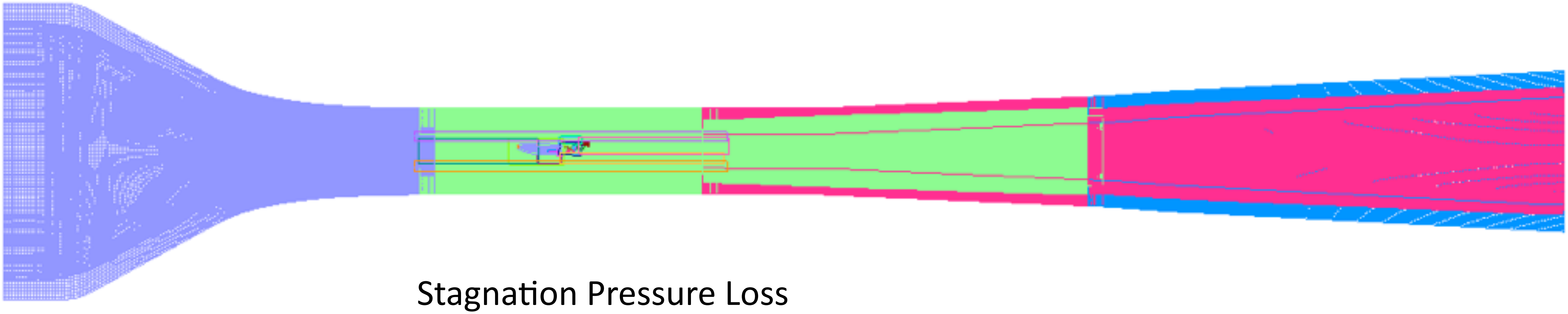
Integrated

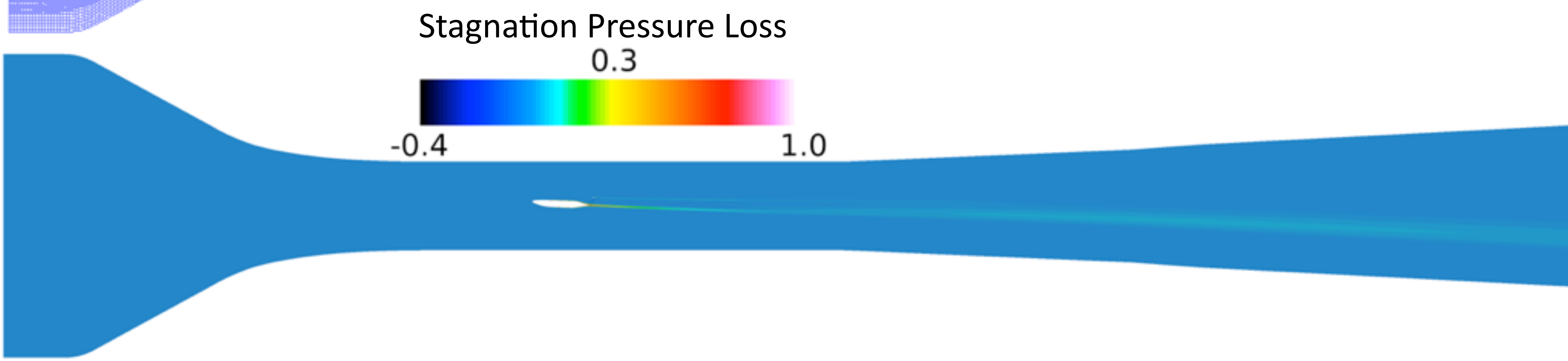




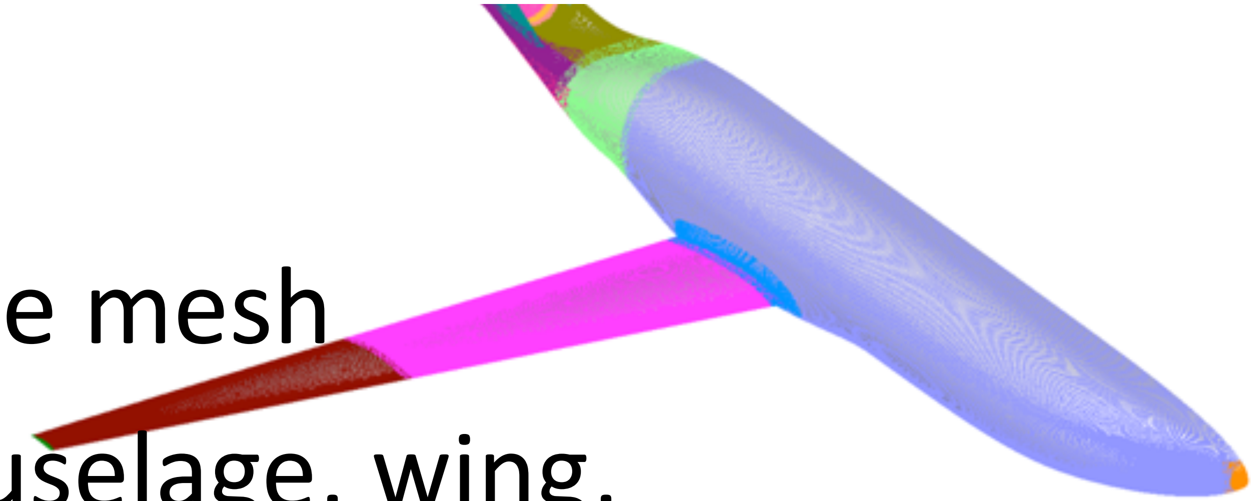
Wind Tunnel Grids

- Inviscid wall boundary condition
- 7 grids (4 wall grids, 3 core grids) + box grids
- Mach and Re number matched at pitot probe

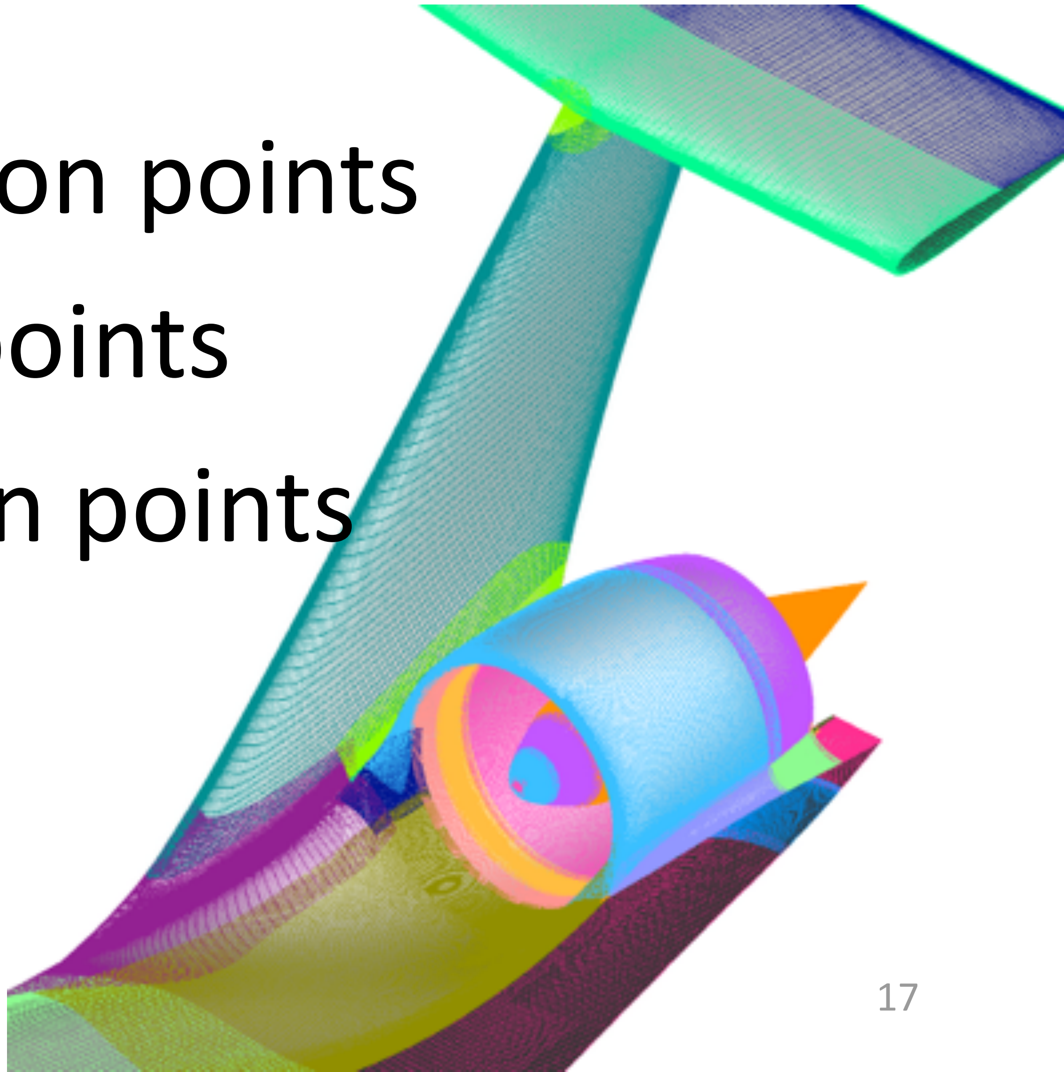




Computational Mesh



- Chimera Grid Tools
  - –Overset surface and volume mesh
    - Same grids for forward fuselage, wing, and WT
  - –Unpowered: 36 grids, 113 Million points
  - –Podded: 49 grids, 130 Million points
  - –Integrated: 64 grids, 135 Million points
  - –y+ ≈ 0.7

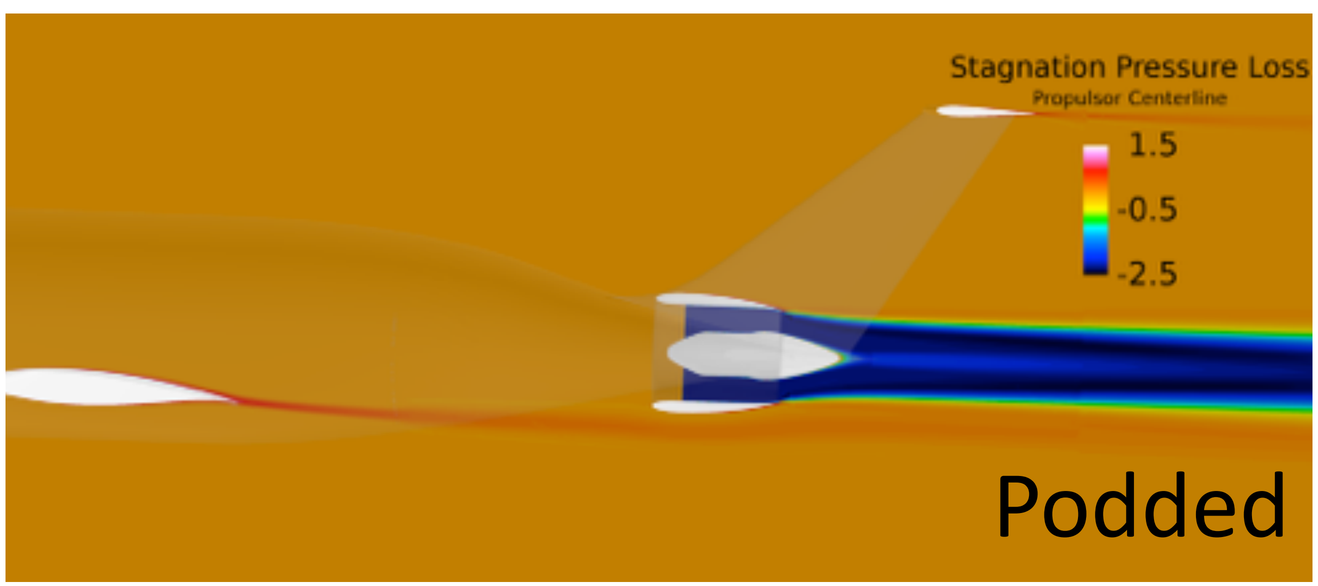


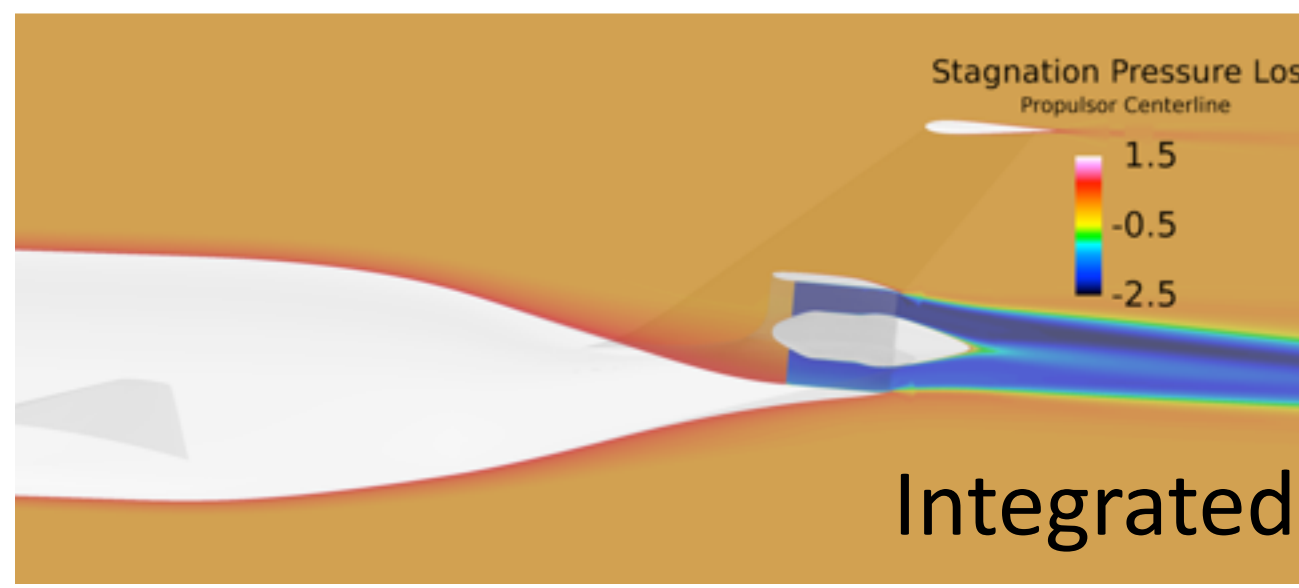
CFD Solver

- OVERFLOW
  - 3D, RANS solver for overset structured grids
  - Diagonalized approximate factorization Scheme
  - 2nd order central difference + artificial dissipation
  - Matrix dissipation
  - RANS SST turbulence model
- Flow Conditions
  - Mach=0.088
  - Re = 44000/in.

Fan Model and its Effect

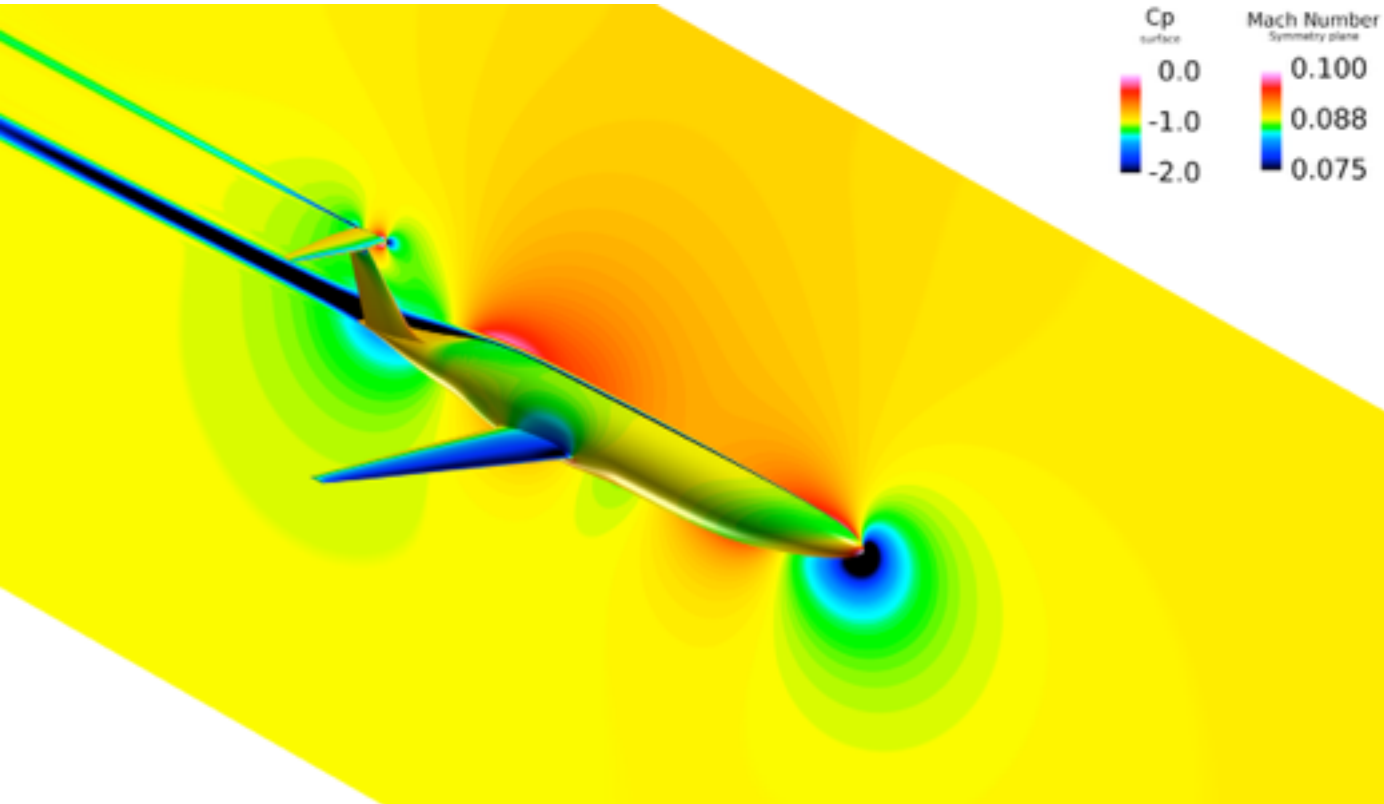
- Actuator disk
  - Uniform pressure jump
- Four cases with increasing pressure jump settings
  - For both podded and integrated
  - Integrated sees a lower mass flow

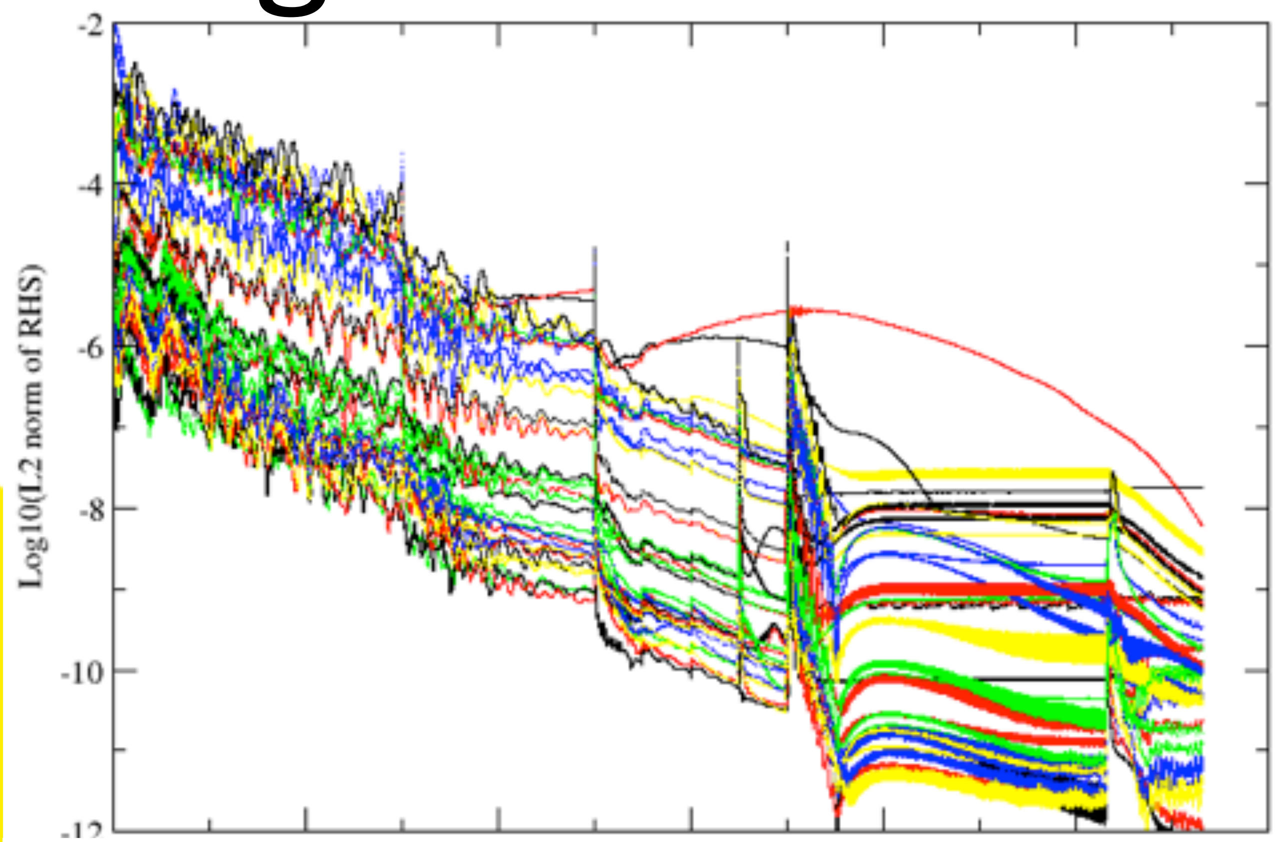


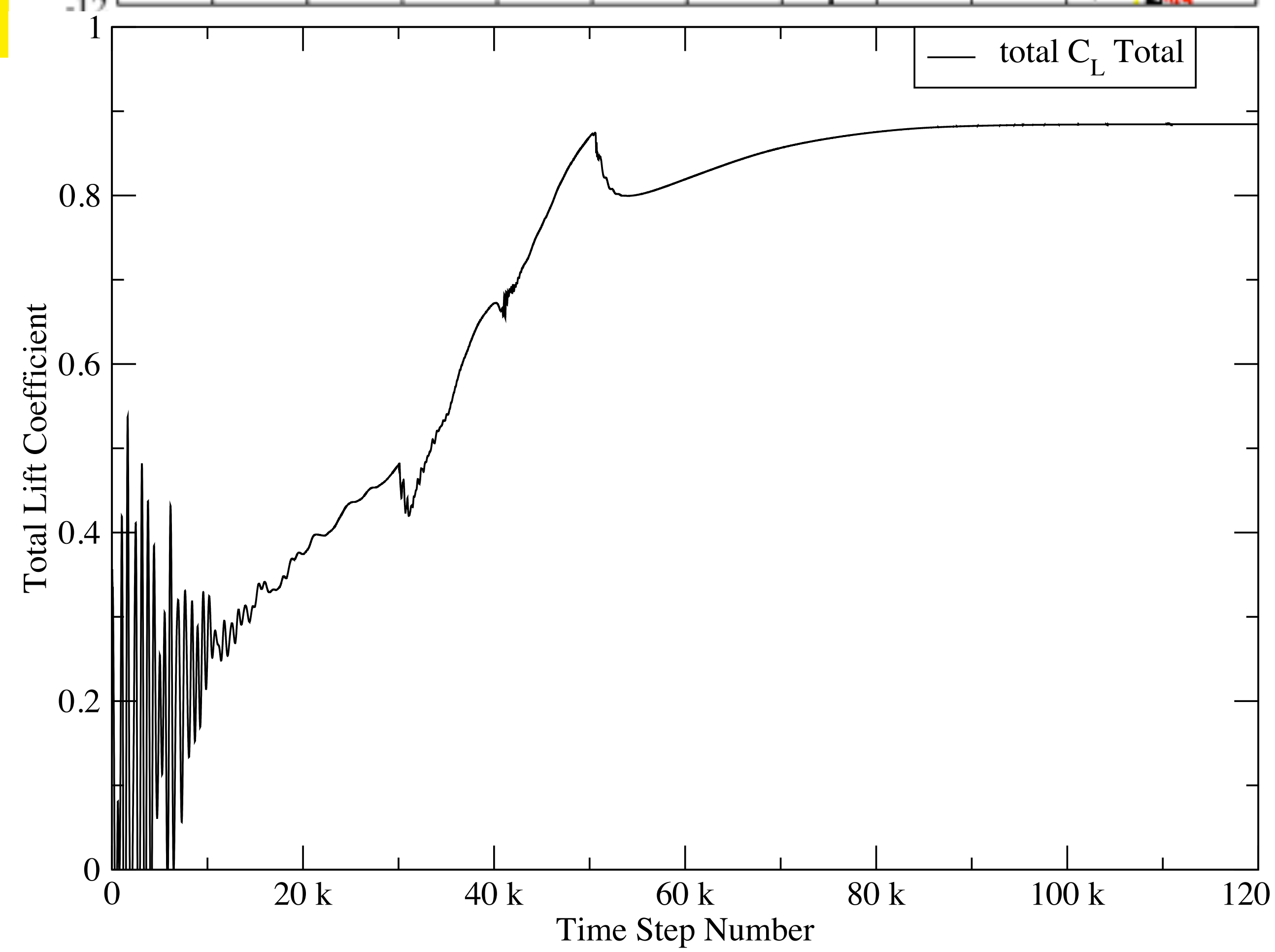


Cuts through propulsor centerline.

Typical Convergence

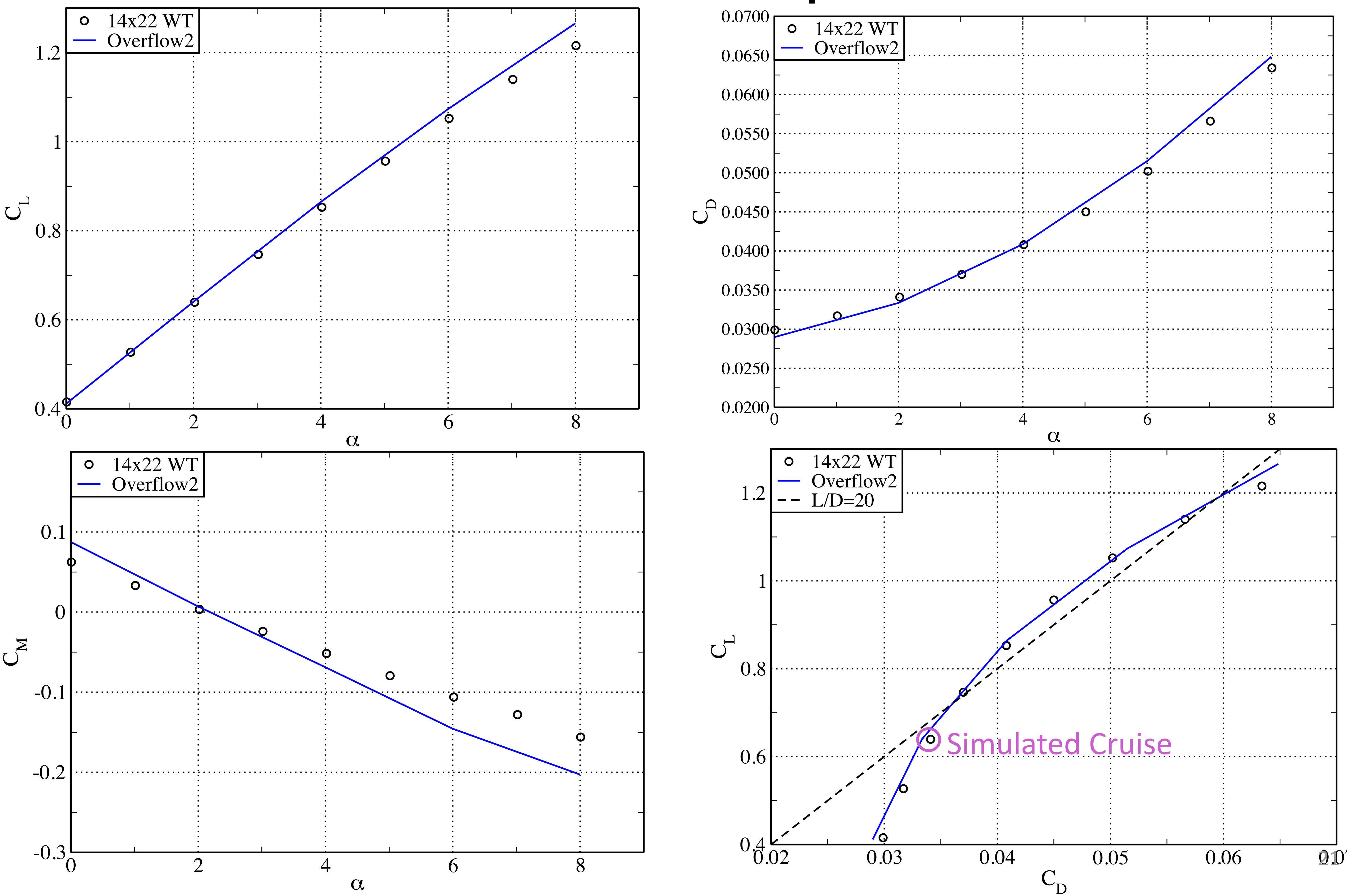






- Simulations without fans
- Alpha sweep
- Compare to Wind Tunnel test data
- Iterations to match Mach & Re at pitot probe

Validation-unpowered



Propulsor Inlet Flow Comparison

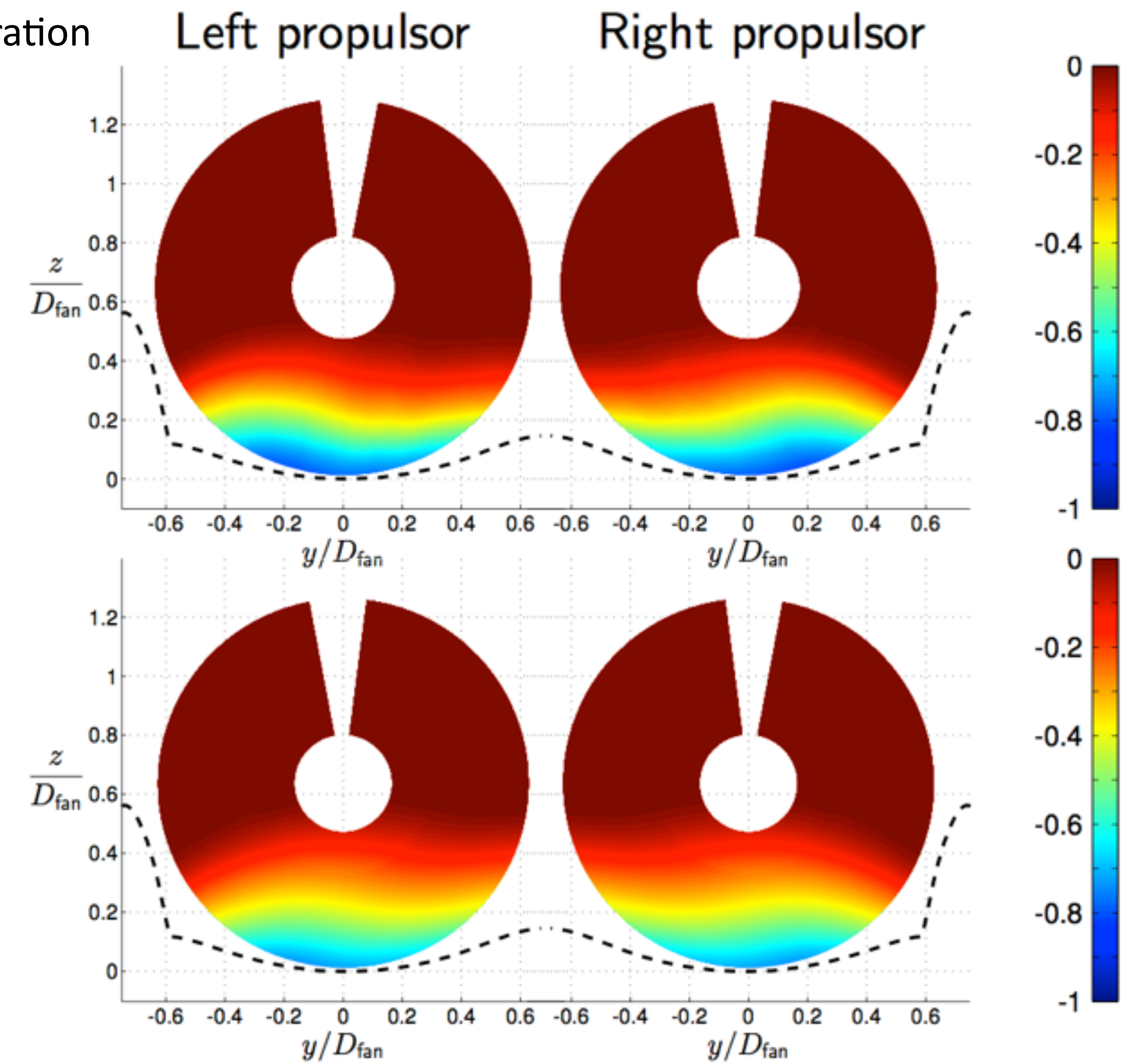
Total pressure coefficient $C_{p_t} = \frac{p_t - p_{t_\infty}}{q_\infty}$

Integrated Configuration

AOA=2°

14x22 WT

Overflow

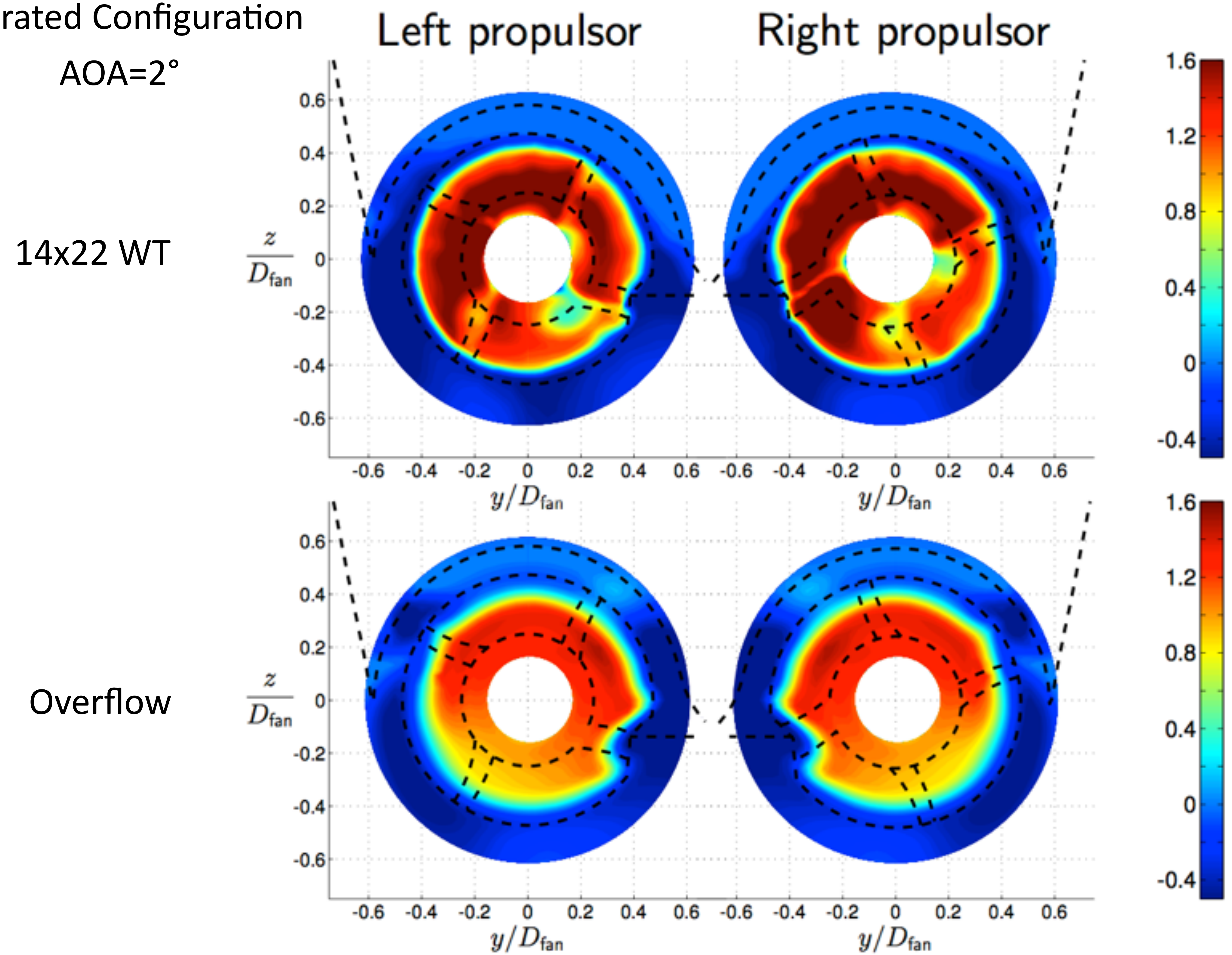


Propulsor Exit Flow Comparison

Total pressure coefficient $C_{p_t} = \frac{p_t - p_{t_\infty}}{q_\infty}$

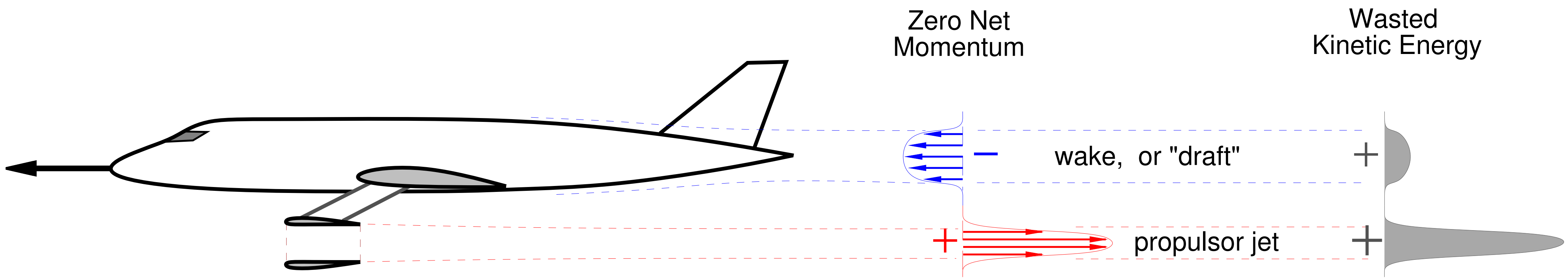
Integrated Configuration

AOA=2°

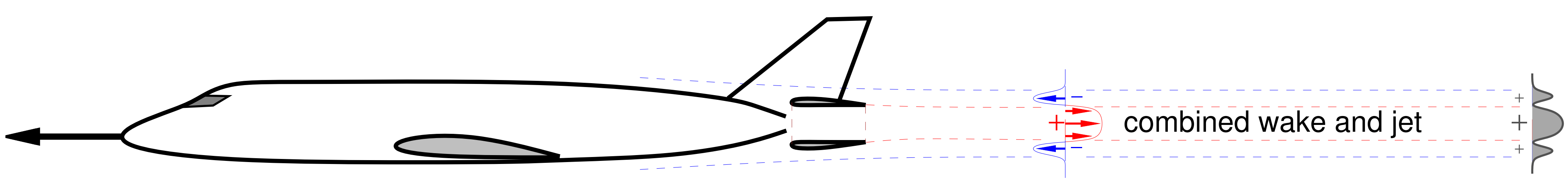


Boundary Layer Ingestion

- Conventional: wake/BL energy lost



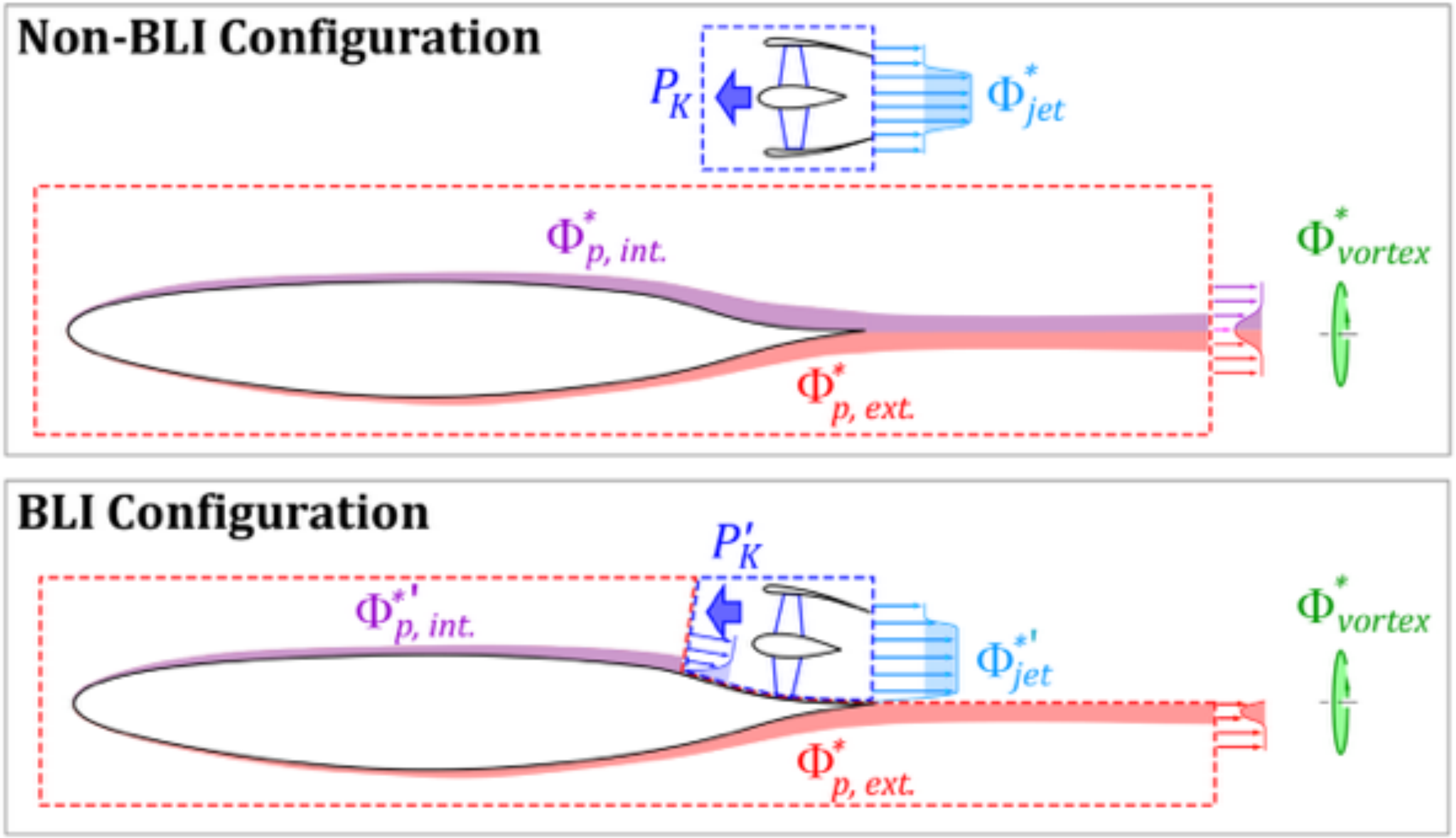
- BLI: Fuselage boundary layer ingested by propulsor
  - –> Reduced viscous dissipation in combined wake + jet
  - –> Reduced flow power required from propulsor



- Use Power-balance method (Drela, 2009, AIAA J.)

Power Balance Method

- Mechanical energy sources and sinks
  - –Sinks: Boundary layer, Wake
  - –Source: Jet



- Power-in (P_K) = Dissipation (Φ)
- Compute dissipation: upstream of the surface of interest, and downstream mixing

BLI Benefit

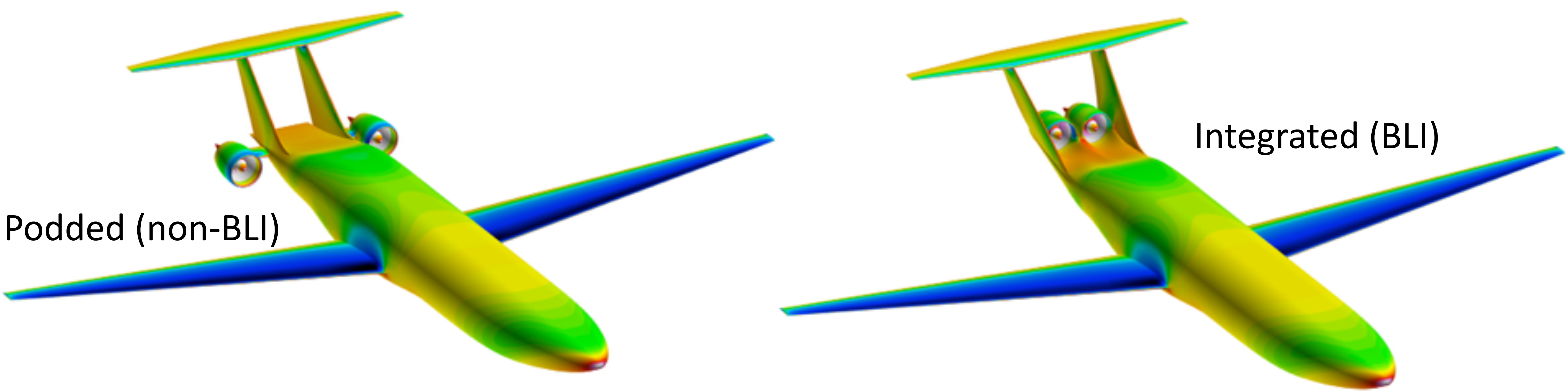
- Compare mechanical flow power:

$$P_K = \oint_{propulsor} (p_{t,\infty} - p_t)\,(\mathbf{V}\cdot\hat{\mathbf{n}})\,\mathrm{d}A\ .$$

  – Power transmitted by propulsor to the flow

- Savings in power required: integrated vs. podded

$$\boxed{\text{BLI benefit} \equiv \left.\frac{P_{K_{\text{non-BLI}}} - P_{K_{\text{BLI}}}}{P_{K_{\text{non-BLI}}}}\right|_{\text{at given } F_X}}$$



Computing BLI Benefit

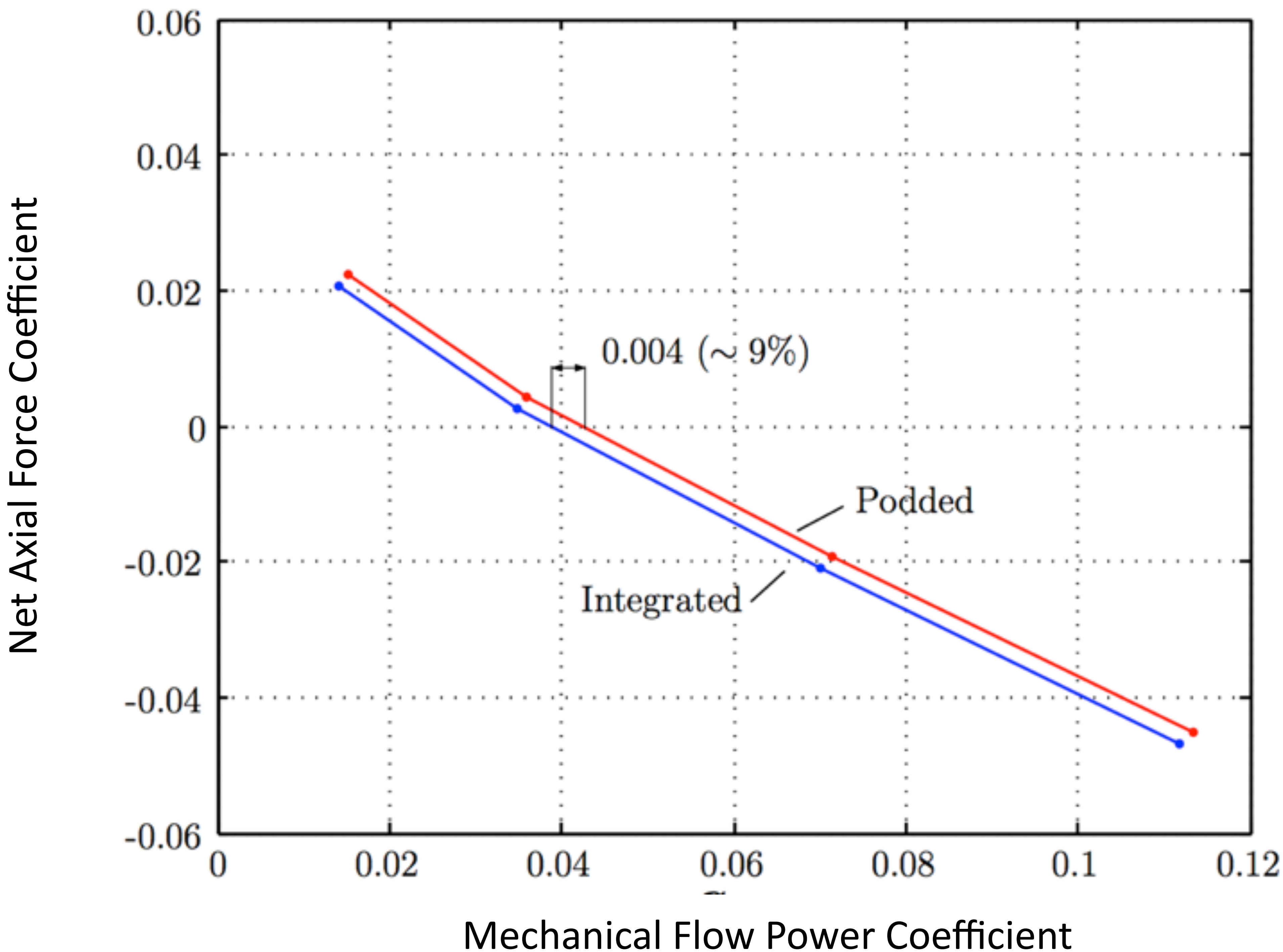
- Mechanical flow power

$$P_K = \oint_{propulsor} (p_{t,\infty} - p_t)\,(\mathbf{V} \cdot \hat{\mathbf{n}})\,\mathrm{d}A\ .$$

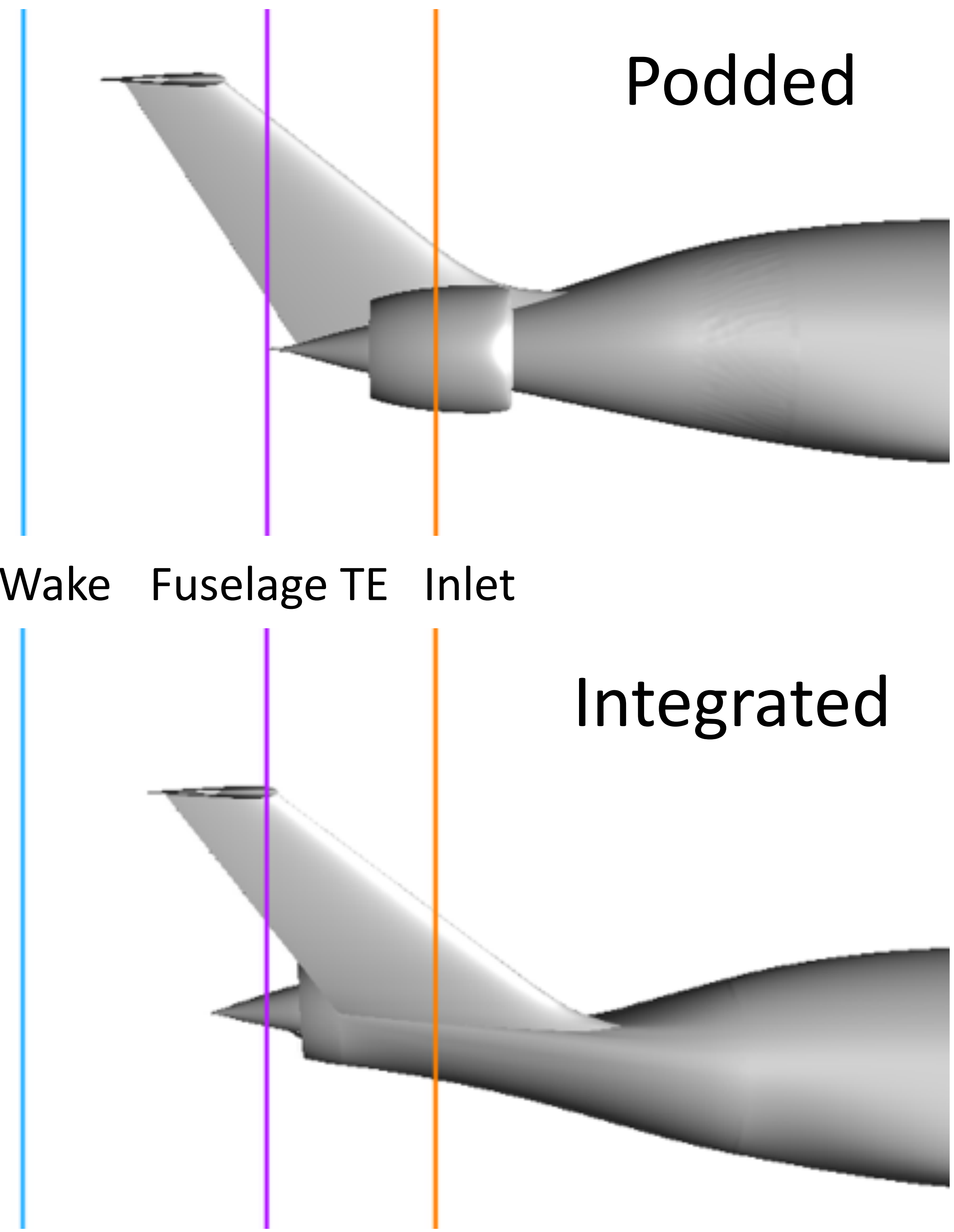
- Net axial force: pressure force + viscous force.
  – On airframe solid surfaces + actuator disk
- Compare podded and integrated configs
  – At cruise condition
    - Net axial force = 0

- Drela, 2009 "PowerBalance in Aerodynamic Flows".

Benefit of BLI (Computational)

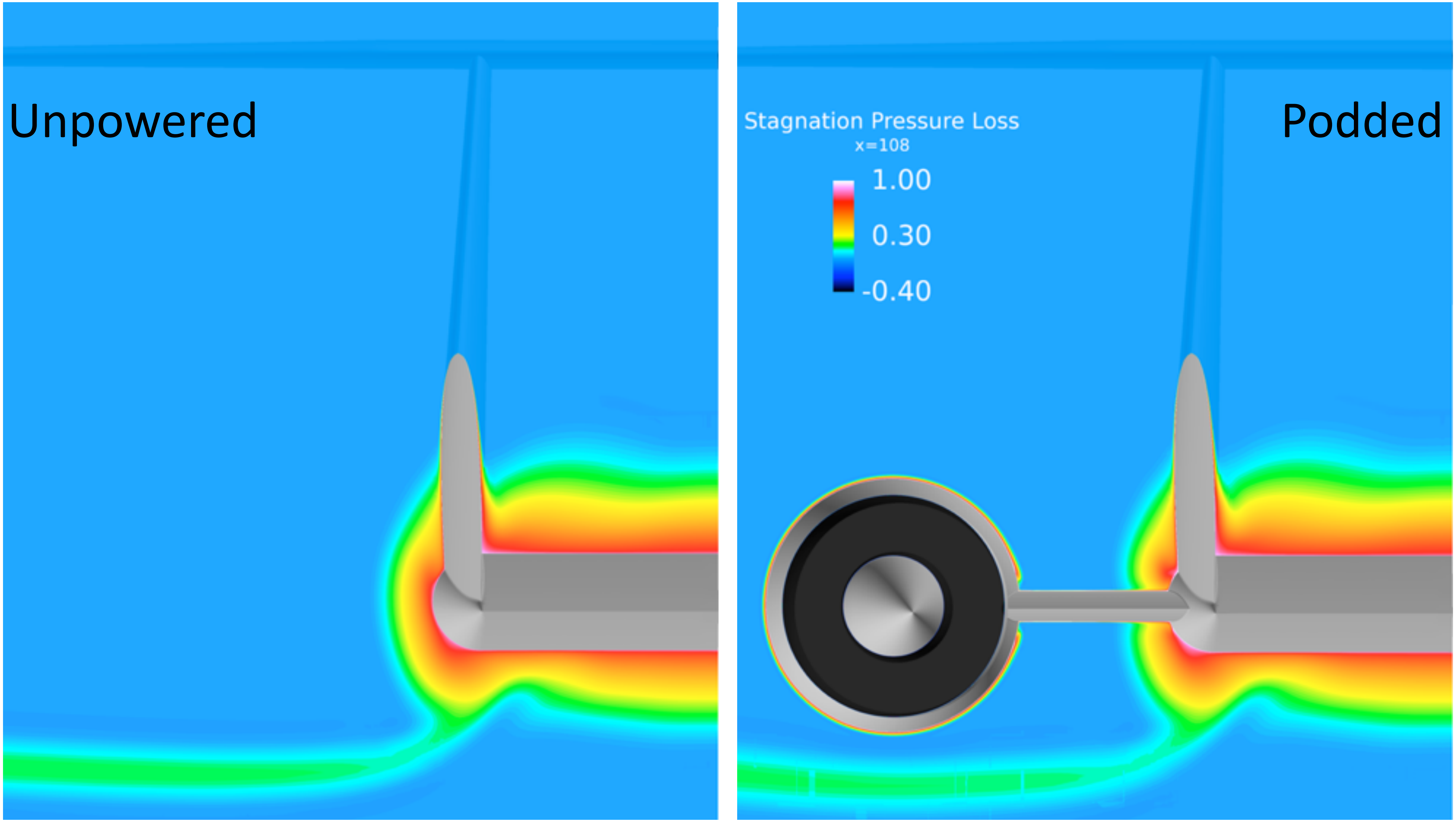


Where is the Benefit Coming From?



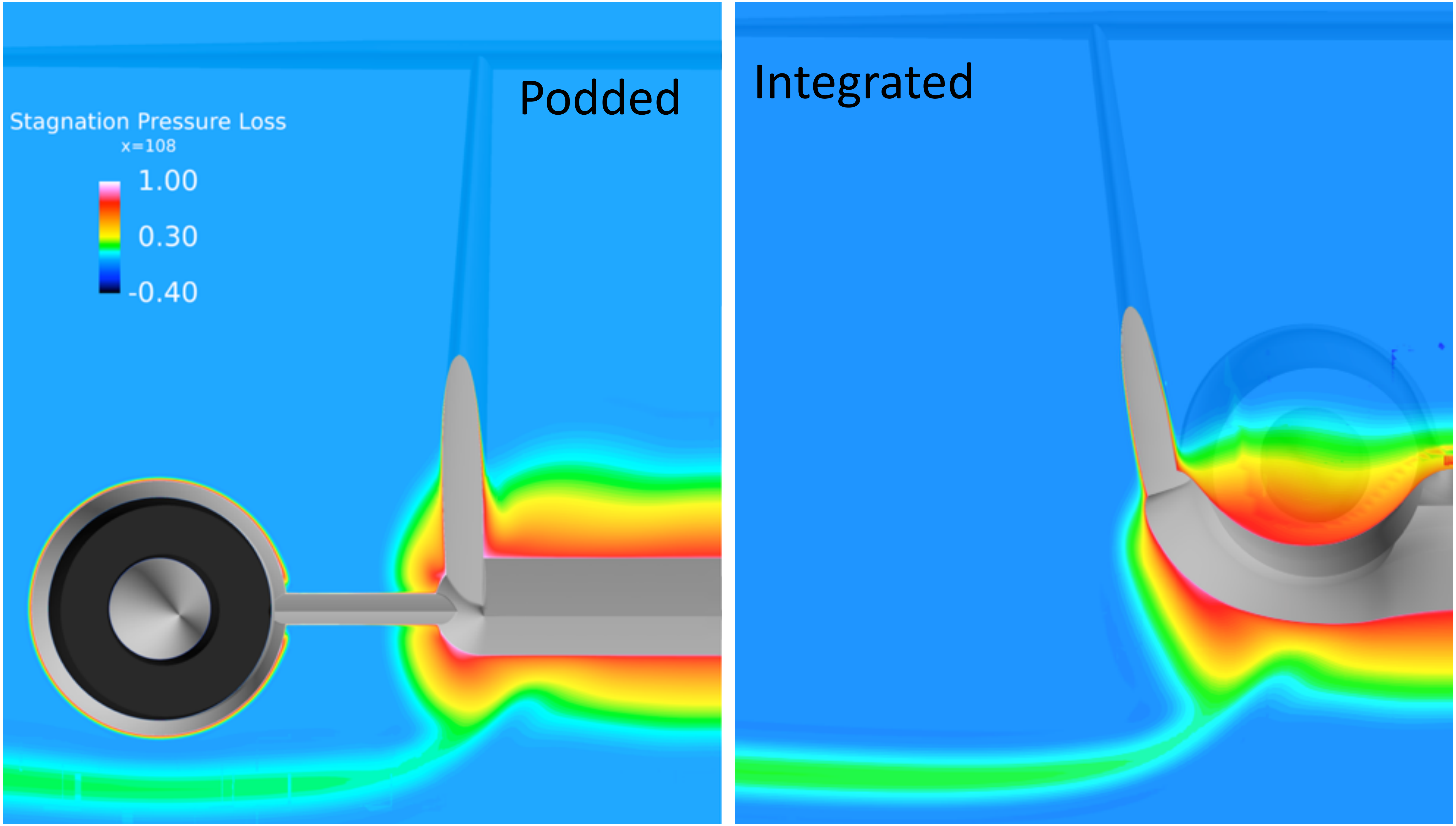
- Identify sinks of power
  - Upstream viscous dissipation
    - measured by stagnation pressure flux
    - We can focus on stagnation pressure loss and dissipation

Inlet

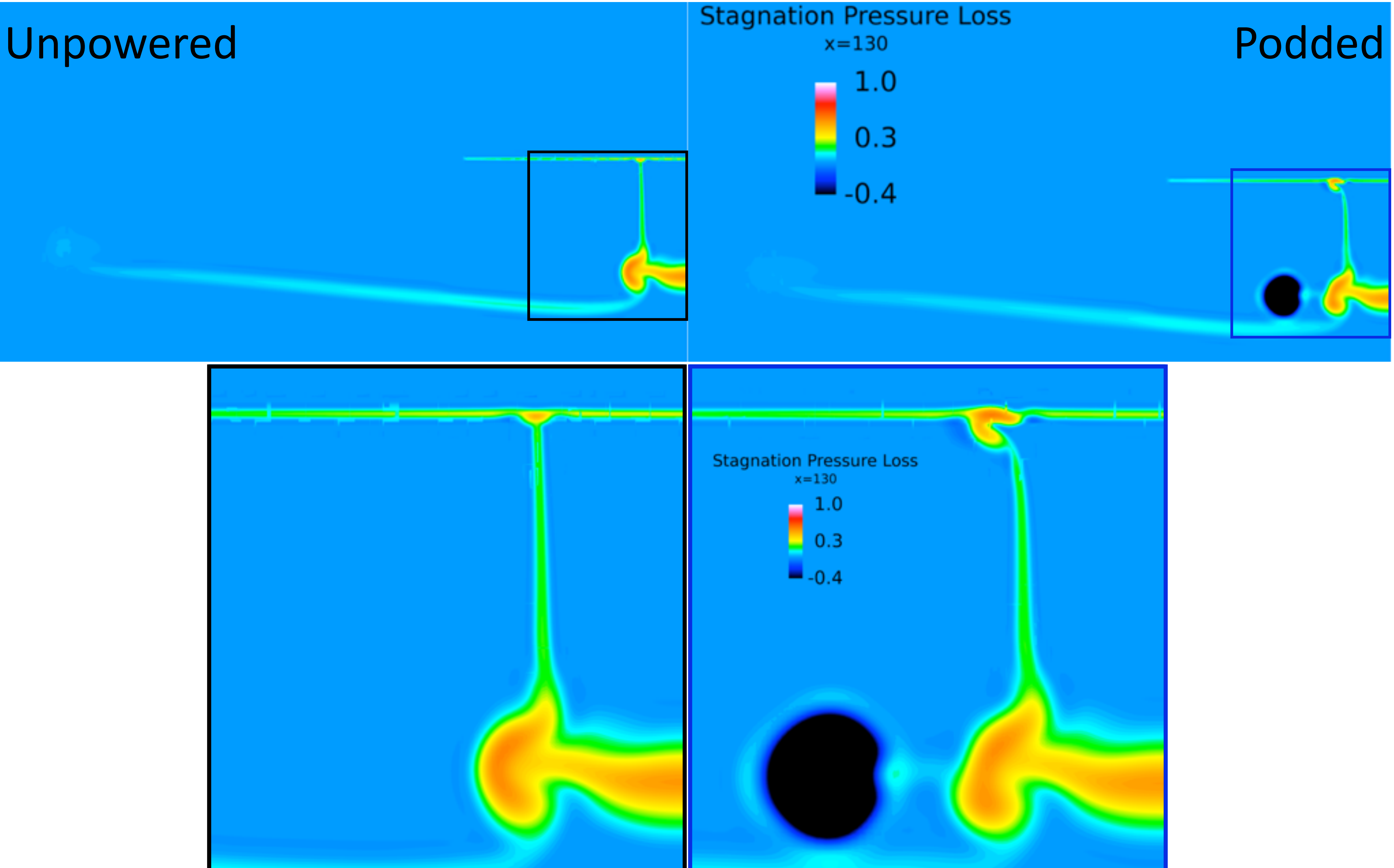


Unpowered
Stagnation Pressure Loss
x=108
1.00
0.30
-0.40
Podded

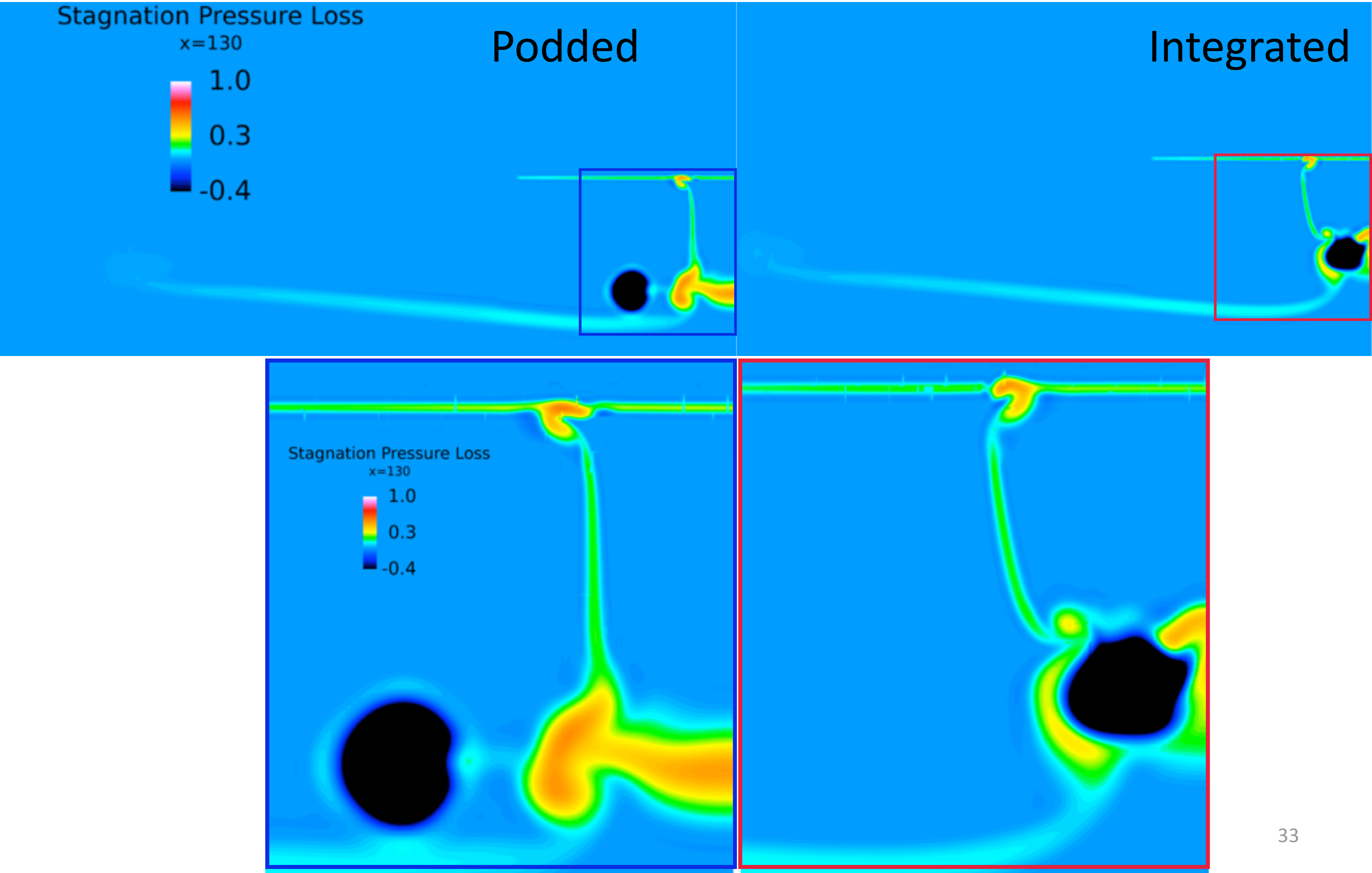
Inlet (cont.)


Podded
Stagnation Pressure Loss
x=108
1.00
0.30
-0.40
Integrated

Wake

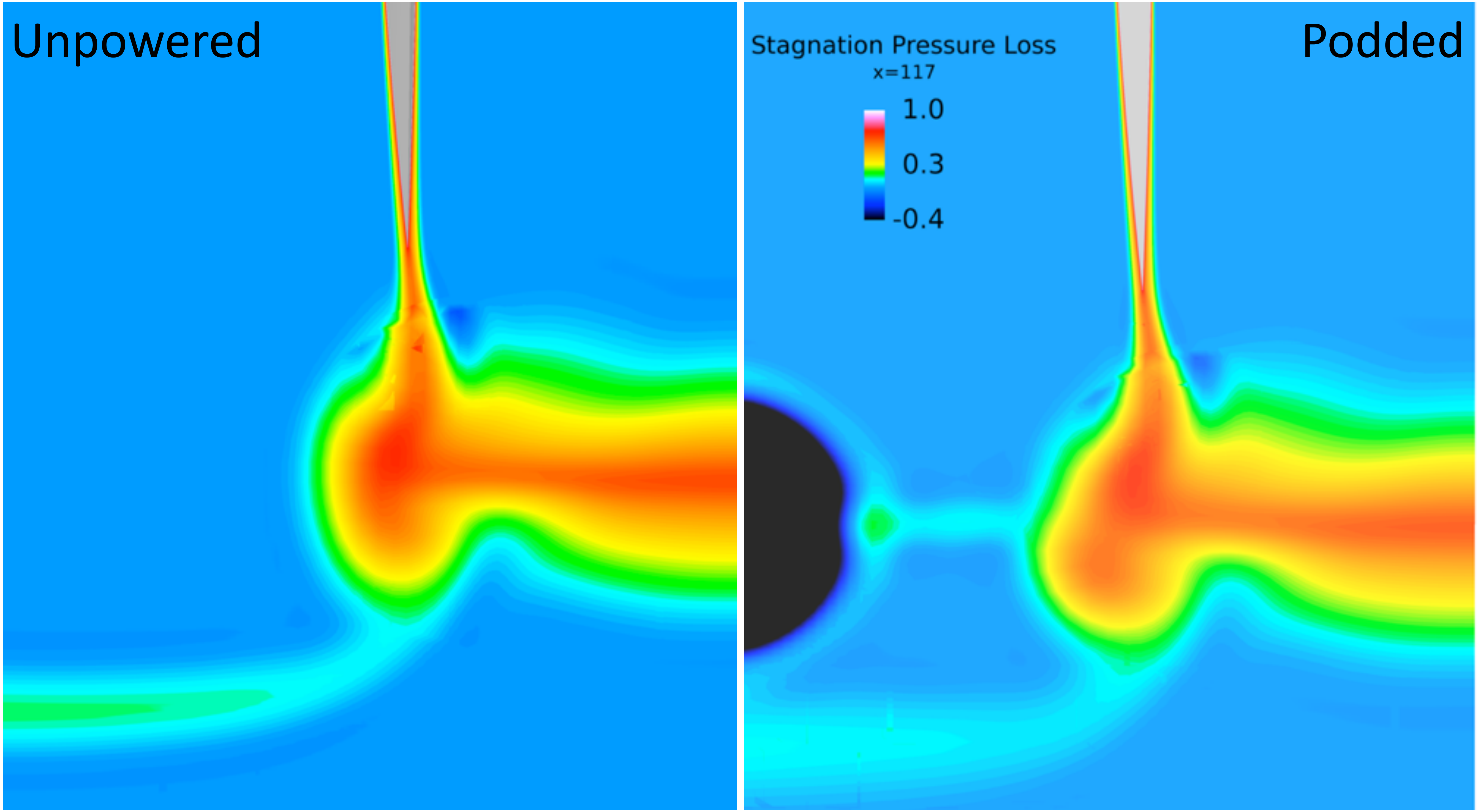

Unpowered
Stagnation Pressure Loss
x=130
1.0
0.3
-0.4
Podded
Stagnation Pressure Loss
x=130
1.0
0.3
-0.4

Wake (cont.)

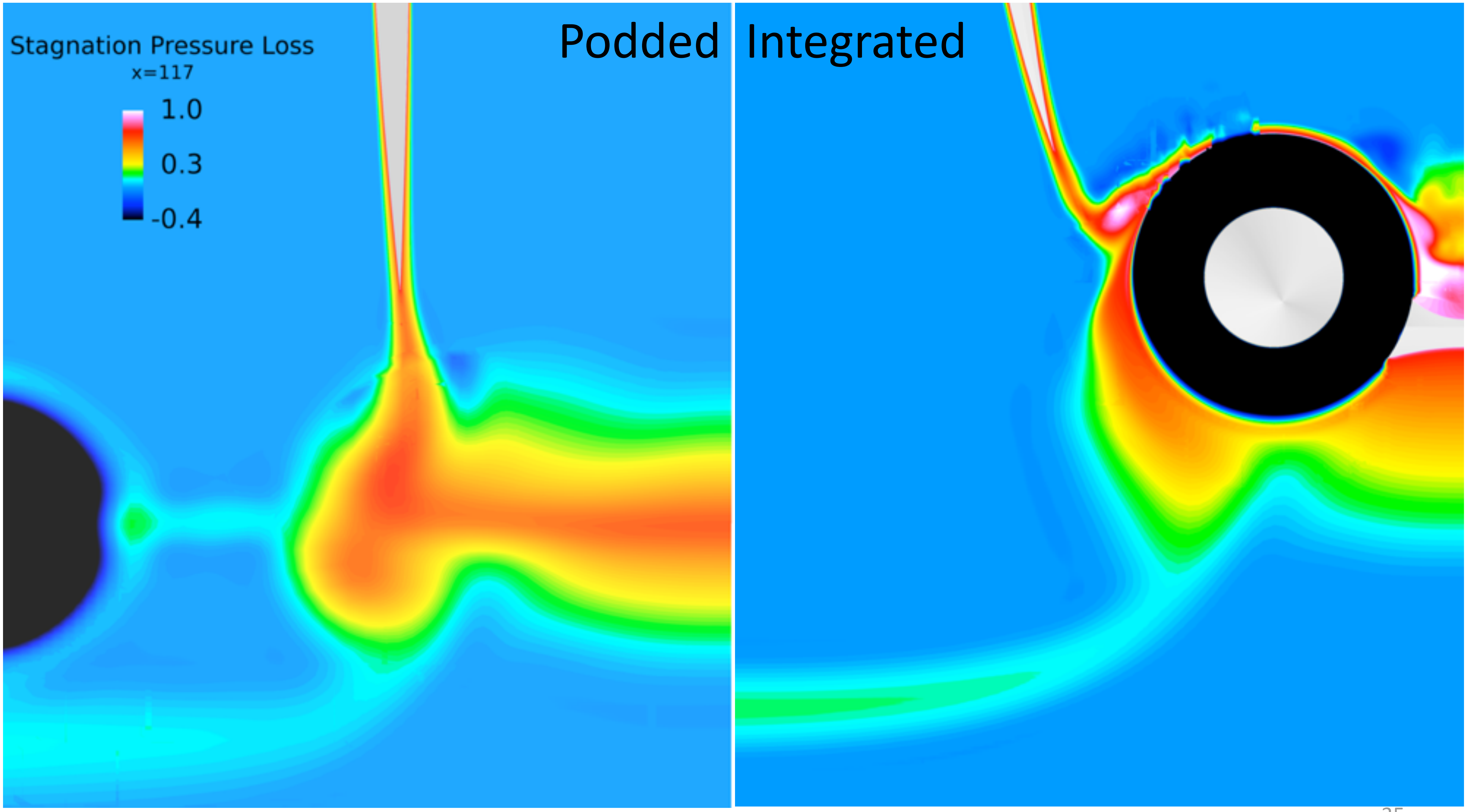


Stagnation Pressure Loss
x=130
1.0
0.3
-0.4
Podded
Integrated
Stagnation Pressure Loss
x=130
1.0
0.3
-0.4

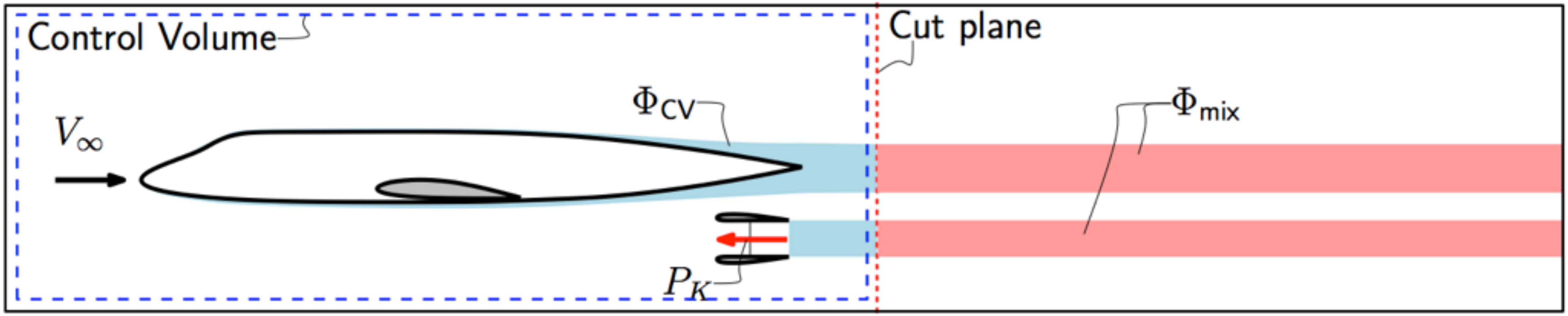
Fuselage Trailing Edge



Fuselage Trailing Edge (cont.)



Viscous Dissipation

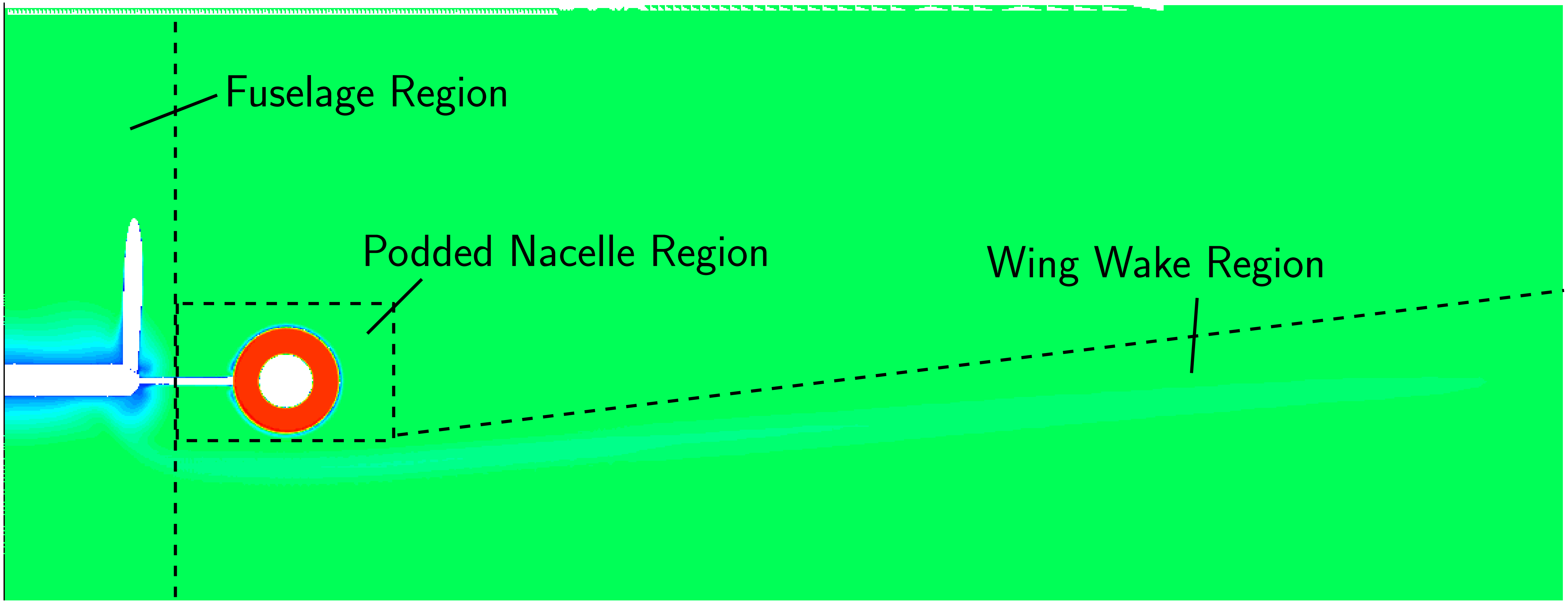


$$\Phi = \Phi_{CV} + \Phi_{\mathrm{mix}} = \left(P_K - \dot{\mathcal{E}}\right) + \Phi_{\mathrm{mix}}$$

$\Phi =$ Dissipation , $P_K =$ Mechanical Flow Power

- Dissipation coefficient: $\zeta = \dfrac{\Phi}{q_\infty S V_\infty}$

Dissipation Computation



- Dissipation computed in each region
  - No separate nacelle for integrated config

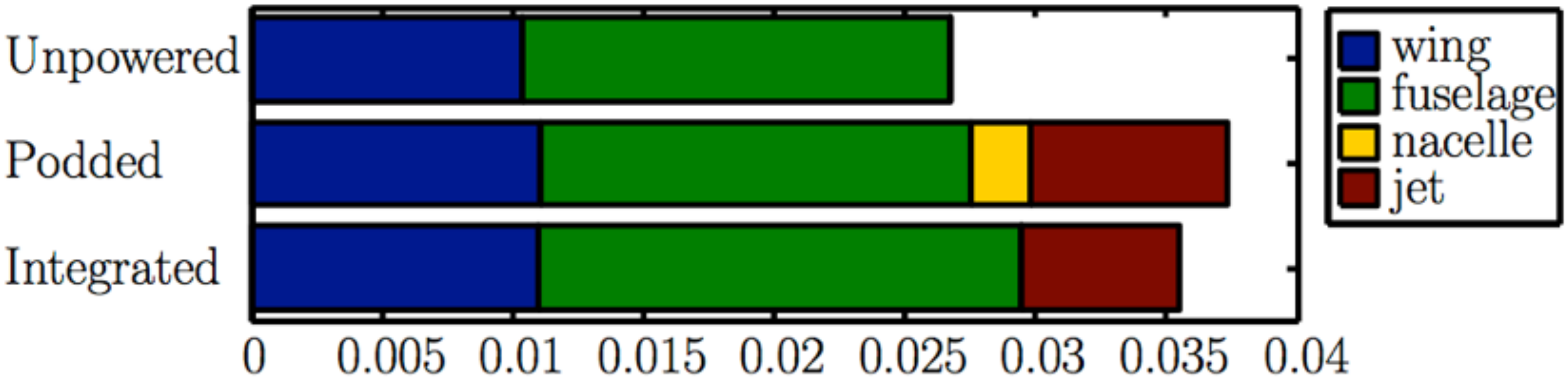
Dissipation at Inlet

	Total	Fuselage	Wing	Nacelle
Unpowered	0.02148	0.01067 (50%)	0.01080 (50%)	0
Podded	0.02425	0.01071 (44%)	0.01132 (47%)	0.0022 (1%)
Integrated	0.02241	0.01129 (50%)	0.01112 (50%)	0
Variation	0.00228	0.00062	0.00052	0.0022

- Minor variations in fuselage and wing regions.
- Only major difference due to presence of podded nacelle.

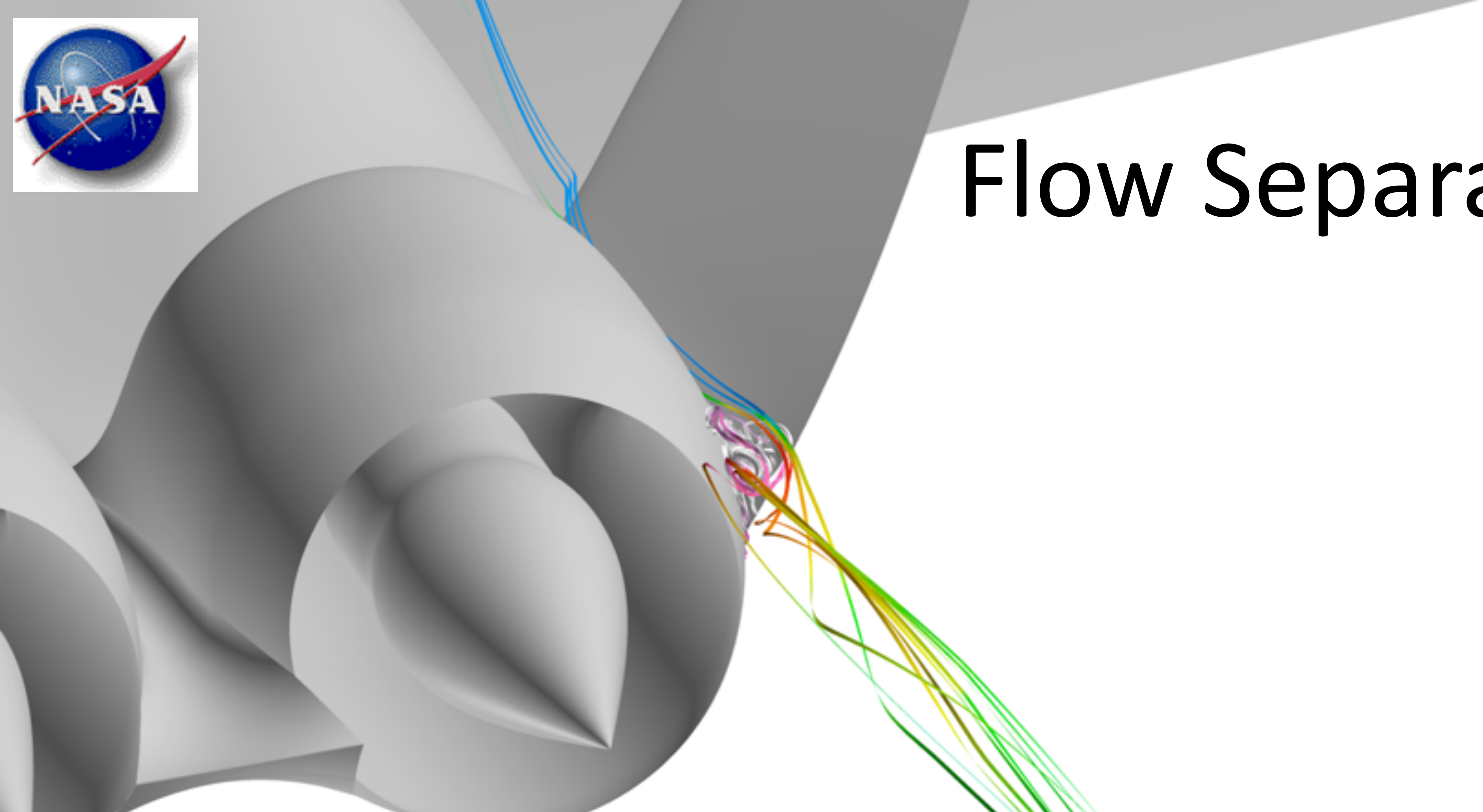
Dissipation in the Wake

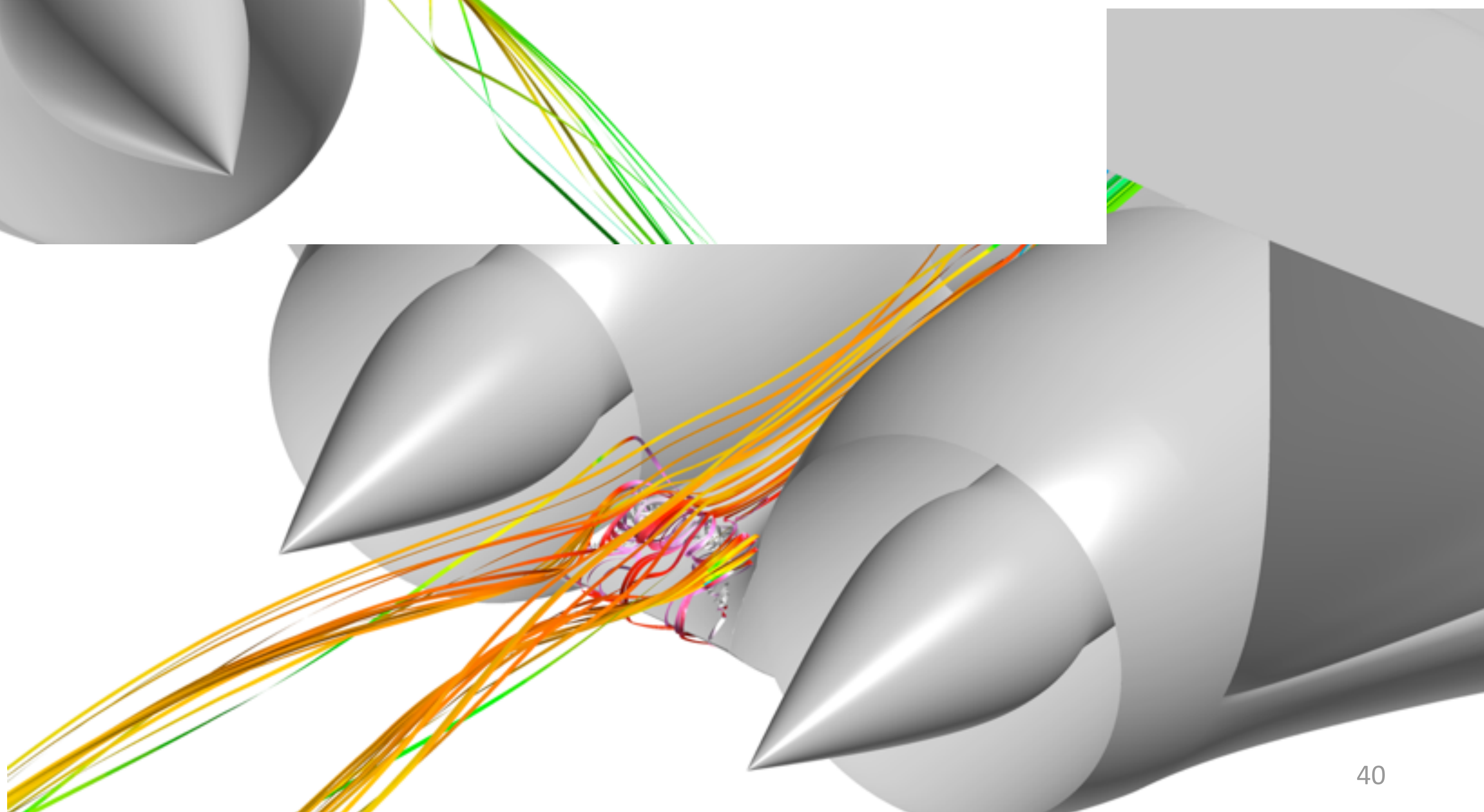
	Total	ζ_{fuse}	$\zeta_{nacelle}$	ζ_{jet}	ζ_{wing}
Unpowered	0.0240	0.0129 (54%)	0	0	0.0111 (46%)
Podded	0.0345	0.0129 (38%)	0.0025 (7%)	0.00760 (22%)	0.0115 (33%)
Integrated	0.0325	0.0149 (46%)	0	0.00603 (19%)	0.0115 (35%)



- Wing dissipation not affected by BLI
- Integrated config. has 6% less overall dissipation
  - –3/4 from lower jet velocity
  - –1/4 from lower fuselage/nacelle dissipation

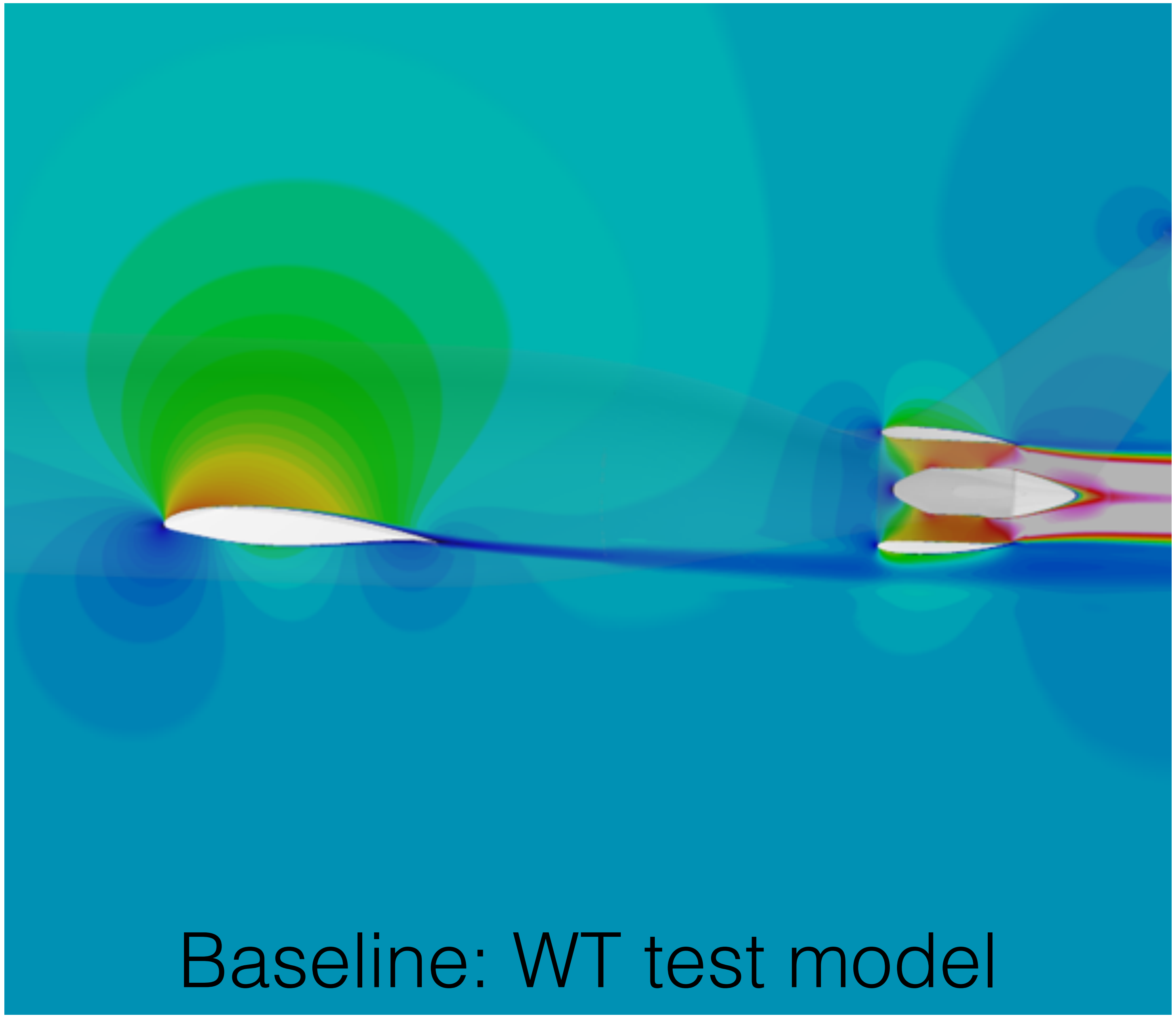
Flow Separation





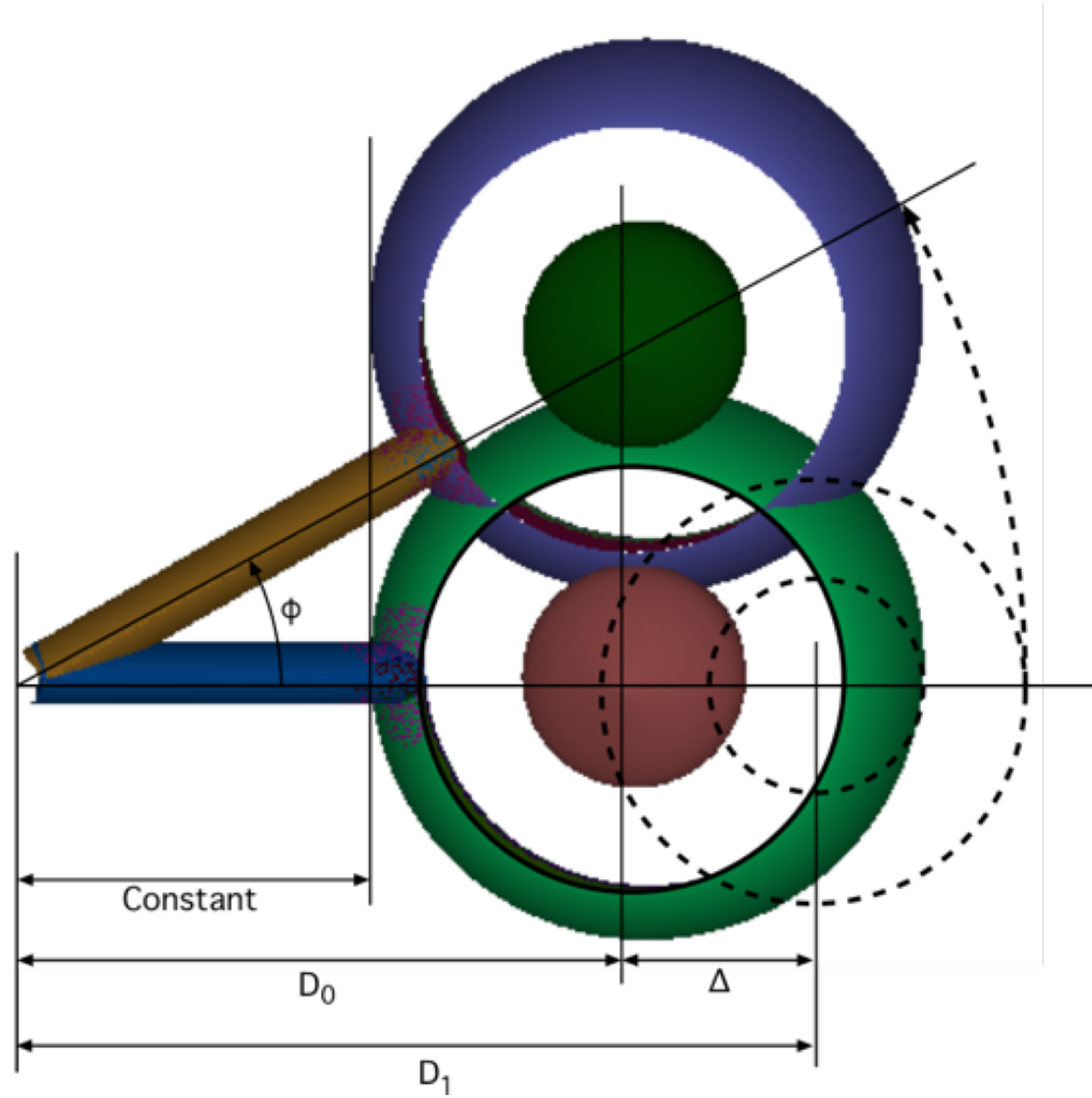
Wake Ingestion

- Previous podded nacelle almost ingested the wing wake
- Can we move the nacelle out of the way?
- What is the effect of nacelle movement on BLI?

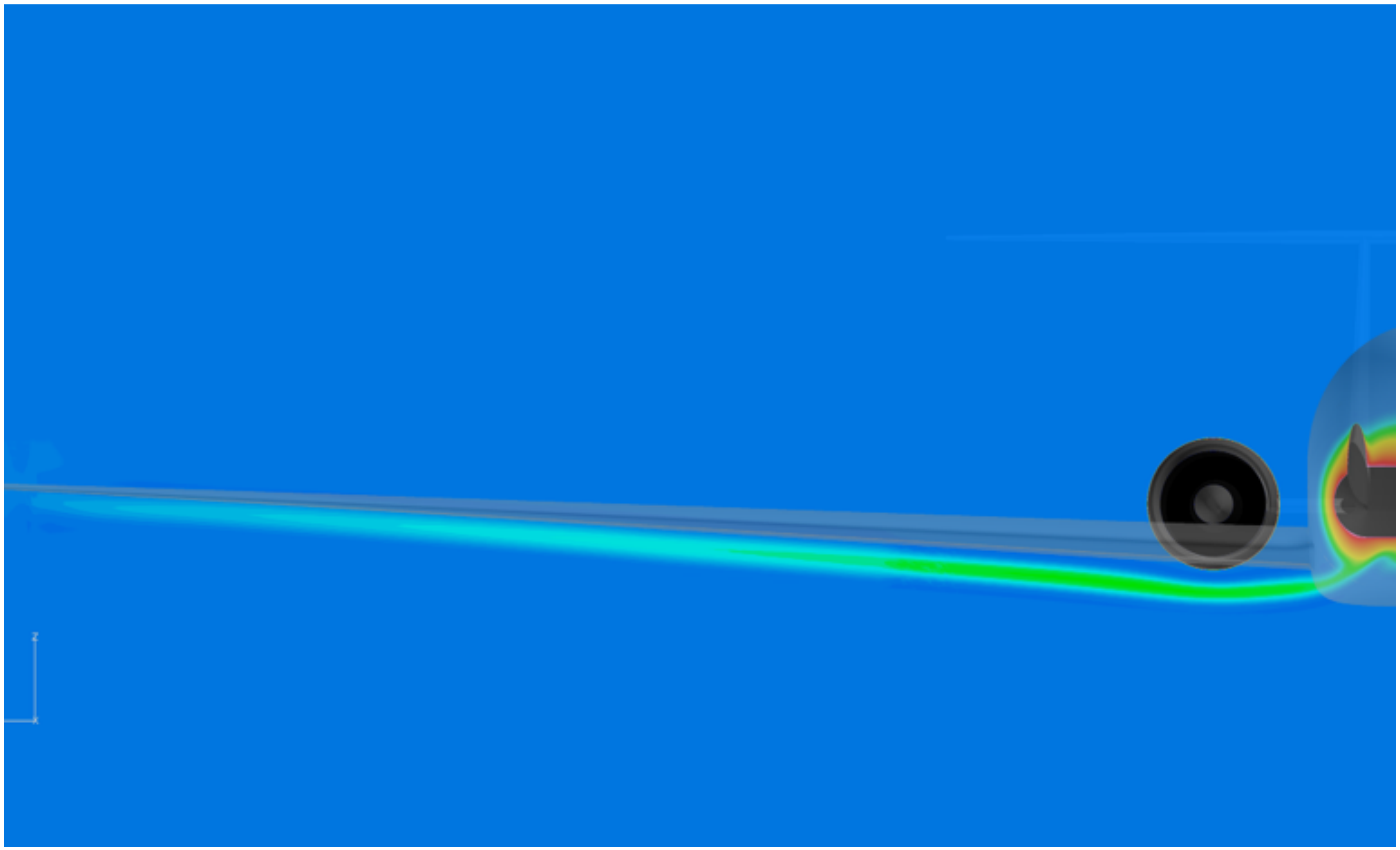


Test Matrix

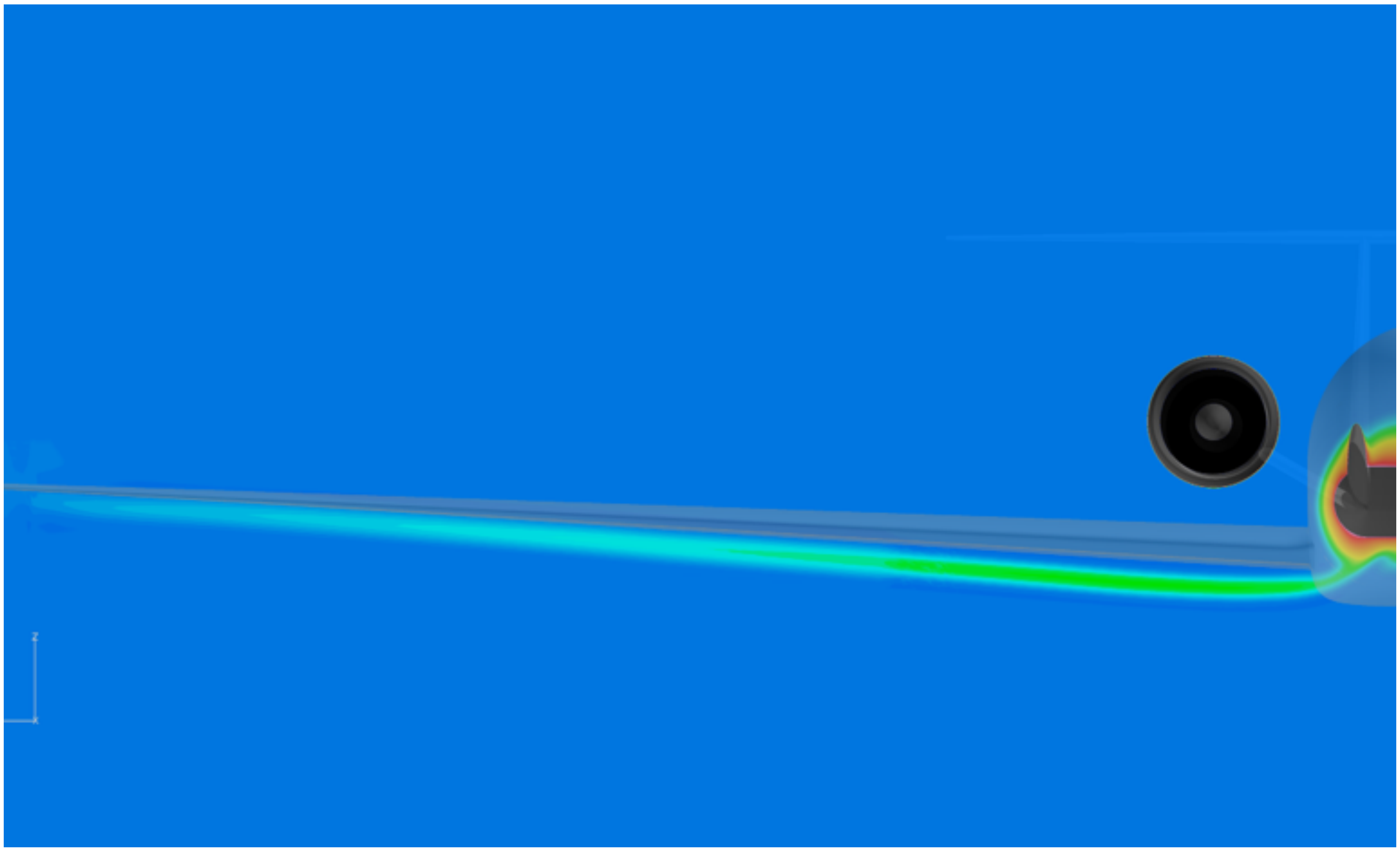
- Deflect the nacelle up and down (-20°,-10°,0°,10°,20°,30°)
- Power setting: closest to WT test setting
- Keep the outboard position and toe angle unchanged
- Compare to the baseline case
- $\Delta = D_1 - D_0 = D_0(1/\cos\theta - 1)$
- Translate by Δ, then rotate by θ



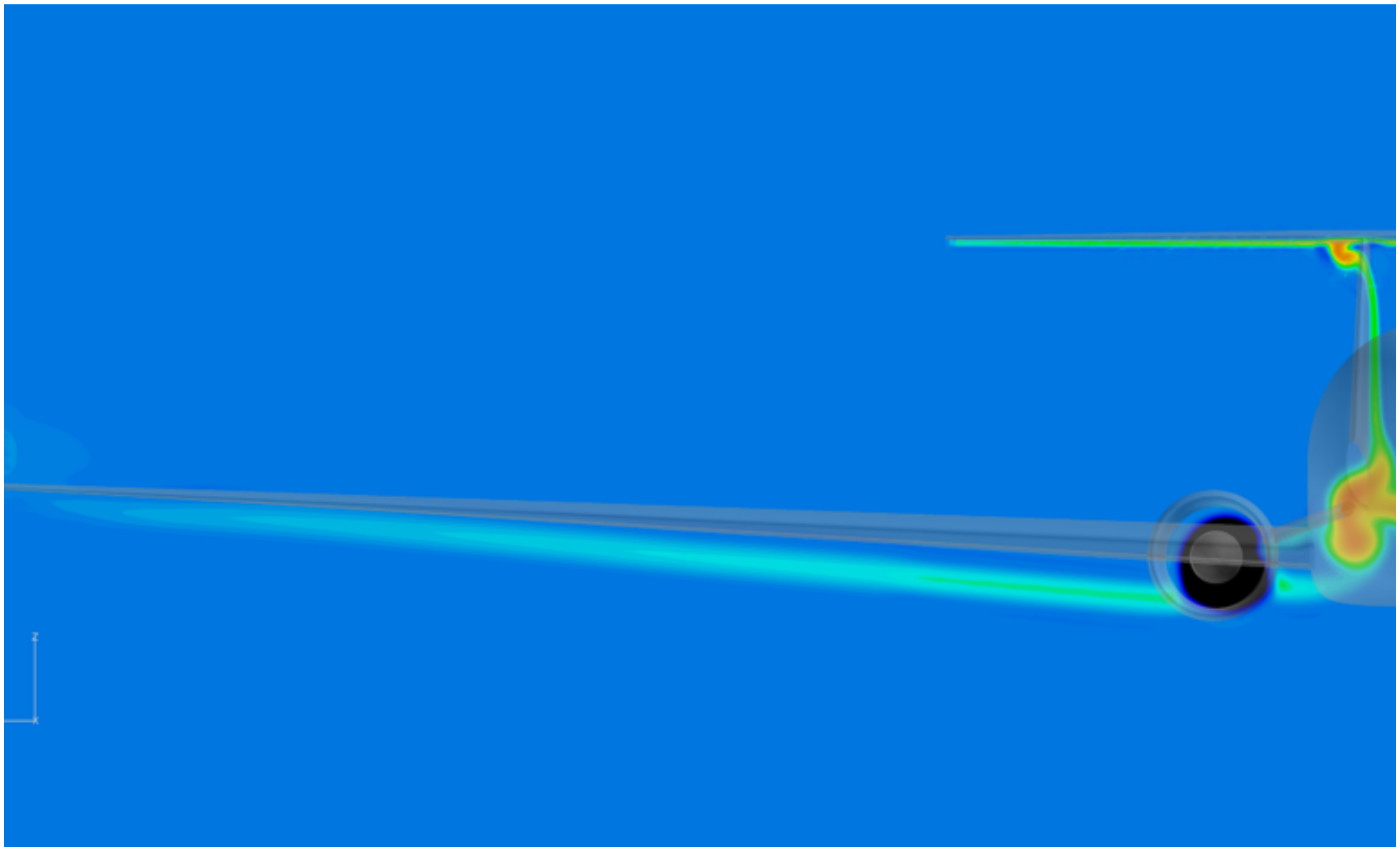
Stagnation Pressure Loss (ϕ=0°) prior to entering the nacelle



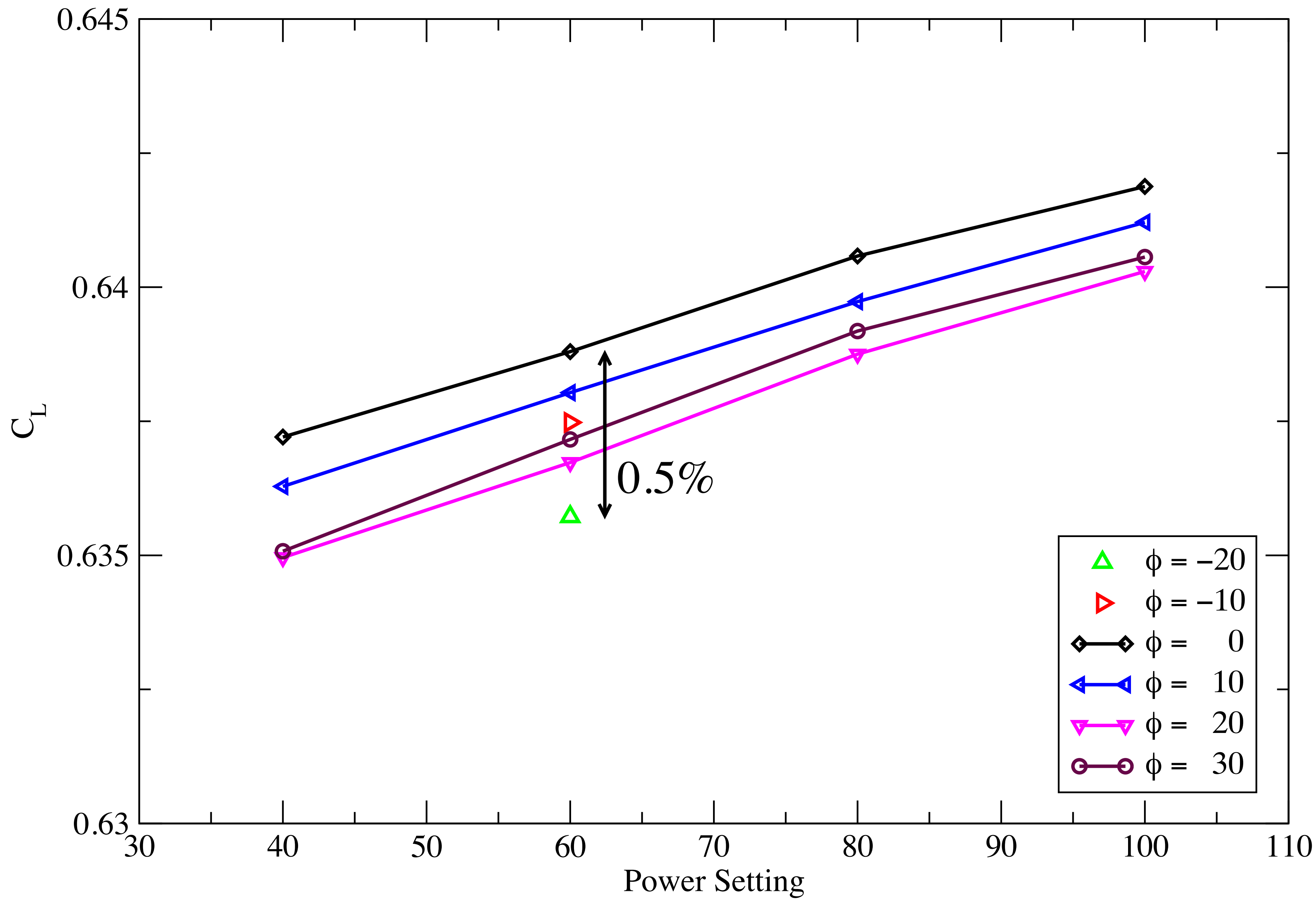
Stagnation Pressure Loss (ϕ=30°) prior to entering the nacelle



Stagnation Pressure Loss (ϕ=-20°) behind the nacelle

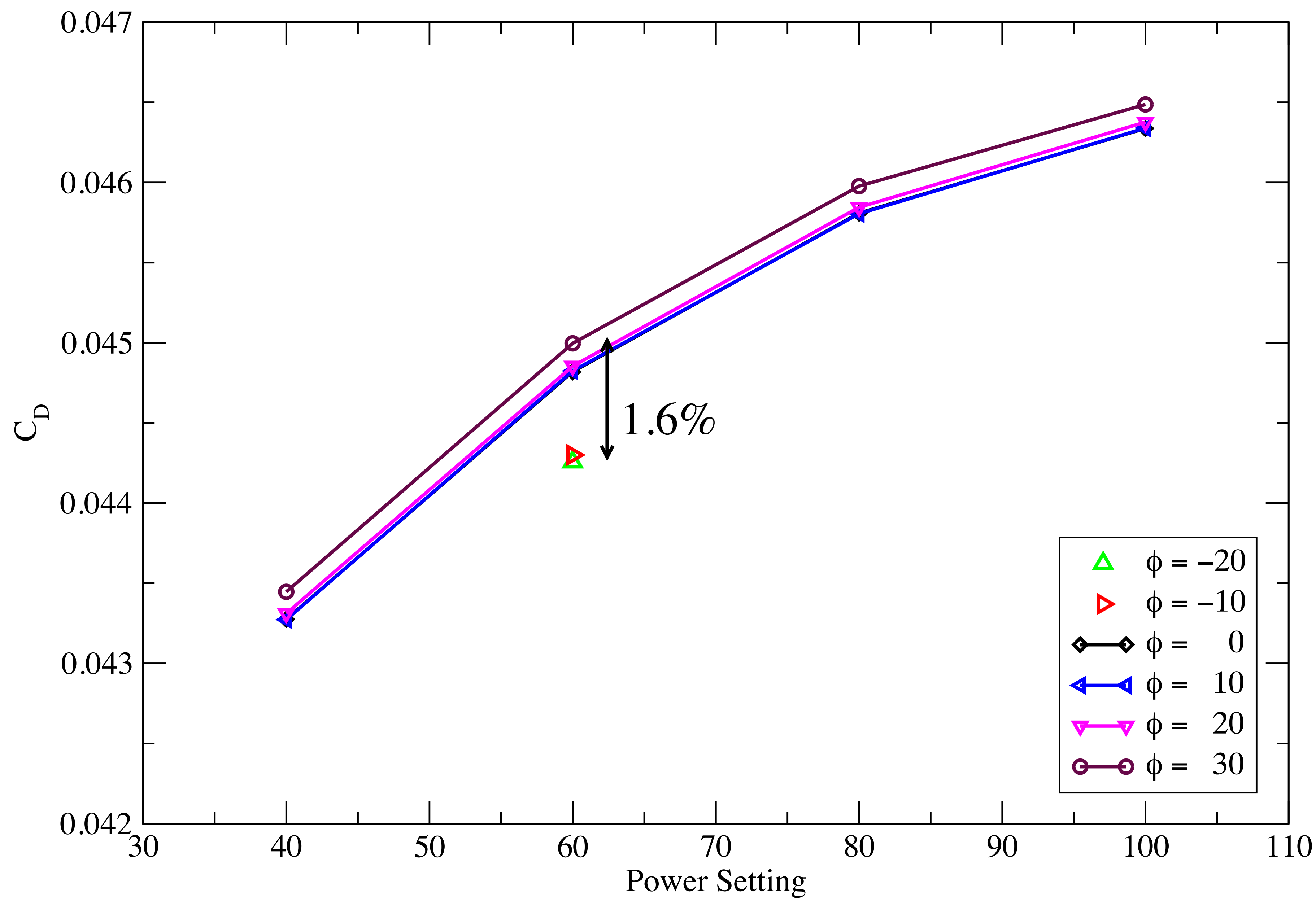


Effect of Pylon Deflection



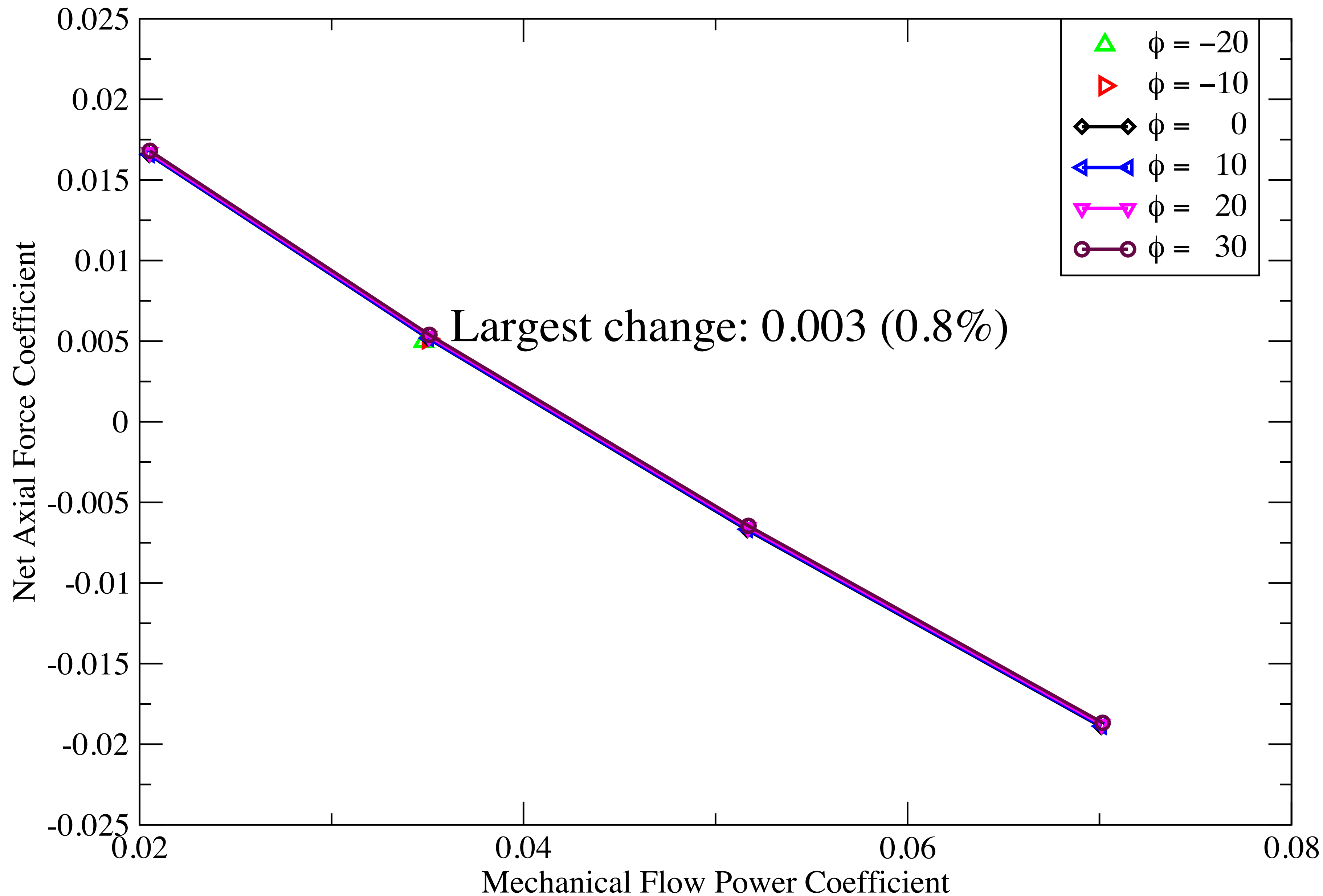
Lift

Effect of Pylon Deflection



Drag

Effect of Pylon Deflection



Axial Force vs. Mech. Flow Power with power settings of 40, 60, 80 and 100%

Concluding Remarks

- BLI benefit is:
  - 9% less Mechanical flow power with BLI
- Wake ingestion benefit is:
  - 0.8% less Mechanical flow power with wake ingestion
- BLI has the potential to reduce fuel burn
- Wake Ingestion is not worth pursuing
- Future Work:
  - Full scale aircraft at cruise Ma, and Re.
  - Other operating conditions
  - Improve actuator disk model

Acknowledgements

- **Thanks also go to:**

MIT
- Mark Drela
- Ed Greitzer
- and the D8 team

NASA (ARC & LaRC)
- William Chan
- Greg Gatlin
- Judith Hannon
- Pieter Buning
- Tom Pulliam

Project
- Nateri Madavan
- Scott Anders
- Sally Viken
- Rich Wahls
- Ruben Del Rosario
- Mike Rogers
- John Koudelka