

Preliminary Assessment of the Boundary Layer Ingestion Benefit for the D8 Aircraft

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NASA Ames Research Center

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  - –Alejandra Uranga



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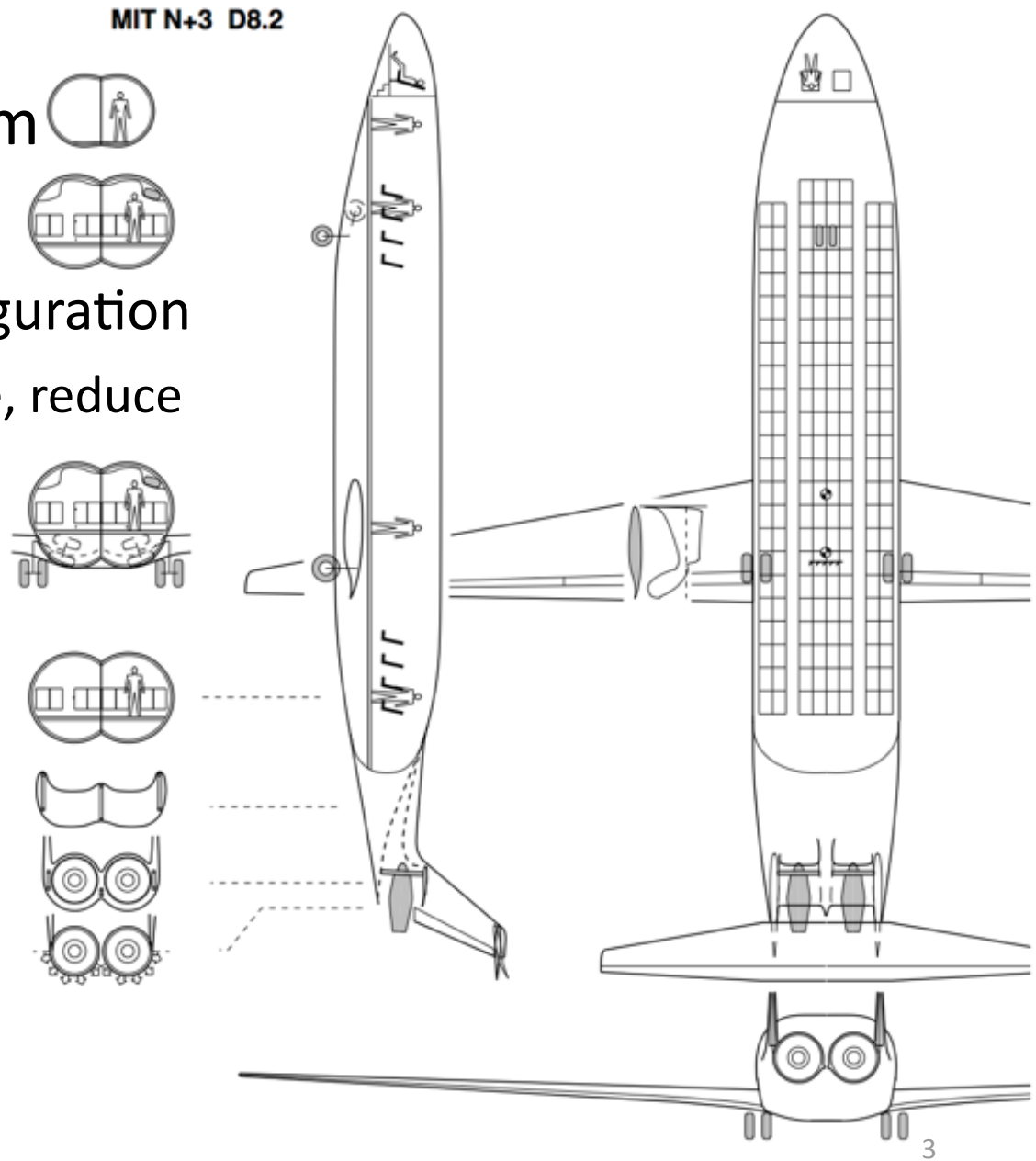
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- Mark Drela
- Ed Greitzer
- and the D8 team

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- Greg Gatlin
- Judith Hannon
- Pieter Buning
- Tom Pulliam

Project
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- Scott Anders
- Nateri Madavan
- John Koudelka
- Ruben Del Rosario
- Rich Wahls

The D8 Aircraft Concept

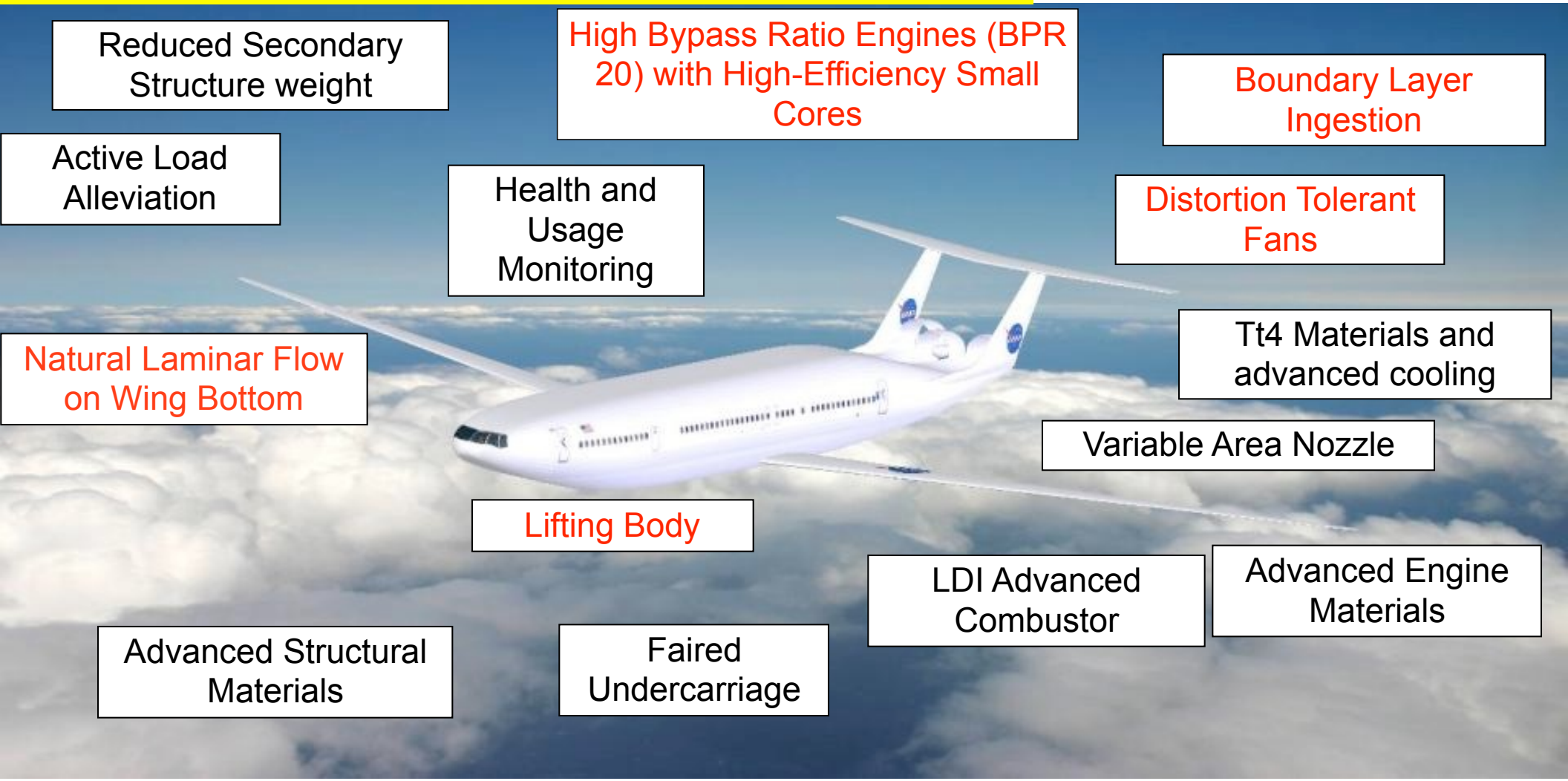
- Fundamental Aero program
  - –Fixed-wing
  - –N+3 advanced vehicle configuration
    - Lower fuel burn, lower noise, reduce emissions
- 180 passengers
- 3000 nmi range
- 118 ft span
- Boeing 737/A320 class
- Lifting fuselage, pi-tail
- Flush-mounted engines



MIT/Pratt & Whitney/Aurora D Series

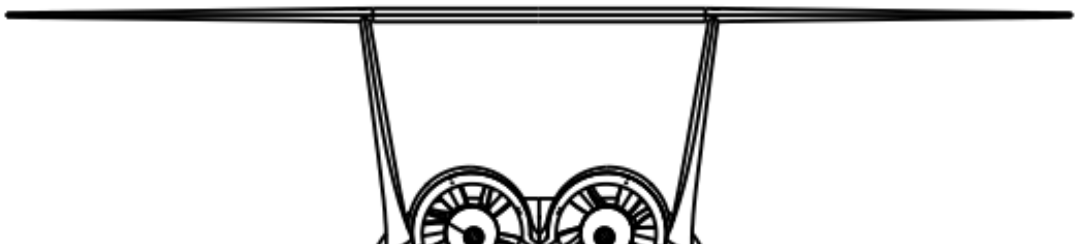
Airframe & Propulsion Technology Overview

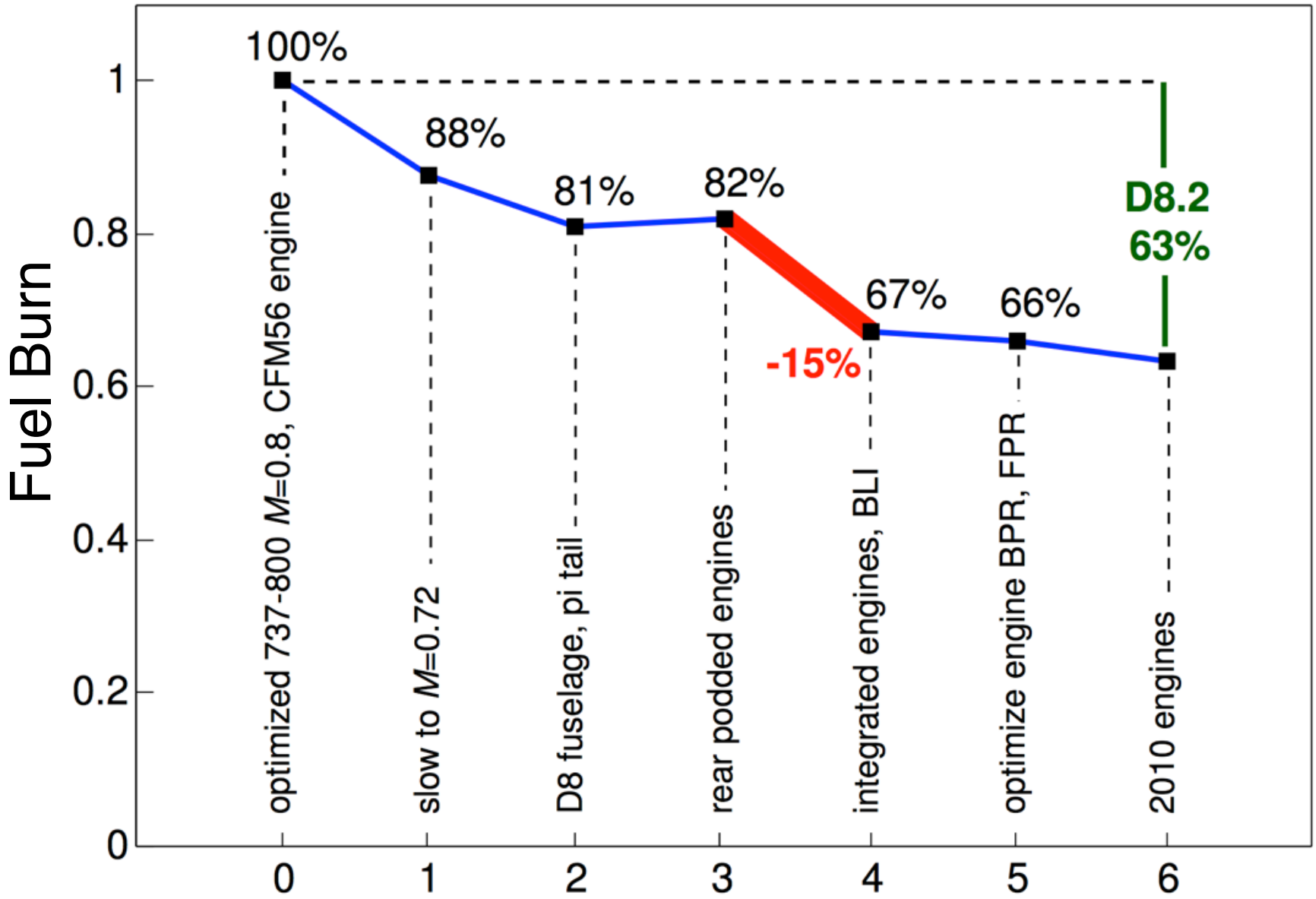
Novel configuration plus suite of airframe and propulsion technologies, and operations modifications



Massachusetts Institute of Technology · Aurora Flight Sciences · Pratt & Whitney, A United Technologies Company

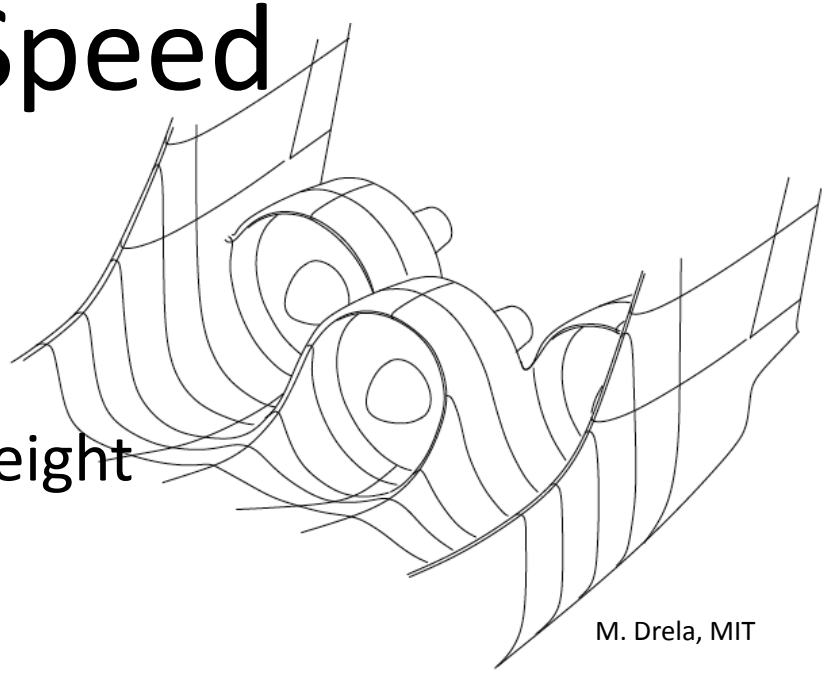
B737-->D8




Fuel Burn
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
100%
88%
81%
82%
67%
66%
D8.2
63%
-15%
optimized 737-800 M=0.8, CFM56 engine
slow to M=0.72
D8 fuselage, pi tail
rear podded engines
integrated engines, BLI
optimize engine BPR, FPR
2010 engines

Lower Cruise Speed

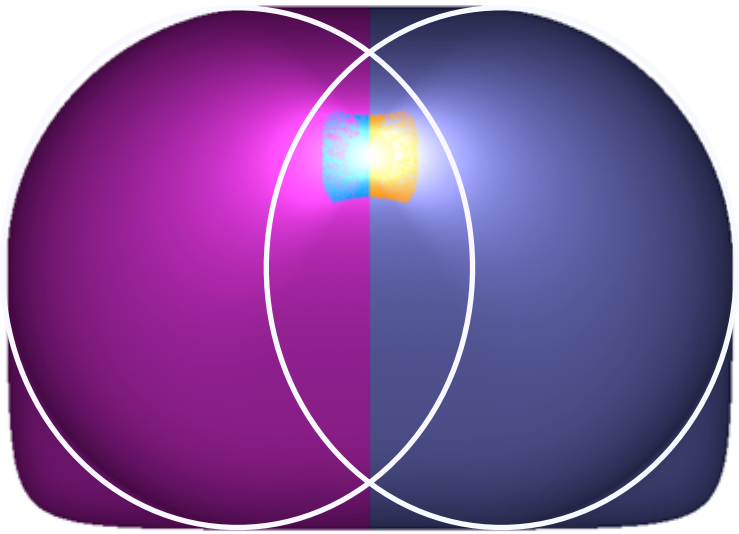
- M=0.72
  - –Lower sweep wing
    - Reduced structural load => Lower weight
    - Increased CL
    - Can eliminate high-lift devices
  - –Proper speed at engine fan face (M=0.6)
    - Reduces nacelle, inlet size
- Reduced nacelle drag
  - –Nacelles embedded in the π-tail and fuselage
  - –Reduced size,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



M. Drela, MIT

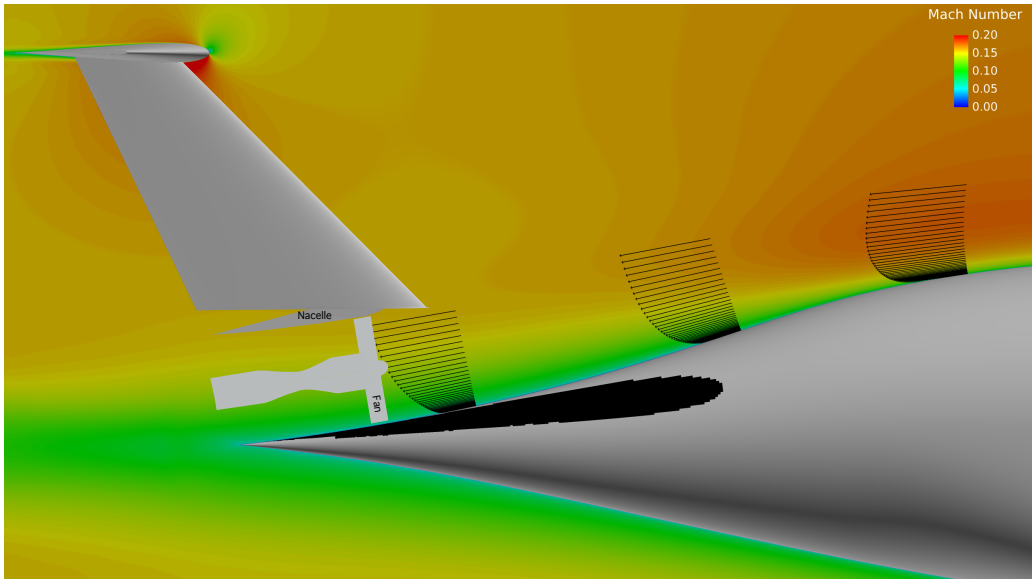
Fuselage Advantages

- "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 moment
  - Shrinks horizontal tail
  - Lighter horizontal tail



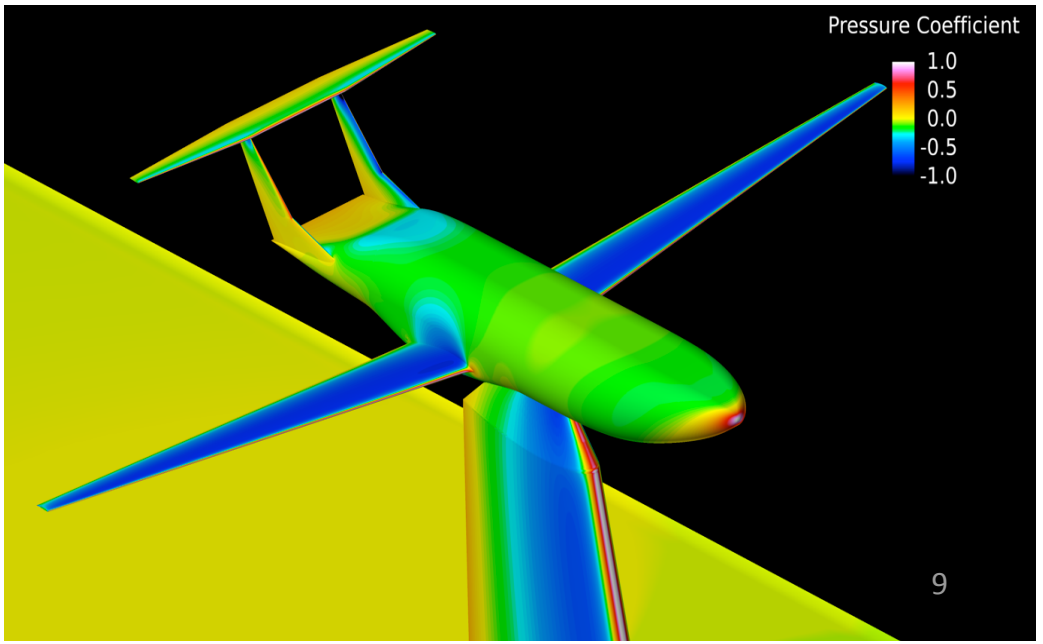
Embedded Rear-Mounted Engines

- 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 shield

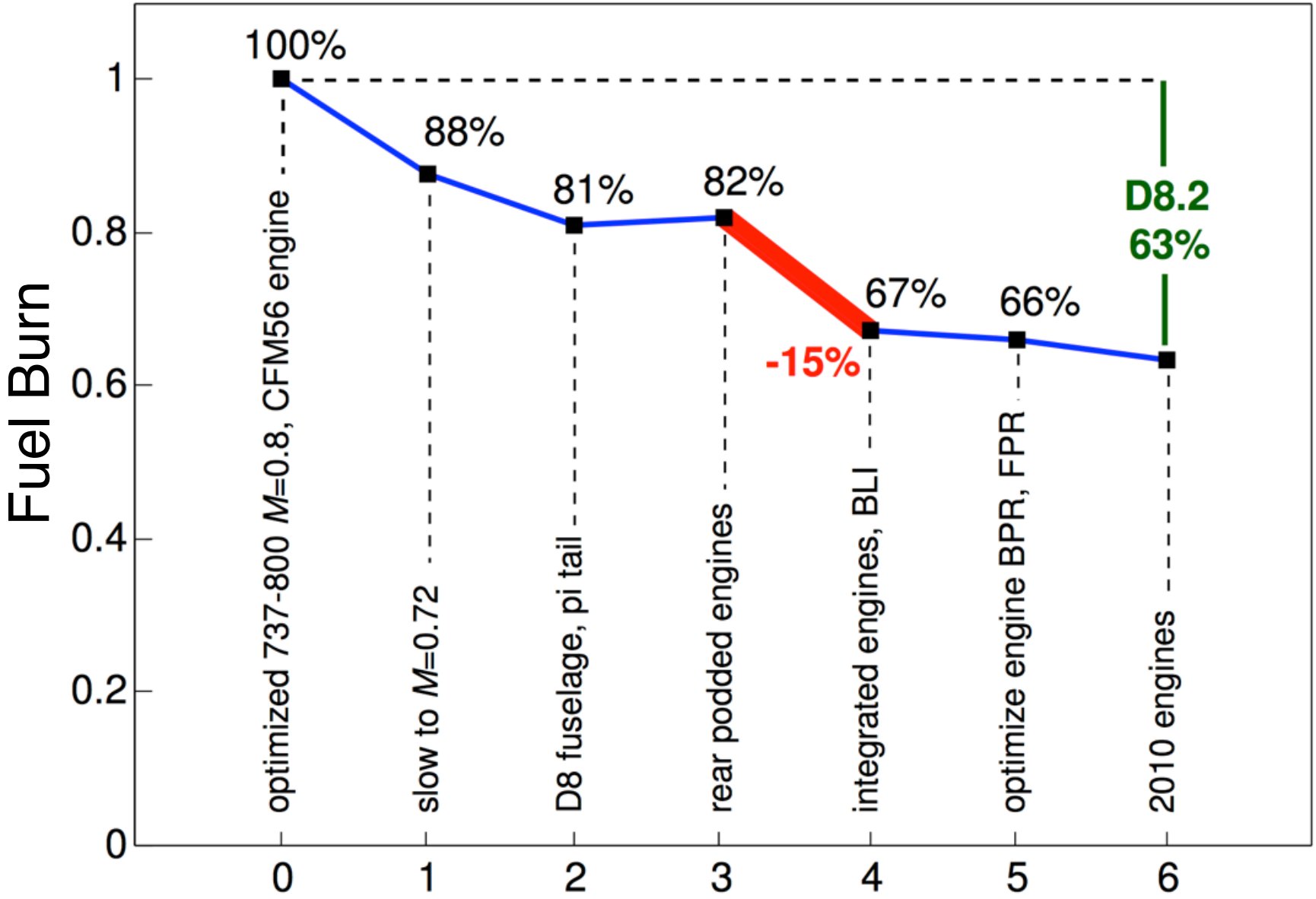


Previous Computational Work

- ICCFD7-4304 paper verified that
  - "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



B737-->D8

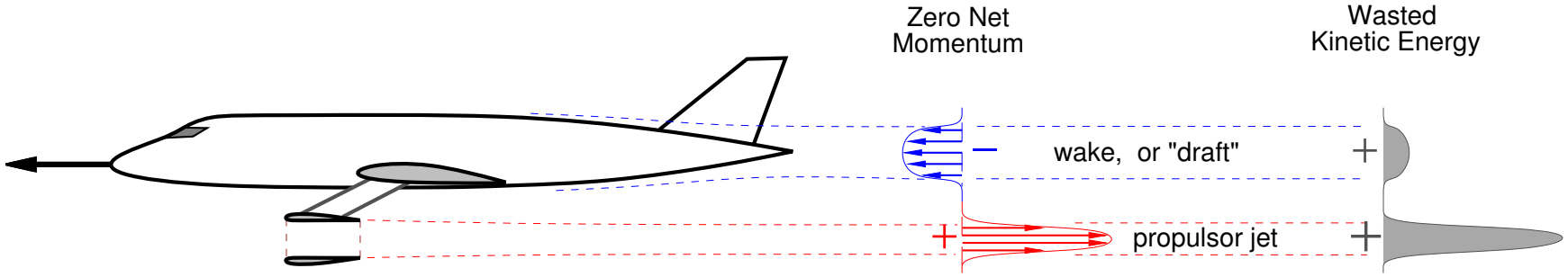

Fuel Burn
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
100%
88%
81%
82%
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66%
D8.2
63%
-15%
optimized 737-800 M=0.8, CFM56 engine
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D8 fuselage, pi tail
rear podded engines
integrated engines, BLI
optimize engine BPR, FPR
2010 engines

Goal and Approach

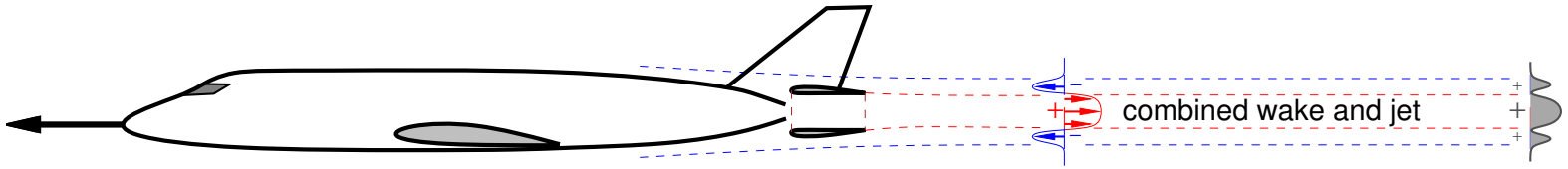
- Goal: Quantify benefits of BLI for the D8
- Approach:
  - Wind Tunnel tests in LaRC 14x22
  - CFD validation
    - NASA LaRC 14x22 WT data for a 1:11 scale model
    - Unpowered configuration
  - Direct Comparison between:
    - Efficient conventional (podded nacelle) configuration
    - BLI (integrated nacelle) configuration
  - Find mechanisms for BLI benefit

BLI

- Conventional: wake/BL energy lost



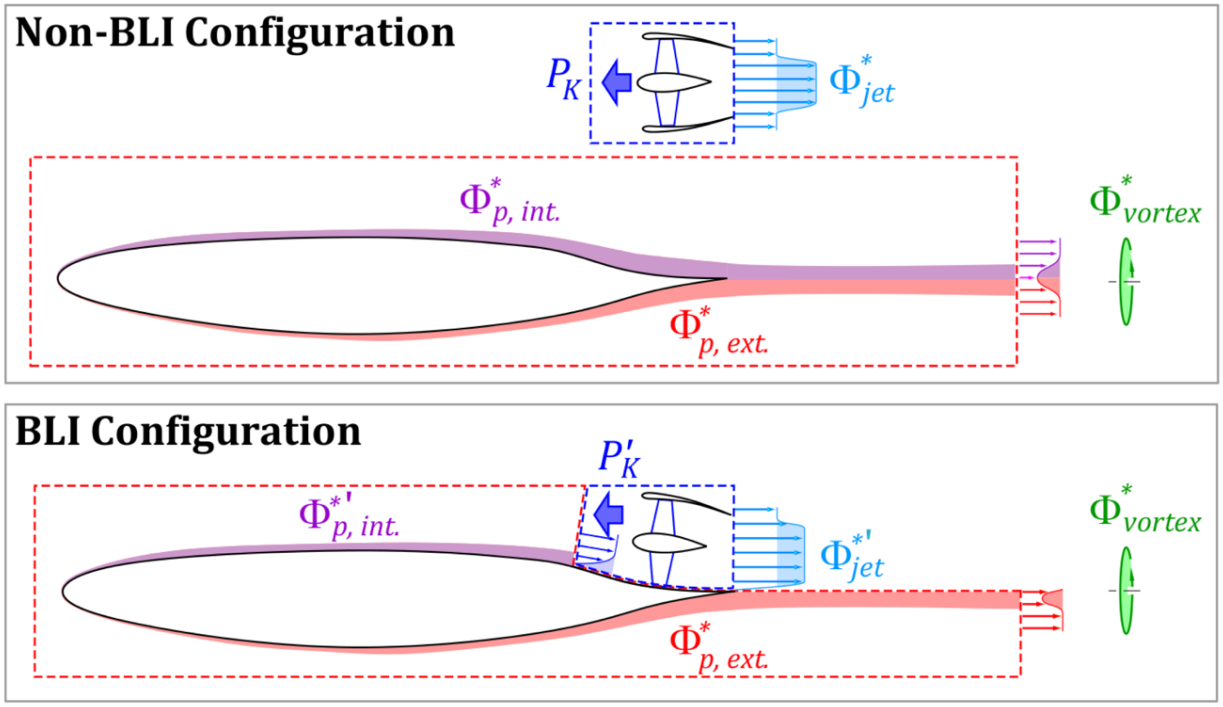
- BLI: Fuselage boundary layer ingested by propulsor
  - –> Reduced viscous dissipation in combined wake + jet
  - –> Reduced flow power required from propulsor



- Use Power-balance method

Power Balance Method

- Mechanical energy sources and sinks



- Power-in = Dissipation
- Dissipation sources: jet, wake, fuselage BL, vortex
- Reduced jet+wake dissipation results in BLI benefit

BLI Benefit

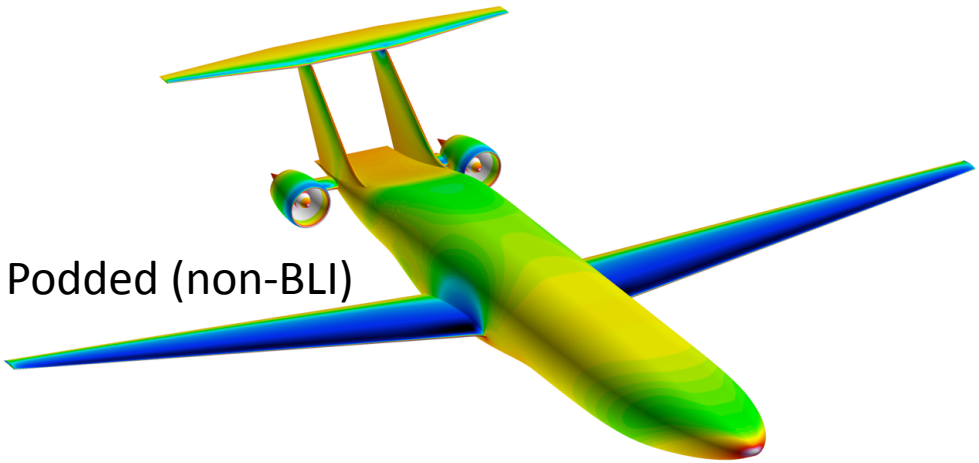
- Compare mechanical flow power

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

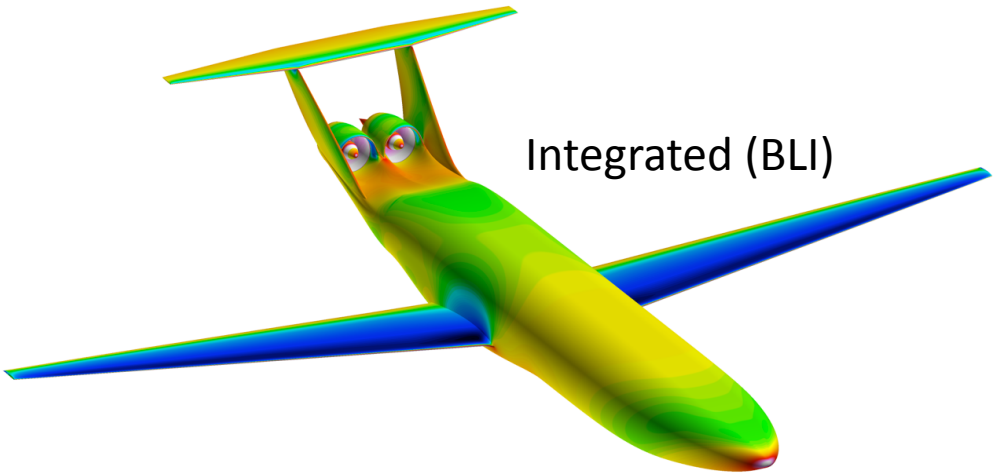
  - Power transmitted by propulsor to the flow

- Savings in power required: integrated vs. podded

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



Podded (non-BLI)



Integrated (BLI)

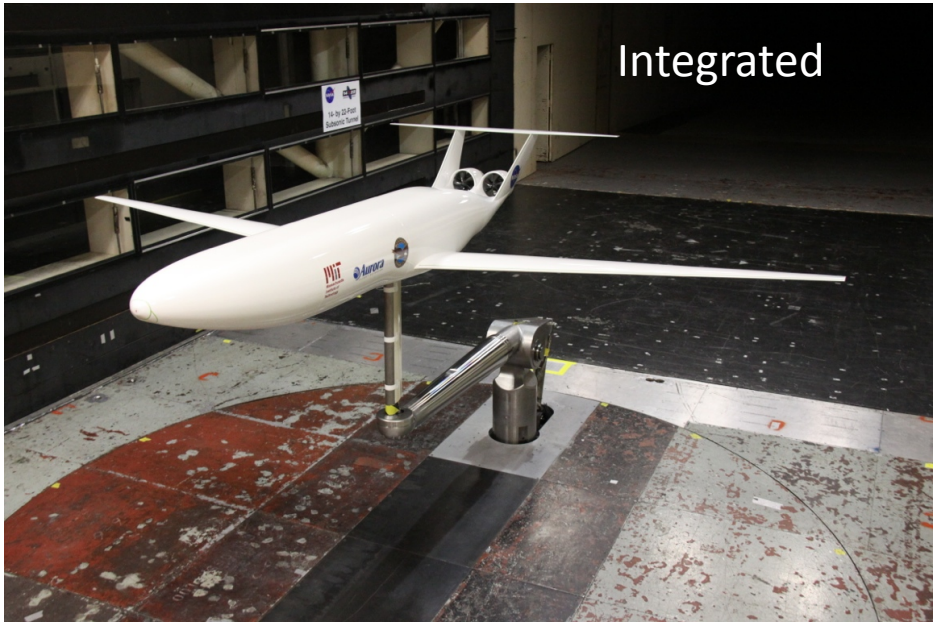
NASA LaRC 14x22 WT

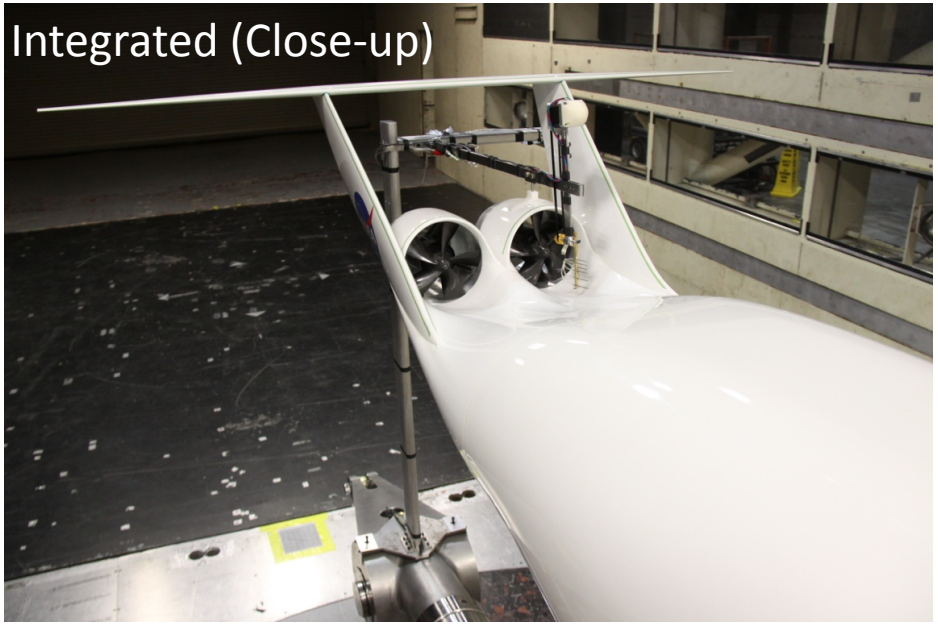


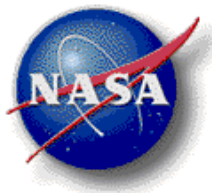
WT Configurations







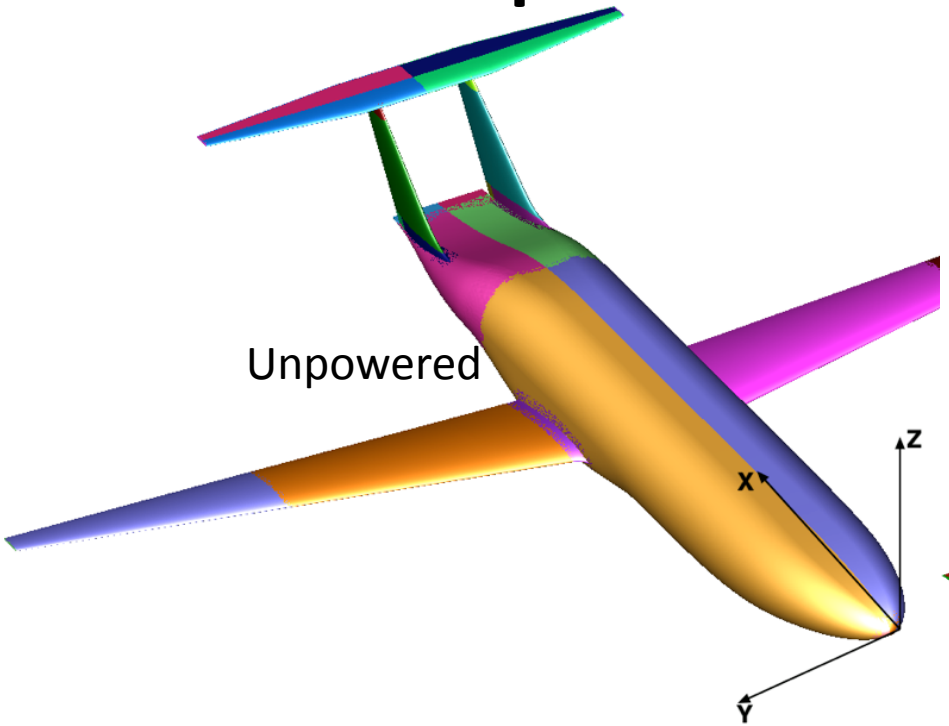


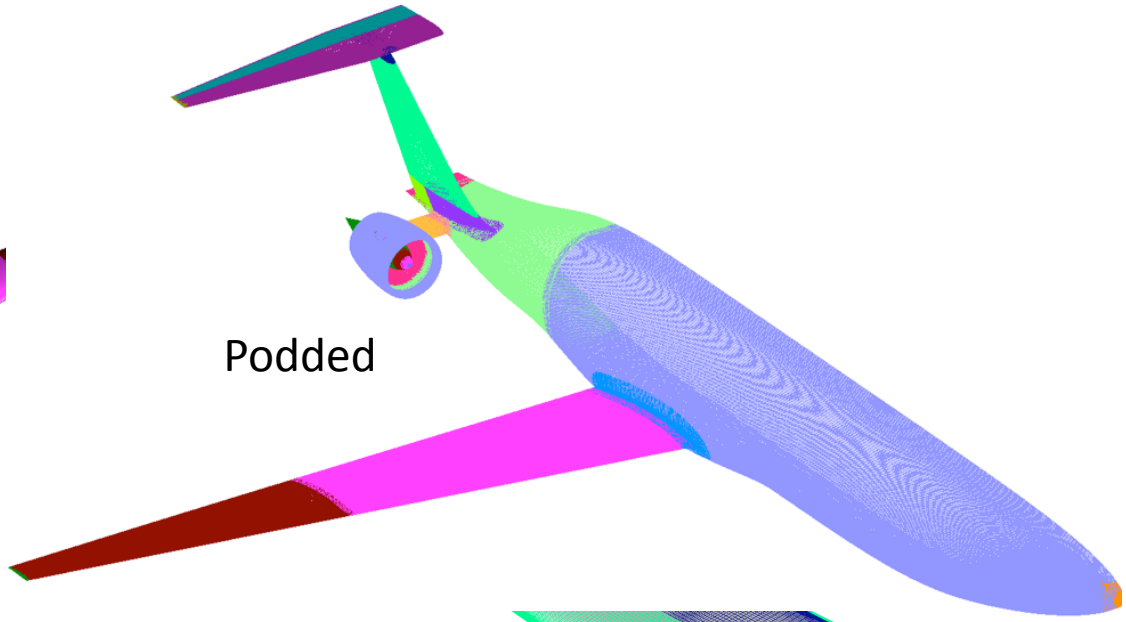


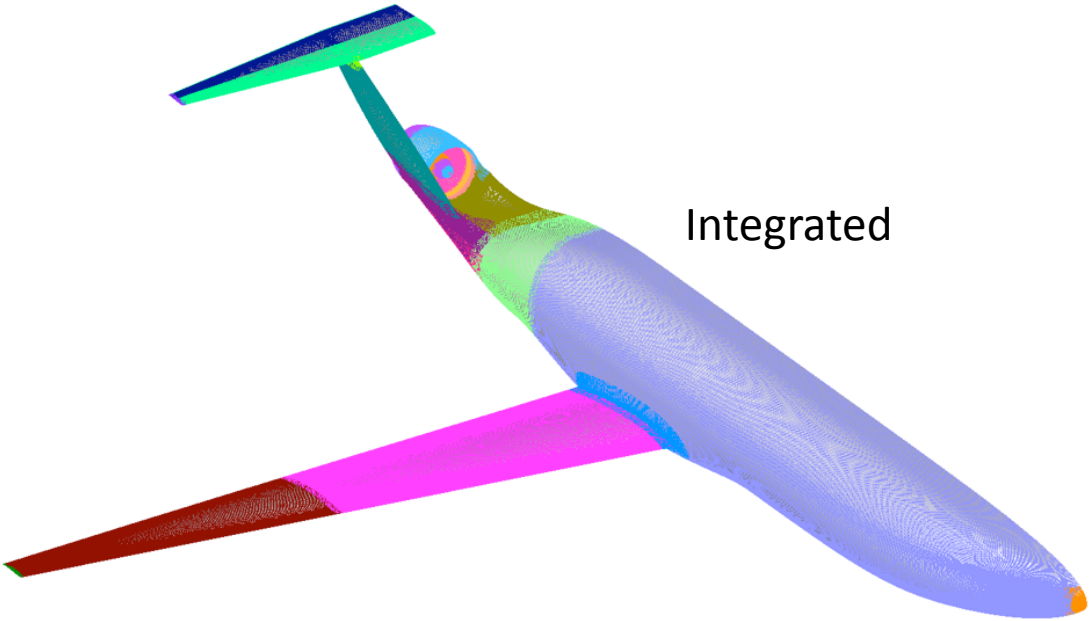
Configuration Details

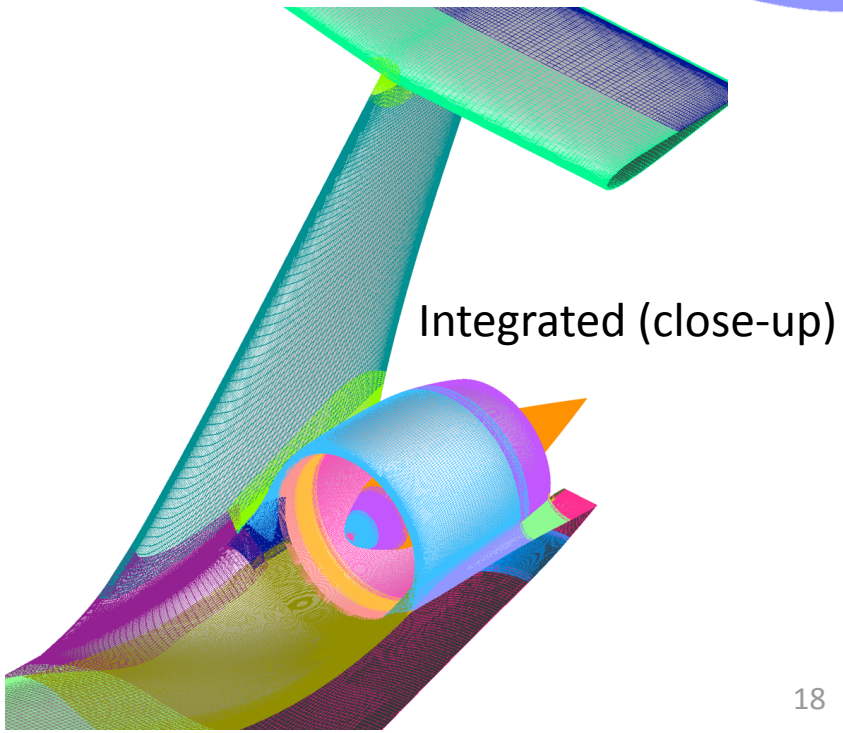
- WT runs at 70 mph, Re_c = 570,000
  - –lower-speed and Re compared to full-size at M=0.72
- 1:11 Scale powered model
- Wing designed for low Mach, low Re
- Same wings
- Most of fuselage is the same
- Same propulsors plug into both podded and integrated configuration empennage sections

Computational Configurations



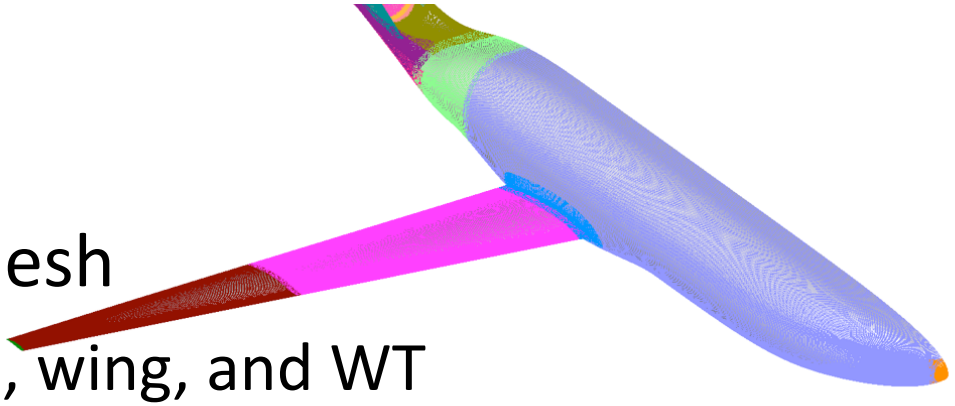


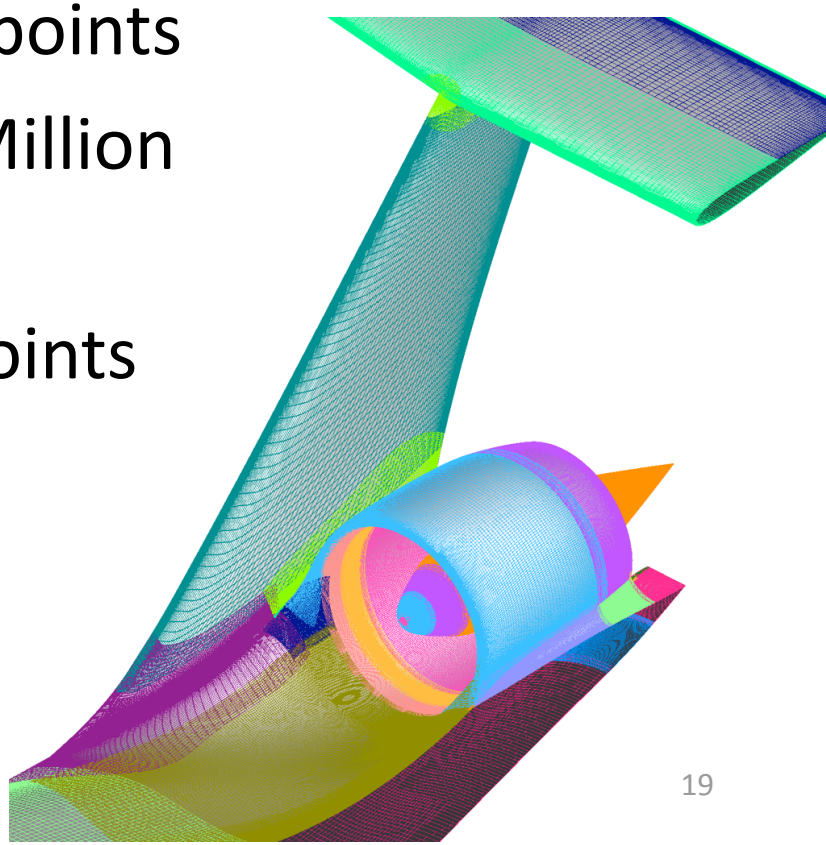




Computational Mesh

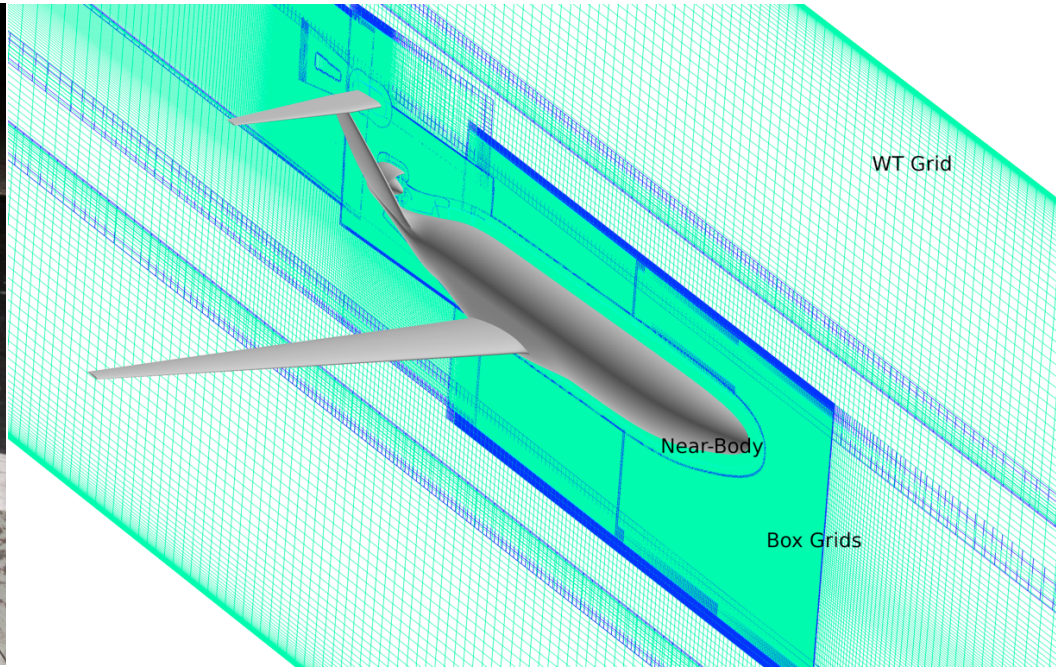
- Chimera Grid Tools
  - Overset surface and volume mesh
    - Same grids for forward fuselage, wing, and WT
  - Unpowered: 36 grids, 113 Million points
  - Podded: 13 additional grids (~15 Million more points)
  - Integrated: 64 grids, 135 Million points
  - No mounting hardware
  - y+ ≈ 0.7





D8 Model

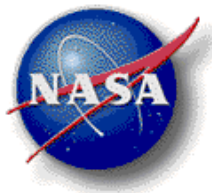




Blue indicates regions of overlap

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

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

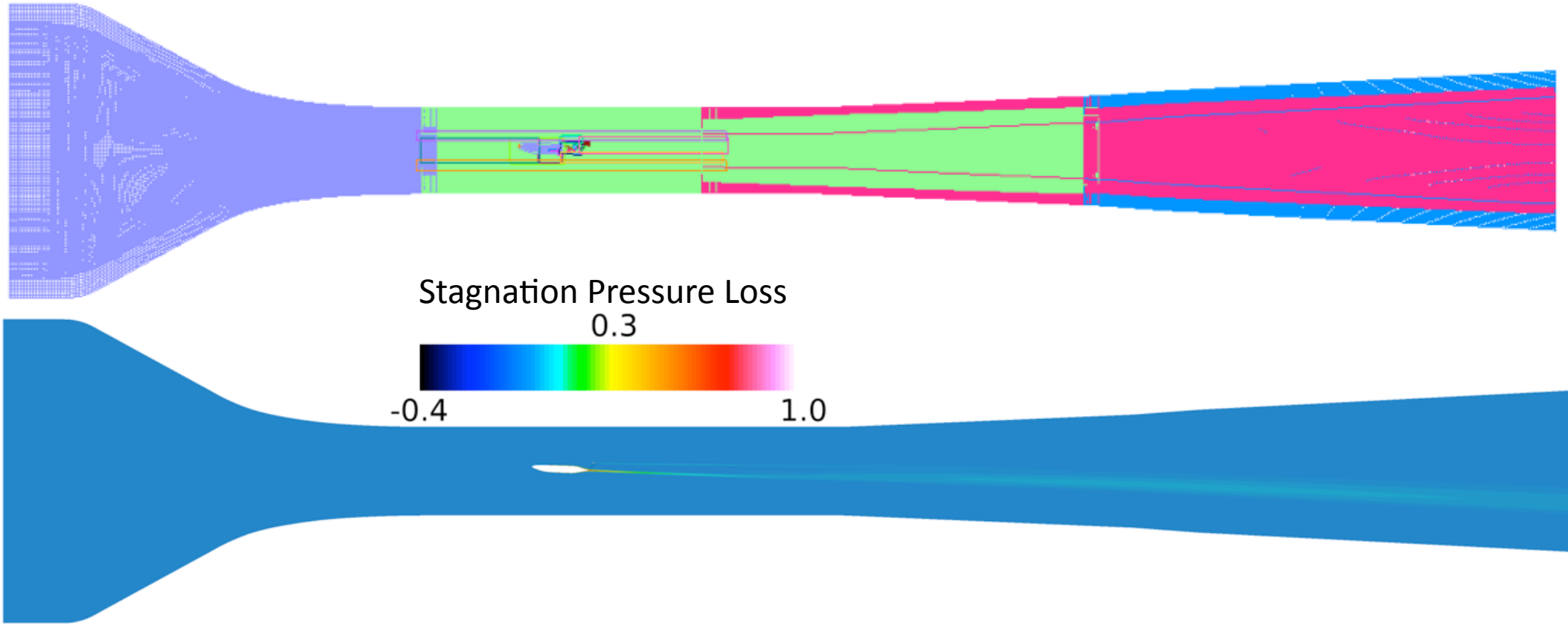


CFD Solver

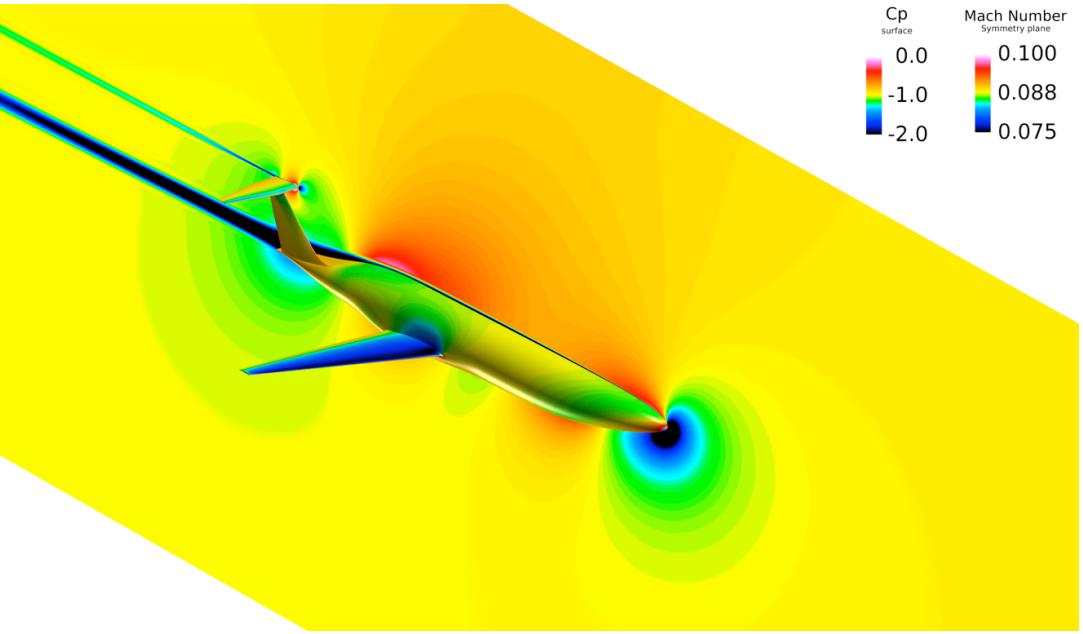
- OVERFLOW
  - 3D, RANS solver for overset structured grids
  - Diagonalized approximate factorization Scheme
  - 2nd order central difference + artificial dissipation
  - Matrix dissipation
  - RANS SST turbulence model
- Flow Conditions
  - Mach=0.088
  - Re = 44000/in.

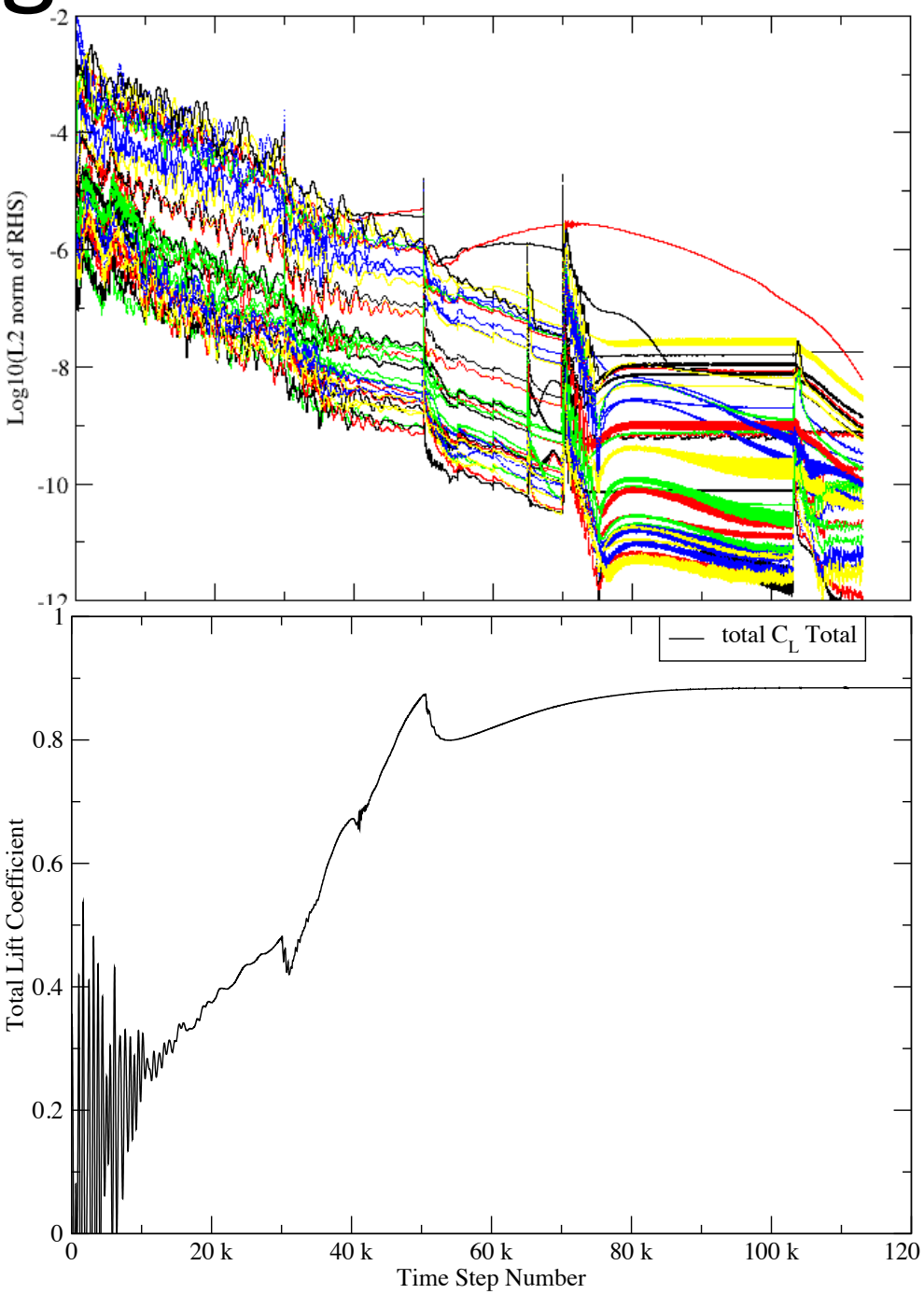
Computational model for the WT

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



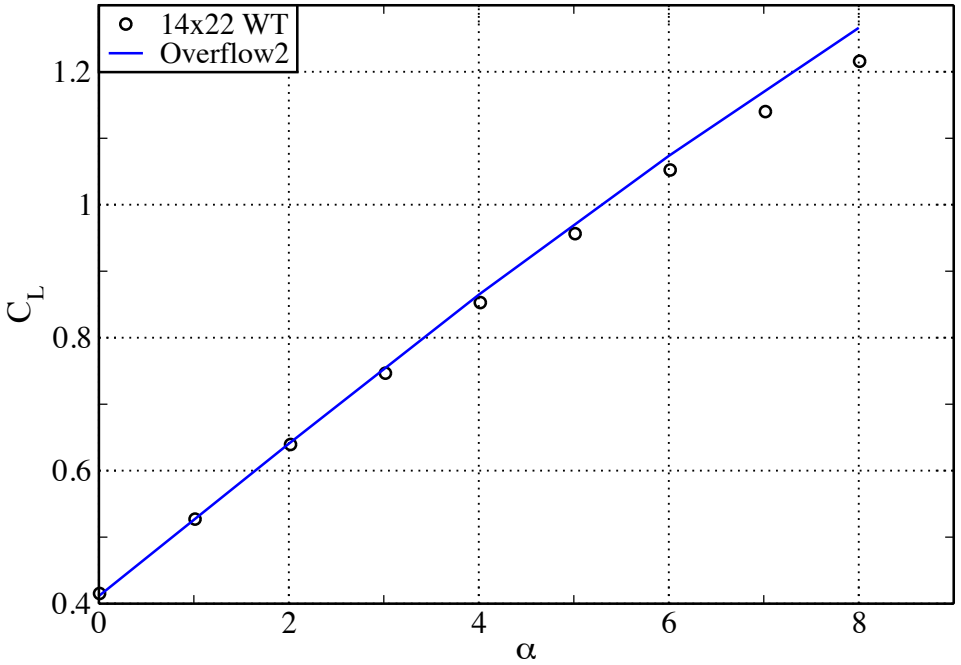
Convergence

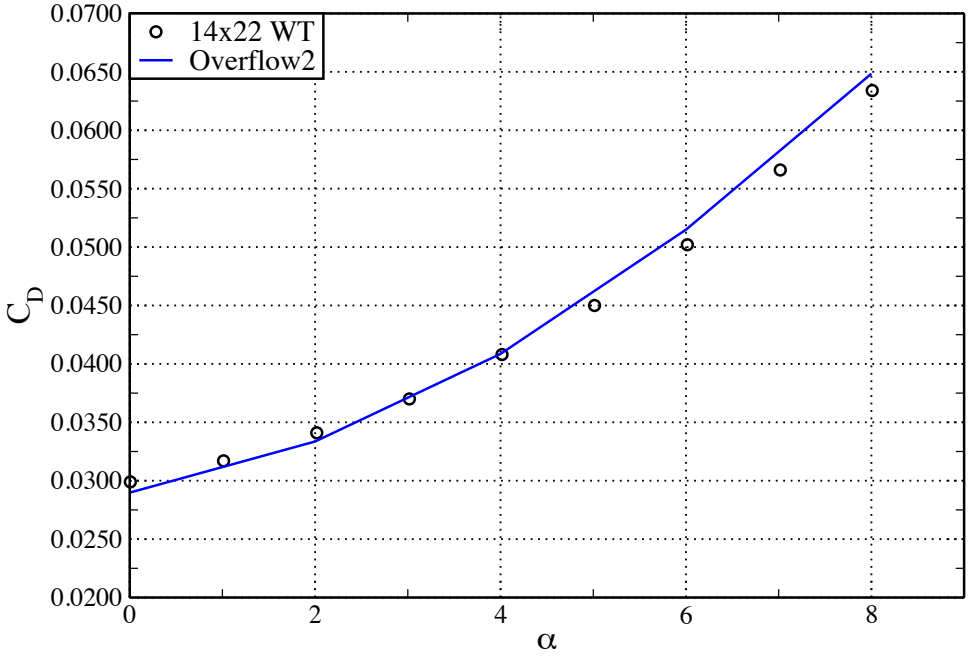


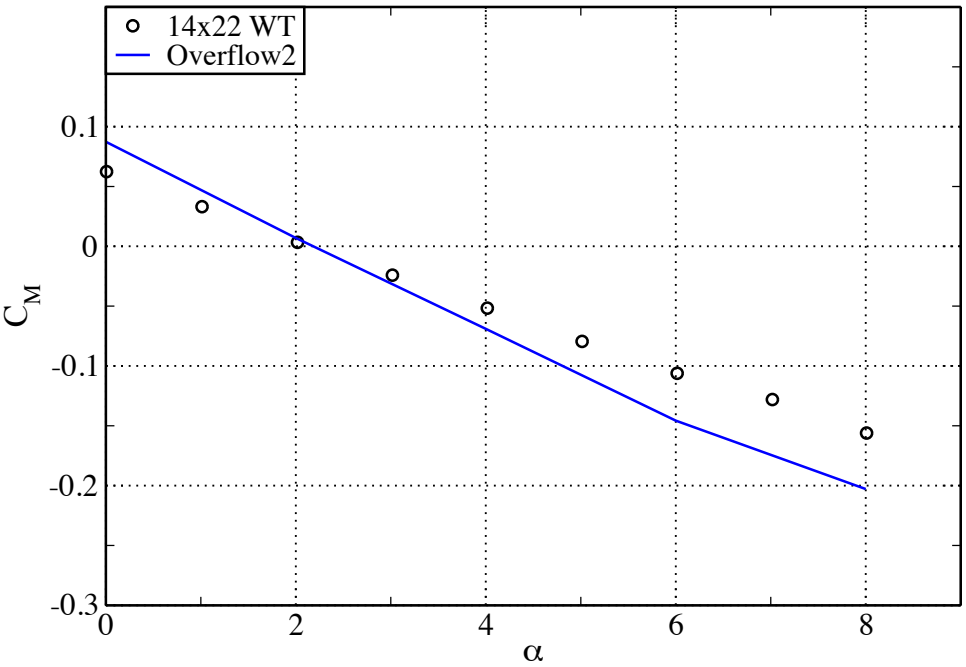


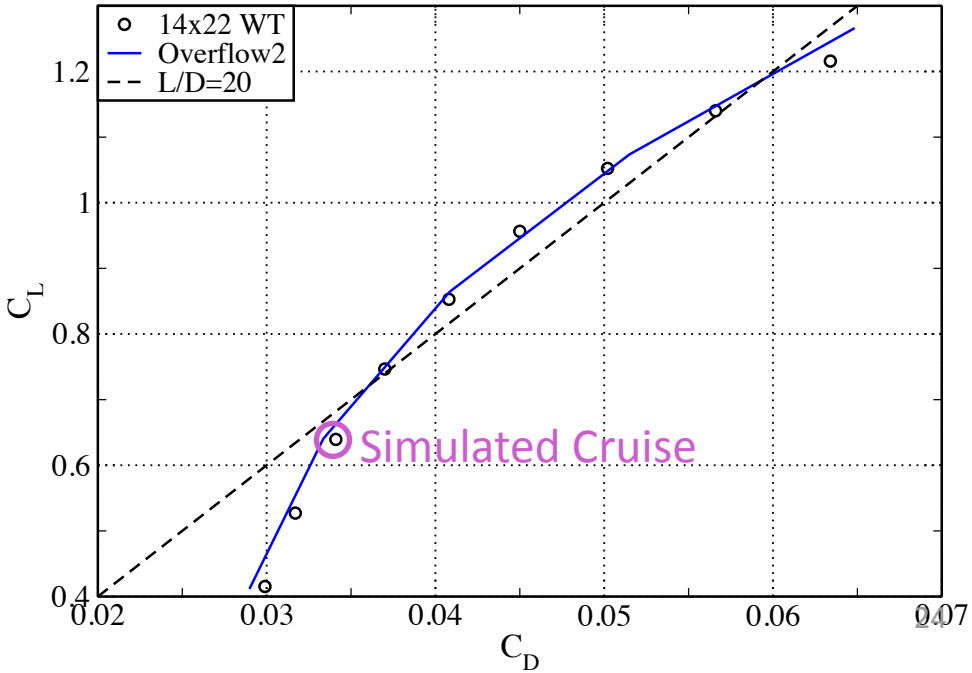
- Simulations without fans
- Alpha sweep
- Compare to Wind Tunnel (WT) test data
- Iterations to match Mach & Re at pitot probe

Validation-unpowered









Propulsor Inlet flow Comparison

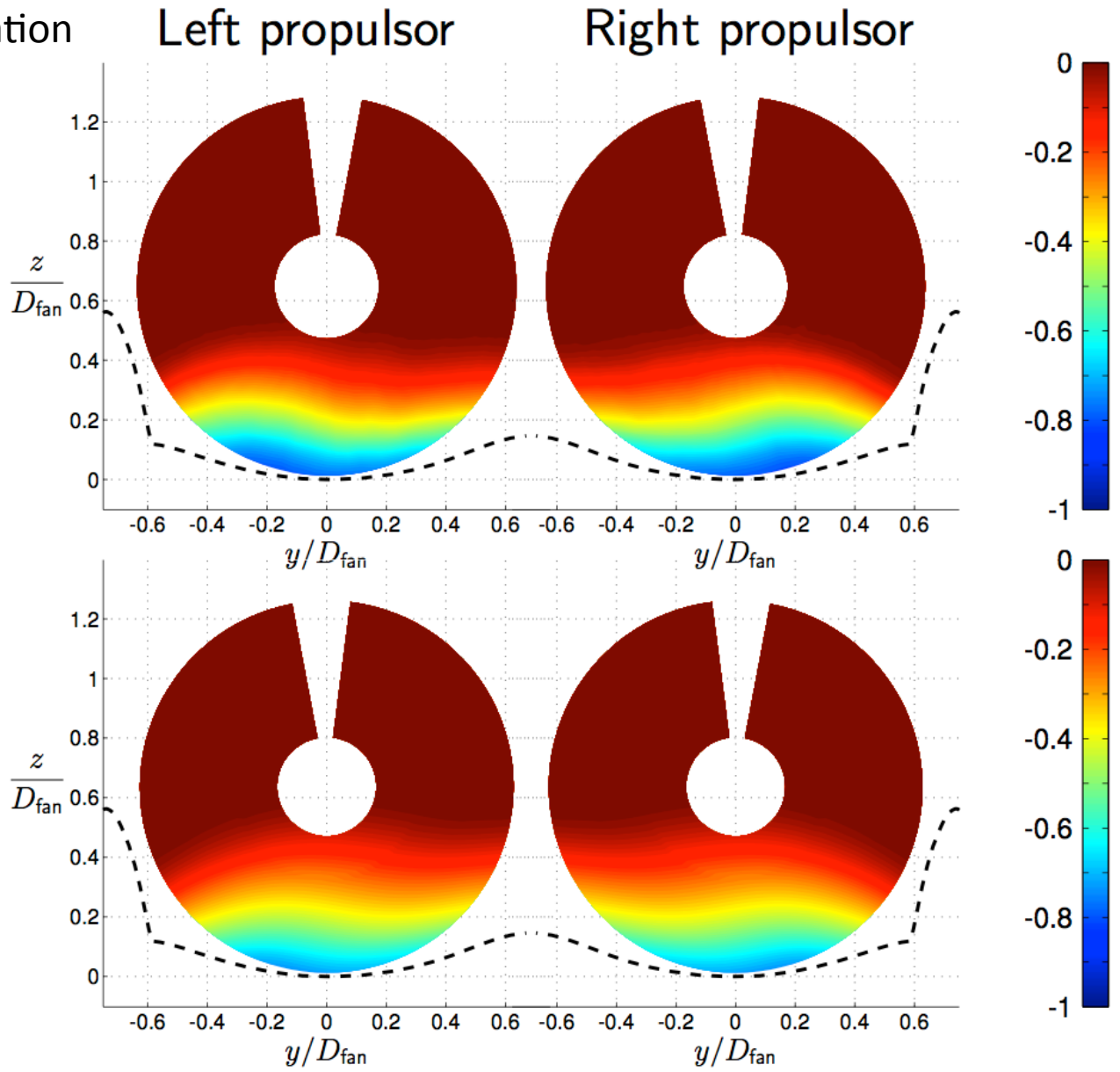
Total pressure coefficient $C_{p_t} = \dfrac{p_t - p_{t_\infty}}{q_\infty}$

Integrated Configuration

AOA=2°

14x22 WT

Overflow



Propulsor Exit flow Comparison

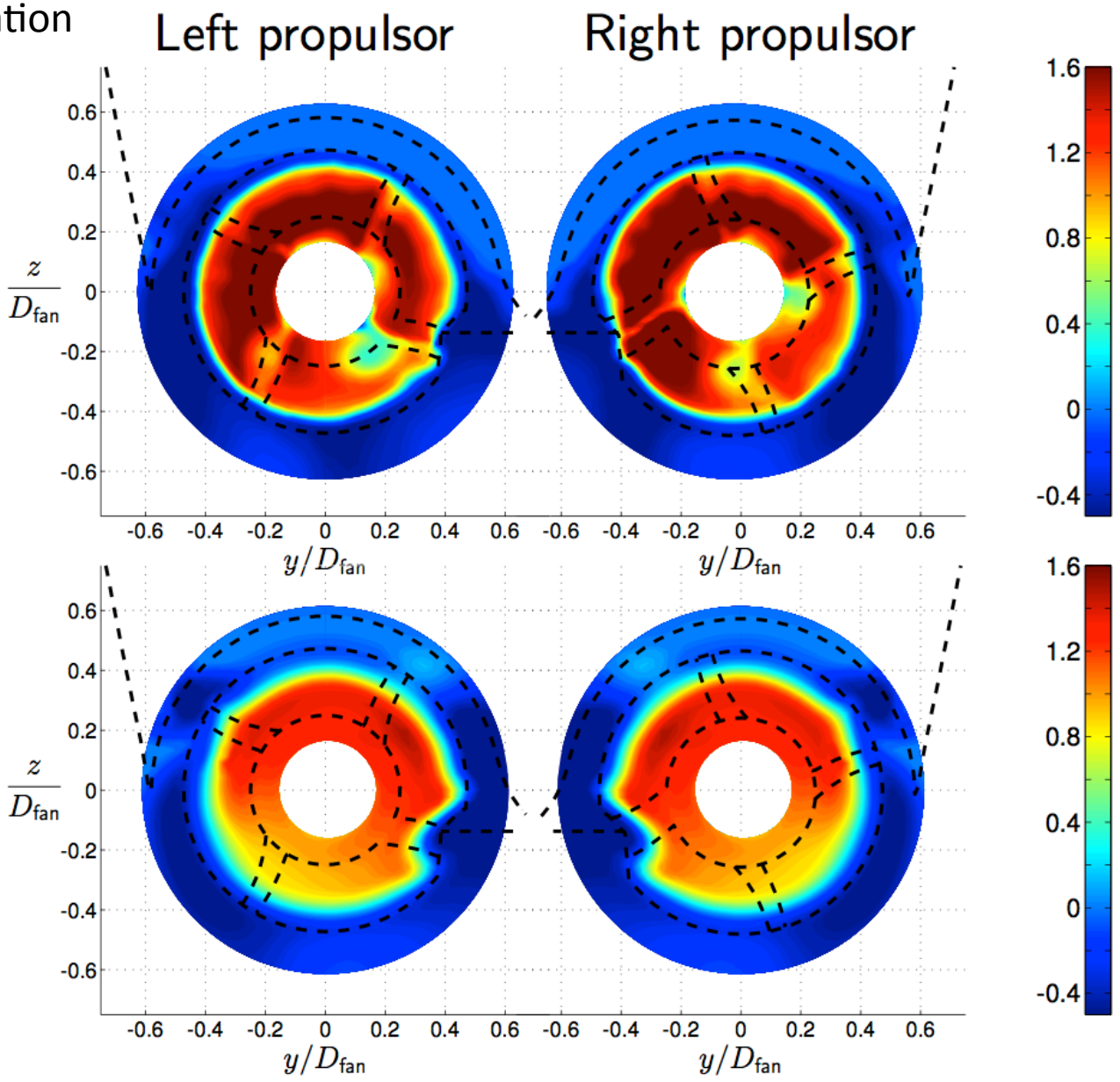
Total pressure coefficient $C_{p_t} = \dfrac{p_t - p_{t_\infty}}{q_\infty}$

Integrated Configuration

AOA=2°

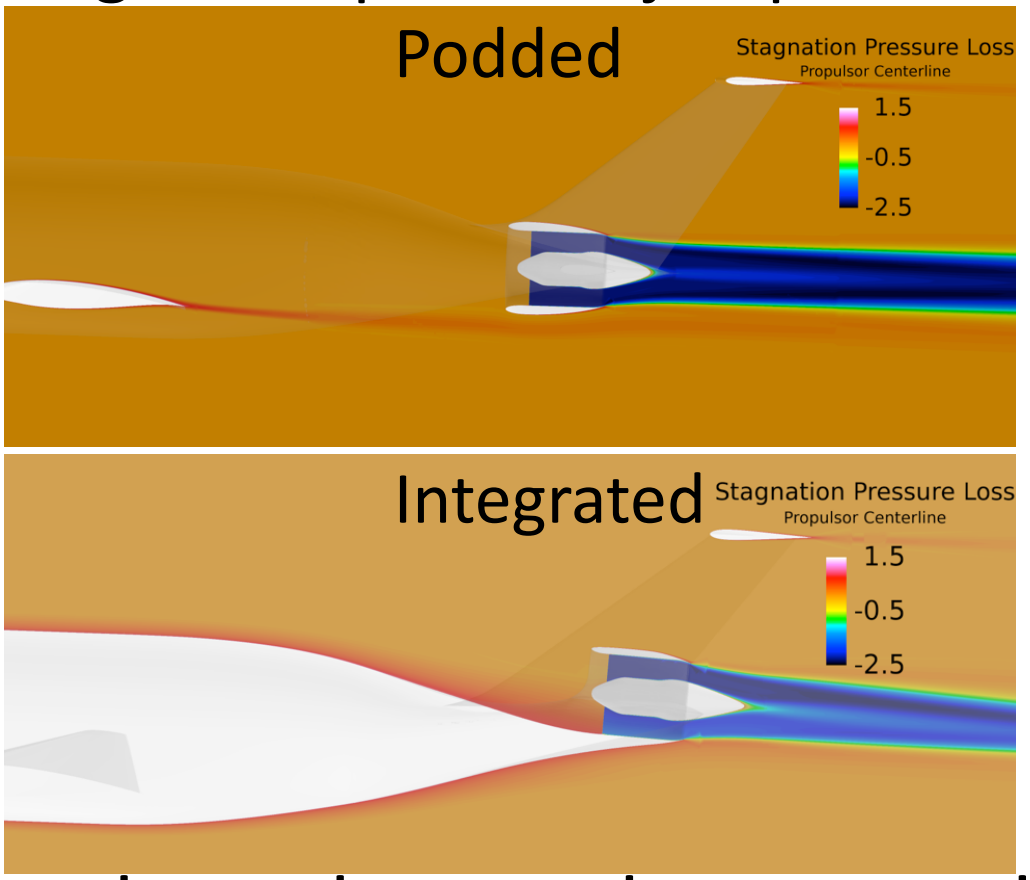
14x22 WT

Overflow



Fan Model and its Effect

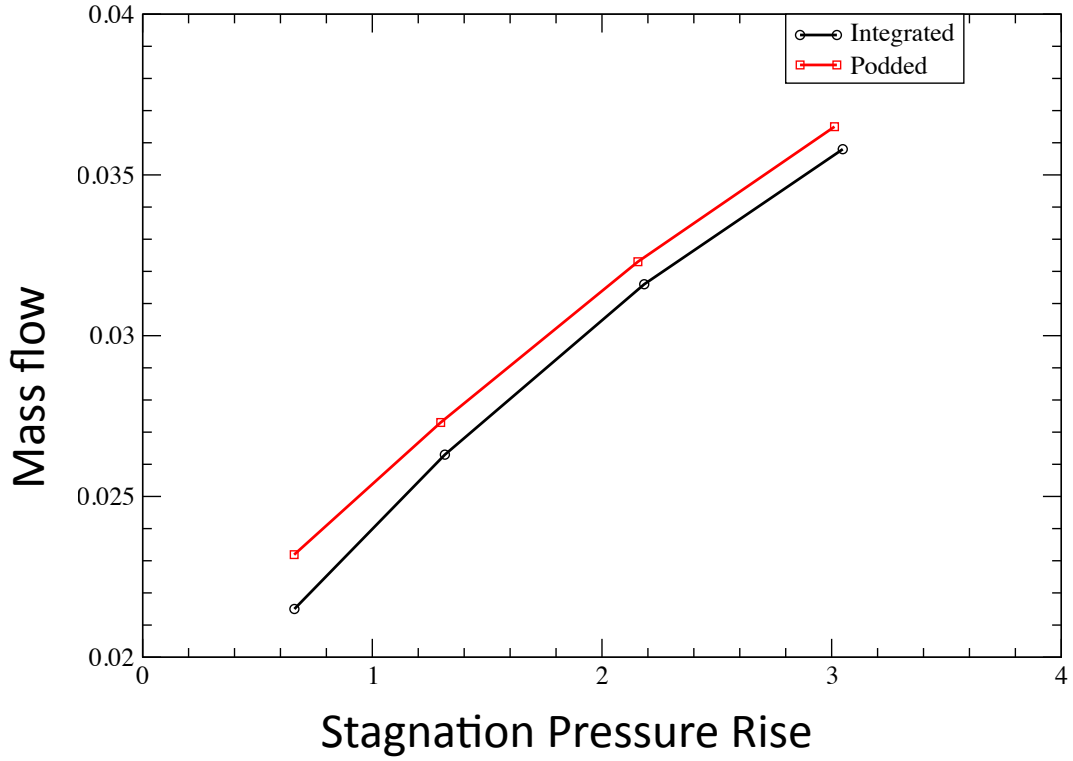
- Actuator disk
  - Uniform pressure jump
  - Same as stagnation pressure jump



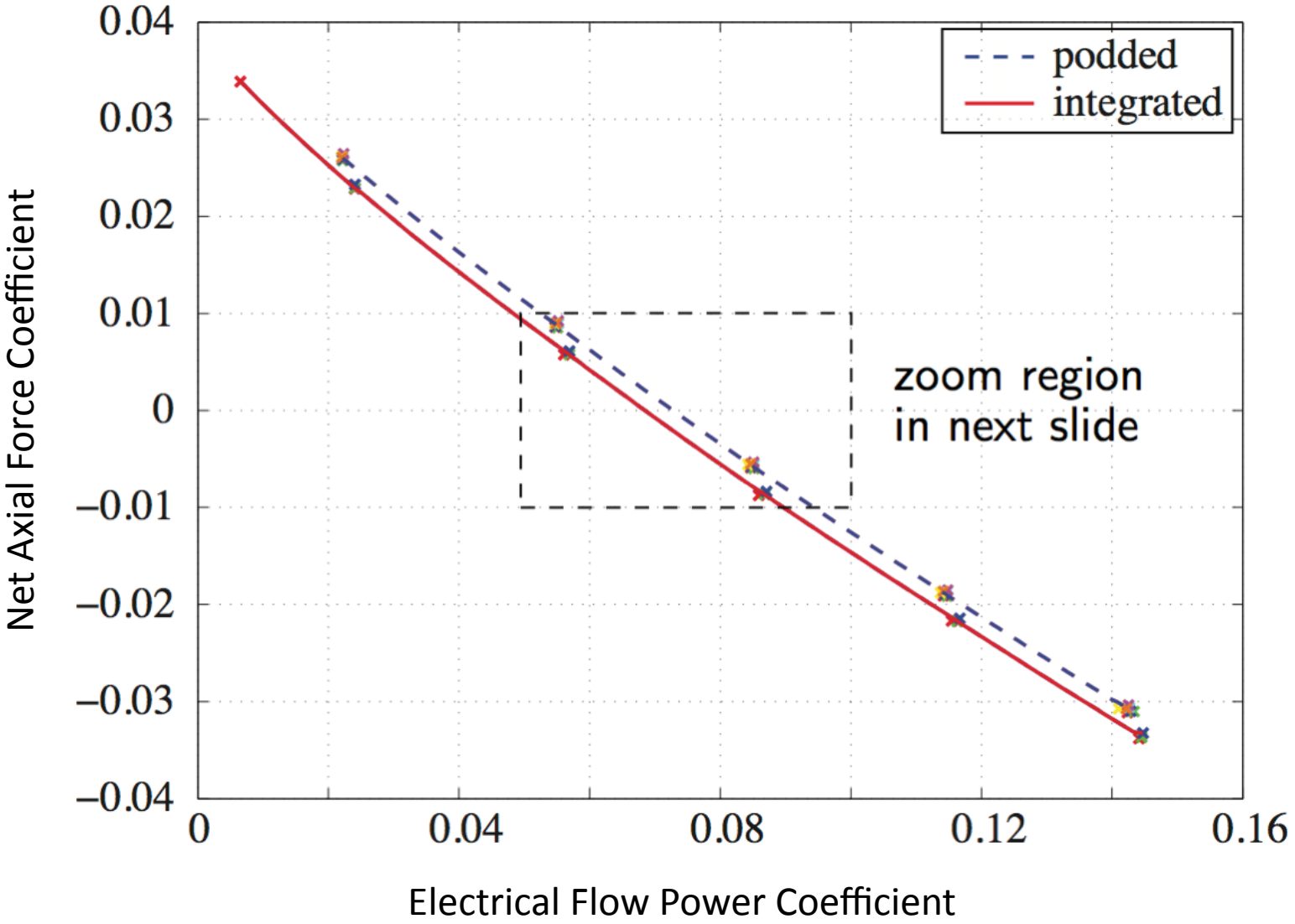
Cuts through propulsor centerline.

Range of Thrust Conditions

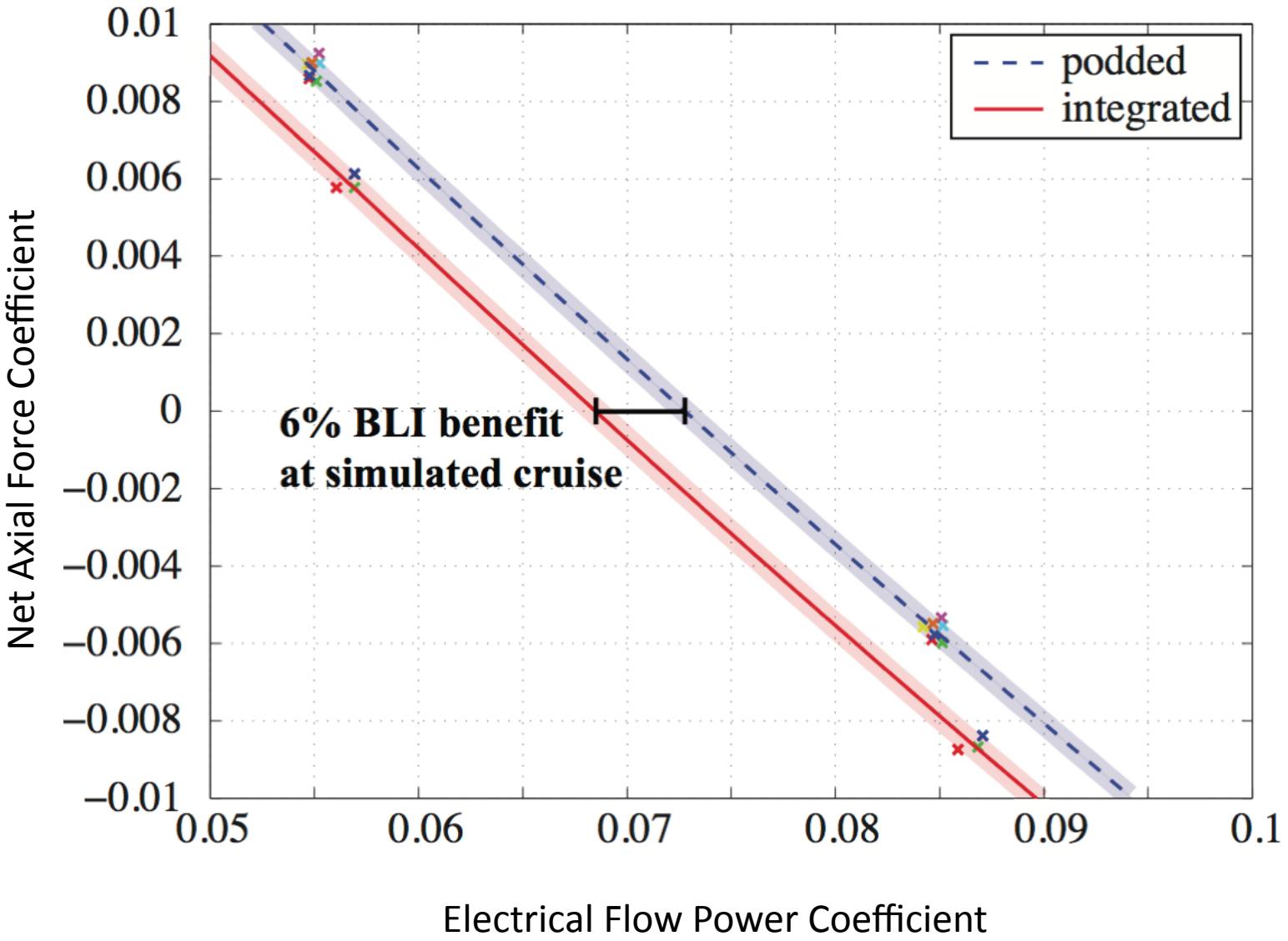
- Four cases with increasing pressure jump settings
  - For both podded and integrated
  - Integrated sees a lower mass flow



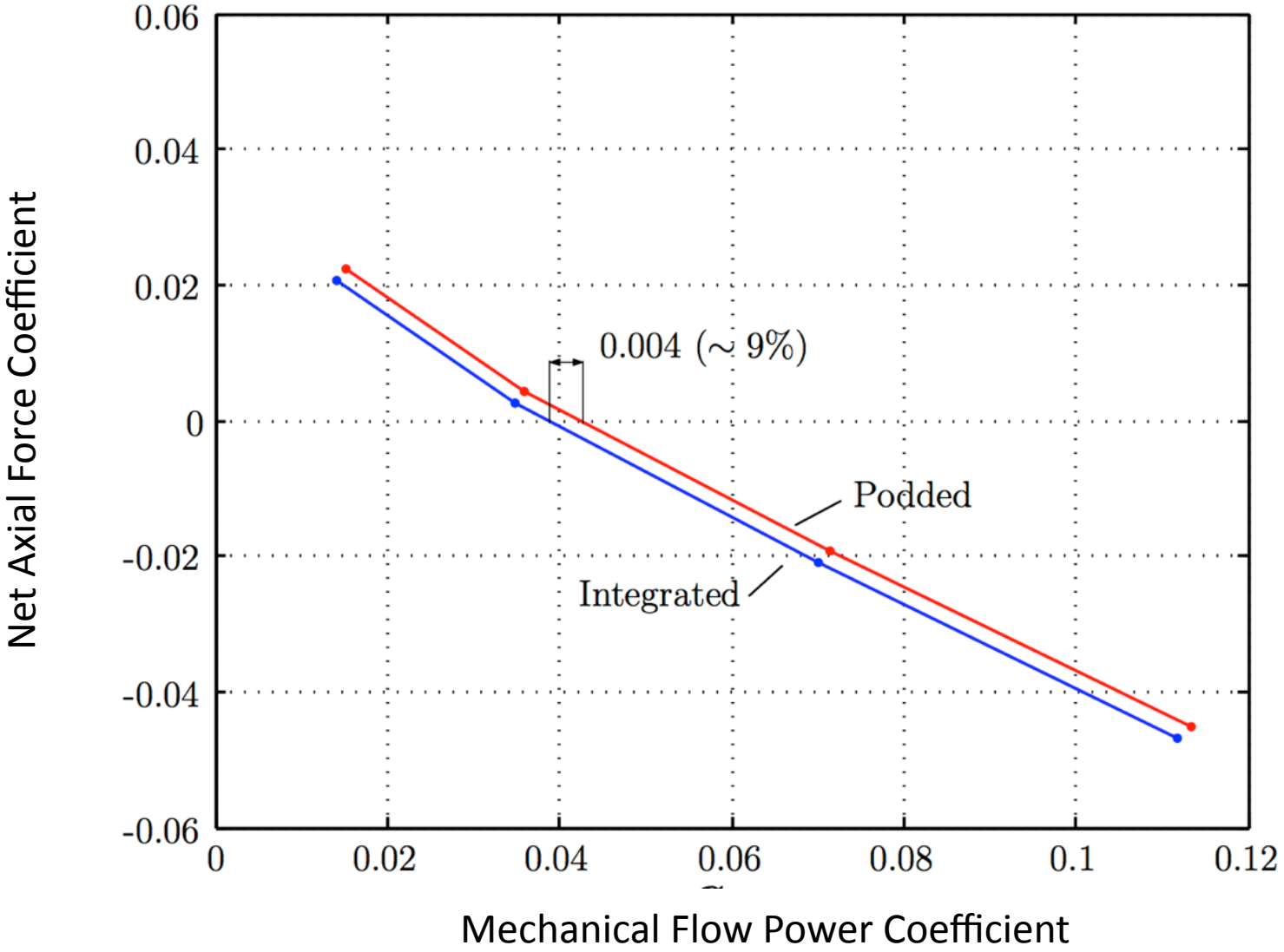
Benefit of BLI (Experimental)



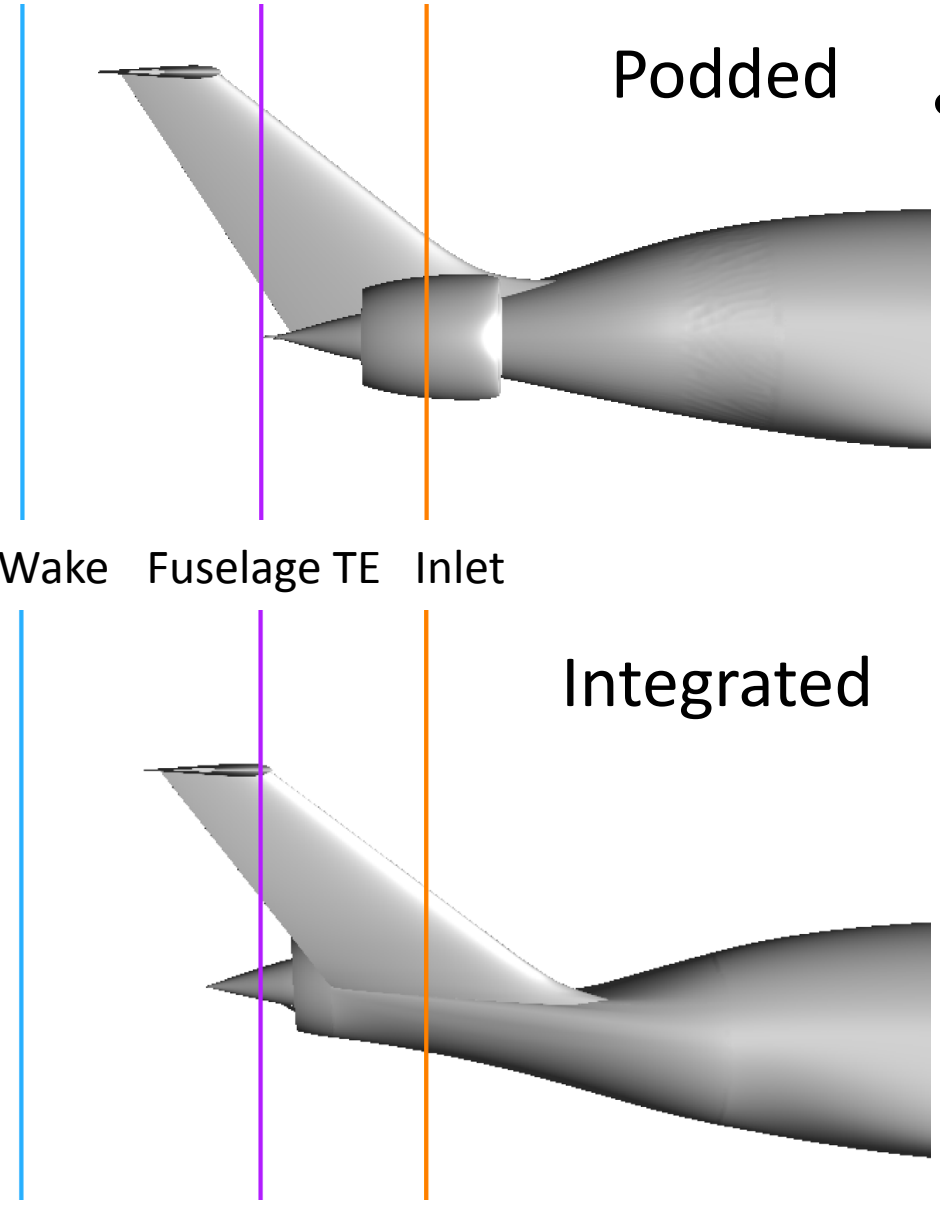
Benefit of BLI (Experimental)



Benefit of BLI (Computational)

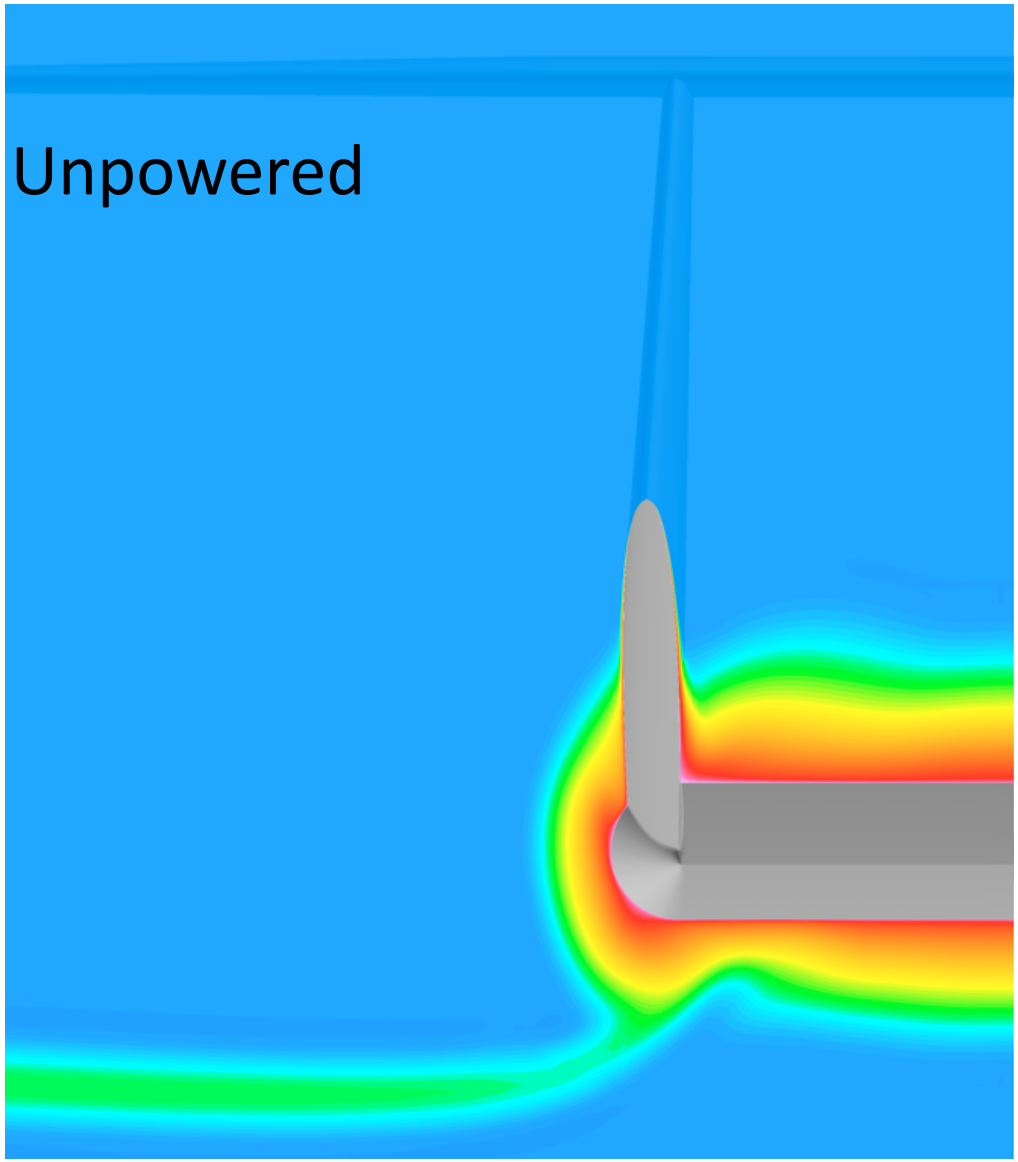


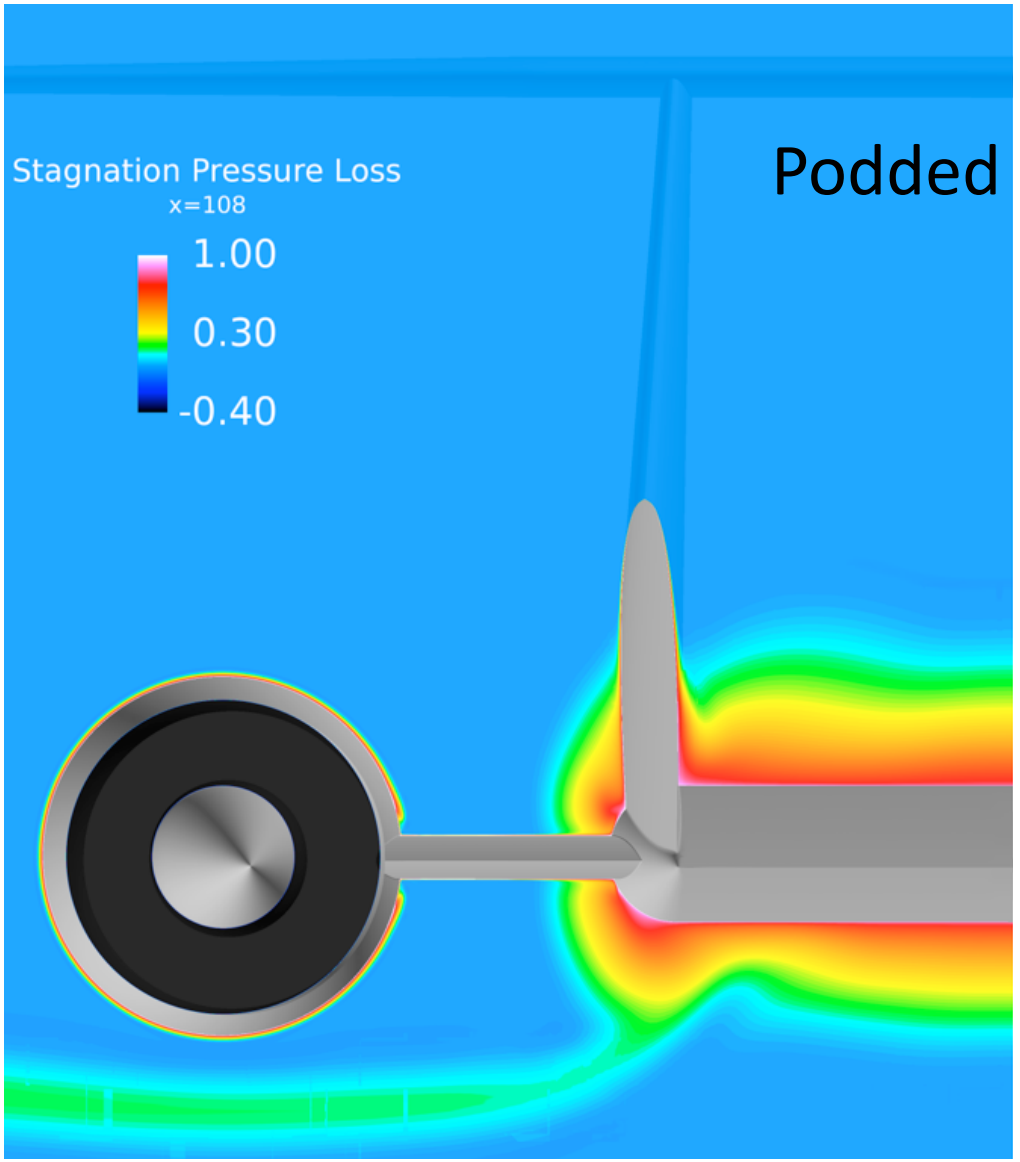
Where is the Benefit Coming From?



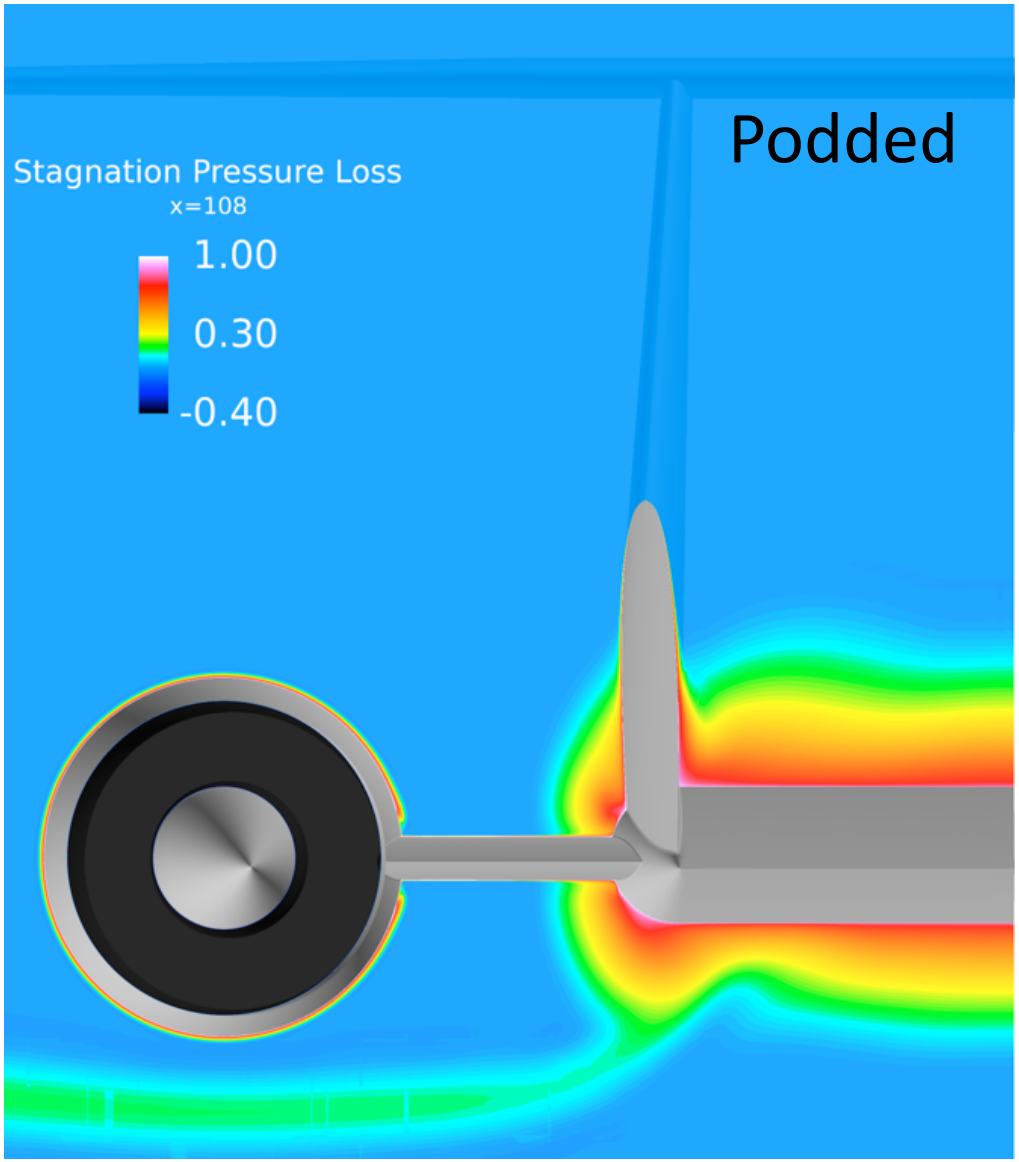
- Identify sinks of power
  - –Upstream viscous dissipation
    - measured by stagnation pressure flux
    - We can focus on stagnation pressure loss and dissipation

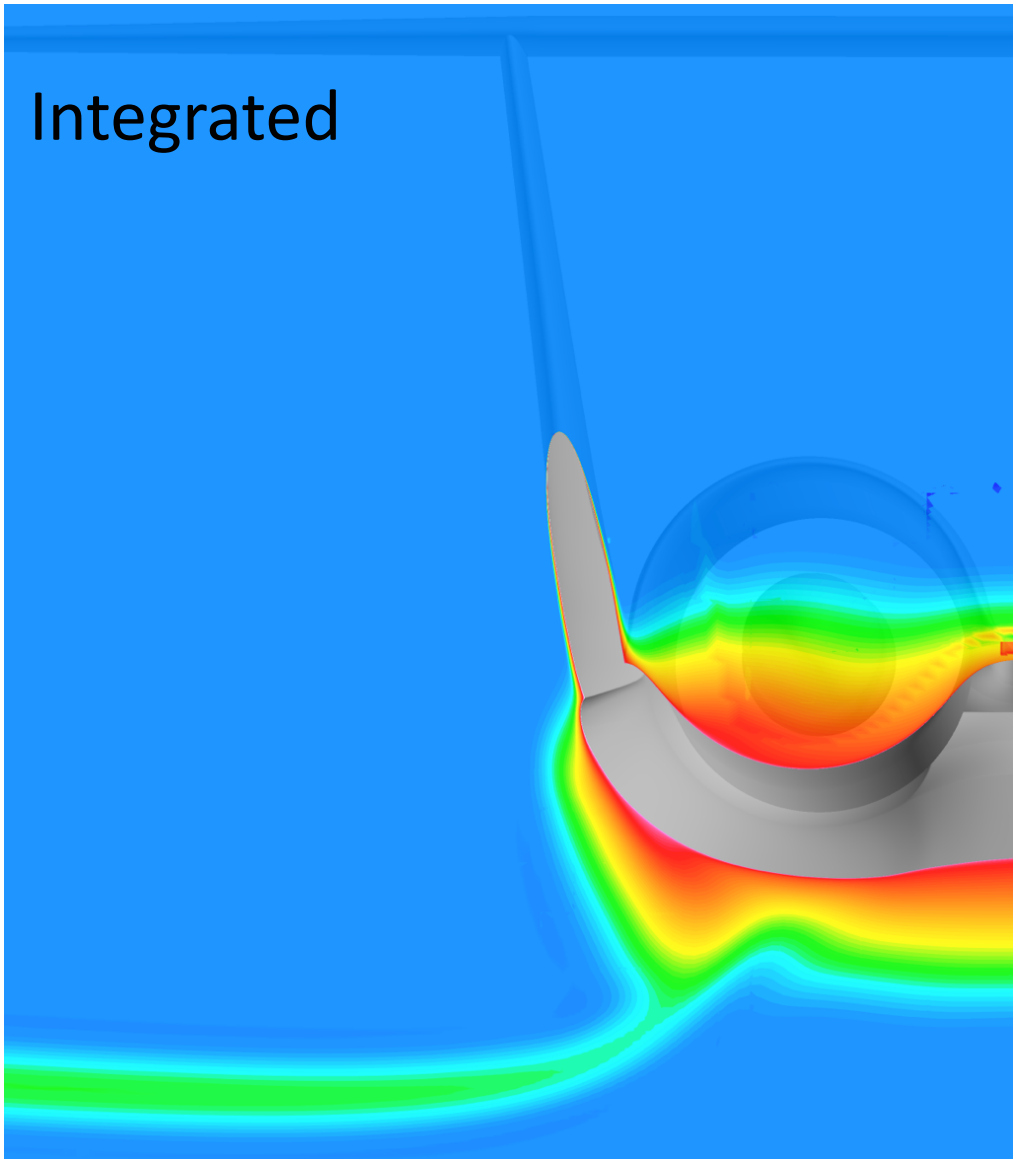
Inlet


Unpowered

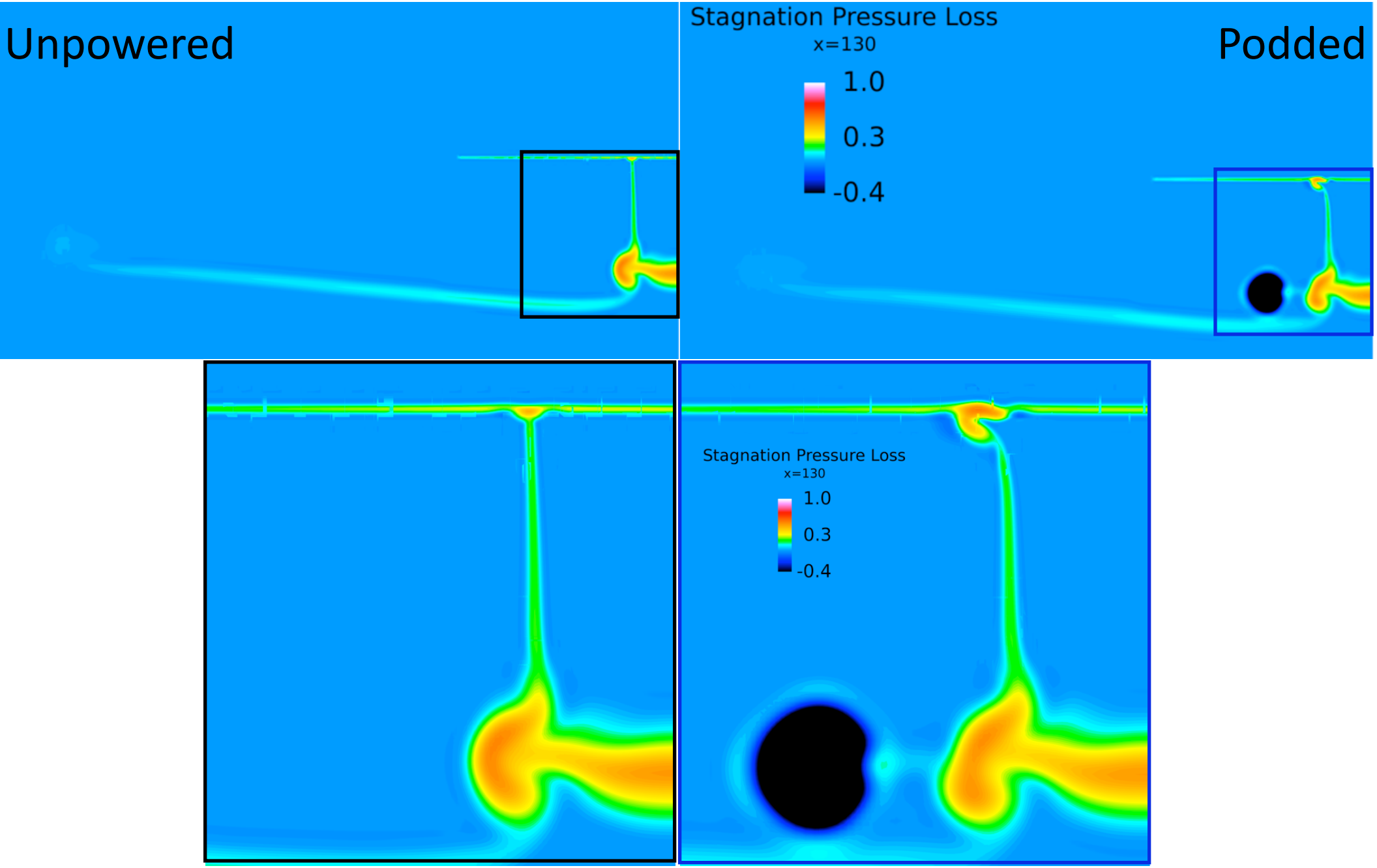

Stagnation Pressure Loss
x=108
1.00
0.30
-0.40
Podded

Inlet (cont.)

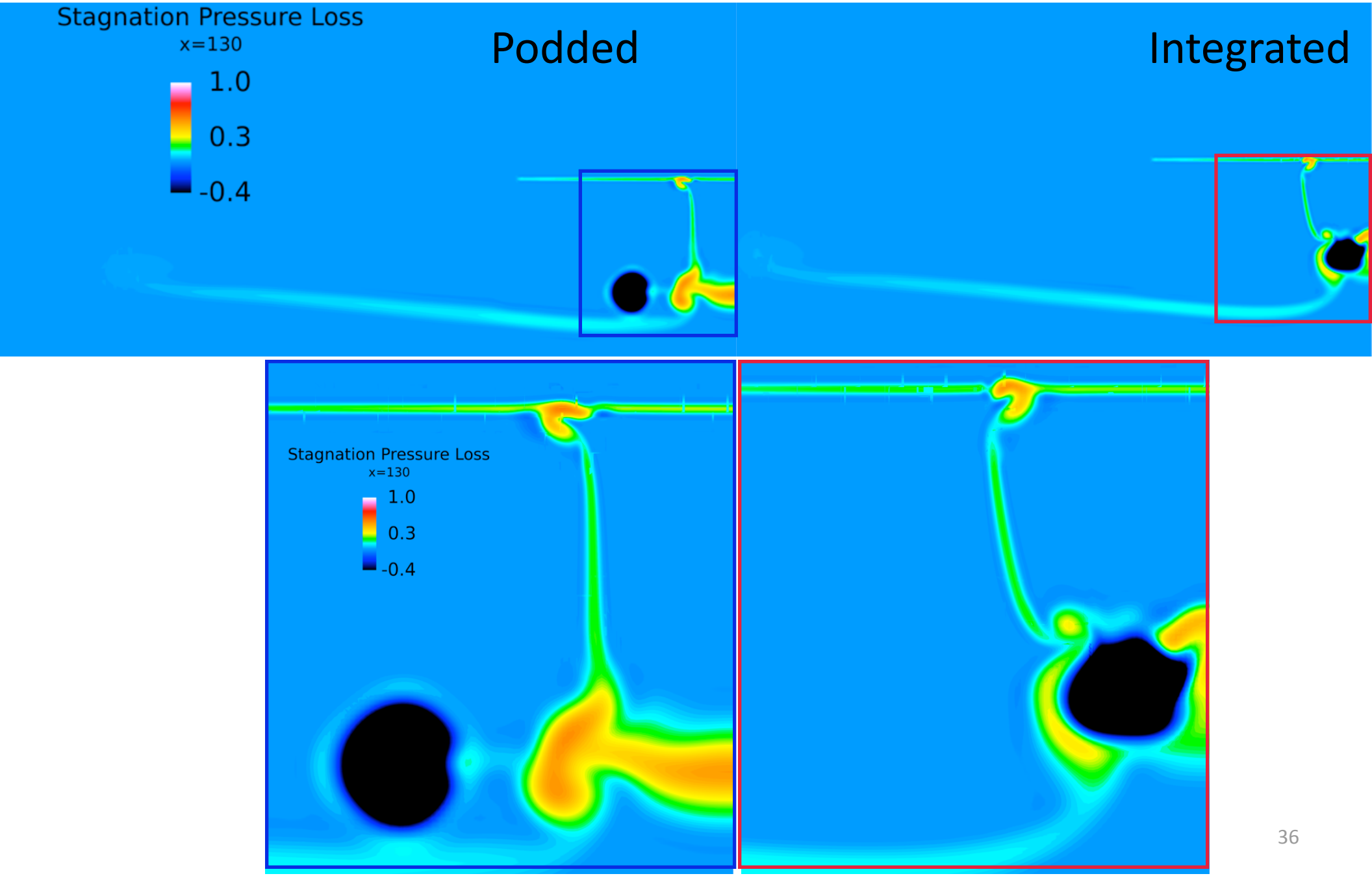

Podded
Stagnation Pressure Loss
x=108
1.00
0.30
-0.40


Integrated

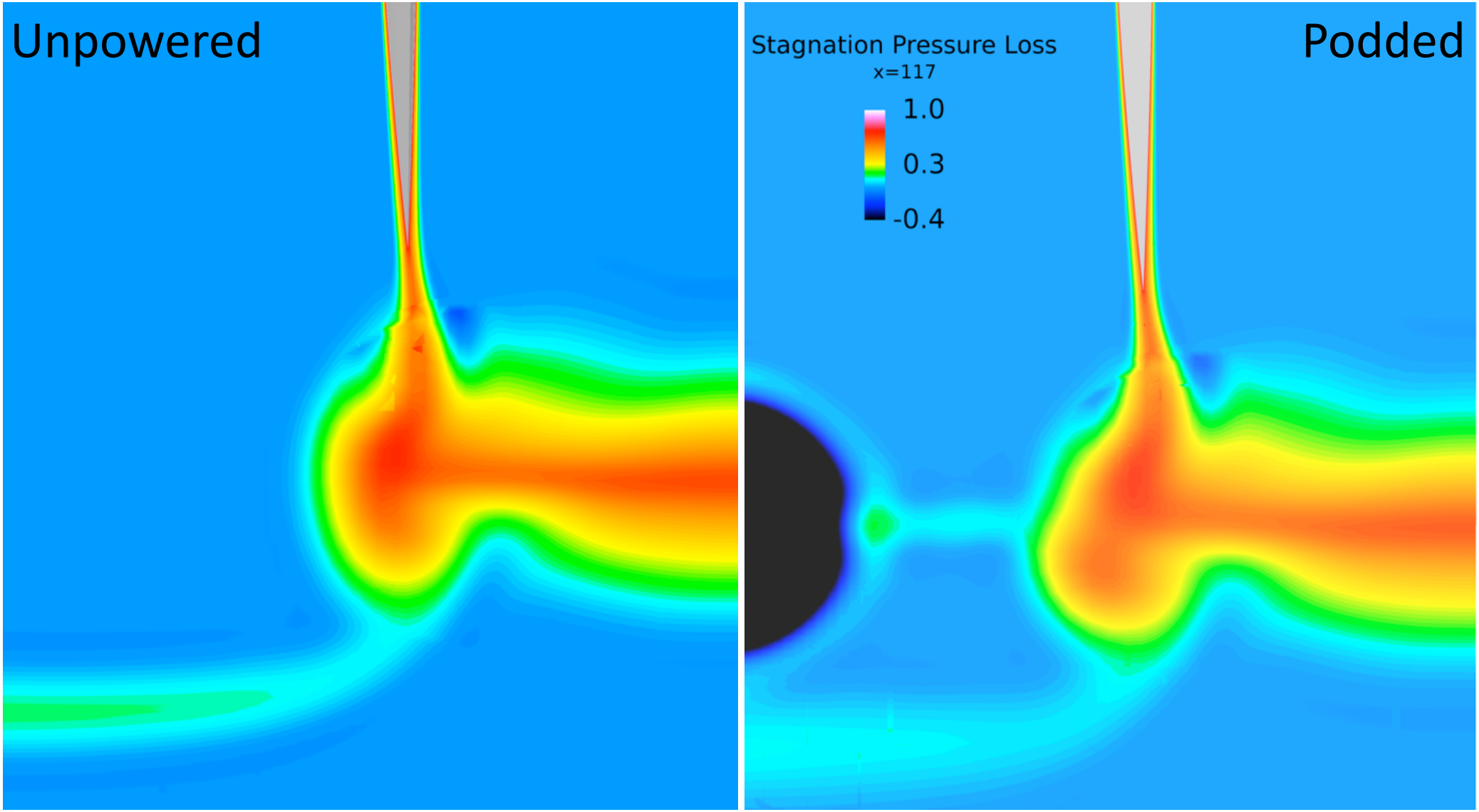
Wake


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

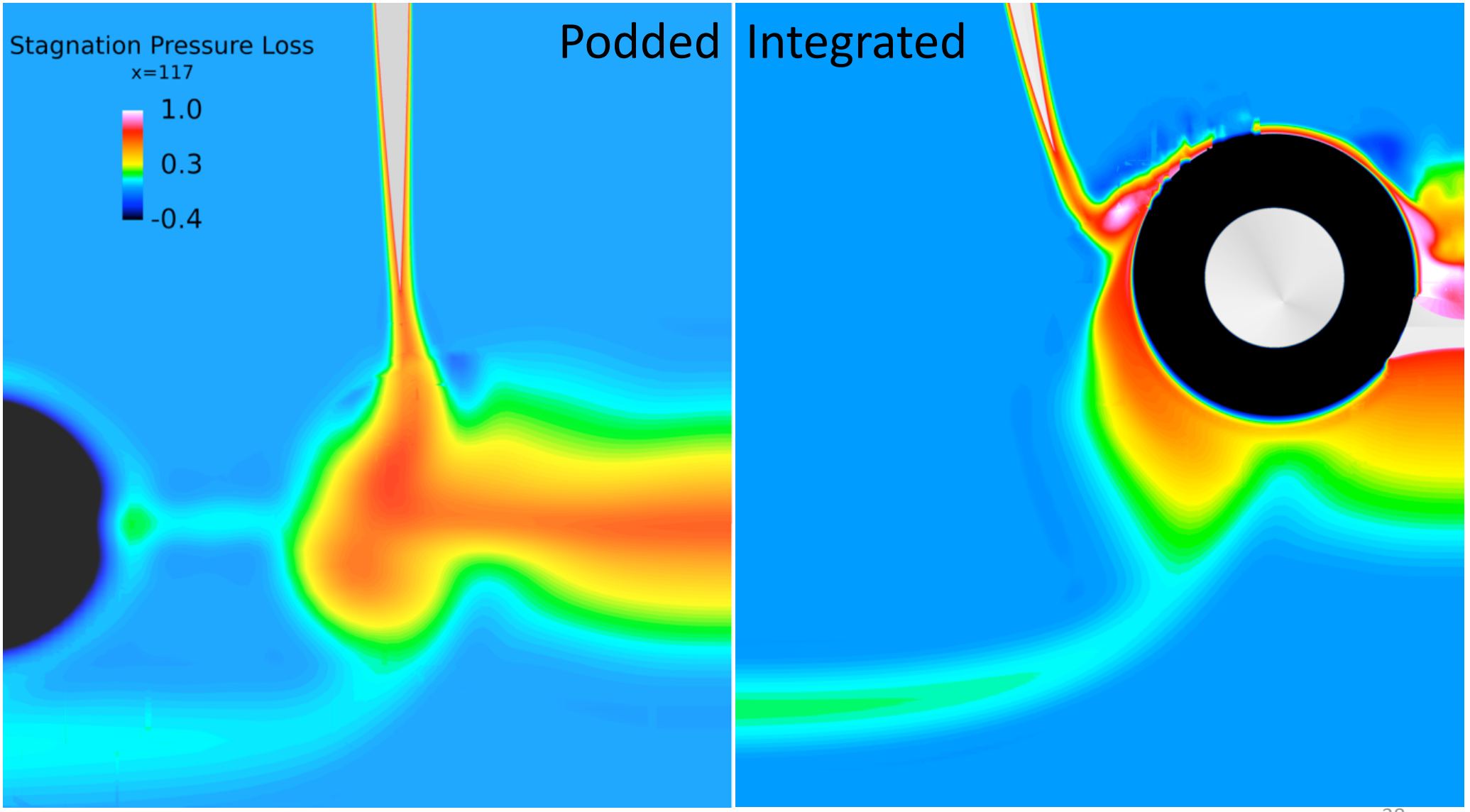
Wake (cont.)


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

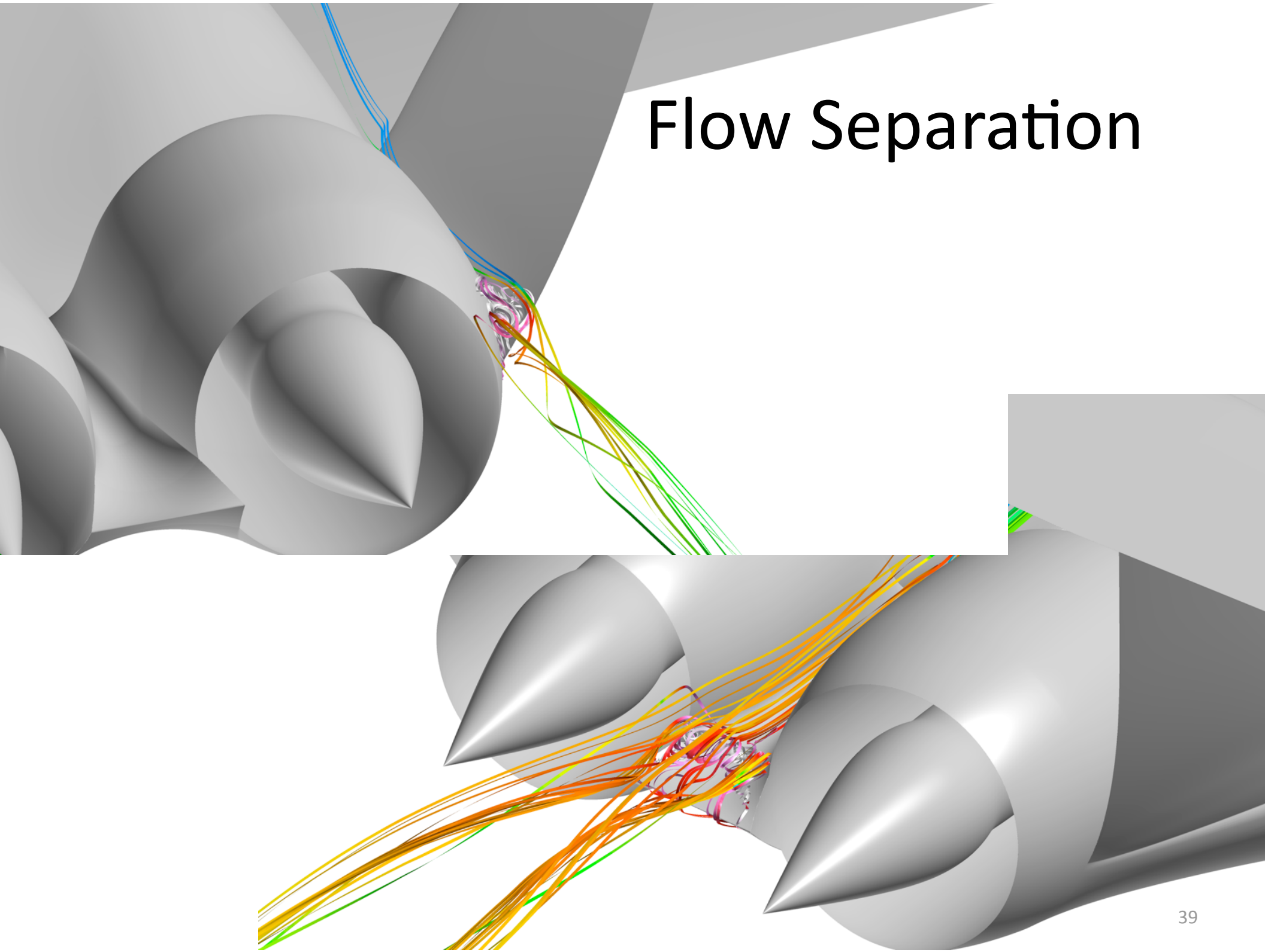
Fuselage Trailing Edge



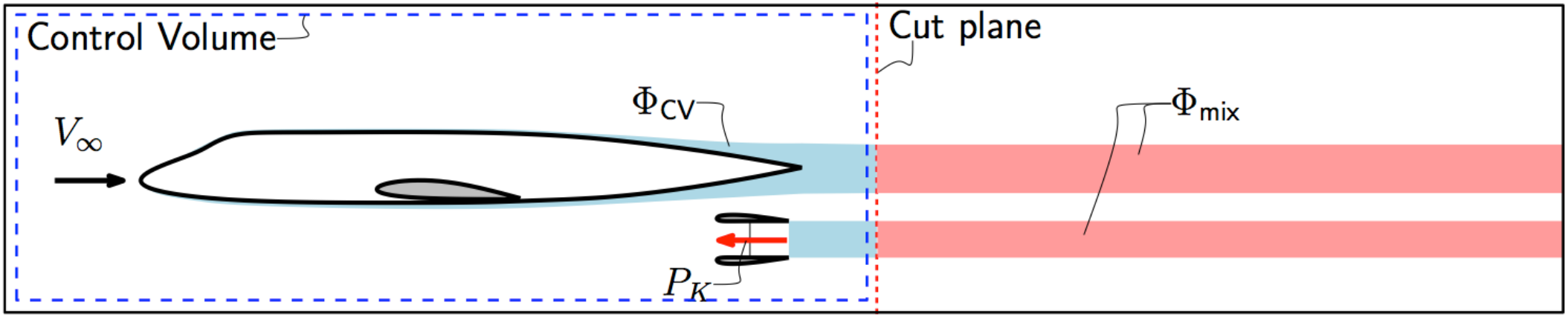
Fuselage Trailing Edge (cont.)



Flow Separation



Viscous Dissipation

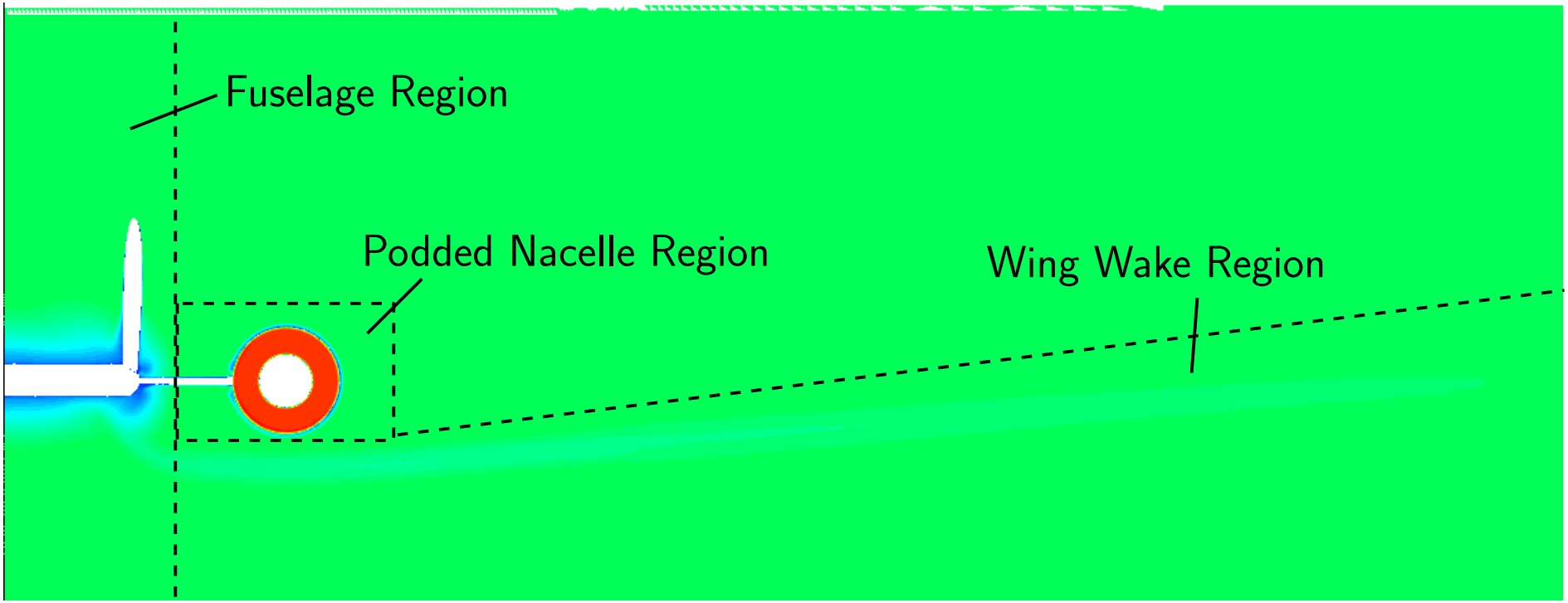


$$\Phi = \Phi_{CV} + \Phi_{\text{mix}} = \left(P_K - \dot{\mathcal{E}}\right) + \Phi_{\text{mix}}$$

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

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

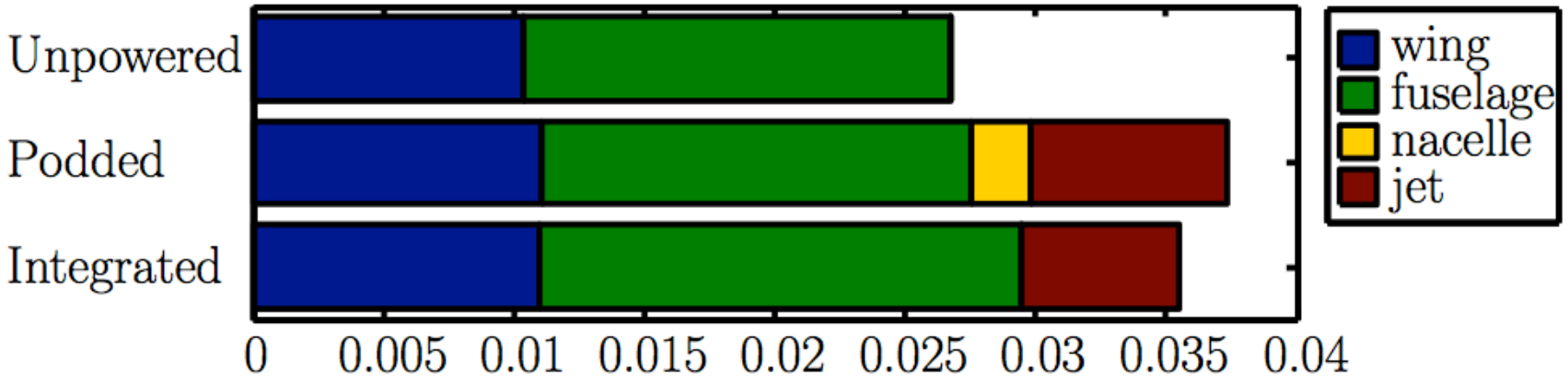
Dissipation Computation



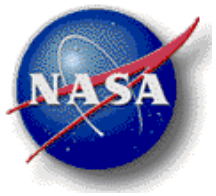
- Dissipation computed in each region
  - No separate nacelle for integrated config

Dissipation 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%)

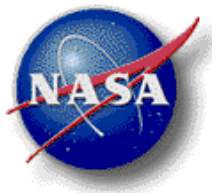


- Wing dissipation not affected by BLI
- Integrated config. has 6% less overall dissipation
  - –3/4 from lower jet velocity
  - –1/4 from lower fuselage/nacelle dissipation



Concluding Remarks

- BLI benefit is demonstrated to be
  - –6% by electrical power
  - –9% by Mechanical flow power
- Further investigation revealed that the integrated configuration has:
  - –lower dissipation
- Most of the benefit from lower jet dissipation
- Some benefit derived from lower wake dissipation
- BLI has the potential to reduce fuel burn



Future Work

- Improve the integrated configuration
  - Reduce flow separation near the nacelles
- Full scale aircraft. (Ma, Re)
  - current work at LaRC
- Other operating conditions
- Advanced actuator disk model