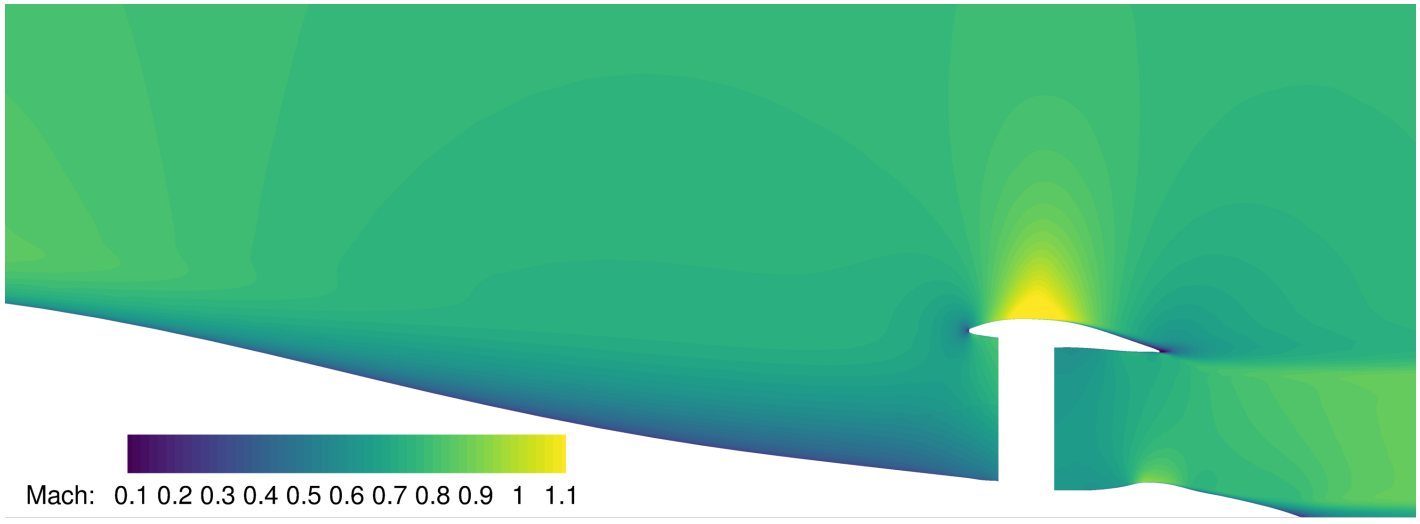


Coupled Aeropropulsive Design Optimization Of a Boundary Layer Ingestion Propulsor

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AEROSPACE ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

"The theory is so incomplete that one is hesitant to use it as a basis for prediction."

A. M. O. Smith. and H. E. Roberts "The Jet Airplane Utilizing Boundary Layer Air for Propulsion", Journal of the Aeronautical Sciences, 1947

Conceptual design studies have predicted 5%-12% fuel burn reduction from Boundary Layer Ingestion (BLI)

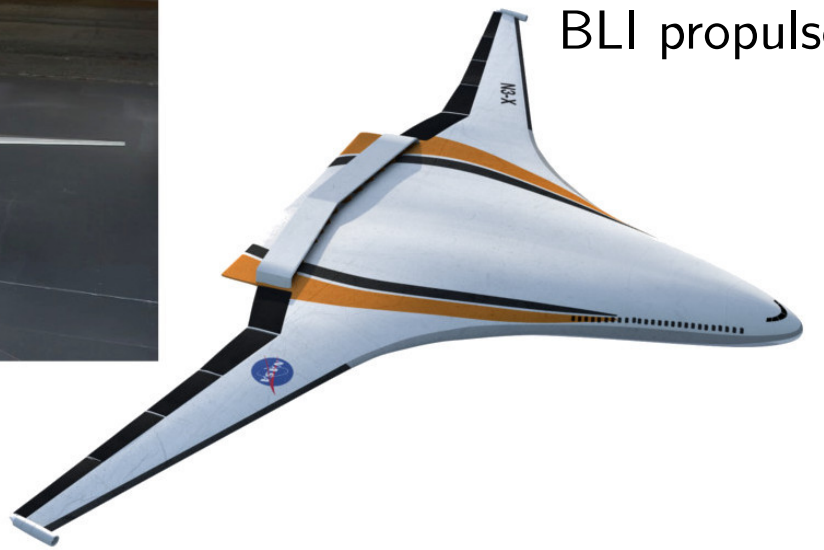


Aft-mounted
BLI propulsor



Aft-mounted BLI engines

Mail-slot inlet
BLI propulsors



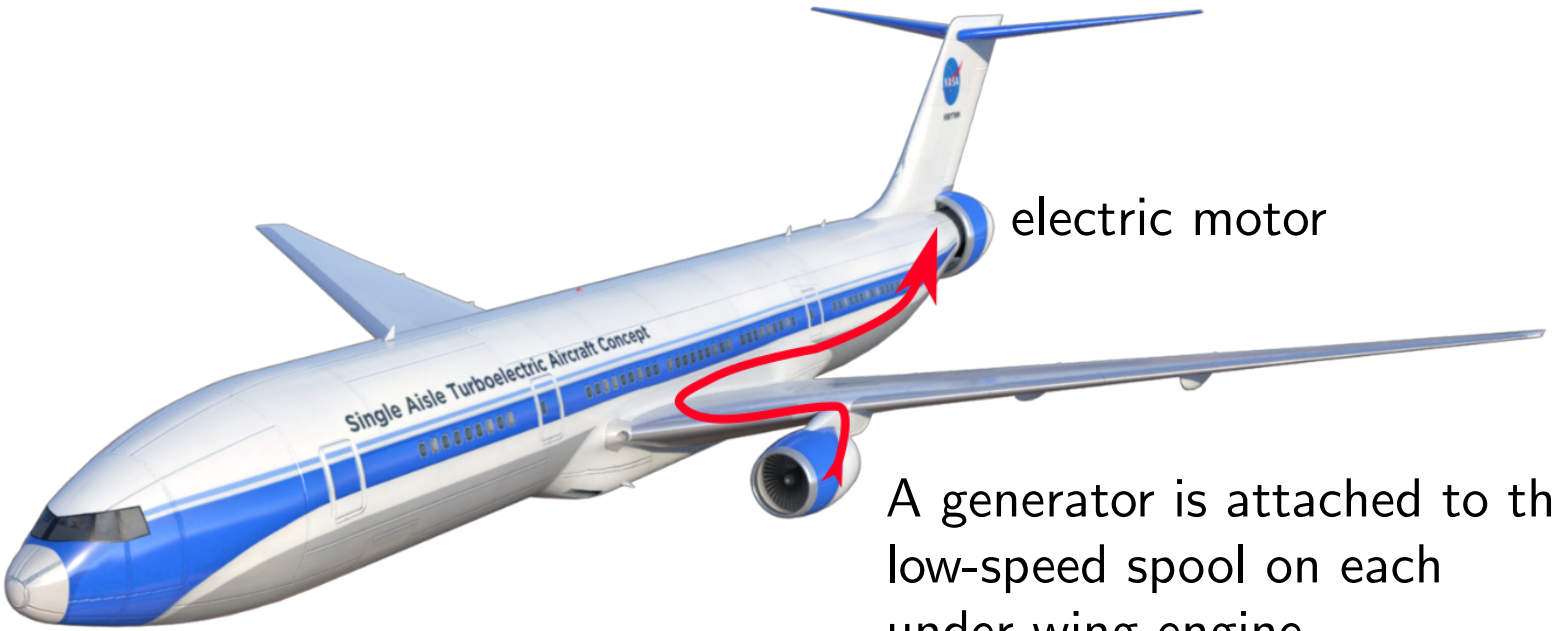
NASAs STARC-ABL configuration applies BLI to a conventional airframe



Electric
BLI propulsor

Tube-with-wing configuration

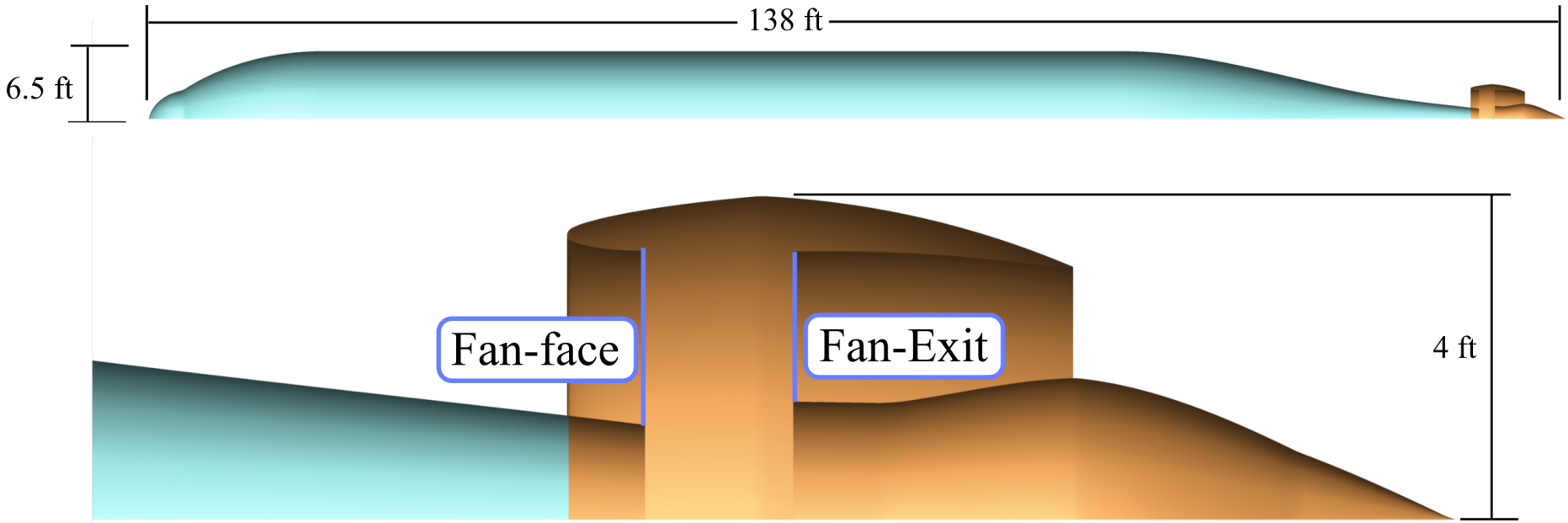
The BLI propulsor is driven by a turbo-electric power system



Traditional power transmission is roughly 90% efficient

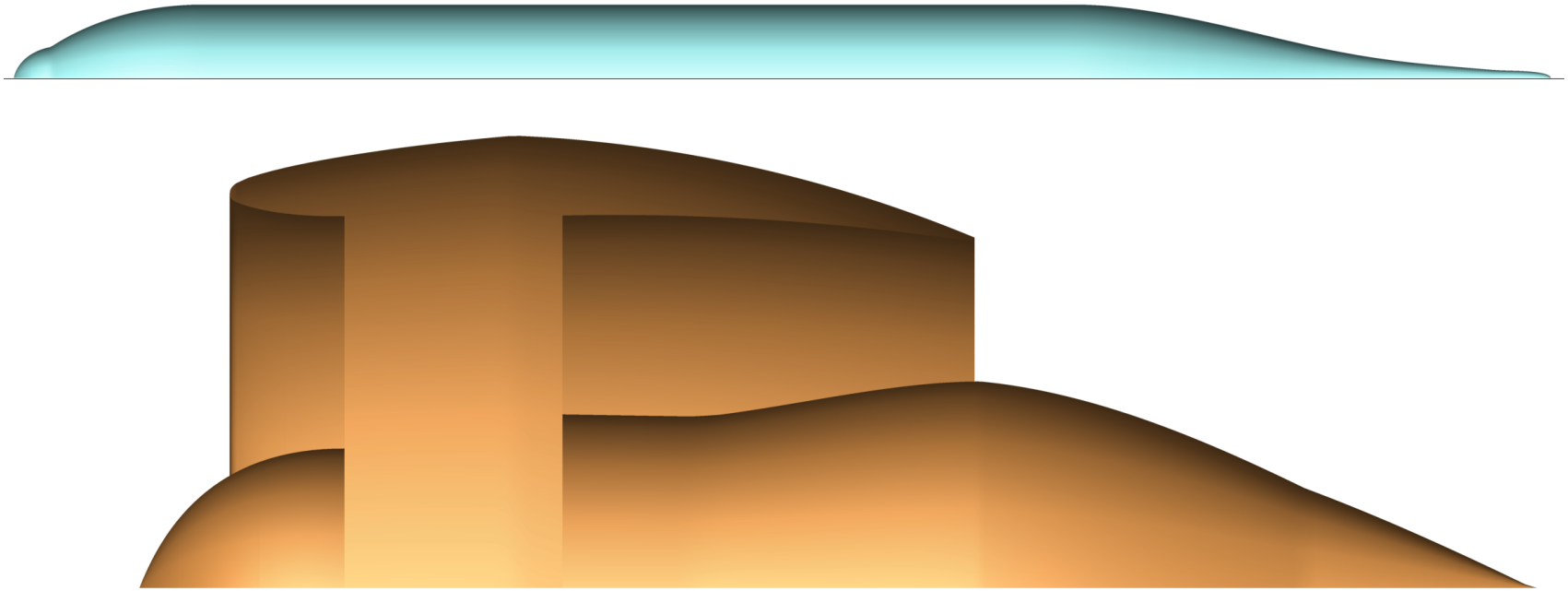
Superconducting power transmission could be 95-98% efficient

We simplified the configuration to focus on the coupled performance of the BLI propulsor



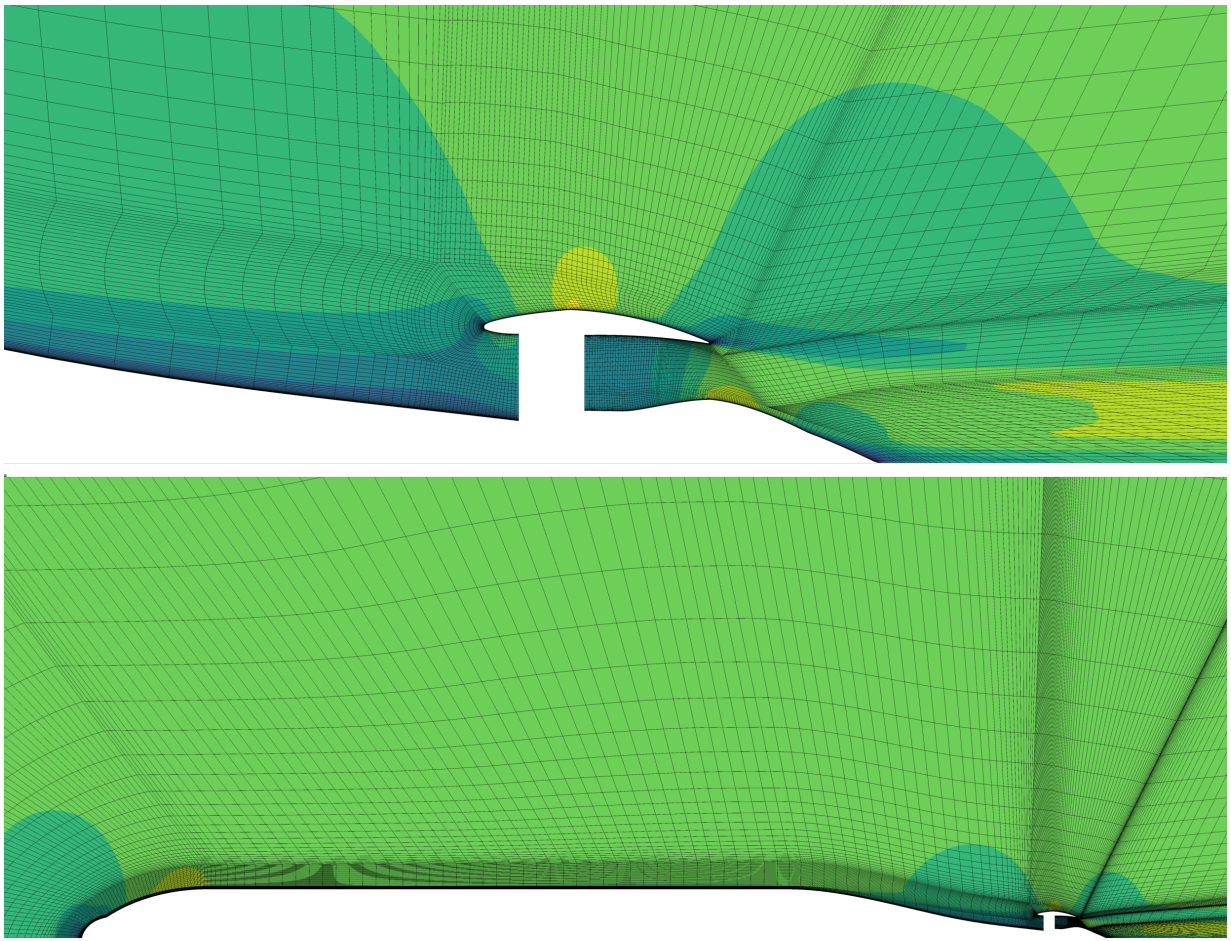
- Loosely based on 737 fuselage dimensions
- Removed wing, tail, and under-wing engines to simplify the analysis
- Examined a cruise case at M=0.785, h=11278 m

An analogous podded configuration was used to compute baseline performance



Exact same propulsor geometry, including inlet, is used for both BLI and podded configurations

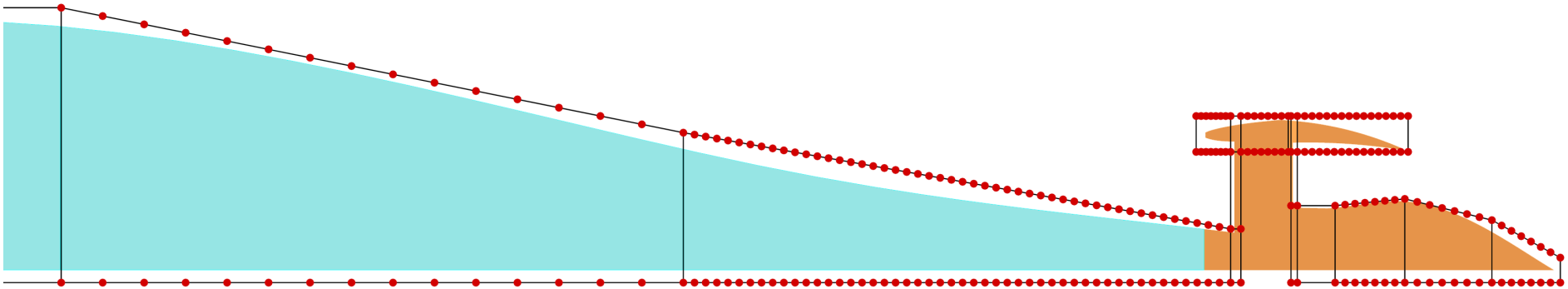
The simplified configuration was modeled using a relatively inexpensive axisymmetric RANS CFD analysis



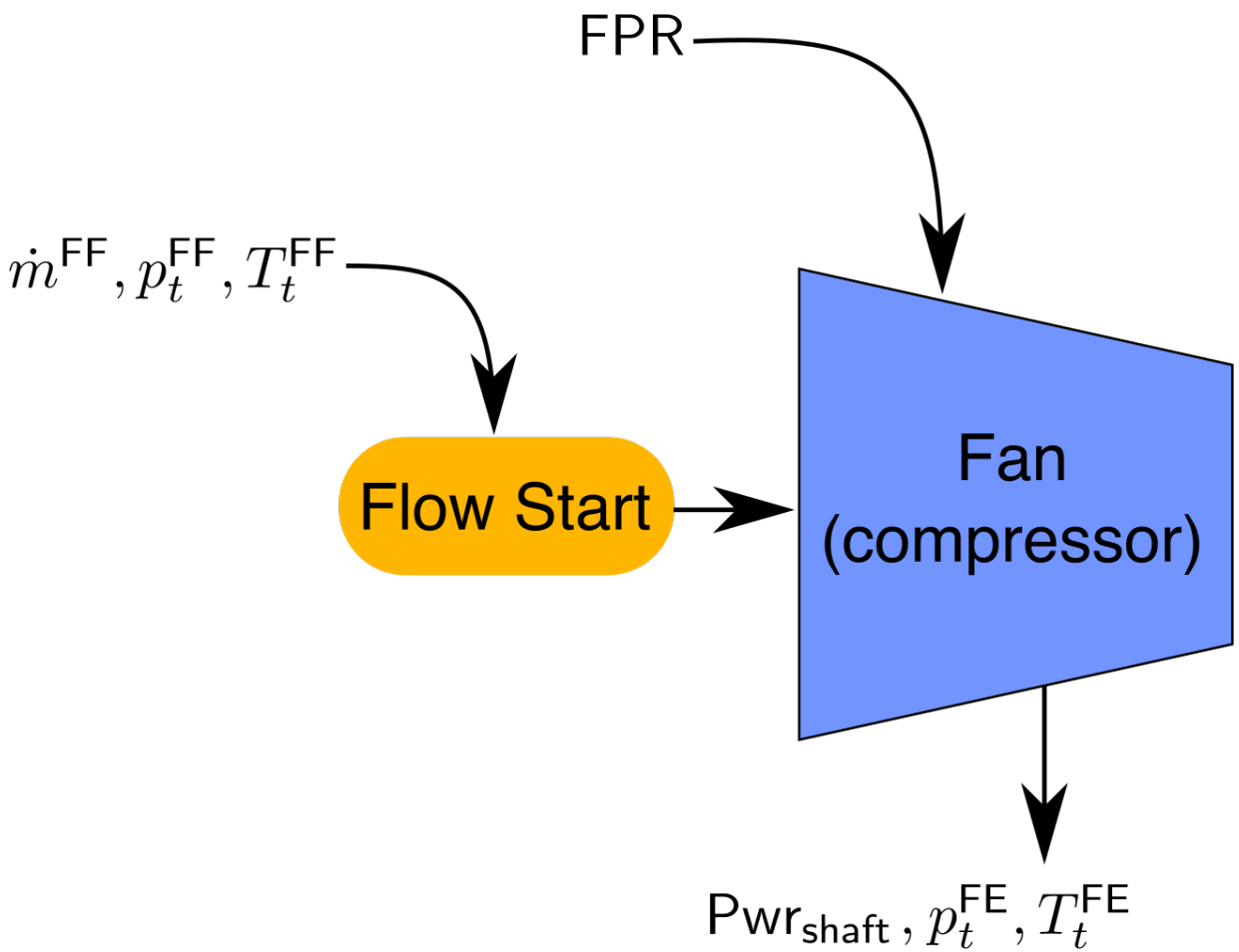
Mach contours on the baseline mesh

- $\approx$ 170,000 cell mesh
- solution time $\approx$ 2 minutes
- free-form deformation (FFD) for geometry changes

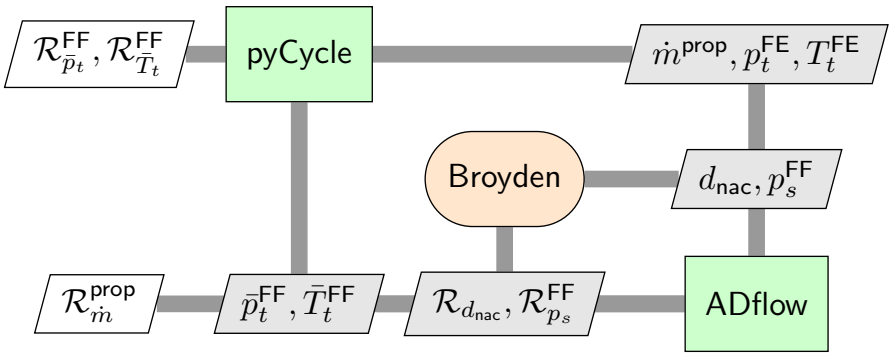
The FFD allows modifications to the fuselage and propulsor shape and gross propulsor sizing



The propulsion model was built in pyCycle, a cycle analysis with adjoint derivative computation



A mutldisciplinary analysis shows that aeropropulsive coupling is a first-order affect that must modeled

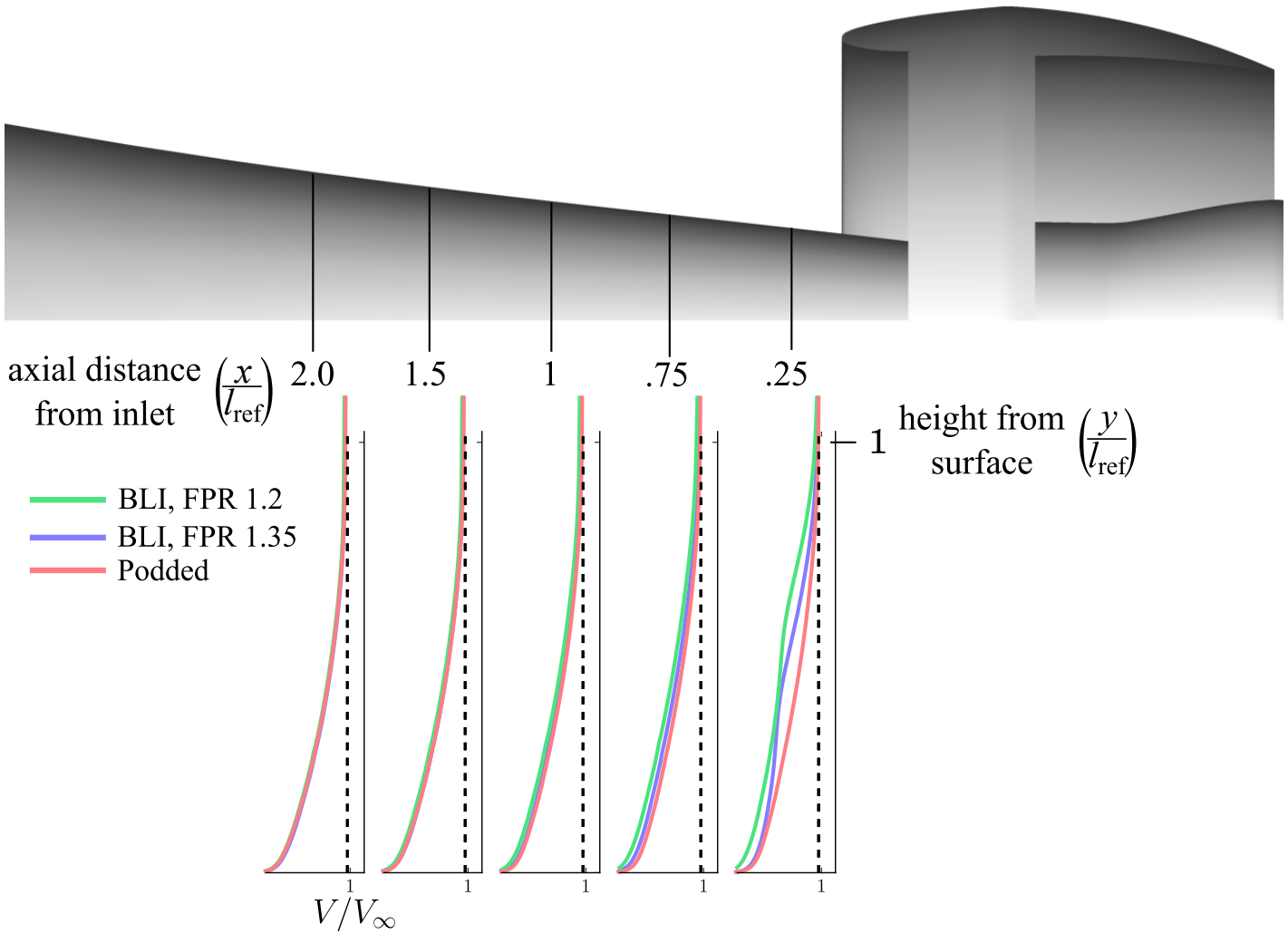


Aeropropulsive model was converged with a broyden solver

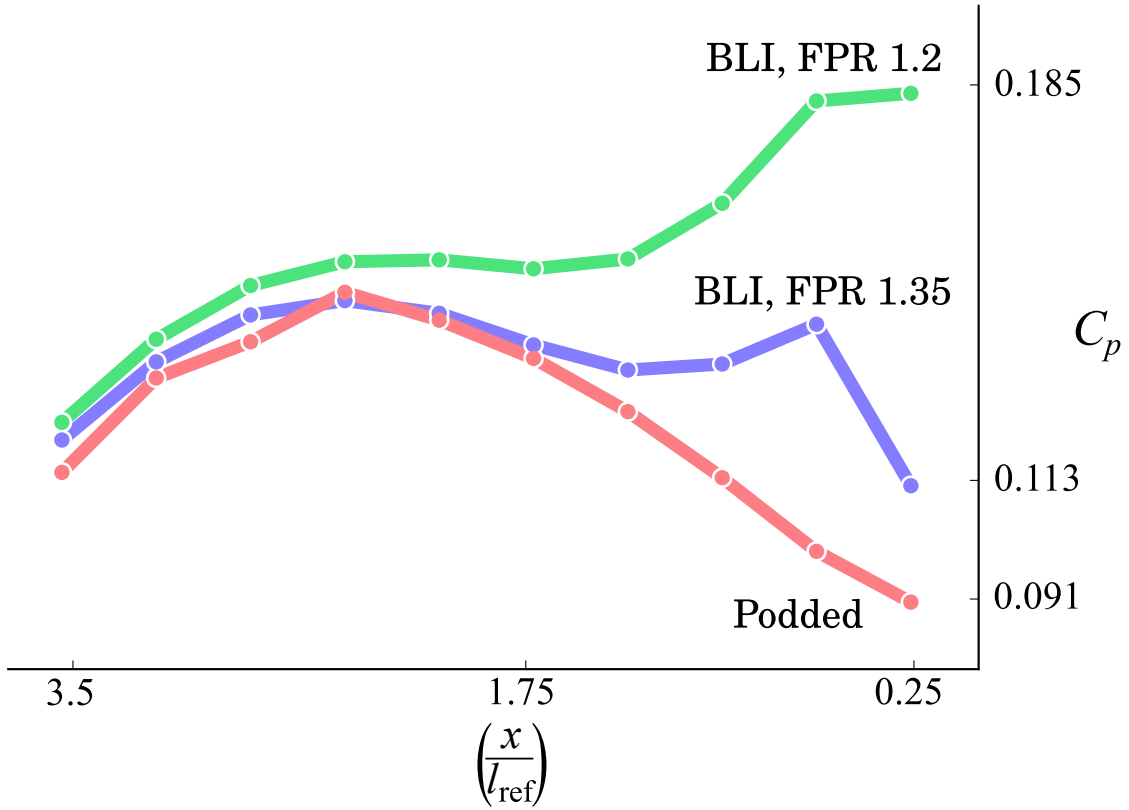
- The propulsor changes the flow upstream of itself
- The boundary layer reduces the total pressure entering the inlet
- The surface pressure distribution on the aft fuselage changes affecting drag and also possibly lift and pitching moment

Modeling Boundary Layer Ingestion Using a Coupled Aeropropulsive Analysis. Justin S. Gray, Charles A. Mader Gaetan K. W. Kenway, Joaquim R. R. A. Martins; Journal of Aircraft: 1-9, 10.2514/1.C034601

Aeropropulsive interactions cause the boundary layer height to vary with changes in FPR and nacelle height

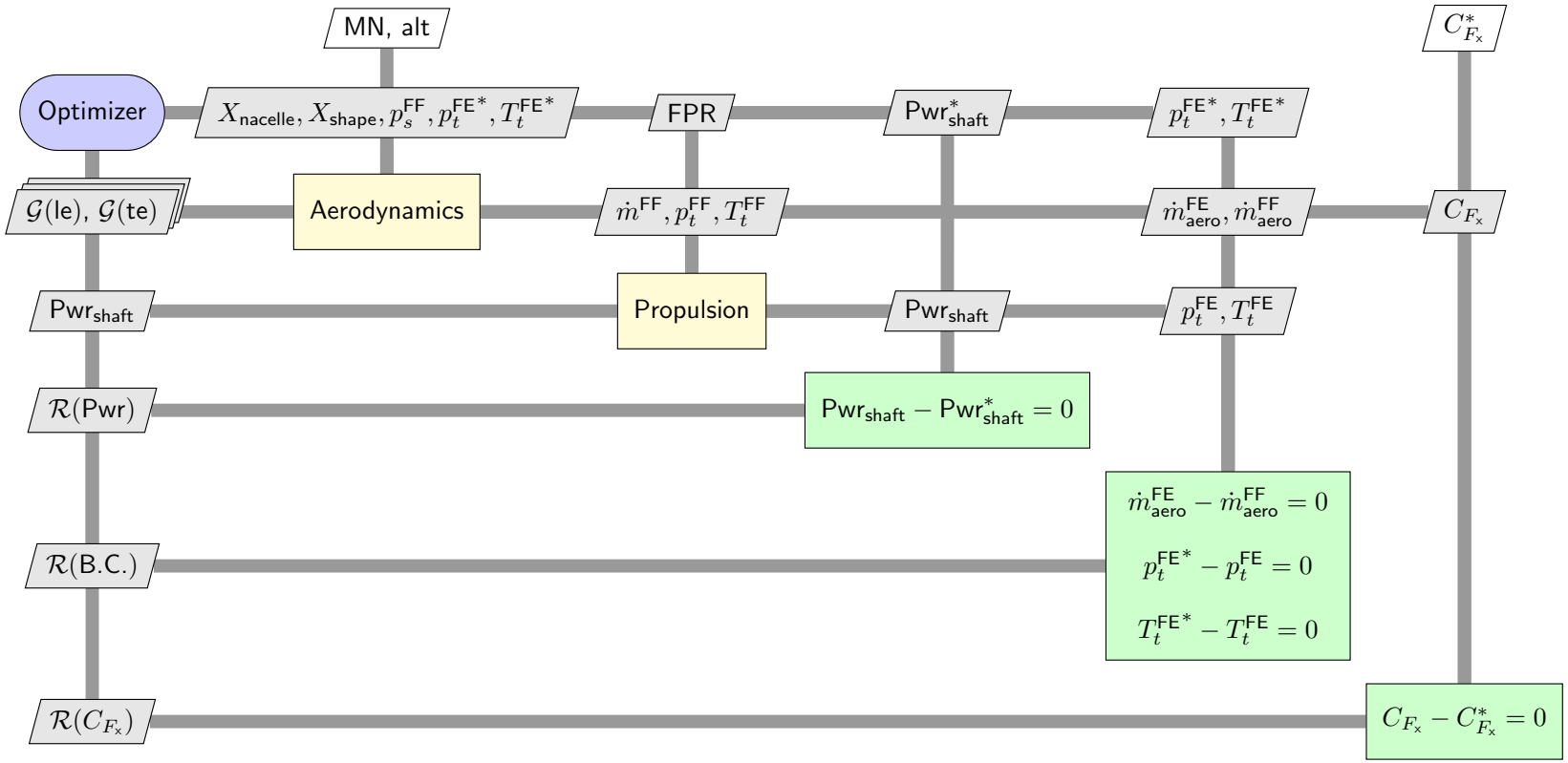


The surface pressure distribution on the aft fuselage is a strong function of FPR



Analysis can demonstrate the aeropropulsive effects, but design optimization is needed to quantify the benefit of the BLI propulsor

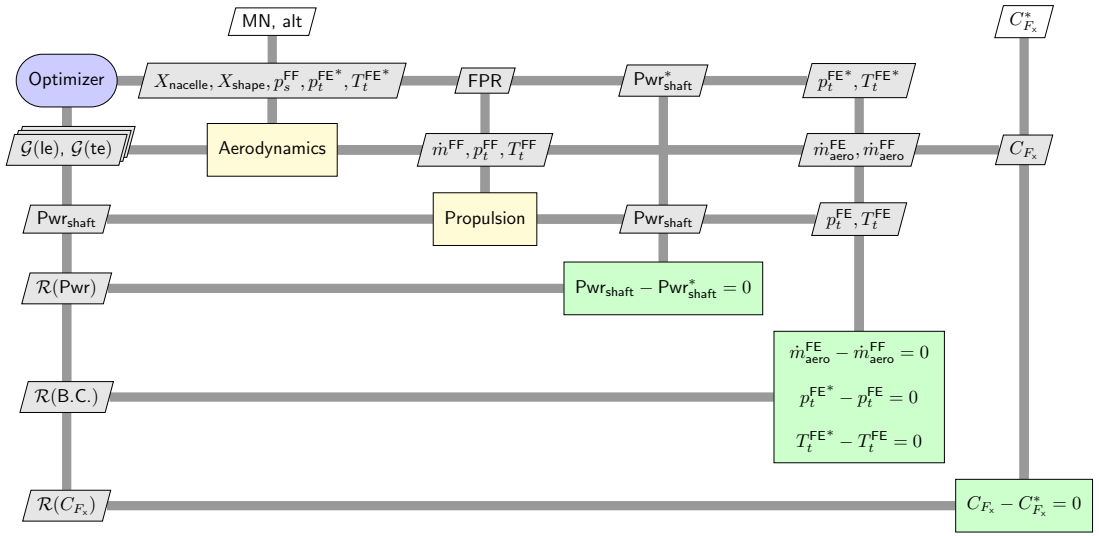
We built a fully coupled aero-propulsive optimization using NASA's OpenMDAO framework



We used a compatibility constraint formulation to couple the aero and propulsion codes via exchange of boundary conditions

OpenMDAO is NASA's open-source framework for efficient multidisciplinary optimization

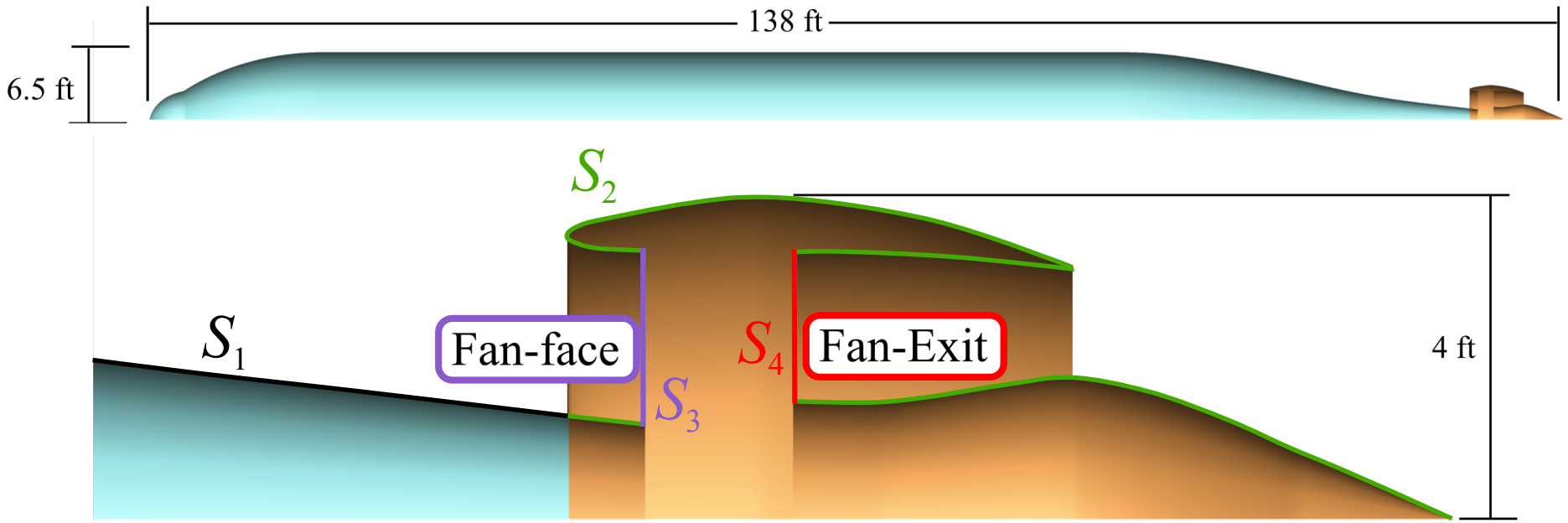
- Written in Python
- MPI based parallel, distributed memory architecture
- Specializing in gradient based optimization with analytic derivatives across multidisciplinary models



We minimize the shaft power with respect to 316 design variables and subject to 11 nonlinear constraints

	Variable/Function	Description	Quantity
minimize	$\mathrm{Pwr}_{\mathrm{shaft}}$	Propulsor shaft power	
with respect to	FPR	Fan pressure ratio	1
	X_{nacelle}	Global nacelle shape variables	3
	X_{shape}	Nacelle and fuselage local shape variables	308
	p_s^{FF}	Static pressure at the fan face	1
	$\mathrm{Pwr}^*_{\mathrm{shaft}}$	Propulsor shaft power target	1
	p_t^{FE*}	Total pressure target at the fan exit	1
	T_t^{FE*}	Total temperature target at the fan exit	1
		Total	316
subject to	$C_{F_x}^{\mathrm{net}} = C_{F_x}^{\mathrm{net}*}$	Specified net force on full body	1
	$\mathcal{R}_{\dot{m}} = 0$	Mass Residual	1
	$\mathcal{R}_{\mathrm{Pwr}} = 0$	Propulsor shaft power residual	1
	$\mathcal{R}_{p_t^{FE}} = 0$	Total pressure residual	1
	$\mathcal{R}_{T_t^{FE}} = 0$	Total temperature residual	1
	$.9 < \mathcal{G}(le) < 2$	Leading Edge Thickness	3
	$.9 < \mathcal{G}(te) < 2$	Trailing Edge Thickness	3
		Total	11

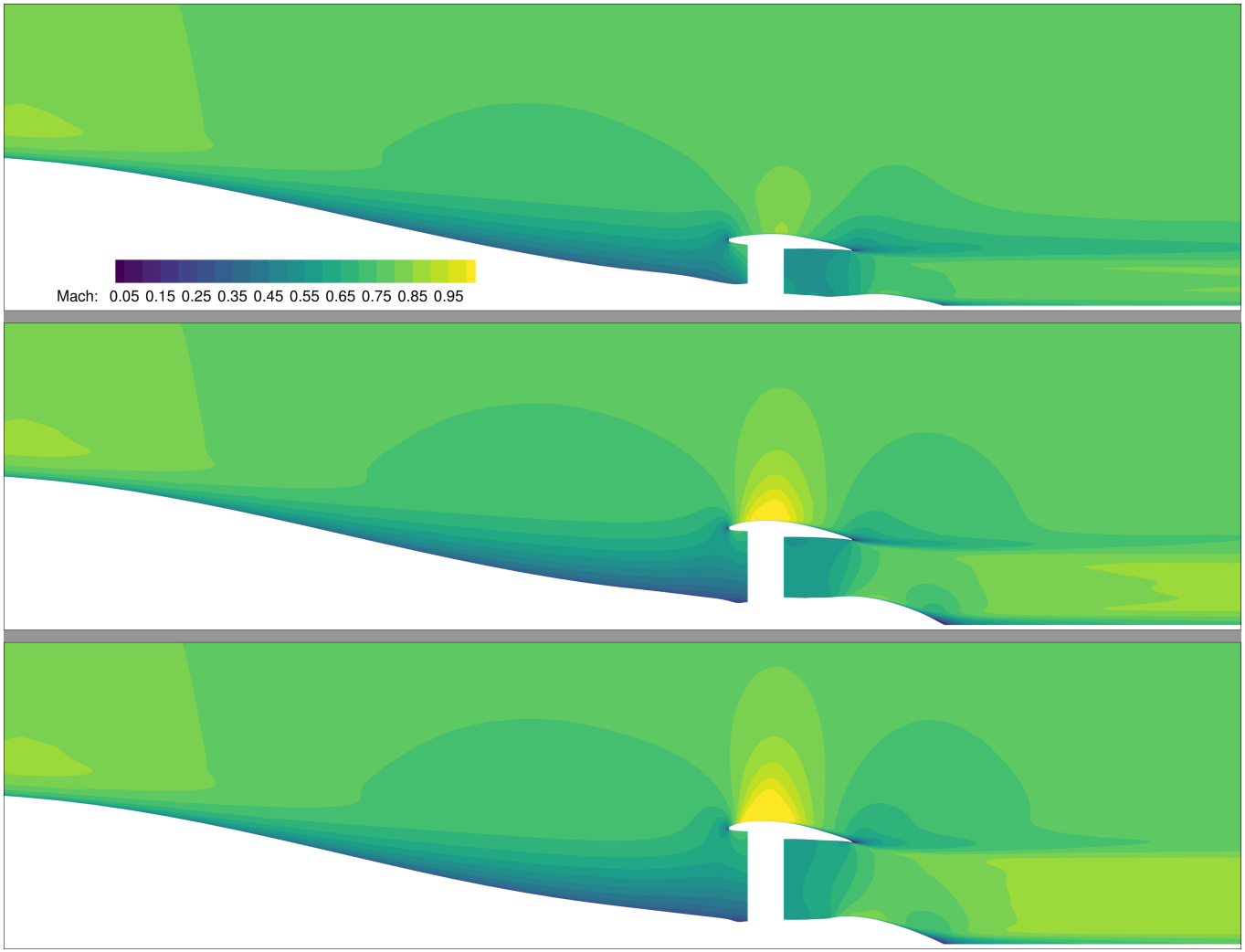
Net axial force coefficient on the body (C_{F_x}) was computed by integrating over all surfaces



$$C_{F_x} = \frac{2}{\rho_\infty V_\infty^2 A_{\text{ref}}} \left(\begin{array}{l} \iint_{S_1} (p\hat{\boldsymbol{n}} + \boldsymbol{f}_{\text{visc}}) \cdot \hat{\boldsymbol{x}} \, dS + \iint_{S_2} (p\hat{\boldsymbol{n}} + \boldsymbol{f}_{\text{visc}}) \cdot \hat{\boldsymbol{x}} \, dS \\ + \iint_{S_3} \left(p\hat{\boldsymbol{n}} \cdot \hat{\boldsymbol{x}} + \rho_3 u_3^2 \right) dS + \iint_{S_4} \left(p\hat{\boldsymbol{n}} \cdot \hat{\boldsymbol{x}} - \rho_4 u_4^2 \right) dS \end{array} \right)$$

We ran a series of optimizations to minimize shaft power for different values of C_{F_x}

Net drag is positive; Net thrust is negative

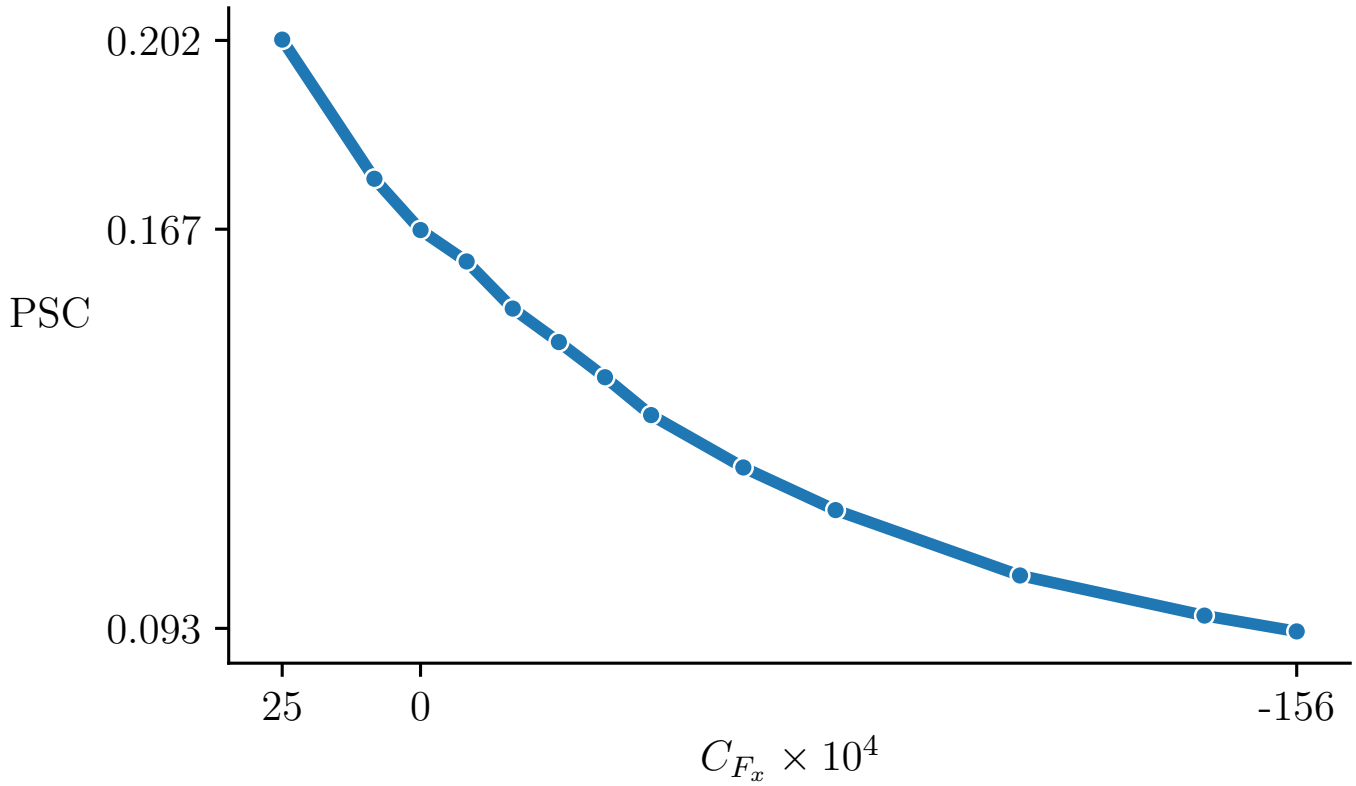


$C_{F_x} = 0.0025$

$C_{F_x} = -0.0041$

$C_{F_x} = -0.0156$

BLI outperforms the podded configuration for all values of C_{F_x}



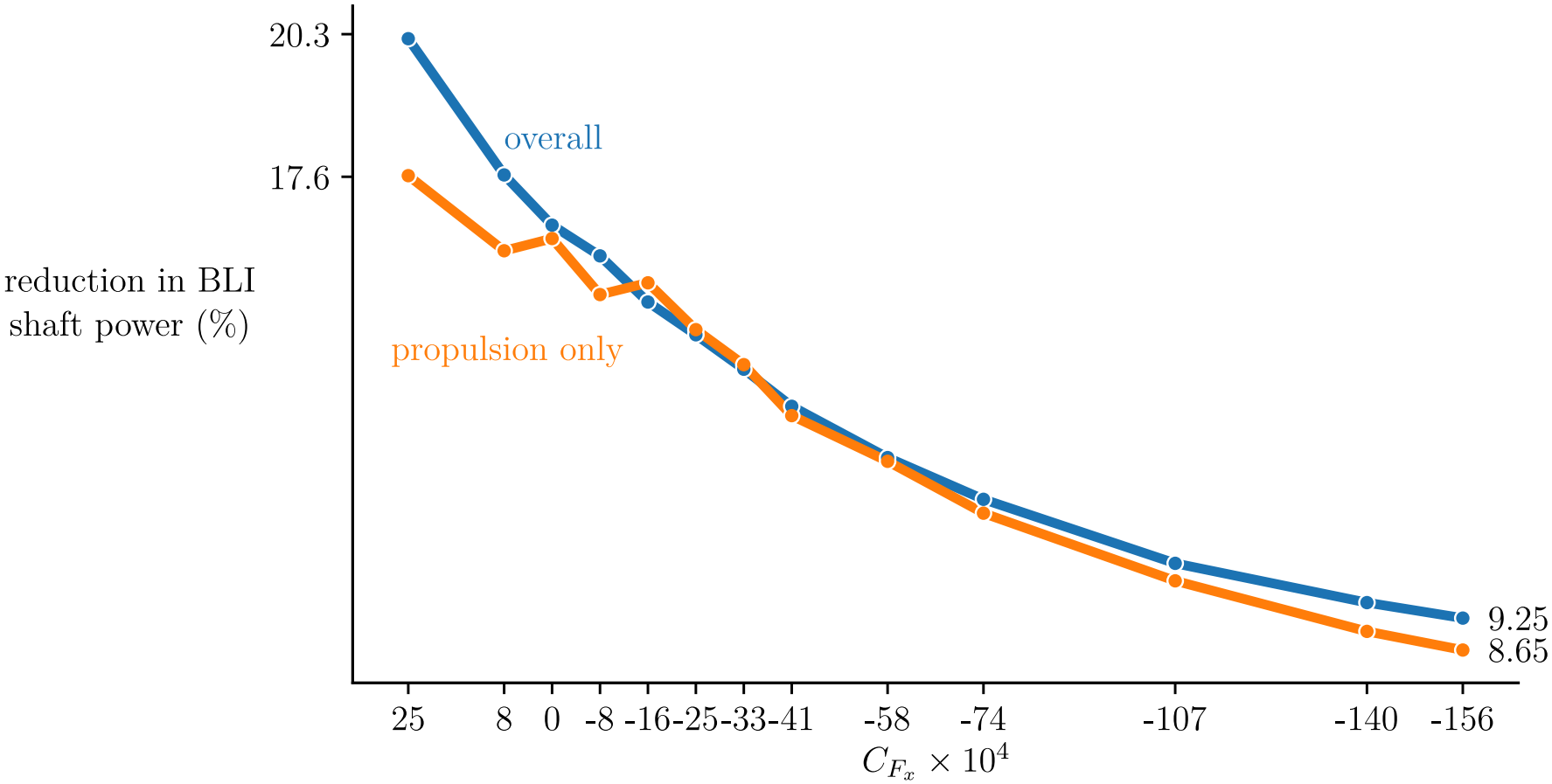
$$\text{Power Saving Coefficient (PSC)} = \frac{\text{Pwr}_{\text{shaft}}^{\text{pod}} - \text{Pwr}_{\text{shaft}}^{\text{BLI}}}{\text{Pwr}_{\text{shaft}}^{\text{pod}}}$$

There are two mechanisms through which BLI improves the overall efficiency

- Propulsive mechanism: By producing thrust more efficiently
- Aerodynamic mechanism: By lowering the "drag" less "thrust" is needed

Any difference between the thrust production efficiency and the overall BLI efficiency can be attributed to the aerodynamic effect

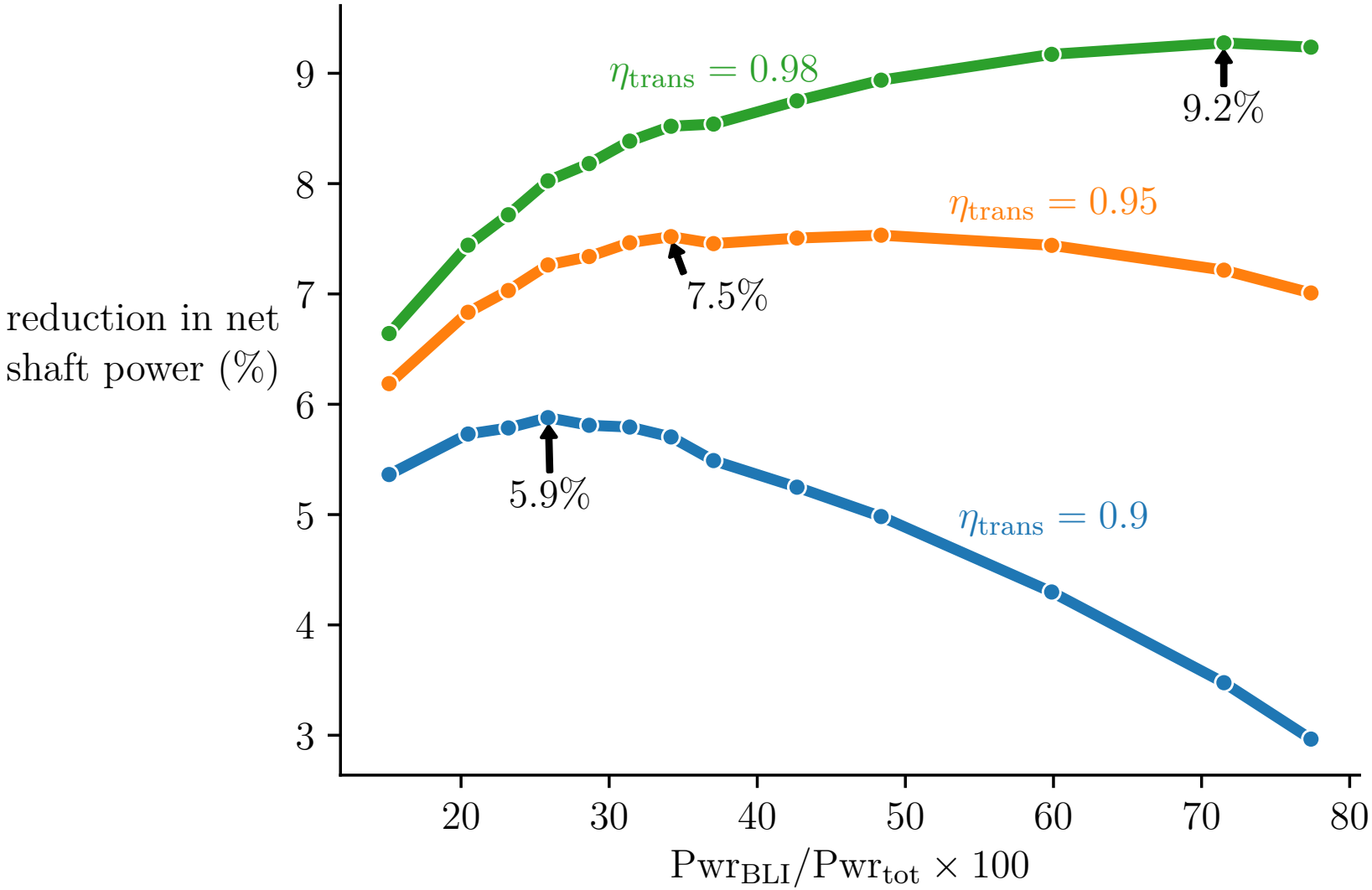
The relative contributions of the aerodynamic and propulsion mechanisms changed as C_{F_x} varied



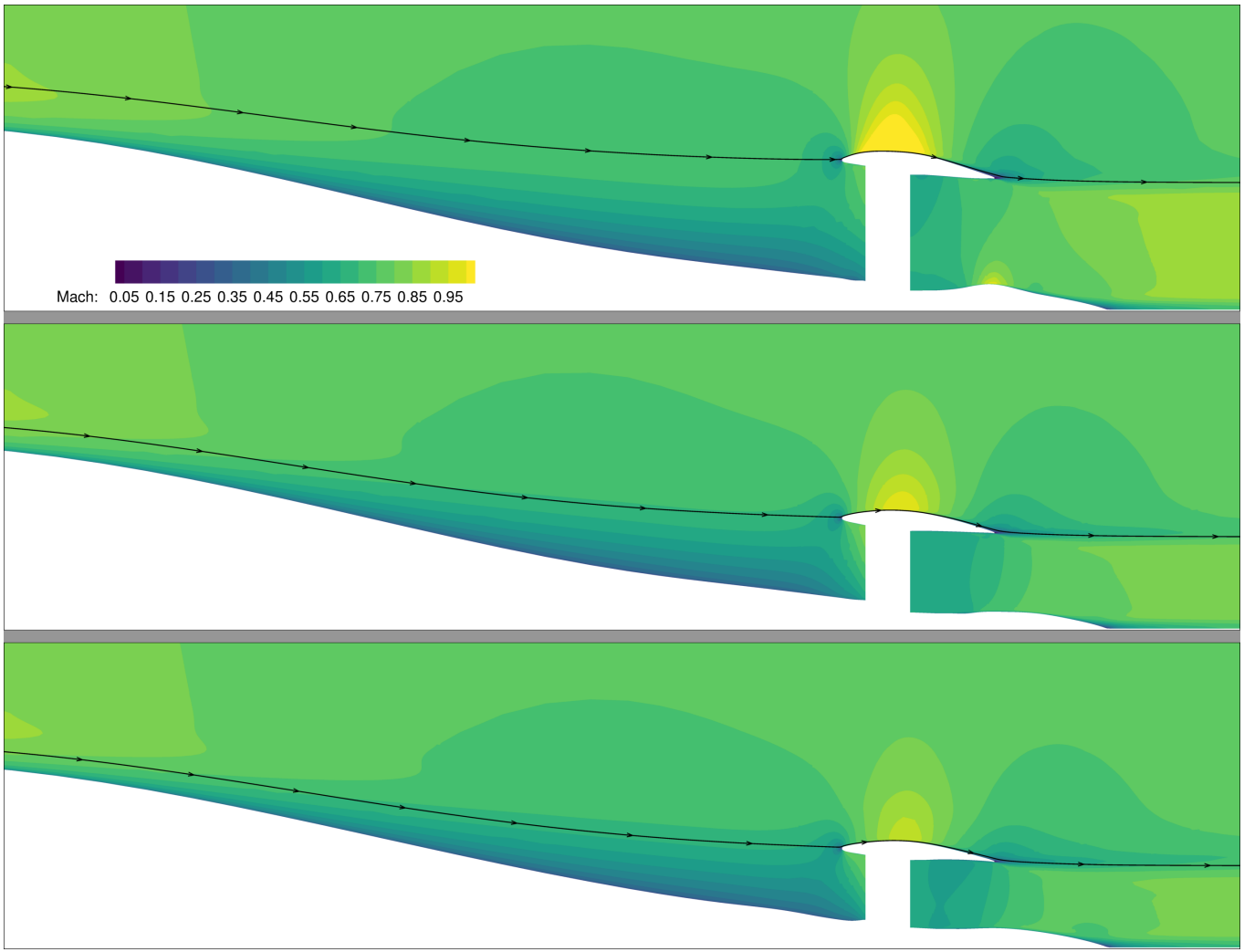
We estimate total cruise efficiency gain using and assumed $C_{D_{\text{wing}}}$

- Assume $C_{D_{\text{wing}}} = 0.0216$; $C_{F_{\text{x-fuse}}} + C_{D_{\text{wing}}} = C_{F_{\text{prop-pod}}}$
- Use $\frac{\text{Pwr}_{\text{shaft}}}{C_{F_{\text{prop-pod}}}}$ to compute shaft power needed from under-wing engines
- $\text{Pwr}_{\text{tot}} = \frac{\text{Pwr}_{BLI}}{\eta_{\text{trans}}} + \text{Pwr}_{Pod}$
  where $\eta_{\text{trans}} =$ transmission efficiency

Accounting for under-wing propulsors, the BLI yields an overall 6%-9% reduction in power required for cruise



Optimal propulsor size grows with improving η_{trans}



$\eta_{\text{trans}} = 0.98$

$\eta_{\text{trans}} = 0.95$

$\eta_{\text{trans}} = 0.9$

Conclusions

- We built a fully coupled aero-propulsive optimization in OpenMDAO
- Both propulsive and aerodynamic mechanisms contribute to the overall performance
- BLI offers 6%-9% reduction in net shaft power required for the STARC-ABL concept, depending on transmission losses

