Parametric Mixer Design Methods for Acoustic Explorations of Internally Mixed Nozzles

NASA Acoustics Technical Working Group

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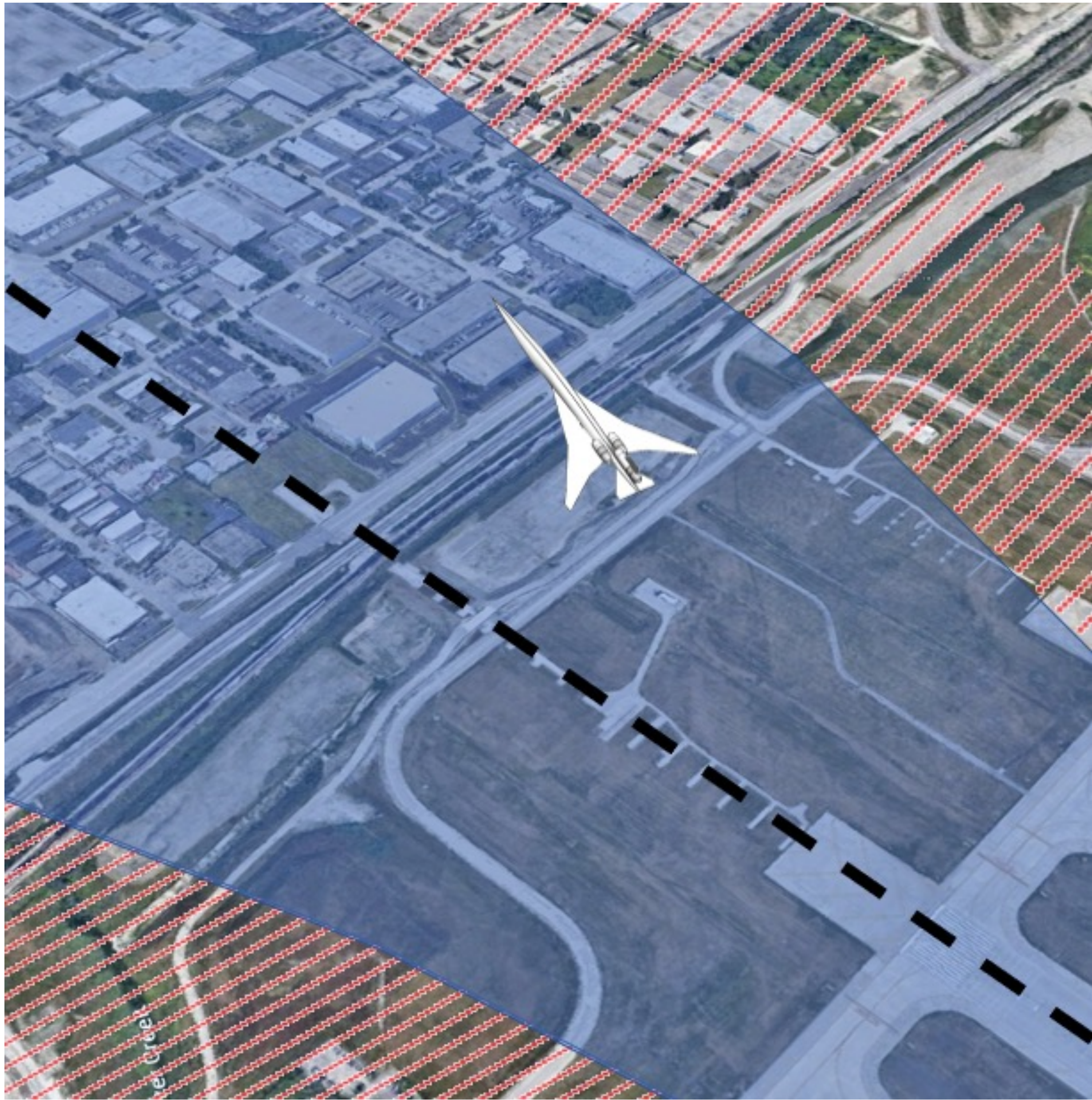


Supported by Commercial Supersonic Technology (CST) Project

New Tech Challenge: Prediction Uncertainty Reduction

Uncertainty in prediction of LTO noise is primarily associated with **configuration differences** between conventional and supersonic aircraft.

- Multi-stage fans behind supersonic inlets
- Variable geometry nozzles

Empirical prediction models only work if based on **relevant** data.

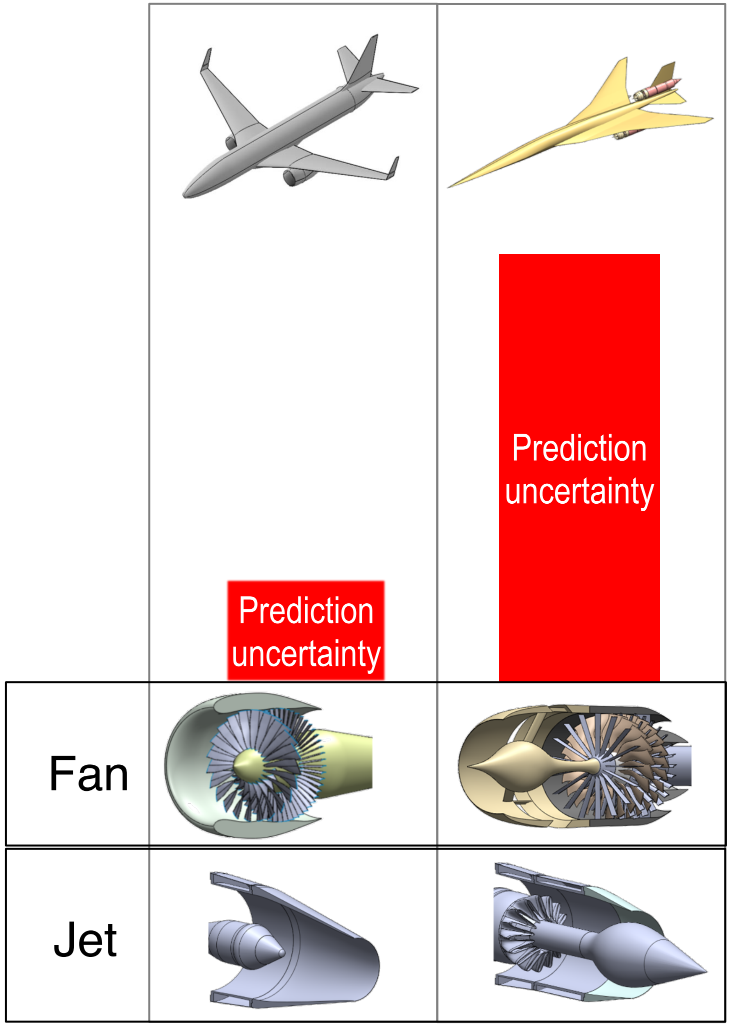
- Noise data for supersonic configurations very limited.

Tech Challenge approach:

- Use **physics-based simulations** (PBS) of supersonic aircraft to produce ‘data’.

The approach requires high-fidelity designs of likely supersonic propulsion components

- Relevant two-stage fan design produced by GE for NASA
- Relevant nozzle system being designed in-house based on OEM input.



Design req'ts for near-term SS exhaust nozzle

Good thrust at Supersonic Cruise

Low boattail angle for low boom, low drag at cruise

Variable A8/A9 (smaller than afterburning nozzle)

Low noise at LTO

Low complexity desired

For cruise Mach < 2, external plug nozzle good for low boattail angle

External plug make thrust less sensitive to A8/A9

Translating plug allows for variable A8 and A9

Low boattail requires internally mixed nozzle

High mixing provides benefits to exhaust performance

- **Noise Damping**
- **Small Thrust Augmentation**

Develop a parametric mixer design methodology with goals to:

- Automate geometry and grid generation, where possible
- Optimize mixing performance with respect to Thrust augmentation & Jet Noise reduction
- Limit initial design space to 5 parameters, to be expanded in the future

Mixer Design Lit Survey - Key References

[1] Kuchar, A.P., and Chamberlin, R. "Scale Model Performance Test Investigation of Exhaust System Mixers for an E3 Propulsion System." *AIAA 18th Aerospace Sciences Mtg*, 1980. doi:10.2514/6.1980-229.

- Examined **lobe count & penetration**, concluding the former had little effect on performance

[2] Kuchar, A.P., and Chamberlin, R. "Scale Model Performance Test Investigation of Exhaust System Mixers for an E3 Propulsion System." *AIAA 21st Aerospace Sciences Mtg*, 1983. doi:10.2514/6.1983-541.

- Examined more advanced mixer geometries and exhaust systems and defined **mixer effectiveness & pressure loss coefficients**

[3] Kuchar, A.P., and Chamberlin, R. "Comparison of Full-Scale Engine and Subscale Model Performance of a Mixed Flow Exhaust System for an E3 Propulsion System." *AIAA 22nd Aerospace Sciences Mtg*, 1984. doi:10.2514/6.1984-283.

- Tested mixer concepts on full-engine tests at GE's Peebles facility, finding **increased mixer effectiveness**

[4] Mengle, V. G., Baker, V. D., and Dalton, W. N. "Lobed Mixer Design for Noise Suppression Plume , Aerodynamic and Acoustic Data." NASA/CR—2002-210823/VOL1, 2002.

- Detailed summary of extensive, acoustics-oriented mixer testing for subsonic applications

[5] Berton, J. "Ideal, Subsonic Mixing Analysis for Convergent or Divergent (Variable-Area) Mixers." 2016.

- Internal document detailing theory behind **thrust augmentation** in mixing

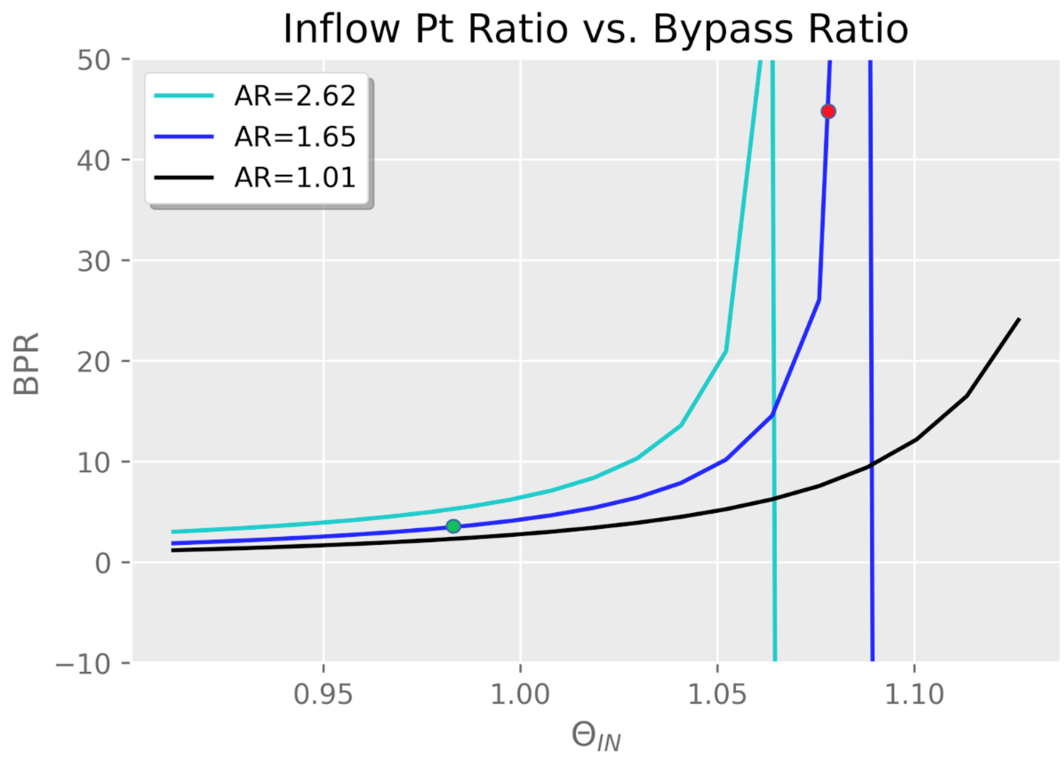
Design Inputs

1-D STCA for a 55t engine serves as flight condition reference

- Interested chiefly in thrust performance → SSCR mission point
- Goal: Match BPR of 3.33 at an area-averaged NPR of 5.89
- Freestream conditions:

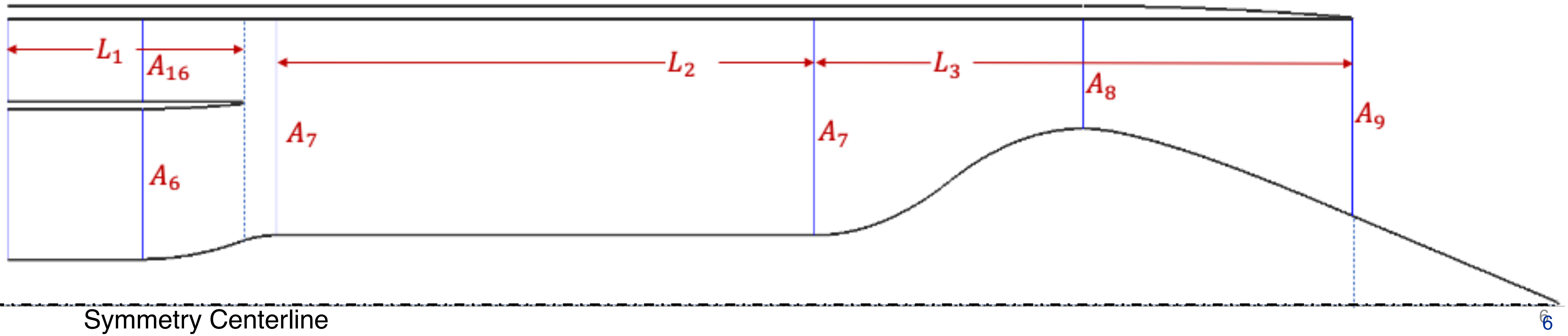
M_∞	*Altitude*
1.4	15000m

- Plot shows Extraction Ratio $\boldsymbol{\theta}$ vs. Bypass Ratio $\boldsymbol{BPR}$
  - Red dot indicates design point
  - Green dot indicates fixed BPR conditions
- Exponential increase of $\boldsymbol{BPR}$ with $\boldsymbol{\theta}$ suggests high sensitivity of dual-stream nozzles to inflow pressures
- Reducing $\boldsymbol{AR}$ flattens the sensitivity
  - $\boldsymbol{AR = 1}$ was chosen for the nozzle design
  - $\boldsymbol{\theta = 1.13}$ produced the target $\boldsymbol{BPR = 3.33}$ in the final duct design



Study Nozzle Geometry

- Common dual-stream nozzle was designed to house all mixers considered
  - **All dimensions shown are kept constant**
- Academic “Constant-Area” design built to isolate mixing process from expansion/contraction
  - $\boldsymbol{AR = 1}$ enforced through inflow duct to Mixer TE
  - Extended mixing region allows detailed analysis of mixing process
  - Total duct area held constant up to C-D section
- C-D nozzle sized to ideally expand flow at SSCR conditions

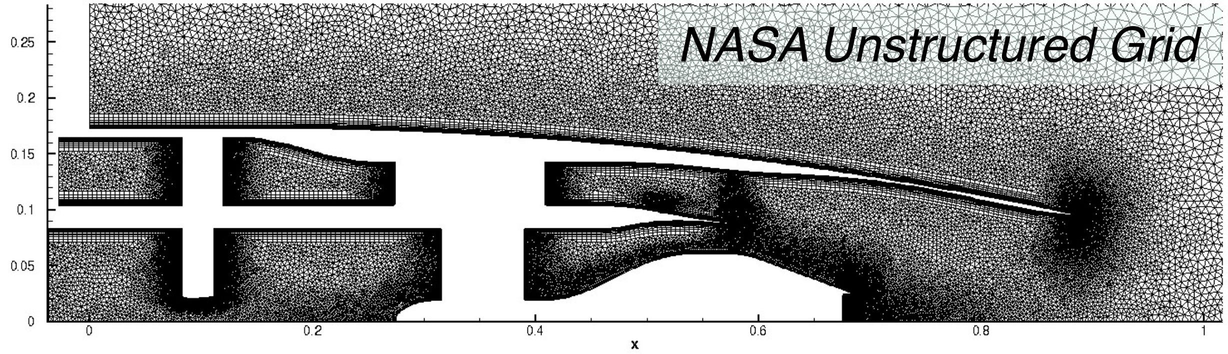


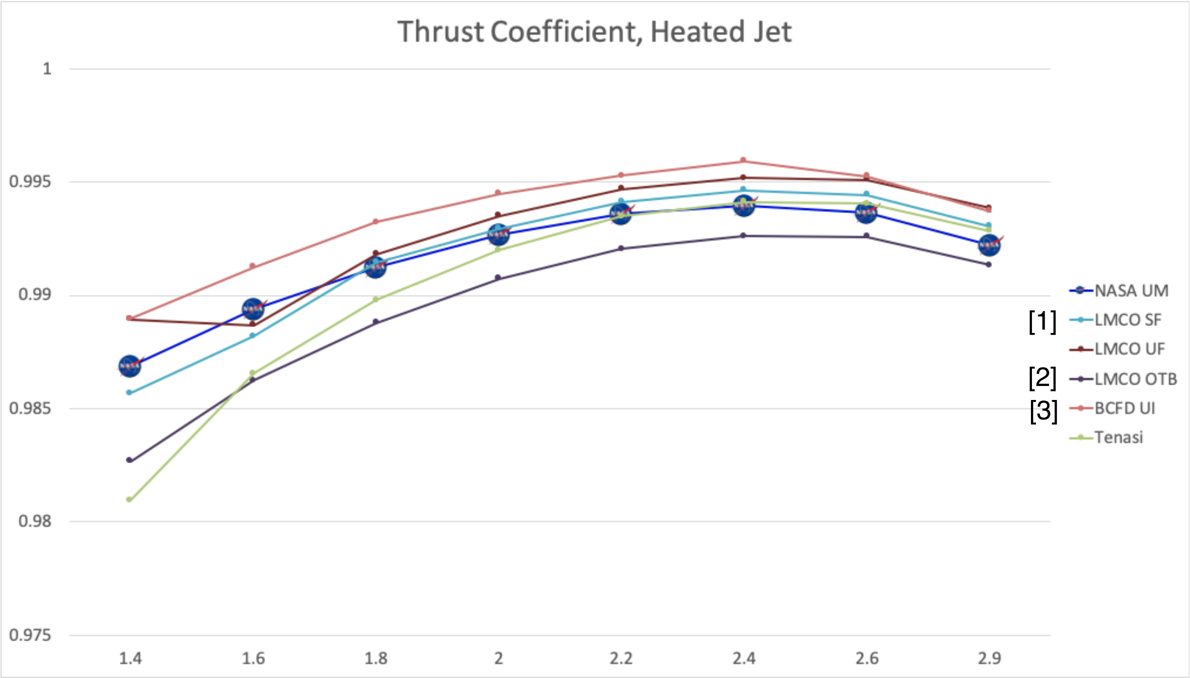
Mixer Constraints

- Phase I of the design study applies the following constraints:
  - Lobe mixer has defined peak and trough radii at the Trailing Edge (TE)
  - Parameterized TE profile, connected to a single plane, perpendicular to the nozzle centerline, defined at x = 20”
  - Mixer extends a length L from the TE in the upstream direction
  - An axisymmetric splitter bifurcates the two streams upstream of the mixer
  - The transition from splitter to TE is defined by a parameterized cubic spline at 30+ azimuthal points
  - Slope of the spline at the junction to the splitter is 0

Approach Validation – PAW3 DMFR Nozzle

- Computational approach validated against DMFR Nozzle results from AIAA's PAW3
- NPR vs. C_{F_g} curves matched well against industry unstructured CFD codes (**Boeing & LMCO**)





[1] Domel, N.D. "Propulsion Aerodynamics Workshop III Nozzle Results". *53rd AIAA/SAE/ASEE Joint Propulsion Conference, 2017,* doi:10.2514/6.2017-4658
[2] Winkler, C.M. "BCFD Analysis for the 3rd AIAA Propulsion Aerodynamics Workshop: Nozzle Results." *53rd AIAA/SAE/ASEE Joint Propulsion Conference, 2017,* doi:10.2514/6.2017-4657.
[3] Sreenivas, K., Webster, R. S., and Hereth, E. A. "Separate and Mixed Flow Nozzle Simulations Using Tenasi." *53rd AIAA/SAE/ASEE Joint Propulsion Conference, 2017*, doi:10.2514/6.2017-4656

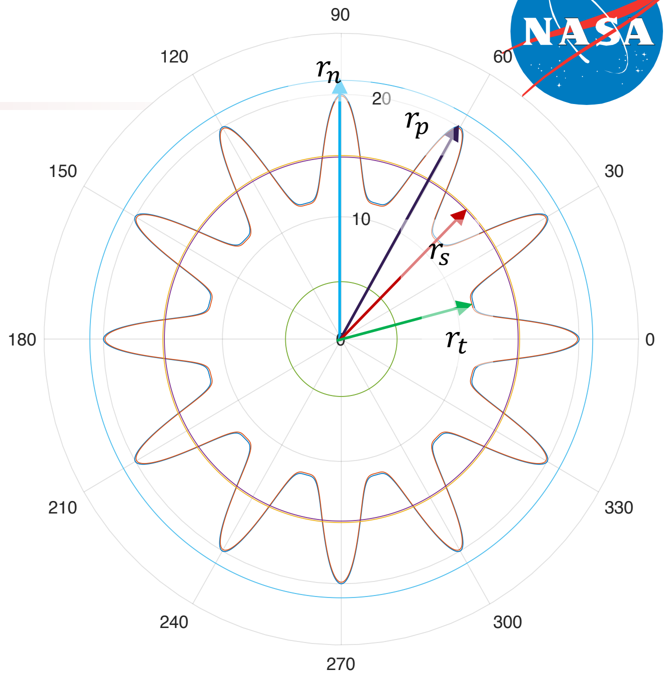
Phase I Parametric Space

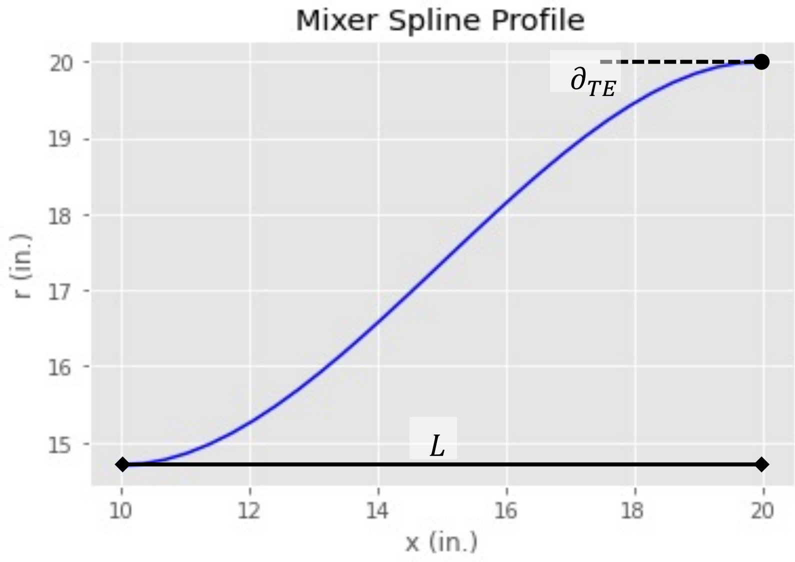
- Phase I mixers were fully defined through the following parameters:

Parameter	Symbol
Lobe Count	$\boldsymbol{n}$
Penetration	$\boldsymbol{\phi}$
Lobe Bias	$\boldsymbol{\eta}$
Mixer Length	$\boldsymbol{L}$
TE Slope	$\boldsymbol{\partial_{TE}}$

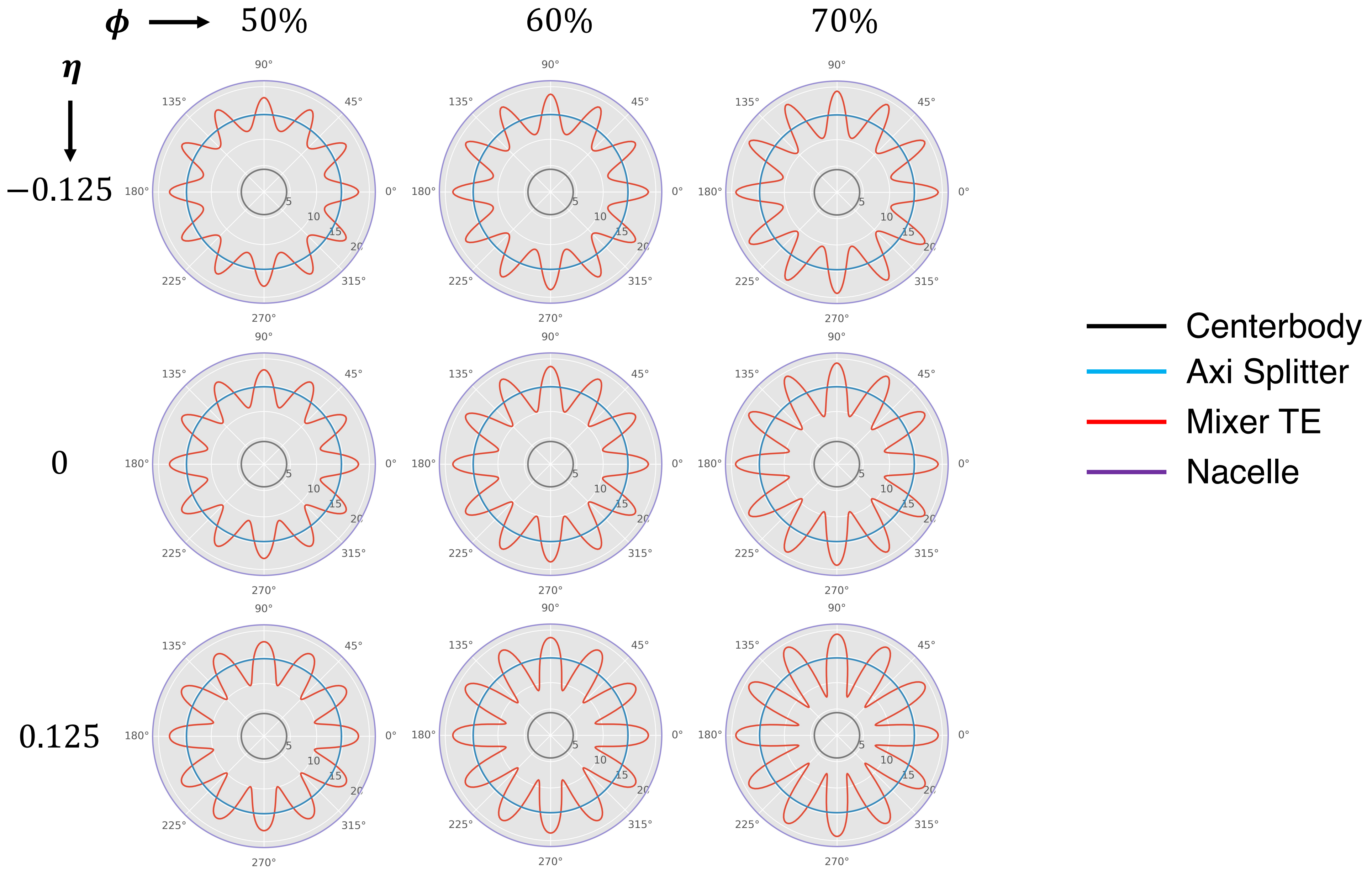
- TE radius was defined in polar coordinates as a function of $\boldsymbol{\theta}$, $\boldsymbol{\phi}$, and $\boldsymbol{\eta}$
  - **Methodology maintains equal bypass & core areas**

- Cubic transition spline was built from $\boldsymbol{L}$ and $\boldsymbol{\partial_{TE}}$

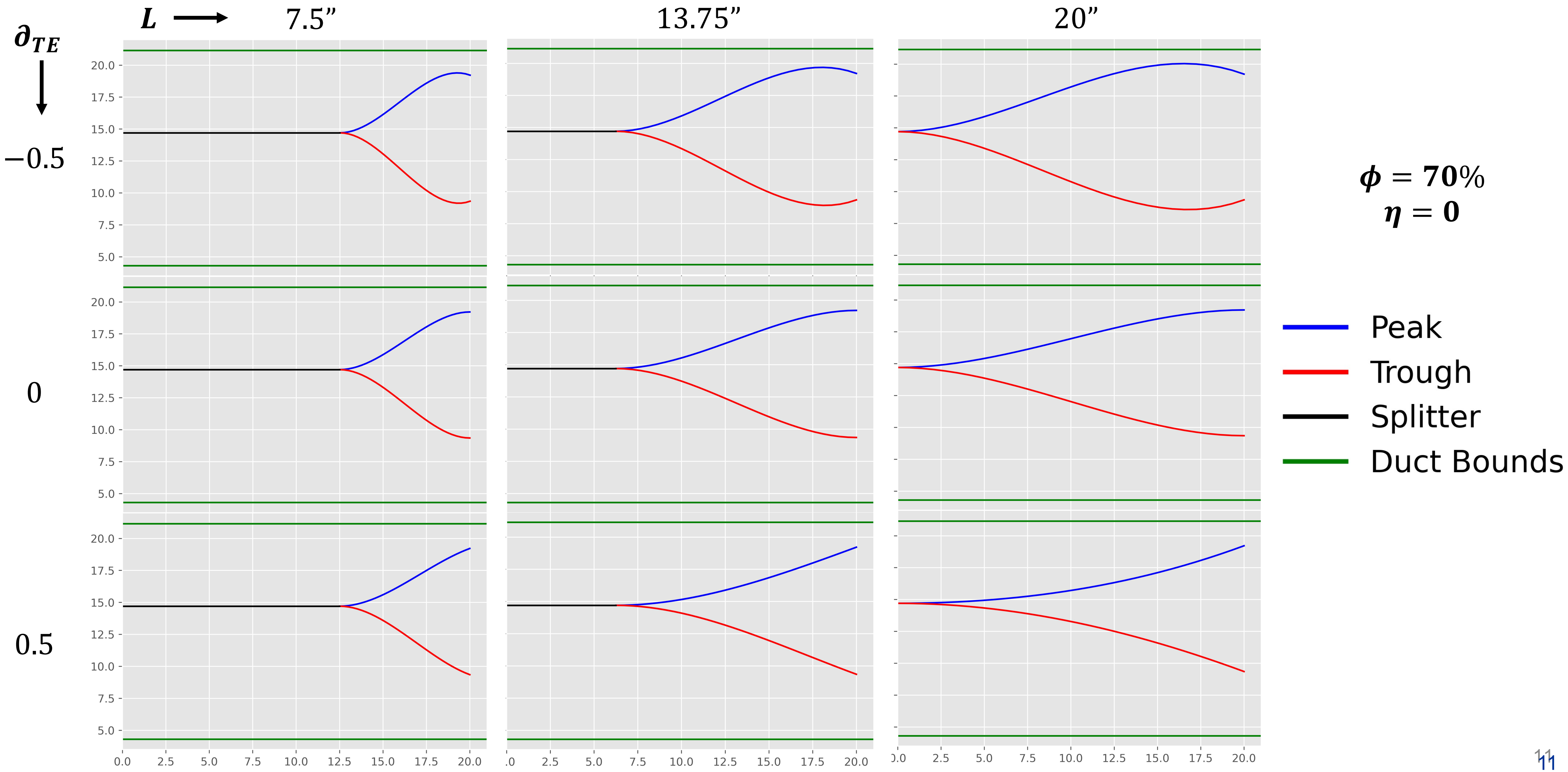




Phase I Parametric Space – ϕ vs. η, TE Profiles



Phase I Parametric Space – L vs. ∂_{TE}, Spline Profiles



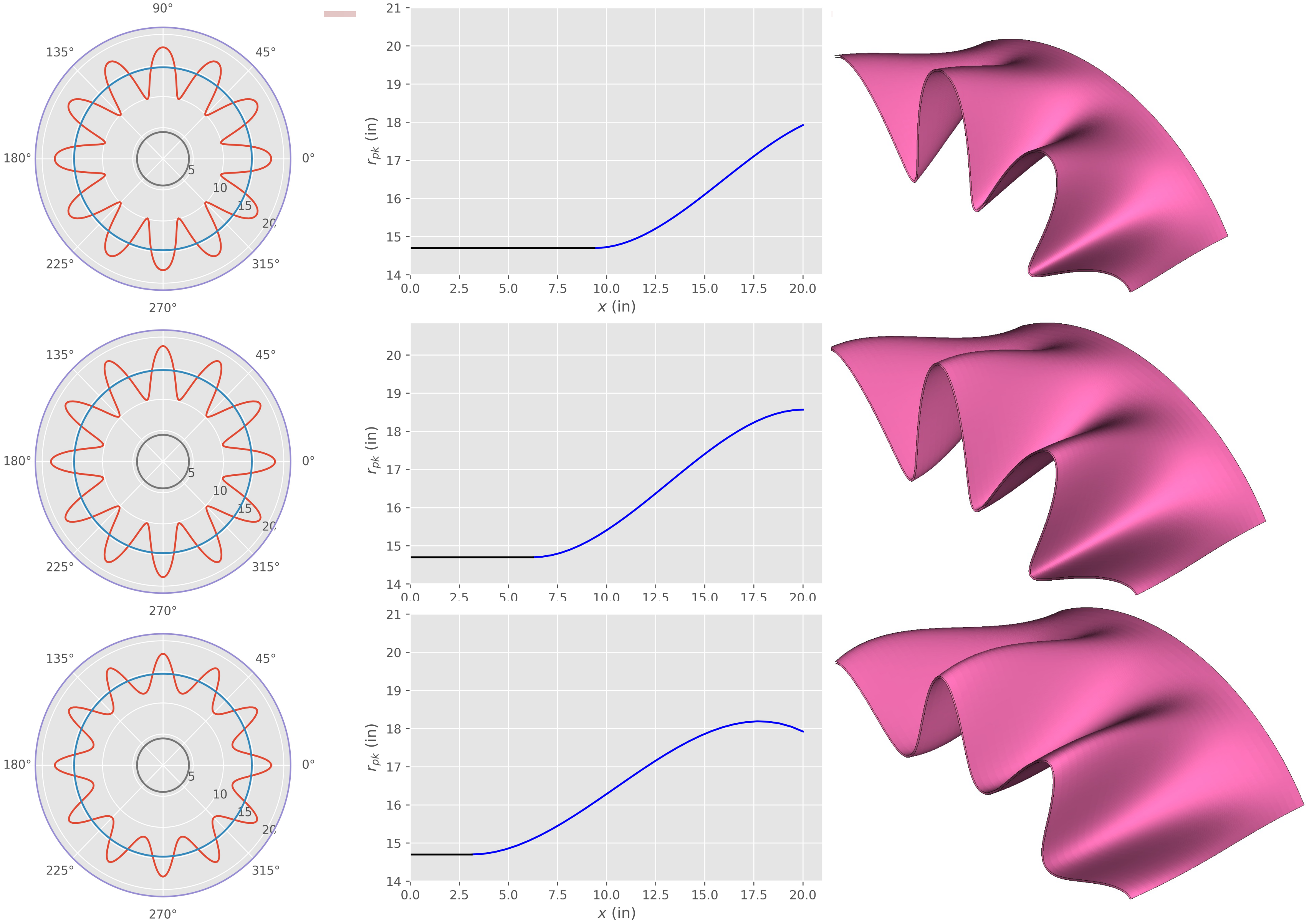
Phase I Parametric Space – Sample Cases

Mixer	1	2	3
n	12	12	12
ϕ	50%	60%	60%
η	0.125	0	-0.125
L	10.625”	13.675”	16.875”
∂_{TE}	0.25	0	-0.25

1.

2.

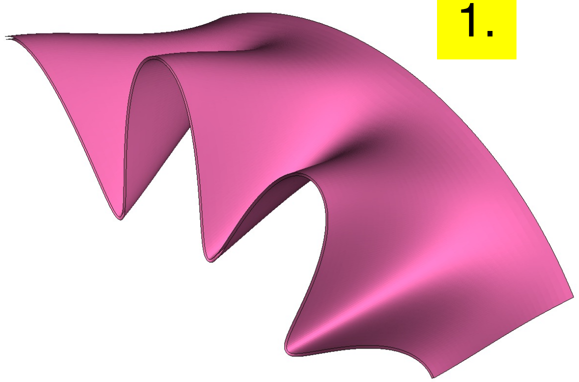
3.



Analysis – Performance Response

- Parameter list:
  - Thrust Coefficient: C_{F_g}
  - Mixing Effectiveness: K_4 (from Kuchar [2])
  - Pressure Loss Coefficient: $C_{\Delta P_t}$ (from Kuchar [2])
  - Temperature Variance: s_T^2
    - Variance in Temperature at the mixing duct outflow plane

Mixer #	C_{F_g}	K_4	$C_{\Delta P_t}$	s_T^2
1	0.9524	0.1577	0.0074	0.4519
2	0.9467	−0.0021	0.0027	0.8848
3	0.9409	−0.0784	0.0012	1.2172



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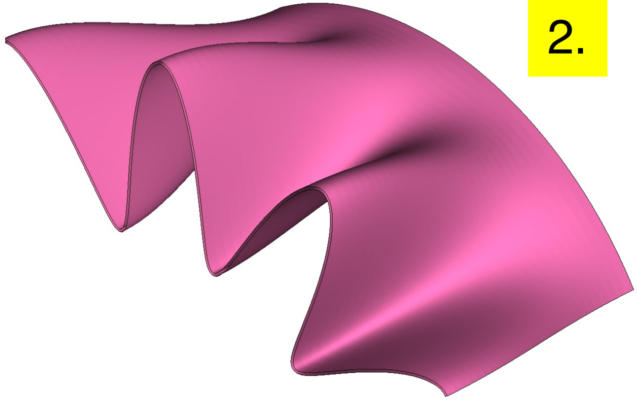

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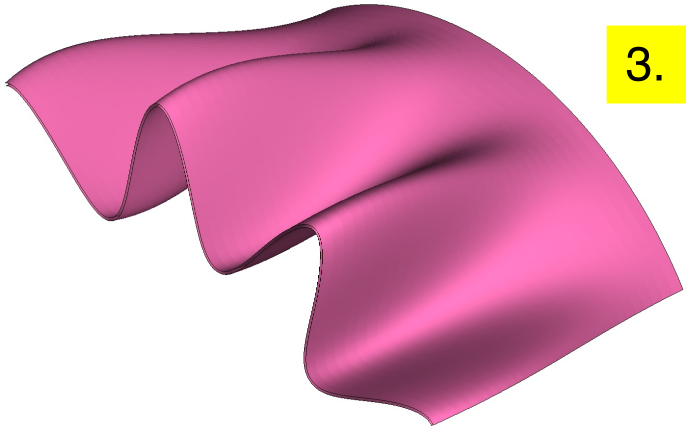


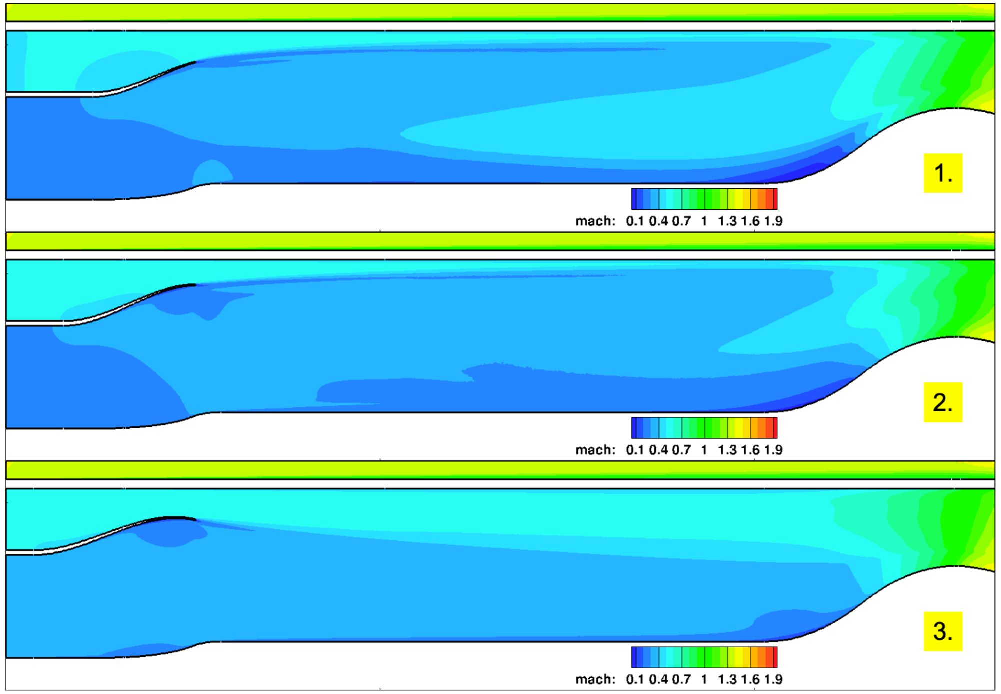
3.

Detailed Flowfields on Following Slides

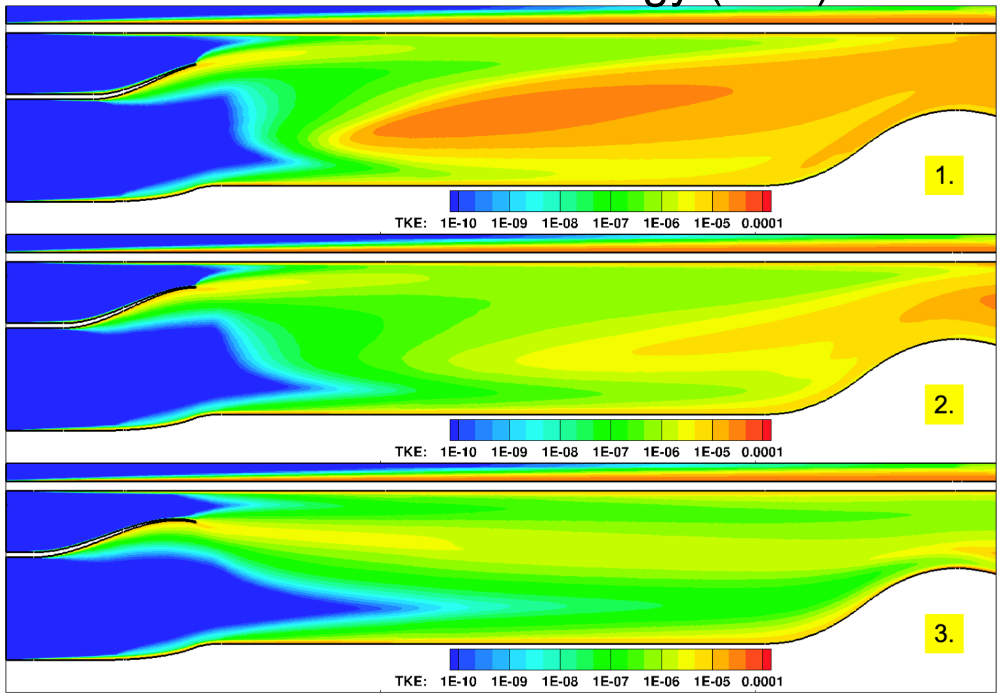
Sample Case Results – Symmetry Plane Contours

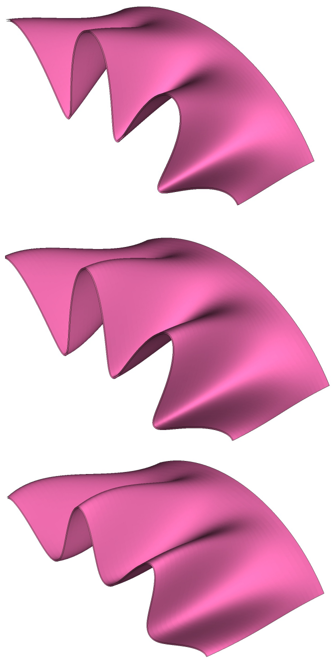
- Mach # plots illustrate general flow patterns
  - Verifies typical dual-stream, choked nozzle
- TKE provides window into major mixing mechanism
  - Predicts mixer 1 as the best-performing design

Mach #



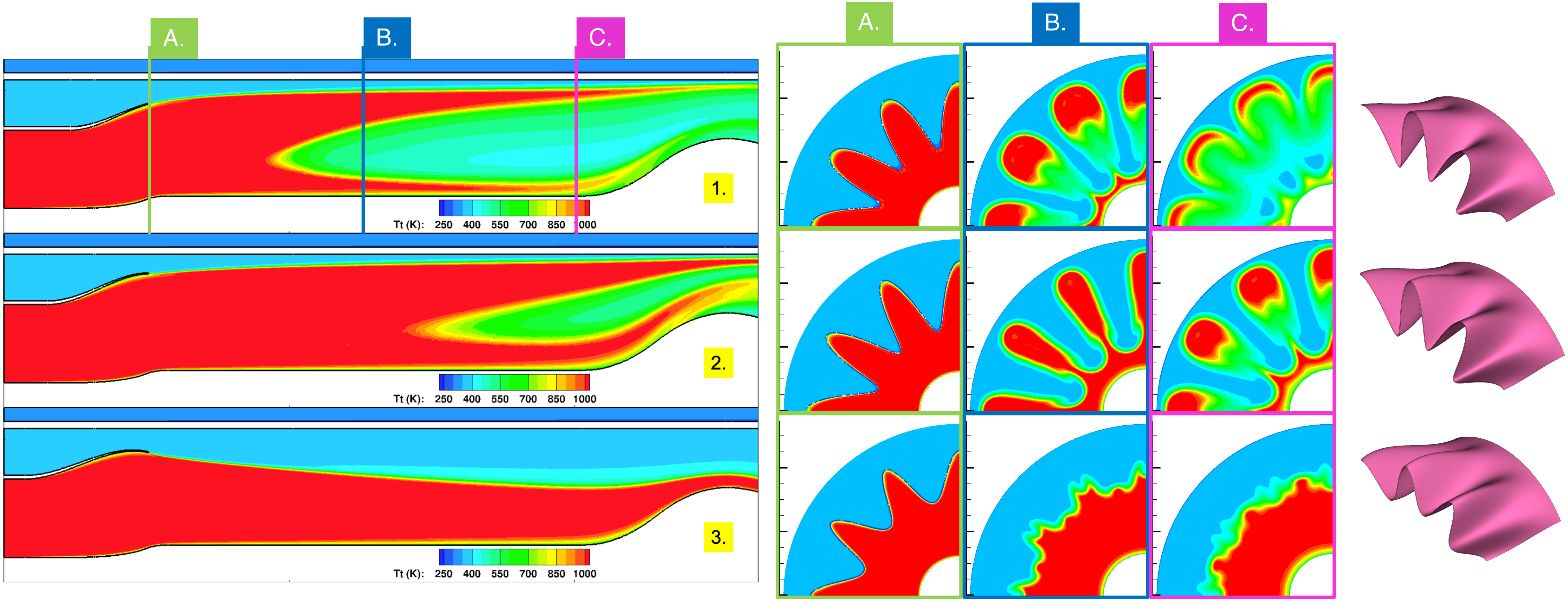
Turbulent Kinetic Energy (TKE)





Sample Case Results – Total Temperature

- T_t provides direct, complete evidence of mixed-ness
  - Supports claim that mixer 1 is the best-performing design

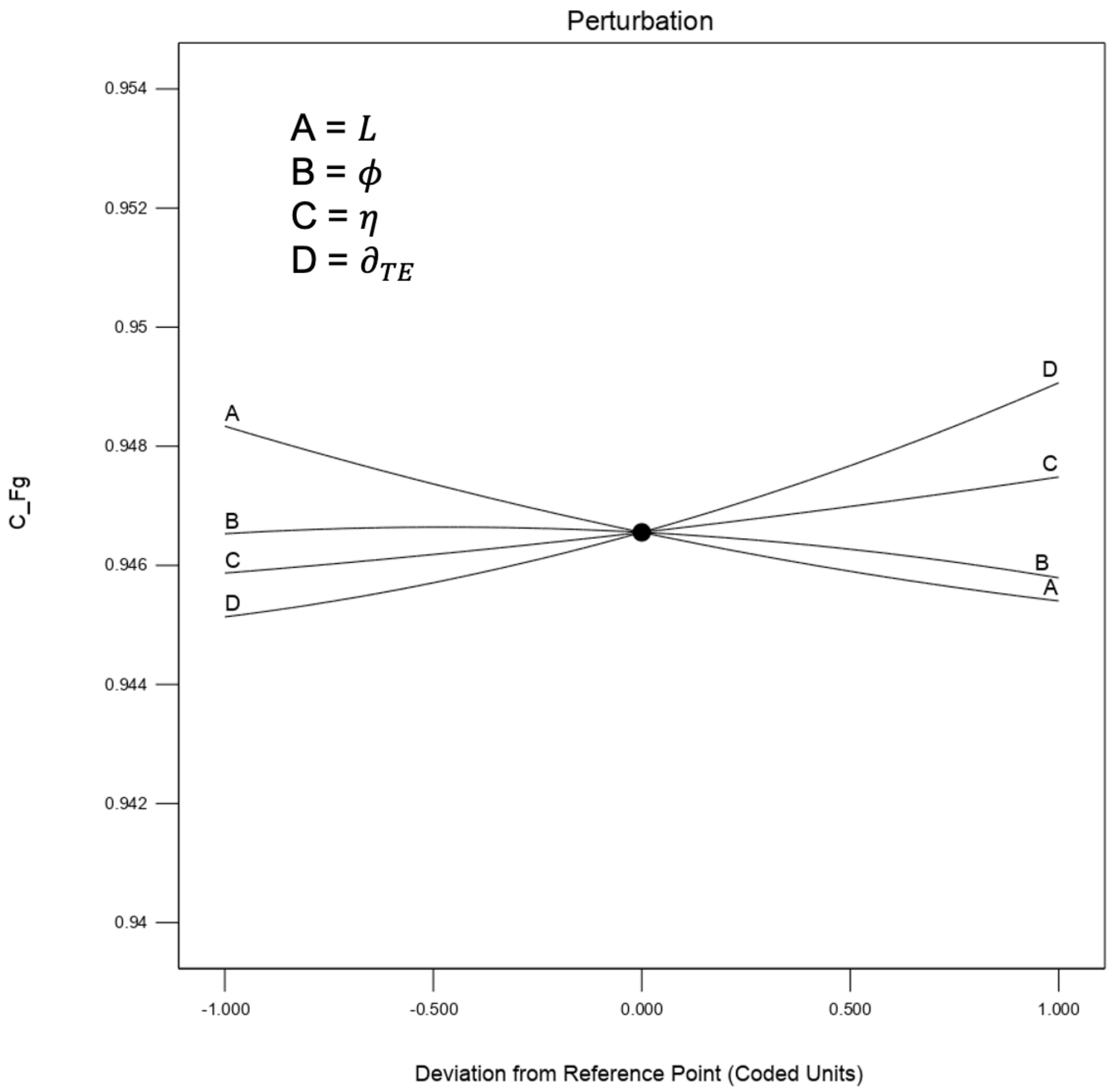


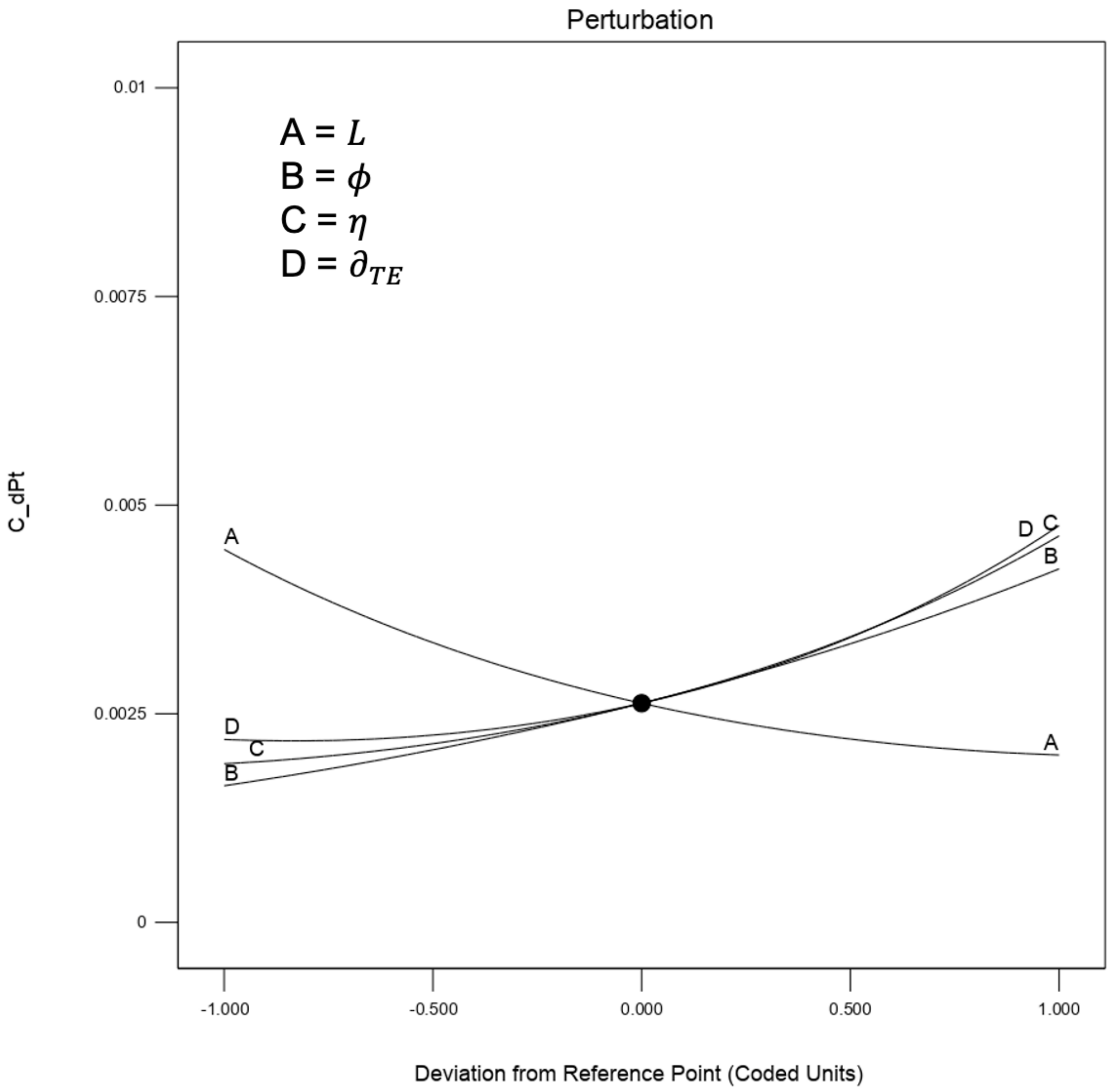
DoE Studies – Design Optimization

- Initial Screening: Test limits
  - Found gridding issues and senseless configurations
  - i.e. $\phi < 40\%$, $n = 20$, $\partial_{TE} < -0.5\ or > 0.5$
- Half Factorial: Performance-based pare-down
  - Recognized patterns to further whittle down design space
  - i.e. $\phi < 50\%\ or > 70\%$, $\partial_{TE} < 0$
  - n is insignificant and will be held constant at 12
- Quadratic Response Surface: 30 design points to build quadratic model
  - Final bounds:

Parameter	Range
n	12
ϕ	50% – 70%
L	10.625" – 16.875"
η	-0.125 – 0.125
∂_{TE}	-0.25 – 0.25

DoE Studies – Perturbation Plots





Future Work

- Phase II will apply advanced parameterized features to a select few Phase I design(s):
  - Cutbacks/Scarf Angle on TE
  - Scalloped Lobes
  - Lobe Vents

- Phase III will explore low-TRL concepts, with or without parameterization
  - Vortex Generators
  - TE Chevrons

Backup Slides

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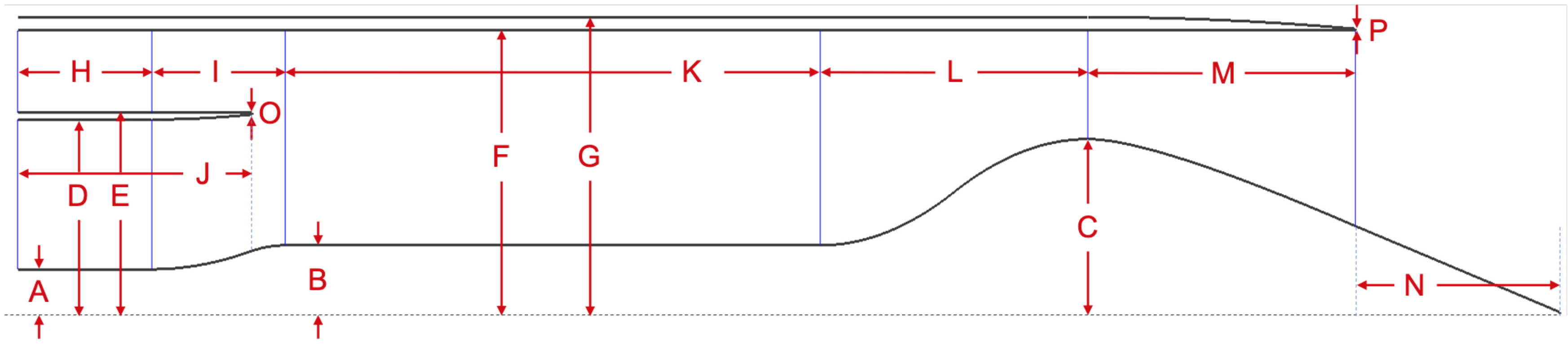
Study Nozzle Geometry

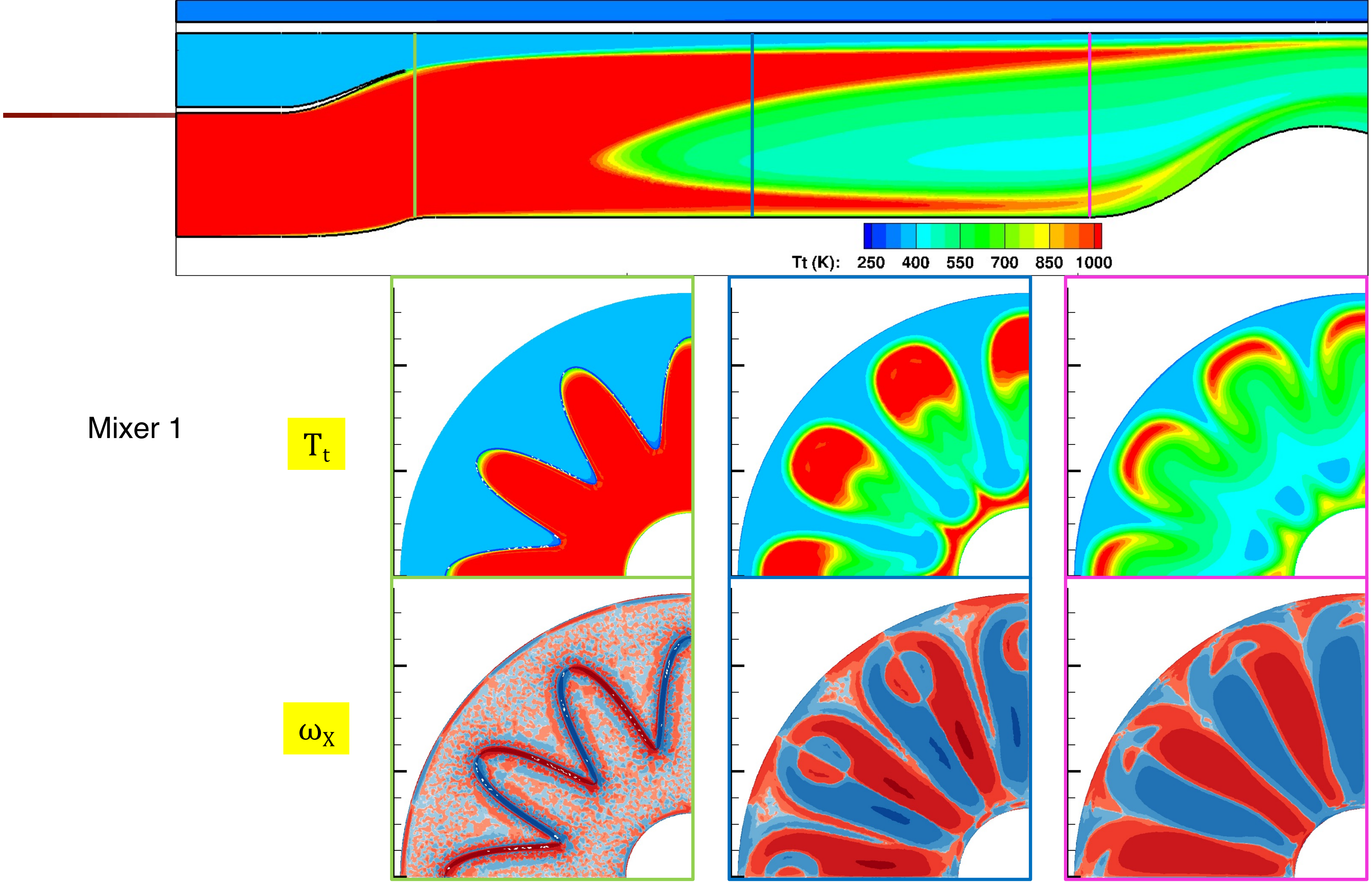
- Common dual-stream nozzle was designed to house all mixers considered

- Academic "Constant-Area" design built to isolate mixing process from expansion/contraction
  - $\boldsymbol{AR = 1}$ enforced through inflow duct to Mixer TE
  - Extended mixing region allows detailed analysis of mixing process
  - Total duct area held constant up to C-D section

- All area changes enforced with the contoured plug
  - Simplifies geometry by confining curvatures to one component
  - C-D nozzle sized to ideally expand flow at SSCR conditions

	Dimension	Description
A	3.4"	Plug Radius @ Inflow
B	5.1044"	Plug Radius @ Mixing Duct
C	13.036"	Plug Radius @ Nozzle Throat
D	14.2"	Splitter Inner Radius
E	14.7"	Splitter Outer Radius
F	21.1466"	Nacelle Inner Radius
G	22.1466"	Nacelle Outer Radius
H	10"	Inflow Duct Length
I	12.5"	Mixer Region Length
J	20"	Splitter+Mixer Length
K	57.5"	Mixing Duct Length
L	20"	Converging Duct Length
M	20"	Diverging Duct Length
N	15"	Plug Exposed Length
O	0.125"	Splitter/Mixer TE Thickness
P	0.125"	Nacelle TE Thickness



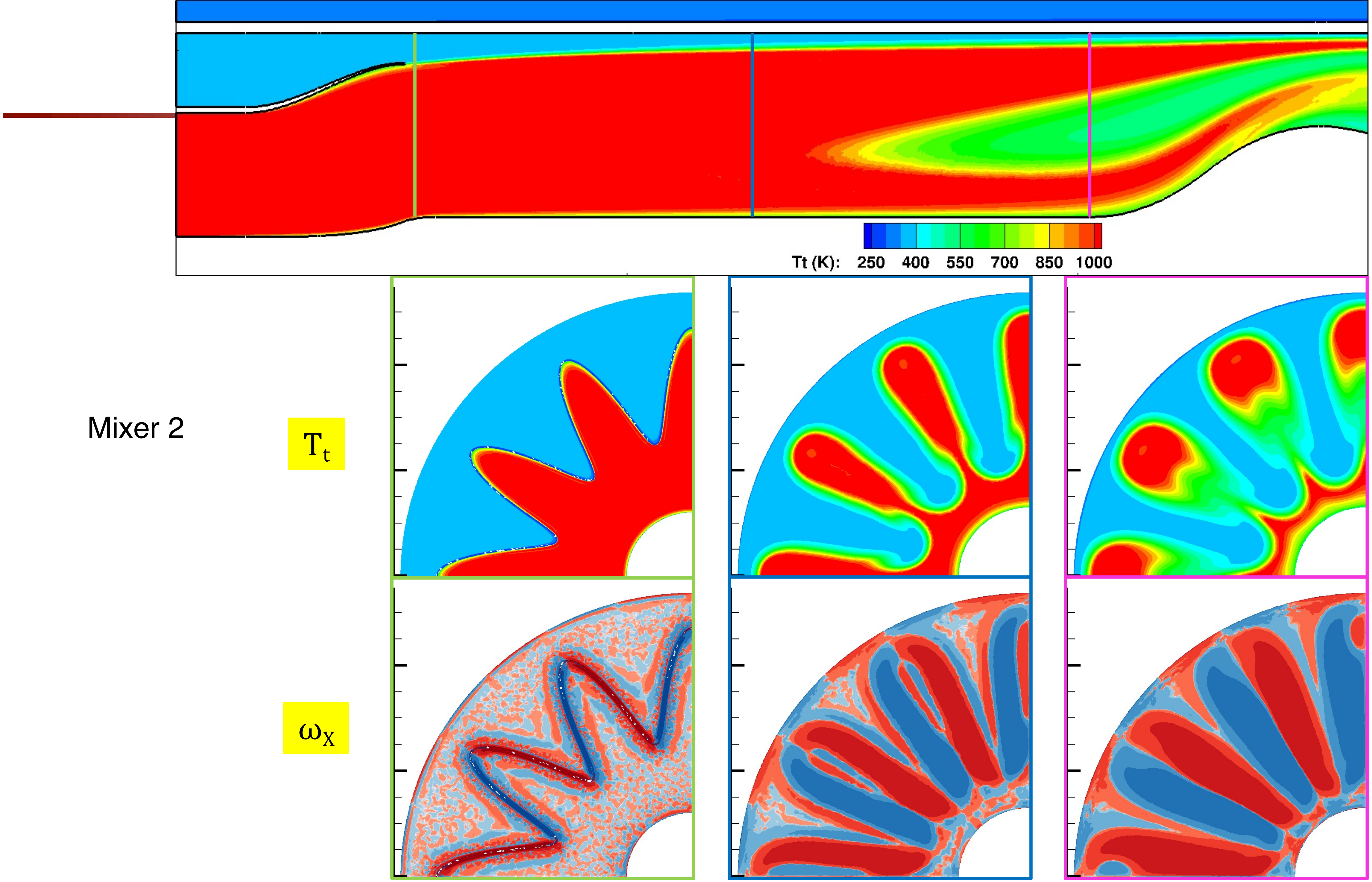


Mixer 1
T_t
ω_X
Tt (K): 250 400 550 700 850 1000

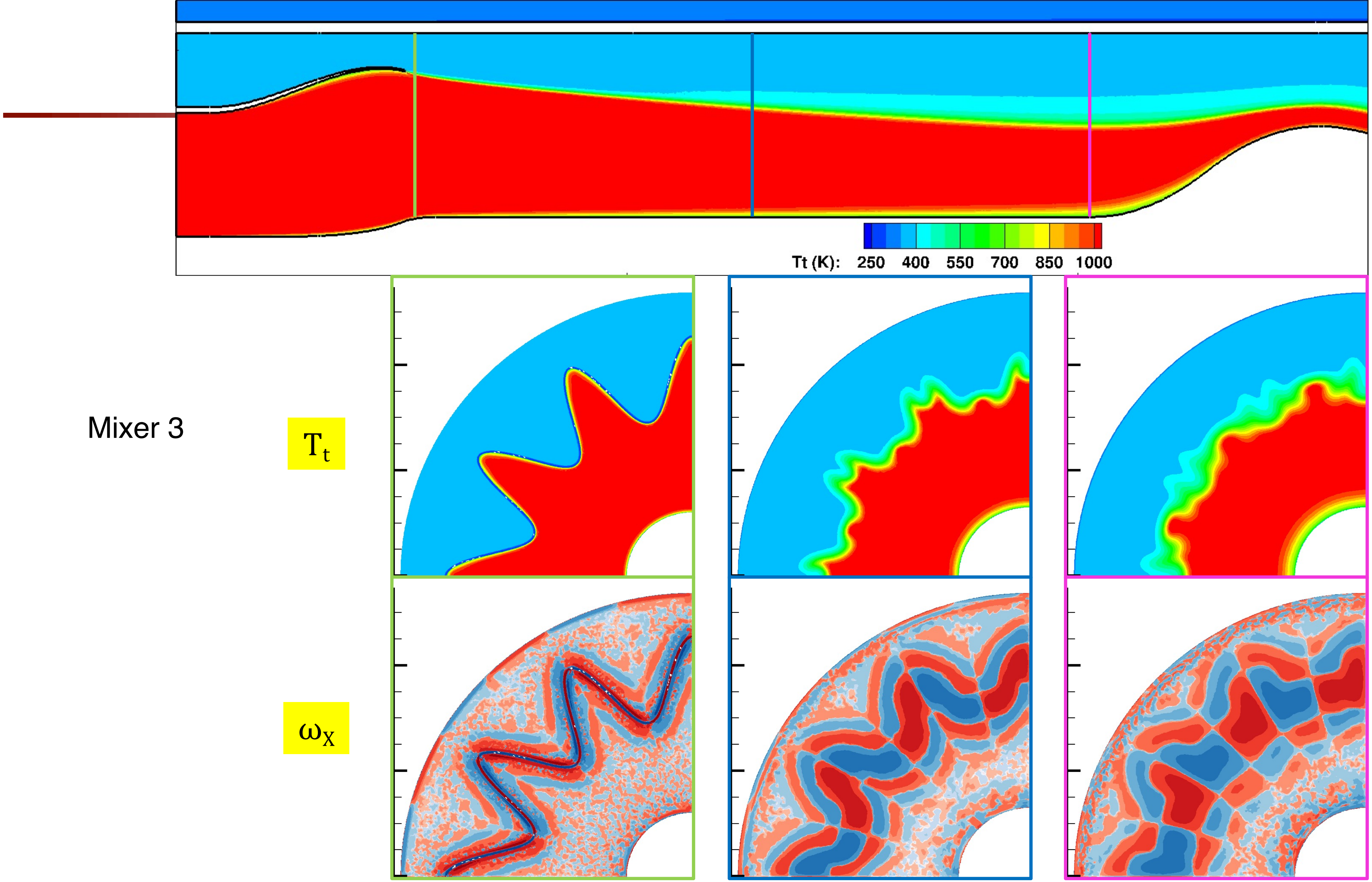
Mixer 2

T_t

ω_X



Mixer 3



Grid Generation

Geometry and grid generation is fully procedural:

- 3-D surfaces (bypass & core sides) are generated from above profiles with NURBS-Python
- .stl surface files are imported into mixer-less nozzle template with Pointwise v18.4
- Connectors are generated with the following spacings:

Description	Spacing
Interior Baseline	0.2"
Exterior Baseline	0.5"
Mixer Surface	0.13"
Mixer TE	0.1"
Mixer TE Thickness	0.0625"
Mixing Buffer	0.13"
Farfield	10"
T-Rex 1st Layer	2e-5"
T-Rex Growth Rate	1.3

- Domains & Blocks are built, then full grid is exported in FUN3D-readable format

Resulting grid is quarter-symmetric about the XY and XZ planes

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Numerical Solution

RANS equations solved with FUN3D v13.6

– SST-v model used to predict turbulent flows

Boundary conditions:

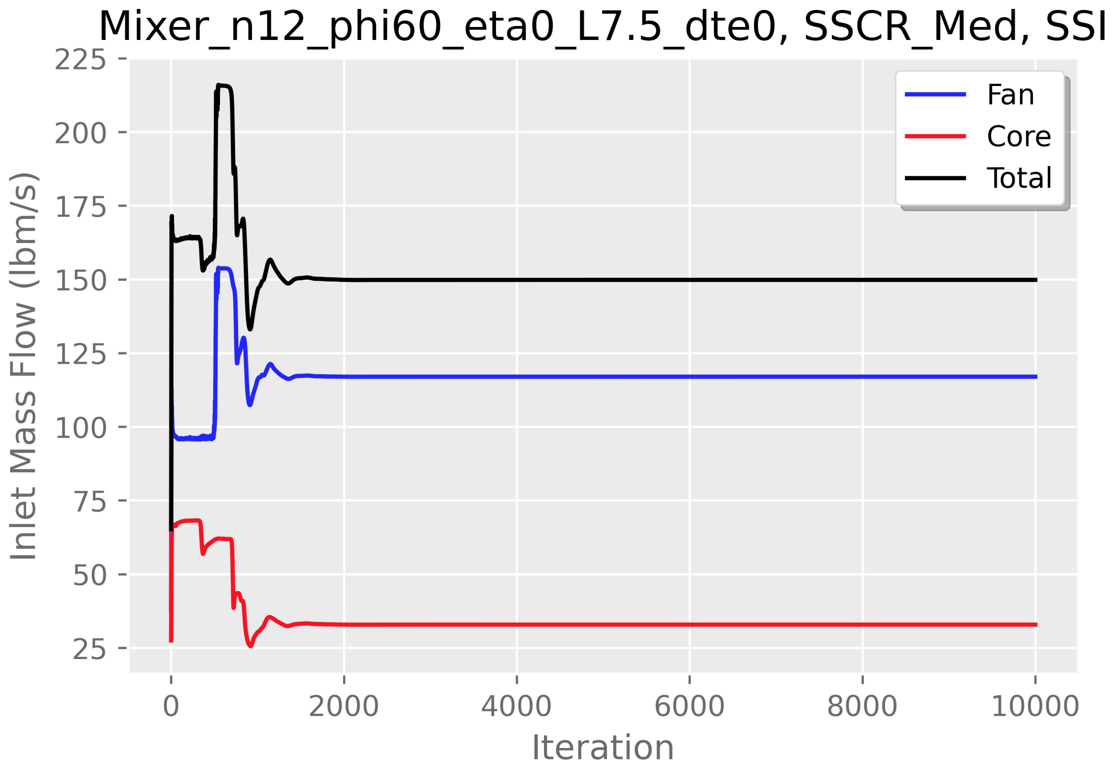
Boundary	Type	Code	λ	NTR
Core Inflow	Subsonic Inflow	7011	5.534	4.654
Bypass Inflow	Subsonic Inflow	7011	6.268	1.736
Y-Symmetry	Symmetry_y	6662	–	–
Z-Symmetry	Symmetry_z	6663	–	–
Farfield Inflow	Freestream	5050	–	–
Farfield	Farfield	5000	–	–
Farfield Outflow	Extrapolate	5026	–	–
Nozzle Surfaces	Viscous Wall	4000	–	–

CFL's # ramped over 1000 iterations

– Convective: 1 to 100

– Turbulent: 0.2 to 20

Convergence typically seen in 3000 iterations, solutions run for 10000



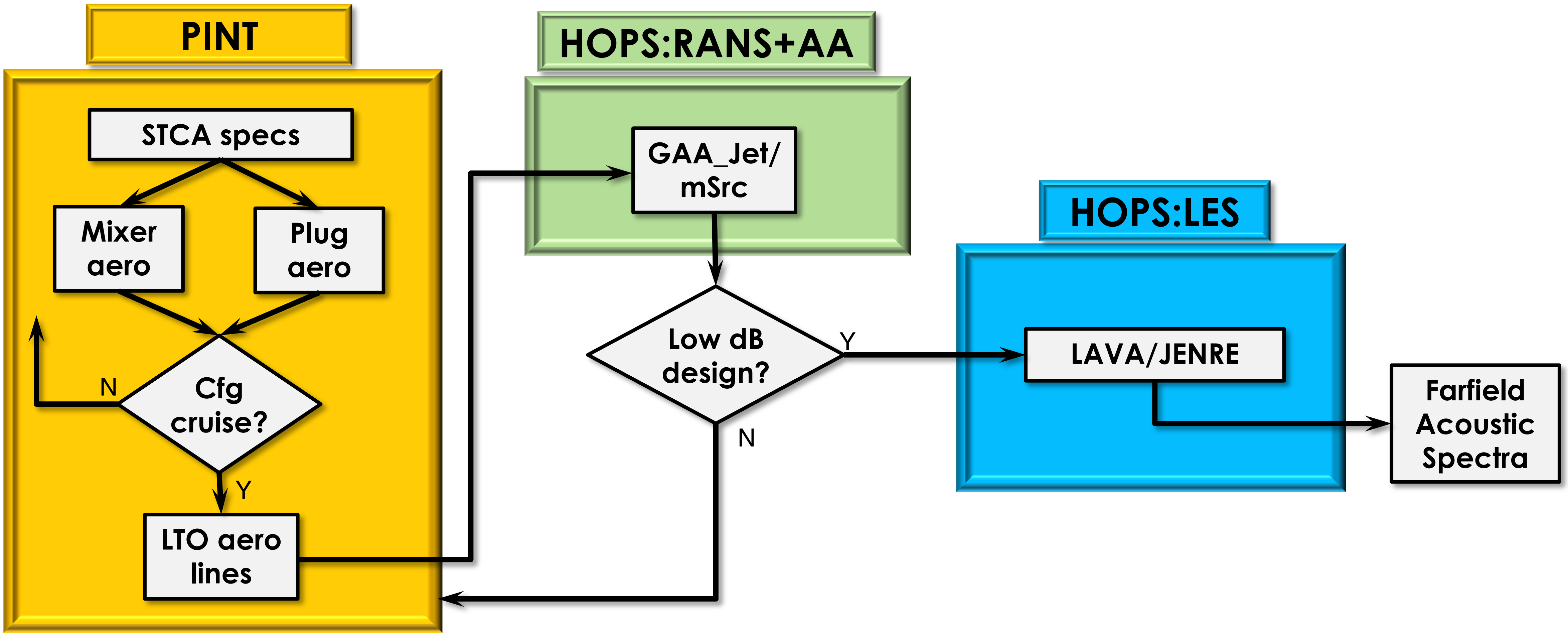
Analysis – Performance Response

- Parameter list:
  - Thrust Coefficient: $\boldsymbol{C_{F_g}} = \frac{F_g}{F_{g,i}}$
  - Mixing Effectiveness: $\boldsymbol{K_4} = \frac{C_{F_{g,HOT}} - C_{F_{g,COLD}}}{\frac{F_{g,i,MIXED}}{F_{g,i,SEP}} - 1}$
  - Pressure Loss Coefficient: $\boldsymbol{C_{\Delta P_t}} = \frac{\Delta P_{t,COLD} - \Delta P_{t,CCM}}{P_{t,IN,COLD}}$
  - Temperature Variance: $\boldsymbol{s_T^2}$ = Variance in Temperature at the mixing duct outflow plane (C.)

HOT: Heated-core case
$COLD$: Unheated-core case
$MIXED$: Ideal, fully mixed flow
SEP: Ideal, fully unmixed flow
CCM: Cold, confluent mixer, aka axisymmetric splitter

Mixer #	C_{F_g}	K_4	$C_{\Delta P_t}$	s_T^2
1	0.9524	0.1577	0.0074	0.4519
2	0.9467	−0.0021	0.0027	0.8848
3	0.9409	−0.0784	0.0012	1.2172

Jet Noise Prediction Toolchains



Bypass Ratio vs. Extraction Ratio vs. Area Ratio

- Plot shows Extraction Ratio $\boldsymbol{\theta}$ vs. Bypass Ratio $\boldsymbol{BPR}$
  - Red dot indicates design point
  - Green dot indicates fixed BPR conditions

- Exponential increase of $\boldsymbol{BPR}$ with $\boldsymbol{\theta}$ suggests high sensitivity of dual-stream nozzles to inflow pressures

- Reducing $\boldsymbol{AR}$ flattens the sensitivity
  - $\boldsymbol{AR = 1}$ was chosen for the nozzle design
  - $\boldsymbol{\theta = 1.13}$ produced the target $\boldsymbol{BPR = 3.33}$ in the final duct design

$$\boldsymbol{BPR = \frac{\dot{m}_{IN,Bypass}}{\dot{m}_{IN,Core}}} \qquad \boldsymbol{\theta = \frac{P_{t,IN,Bypass}}{P_{t,IN,Core}}} \qquad \boldsymbol{AR = \frac{A_{IN,Bypass}}{A_{IN,Core}}}$$