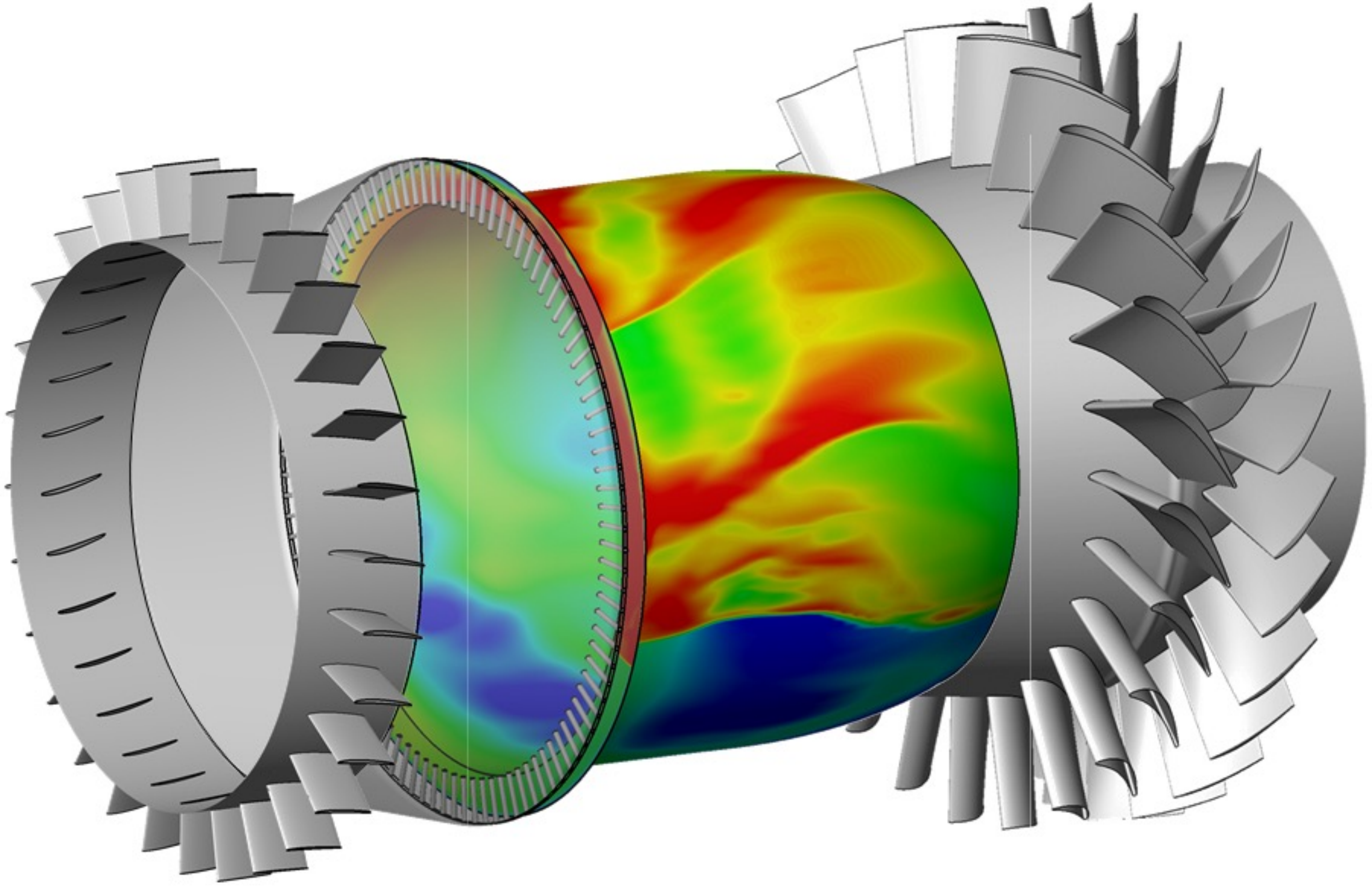
Physics-based Integration of H2-Air Rotating Detonation into Gas Turbine Power Plant (HydrogenGT)



Purdue Experimental Turbine Aerothermal Lab

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Overall aim: develop a high-speed diffuser-turbine to enable integration of rotating detonation combustors (RDC) into industrial turbines

TASKS

2. Loss budgeting in a combustor & transition element & turbine 1st stator (nozzle guide vane)

4. Scale exp. & comp. studies to F-class and aero-derivative RDE gas turbine integrated system

3. Demonstration RDC-transition-NGV coupling towards work production

2. Loss budgeting in a combustor & transition element & turbine 1st stator

2.1 Identification of loss mechanisms for the combustor with diffuser and turbine 1st stator

- *Study an existing combustor/diffuser/NGV geometry*
- *Computational model validation & predict the combustor losses*

2.2. Quantification of the combustor performance metrics with turbine 1st stator

- *representative metric of combustor/diffuser/NGV performance*
- *CARS & PIV data will be used to validate*

2.3. Uncertainty quantification of loss mechanisms by integrating high fidelity simulations with the experimental data

- *Large Eddy Simulations of the tested optical transparent RDC*

Subtask 2.1 Identification of loss mechanisms for the combustor with turbine 1st stator

Goals

1. Identify the combustor loss mechanisms from diffuser/turbine 1st stator
2. Provide benchmark validation data for high-fidelity simulations

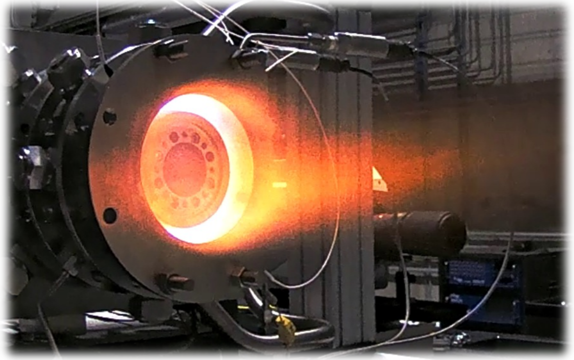
Diagnostic implemented

- High frequency wall-pressure measurements ($p_{stat.}$)
- MHz rate simultaneous orthogonal OH* chemiluminescence and OH-PLIF (χ^{OH*} and χ^{OH})
- Exhaust chemiluminescence (χ^{OH*})
- Femtosecond Laser Activation and Sensing of Hydroxyl radical (FLASH) velocimetry (v)
- Coherent vortex-velocimetry (v)

Diagnostics being development for this program

- MHz rate high speed optical parametric oscillator
  - OH-PLIF measurements
  - FLASH
  - Coherent vortex-velocimetry
- 100 kHz – 1MHz ps-CARS system for
  - Exhaust temperature measurements
- 1 kHz hybrid CARS system (fs/ps CARS)

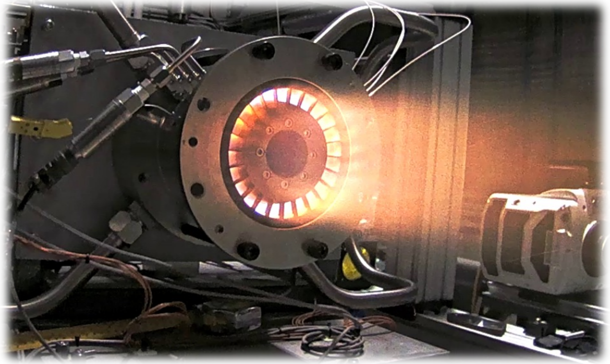
No NGV installed



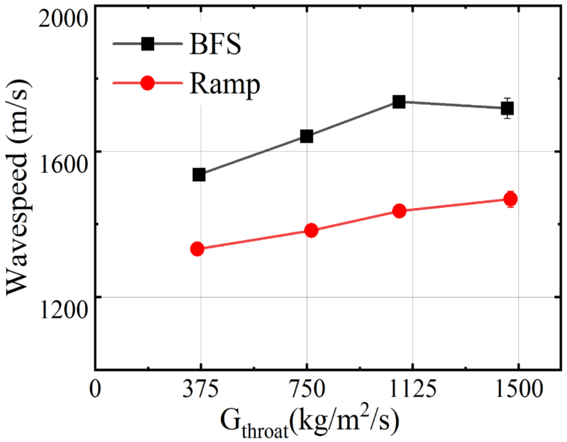
Summary of results

- 2.1: Identification of additional loss mechanisms:
  - Azimuthal Reflected Shock Combustion (ARSC) – **P_{tot} Loss** mechanism
  - Ramp Combustor has lower performance than BFS
  - Mixing/Deflagrative influences on RDE performance
- 2.2: Total pressure measurements

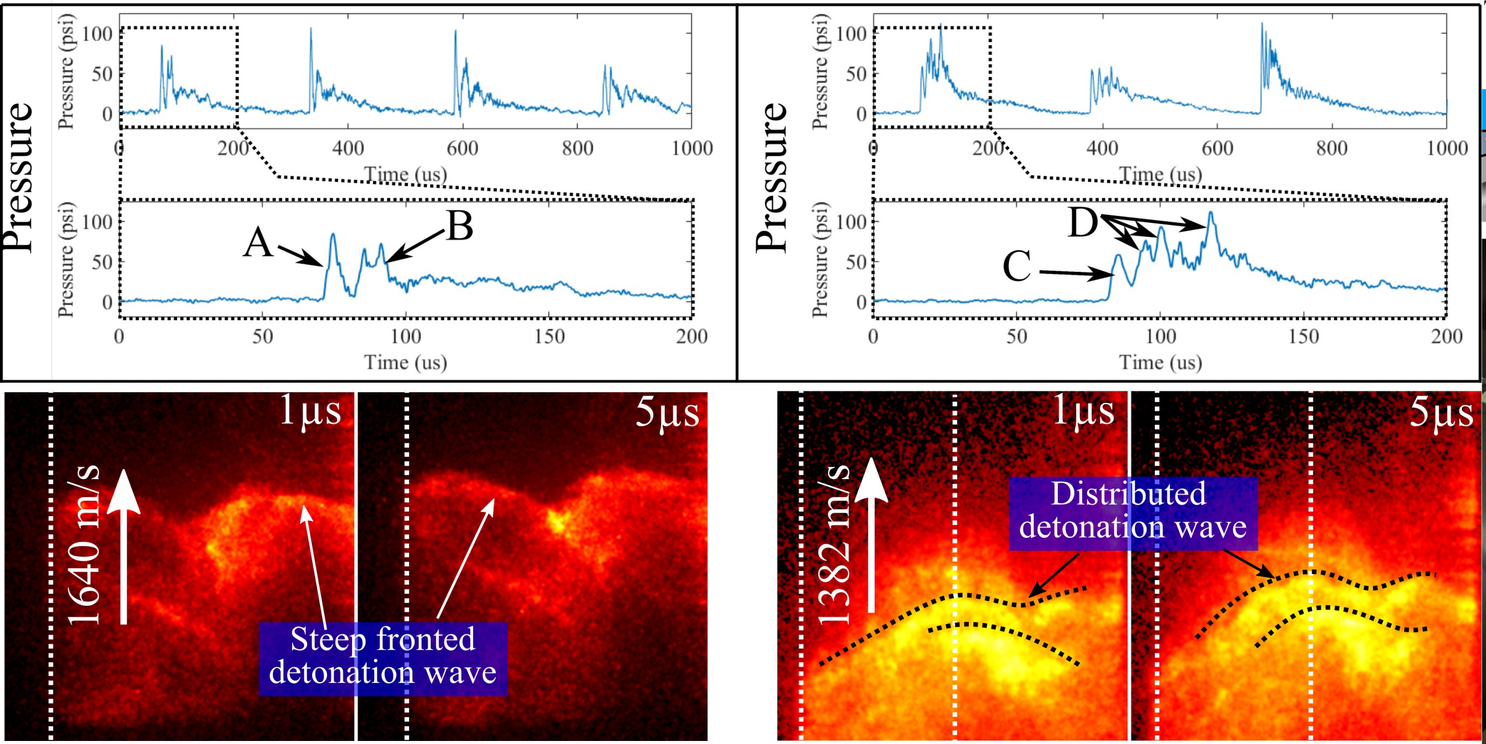
NGV installed

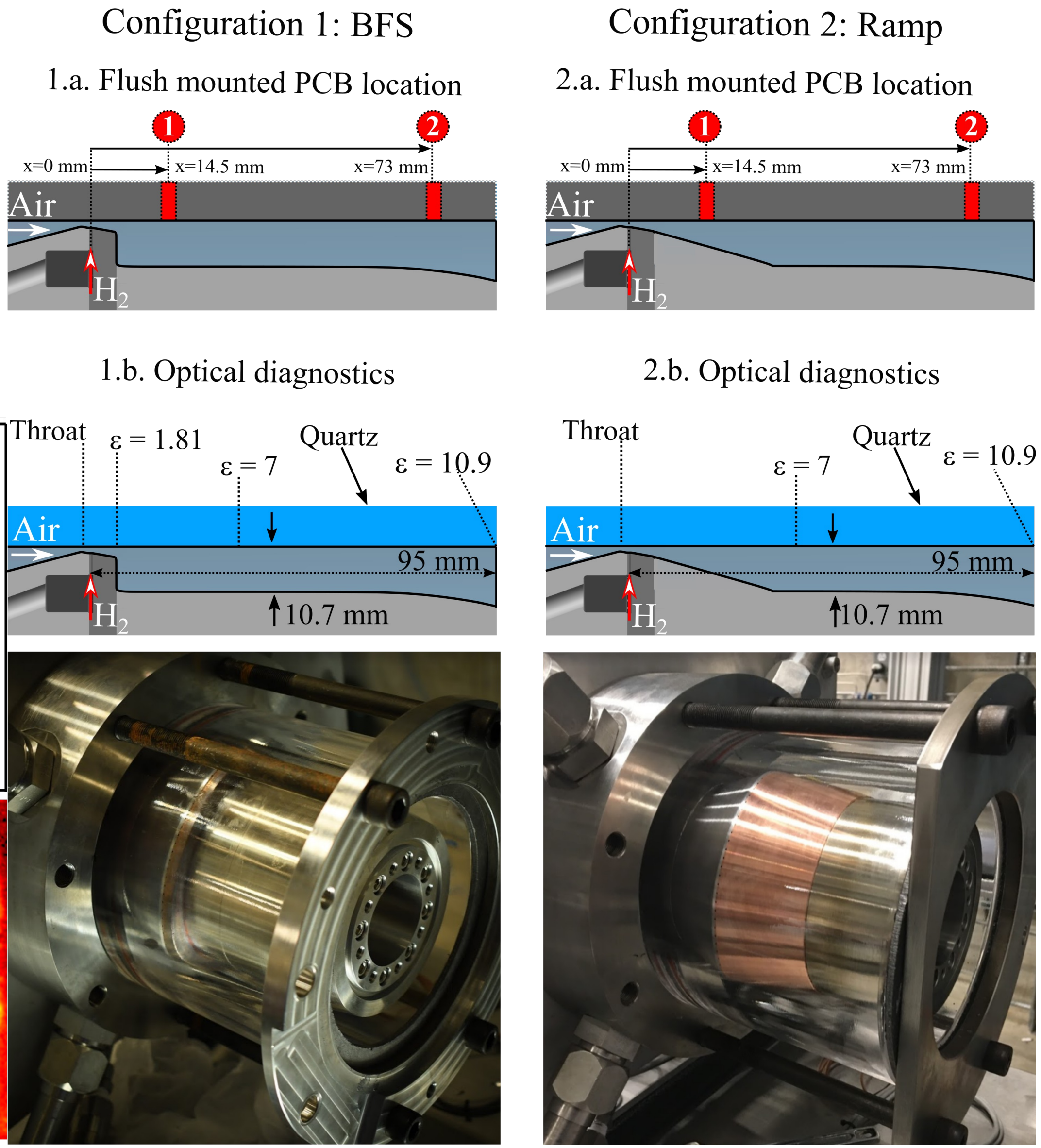


2.1: Combustor loss mechanism – Comparison of Straight Channel vs Ramp



(a) PCB 1 (15 mm from injector)- Test #2 - BFS (b) PCB 1 (15 mm from injector)- Test #6 - Ramp

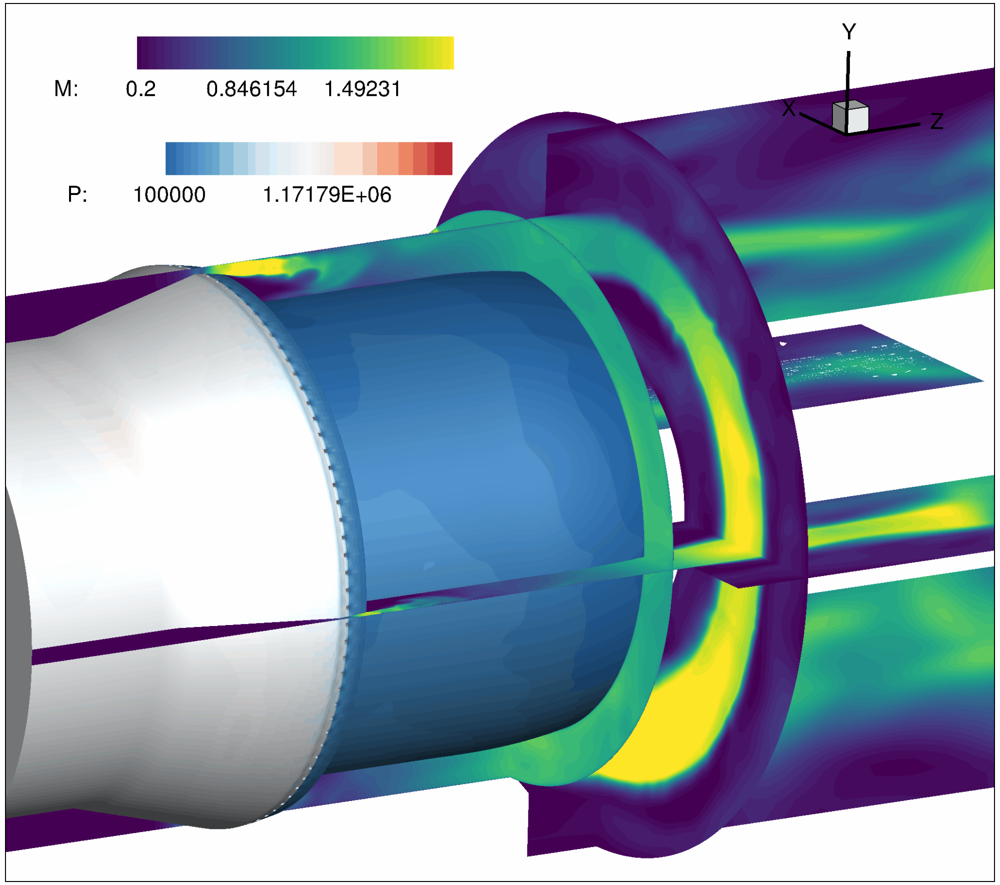


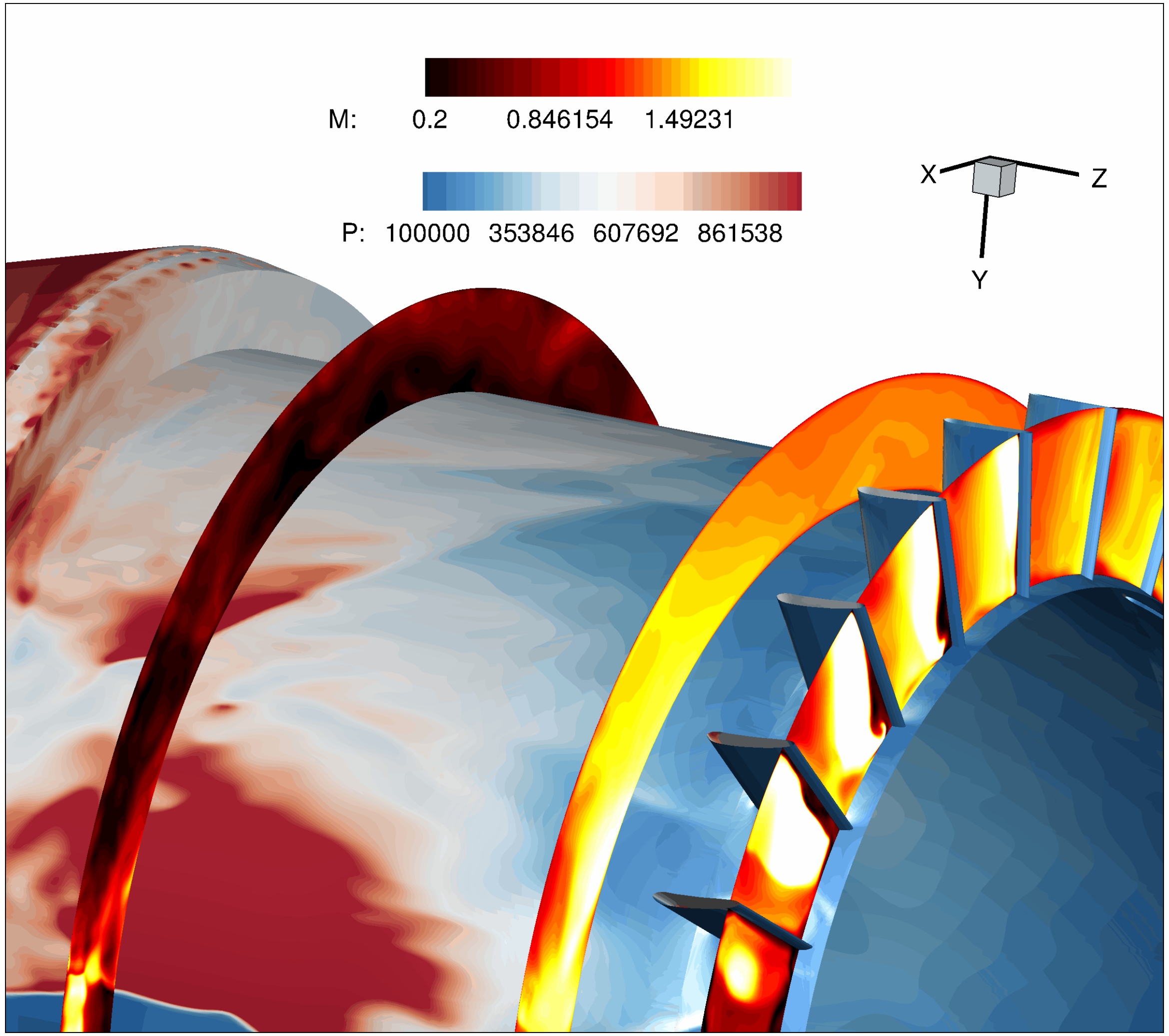


[1] Athmanathan, Venkat, James Braun, Zachary M. Ayers, Christopher A. Fugger, Austin M. Webb, Mikhail N. Slipchenko, Guillermo Paniagua, Sukesh Roy, and Terrence R. Meyer. "On the effects of reactant stratification and wall curvature in non-premixed rotating detonation combustors." *Combustion and Flame* 240 (2022): 112013.

2.1: URANS Simulations

URANS with chemistry without turbine stator vs with the turbine stator



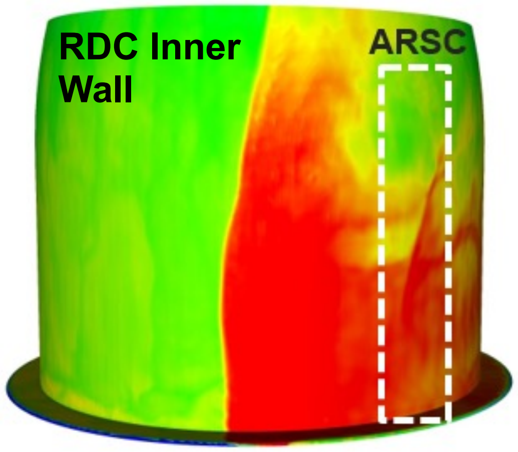


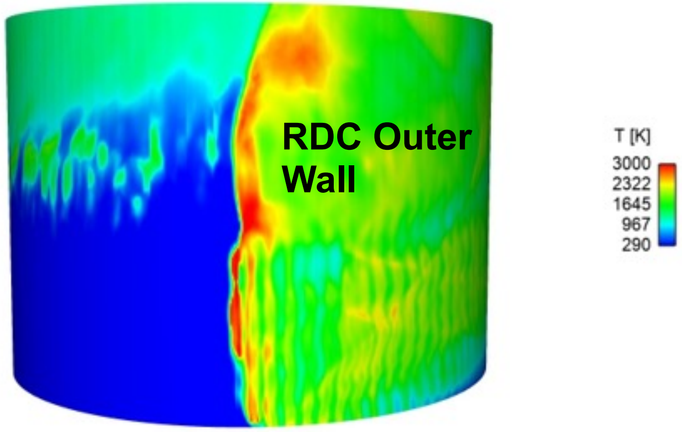
Subtask 2.3 Investigation of loss mechanisms in the RDC

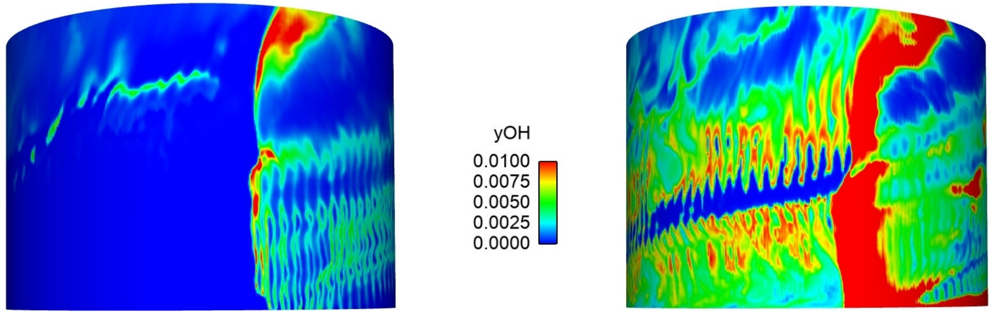
High-fidelity Large-eddy Simulation (LES) of THOR H_2/air RDC

Argonne NATIONAL LABORATORY

- Single detonation wave behavior is observed
- An azimuthal reflected shock combustion (ARSC) wave trails behind the leading detonation wave
- LES depicts similar structures as experiments
- Combustion behavior is further analyzed using species profiles and chemical explosive mode analysis (CEMA)
- Deflagrative combustion is observed in the fill region, varying with the radial location
- Flow profiles at the exit of the transition element

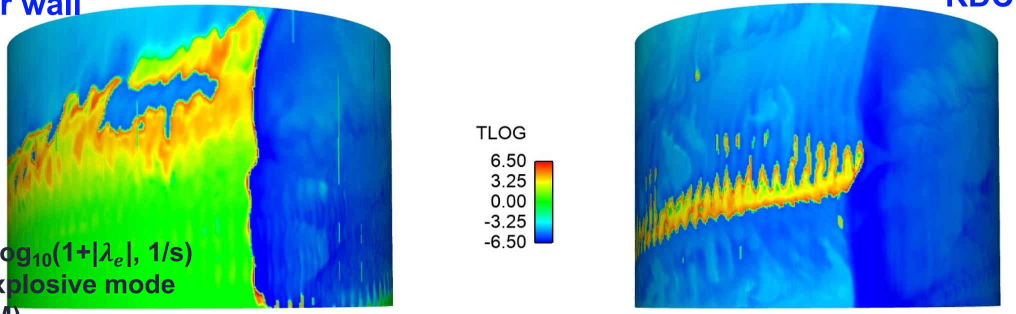


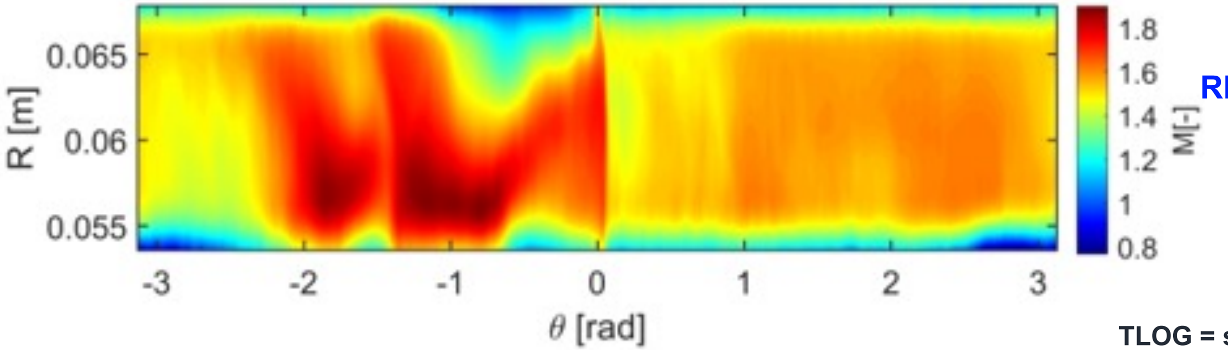




RDC outer wall

RDC mid-plane



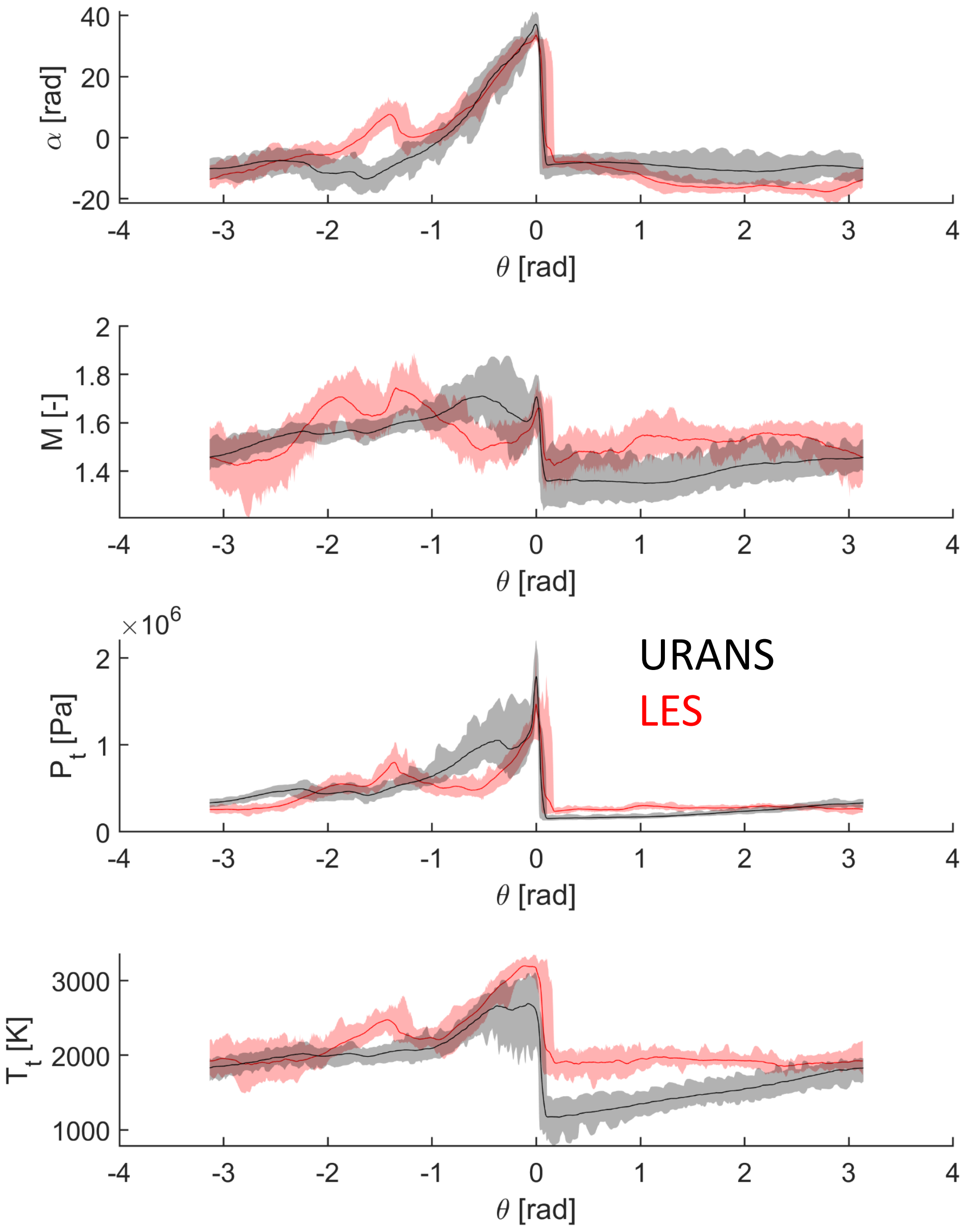


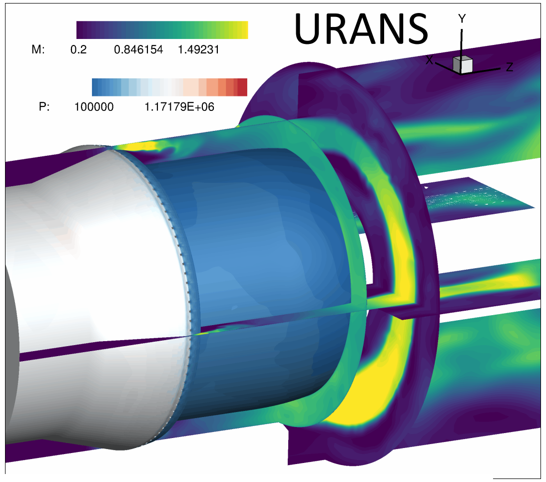
Exit Flow Ma Profile

TLOG = sign(λ_e)×$\log_{10}$(1+|λ_e|, 1/s)
λ_e→ Chemical explosive mode (CEM)

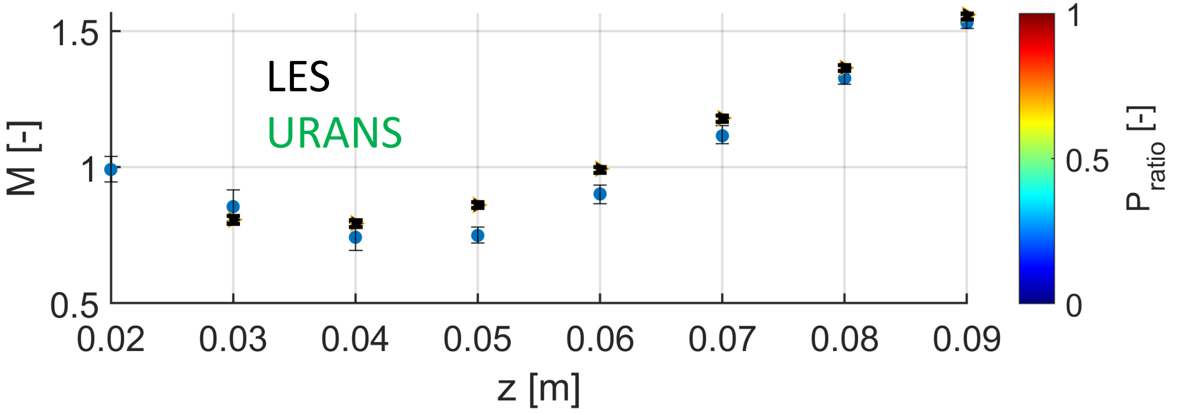
Pal et al., AIAA Aviation 2023-4271

Subtask 2.3 Uncertainty quantification of loss mechanisms

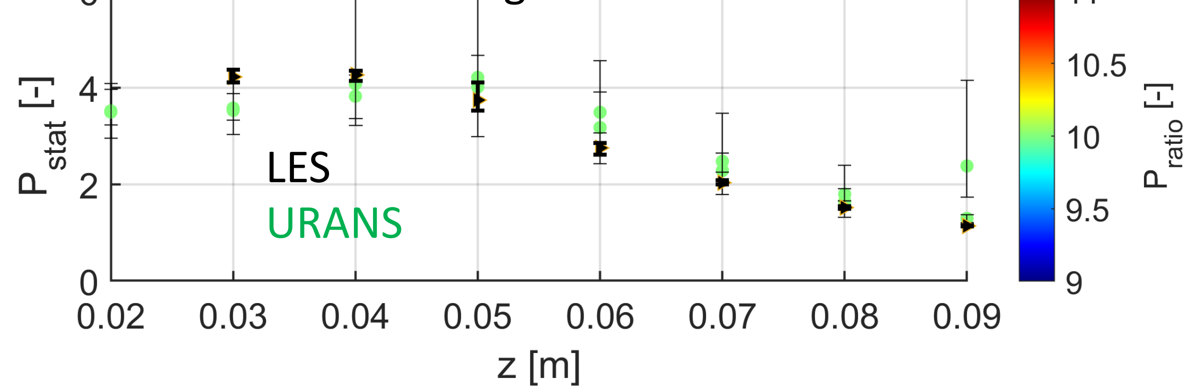




Mach number along the axial direction



Pressure along the axial direction



4. Scale all our studies to F-class and aero-derivative class RDE GT system

4.1. Cycle analysis of the scaled-down RDC-diffuser-turbine

4.2. Cycle analysis to predict the F-class turbine power plant's performance

4.3. Scale lab-scale experimental and computational studies to F-class and aeroderivative class RDE-gas turbine integrated systems

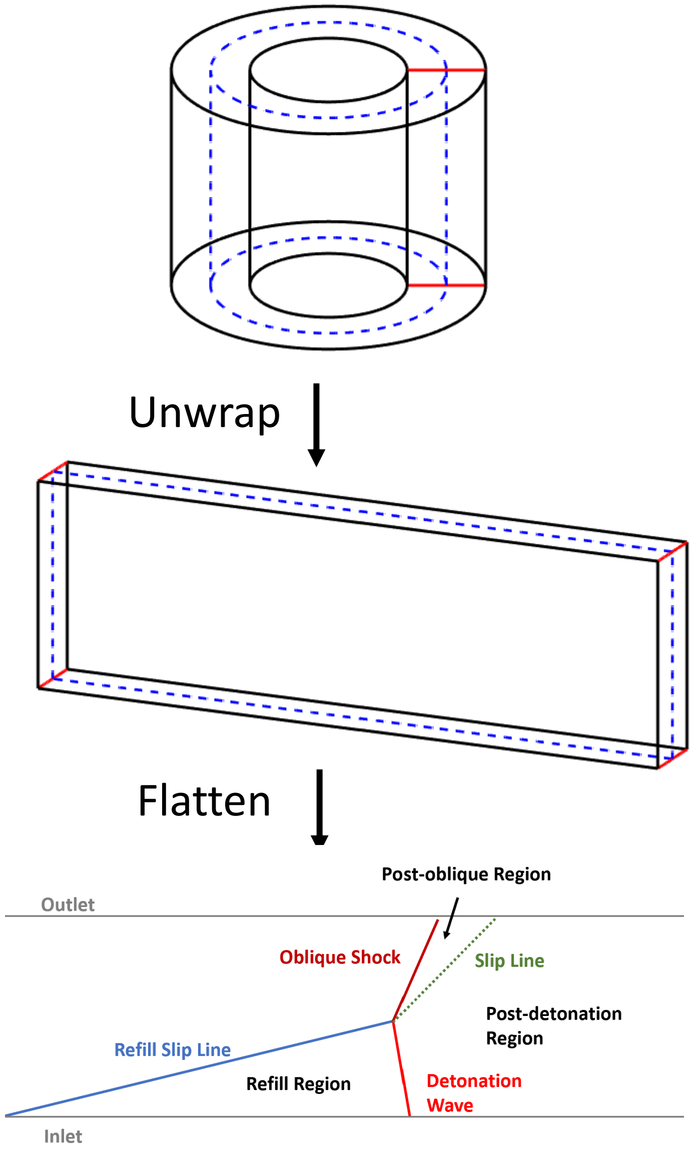
Subtask 4.1 Cycle analysis of the scaled-down RDC-diffuser-turbine

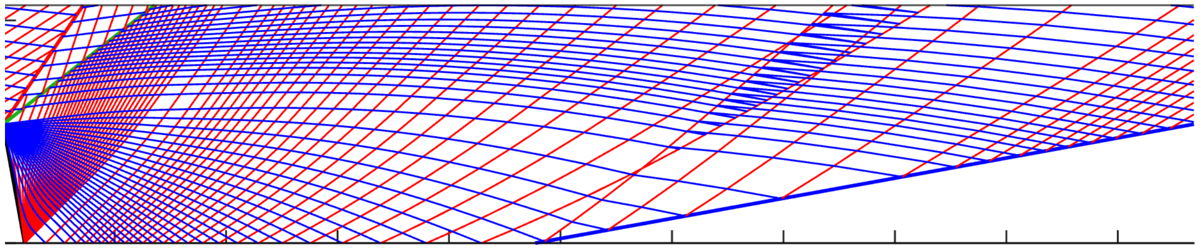
Method of Characteristics

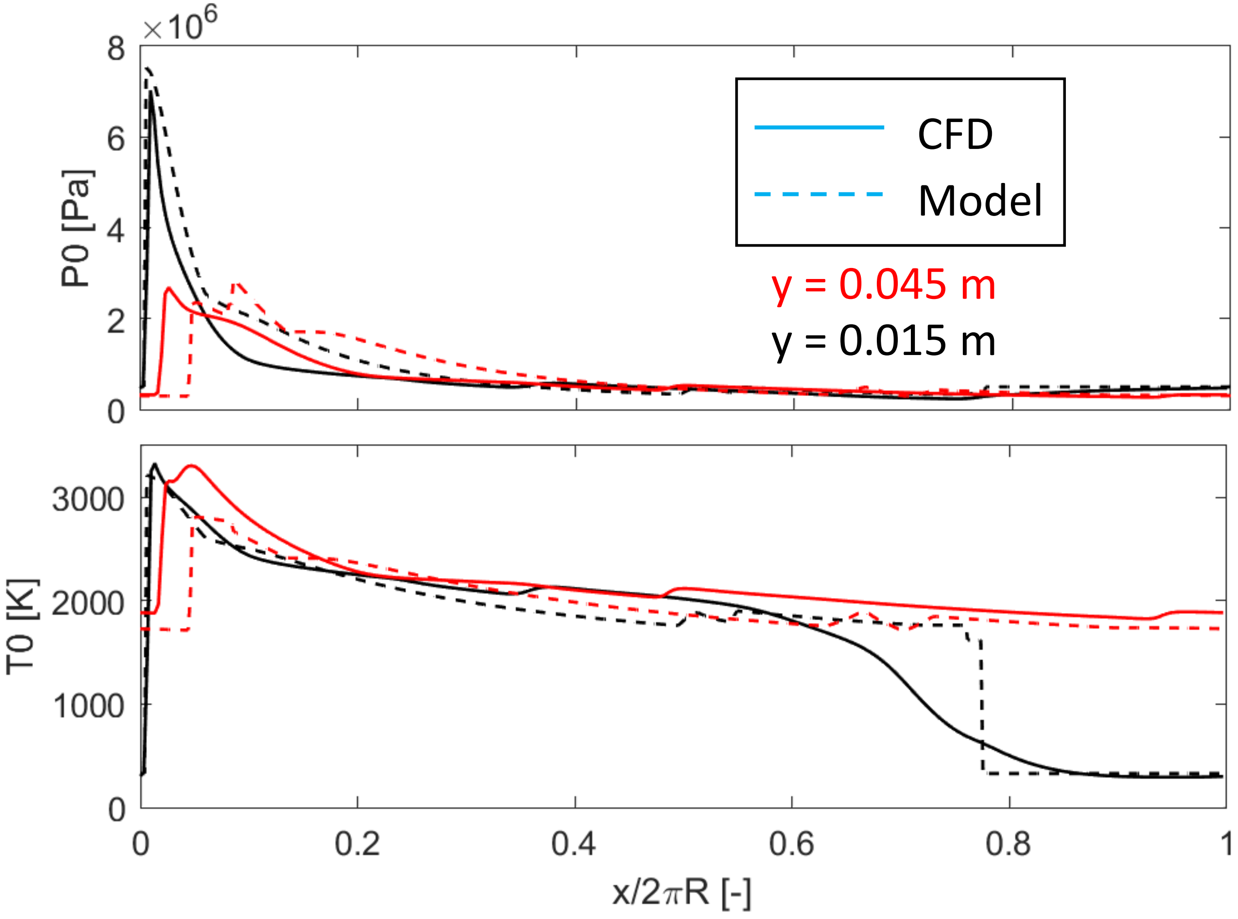
Real 3D combustor

Unwrapped 3D combustor

Flattened 2D combustor







3. Demonstration RDC - transition element – turbine 1st stator towards work production

3.1. Overall transition element optimization

3.2. Computational multi-objective optimization of the turbine 1st stator

3.3. Experimental demonstration of the optimal turbine 1st stator @warm conditions

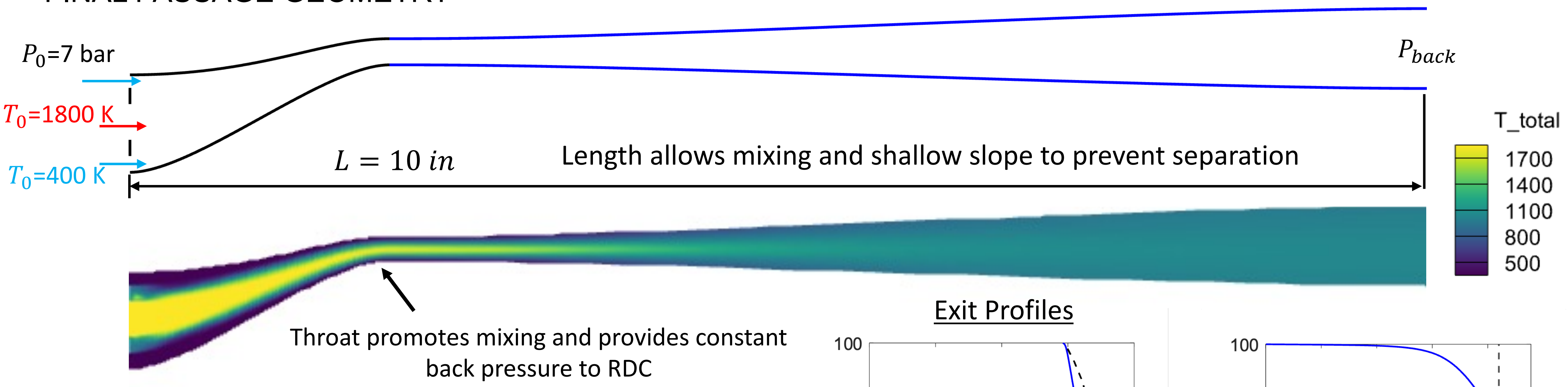
- *Multiple Optimized NGVs characterized in an annular configuration (BRASTA)*
- *Inlet Mach number [0.6 - 1.0]; Reynolds [$7.5*10^5$ - $2*10^6$]*
- *Instrumentation: pressure taps, Kiel & 5H probe traverses, turbulence intensity & oil visualization*

3.4. Experimental demonstration of the RD combustor and turbine @hot conditions

- *RDC + transition element tested first independently, characterization of component performance + turbine inlet flow field.*
- *Instrumentation: pressure taps, Kulites, high-frequency Kiel probes, TCs (low & high freq.), high-frequency 3H probe, ALTPs (high-frequency heat flux)*
- *RDC + transition element integrated with Rolls-Royce M250 turboshaft engine*

Subtask 3.1 Overall transition element optimization

FINAL PASSAGE GEOMETRY

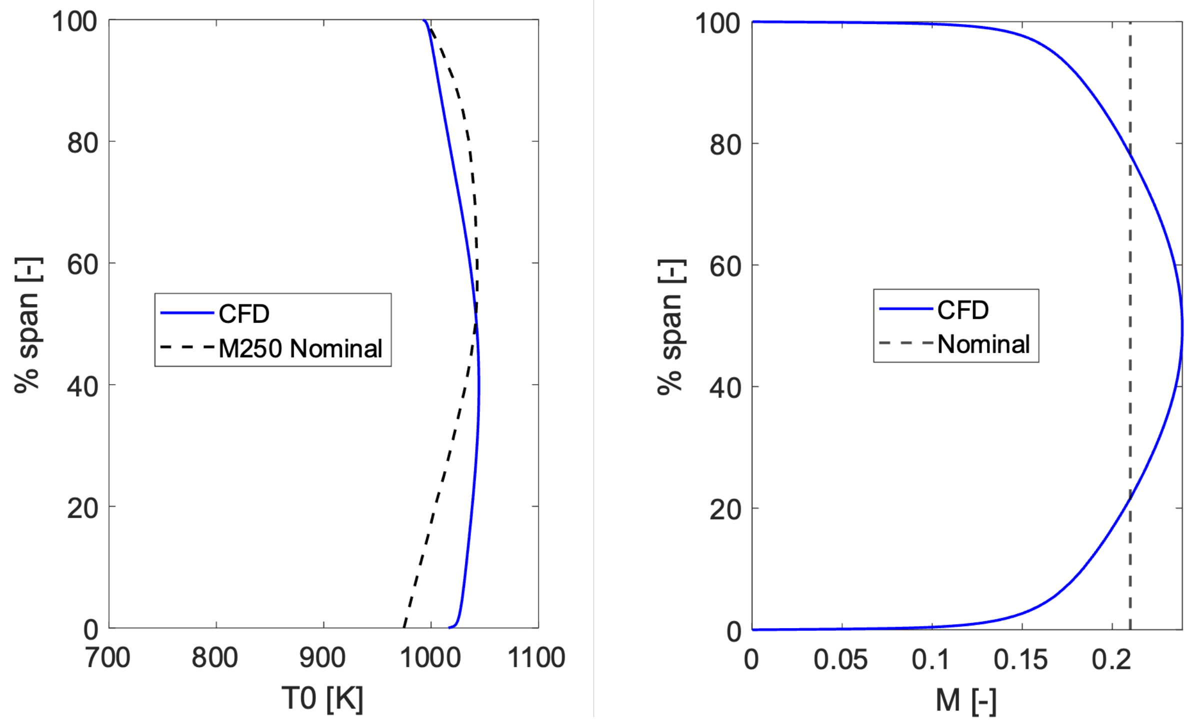


Performance vs. back pressure

$P_{0,RDC}$ $[bar]$	P_{back} $[bar]$	Peak Mach	$\dot{m}$ $[kg/s]$	Exit Mach	Peak T_0 [K]	$P_0\ loss$ [%]
7.0	5.0	1.48	2.00	0.25	1033	25.5
7.0	5.5	1.37	2.00	0.23	1032	18.6
7.0	6.0	1.09	2.00	0.21	1031	11.7
7.0	6.5	0.60	1.60	0.16	1035	5.56

Design condition

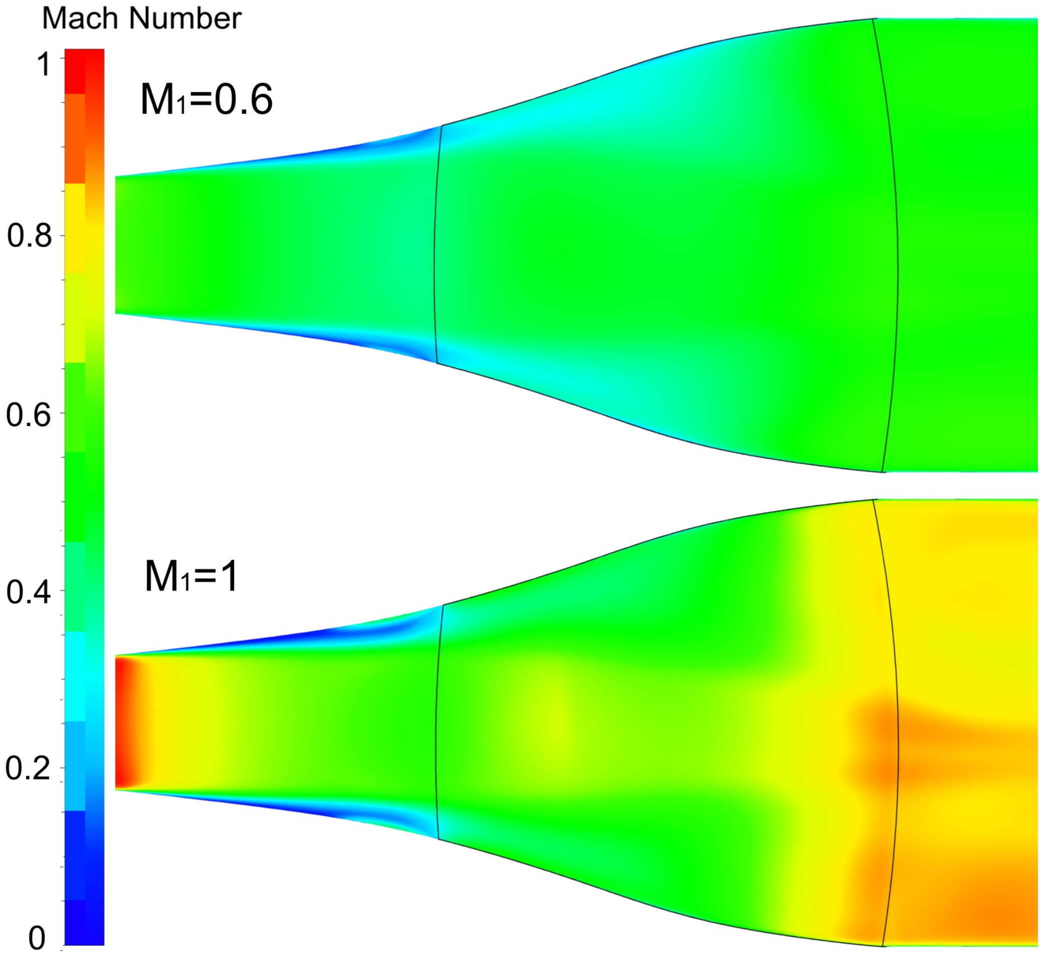
Exit Profiles



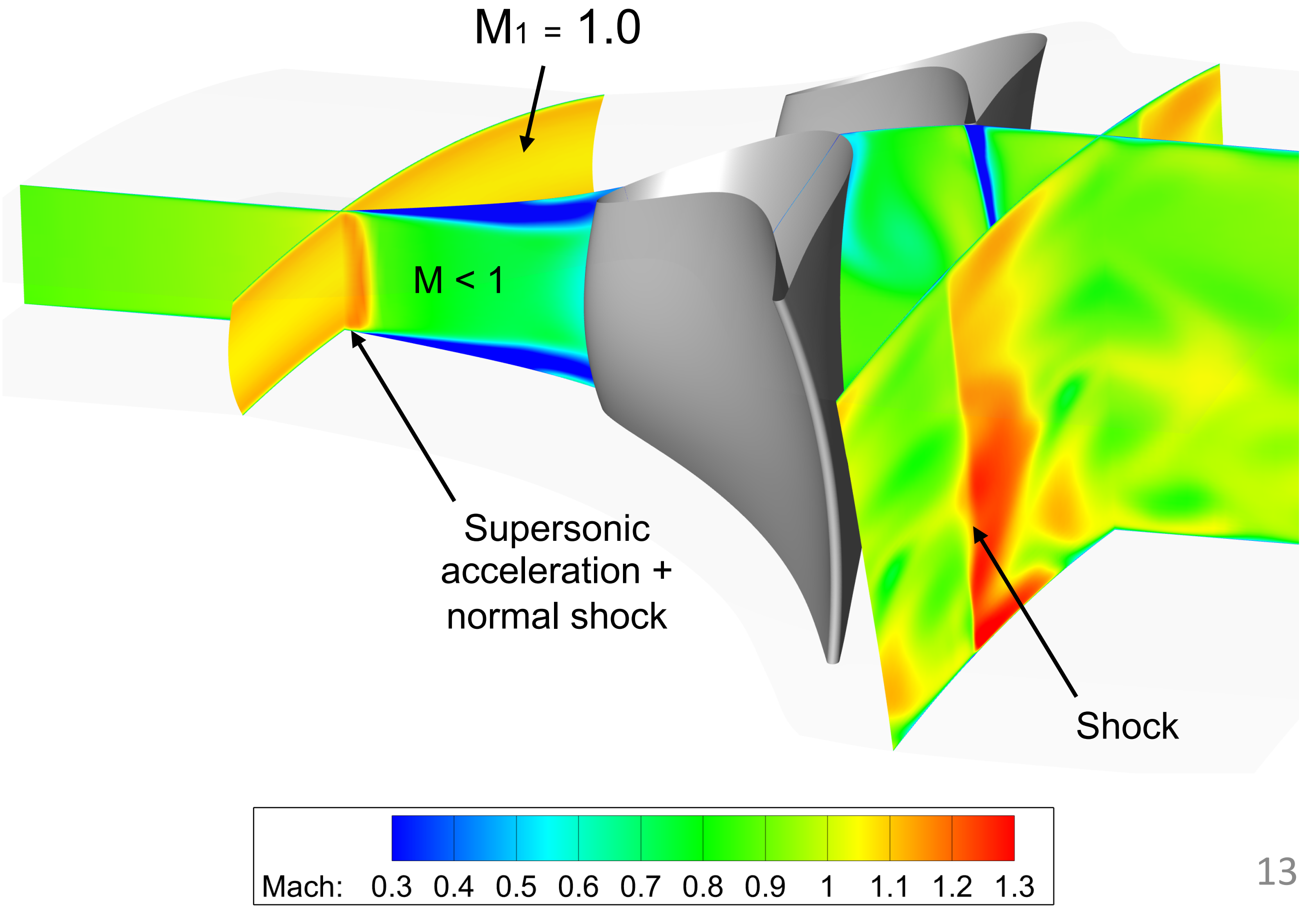
Subtask 3.2 Computational multi-objective optimization of the turbine 1st stator

- Optimized NGV design from Subtask 3.2. Design condition $M_1=0.6$
- Designed for a large operating range, M_1 up to 1 (full subsonic operability)
- High turning ($\alpha_2 \simeq 70°$) → high power

Meridional View

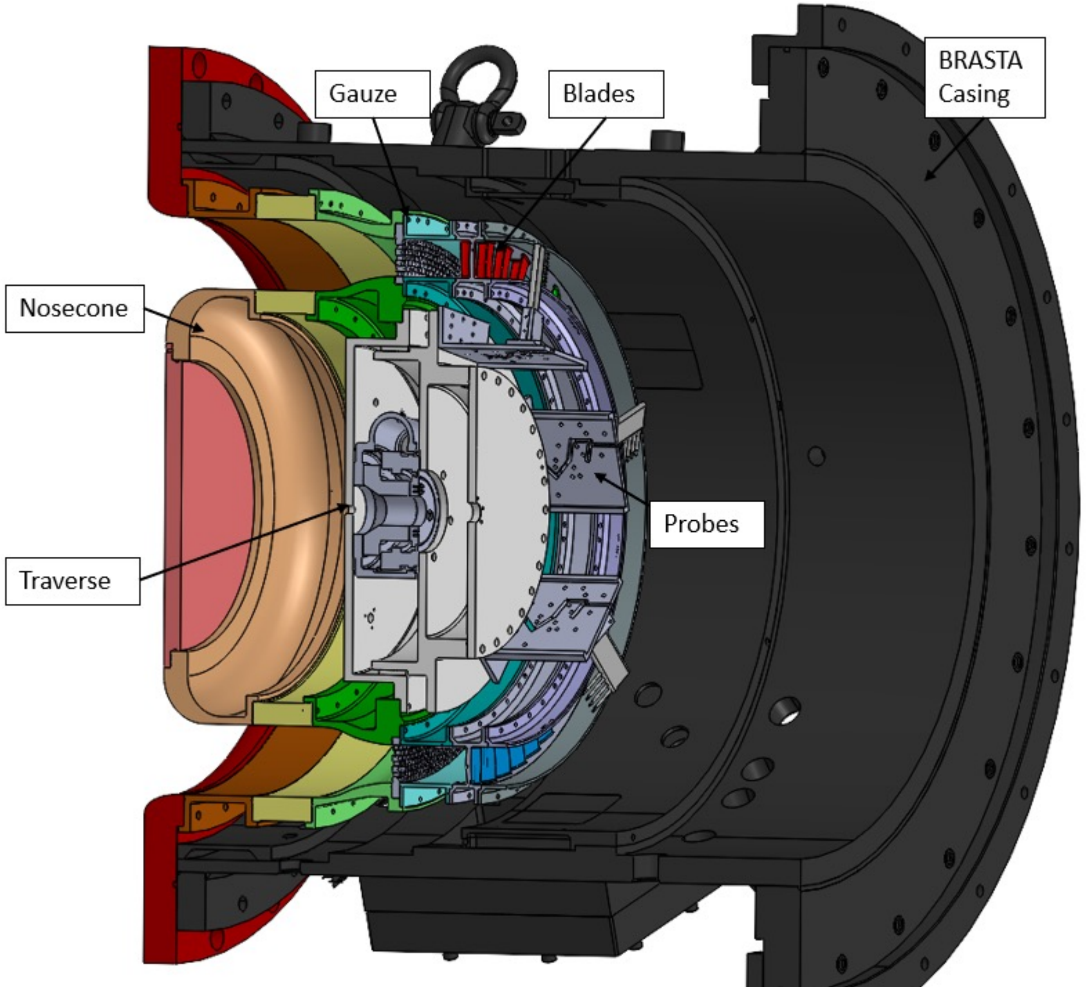


Can be pushed to high pressure ratios: $P_{01}/P_2 = 2.1$, $M_2 = 1.03$

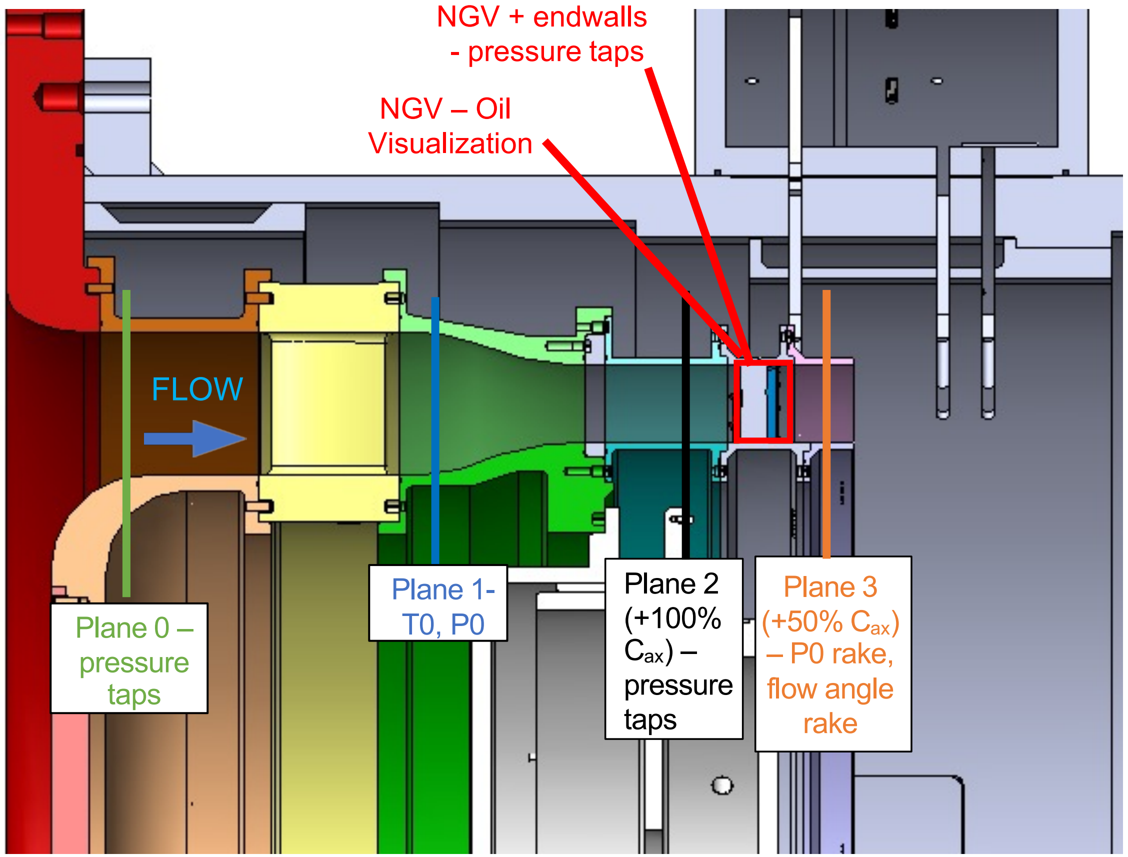


Subtask 3.3 Experimental demonstration of the optimal turbine 1st stator

- BRASTA: Pressure-driven Annular Test Section
- 4 geometries to test:
  - Baseline & Optimized (Design case 1)
  - Baseline & Optimized (Design case 2)

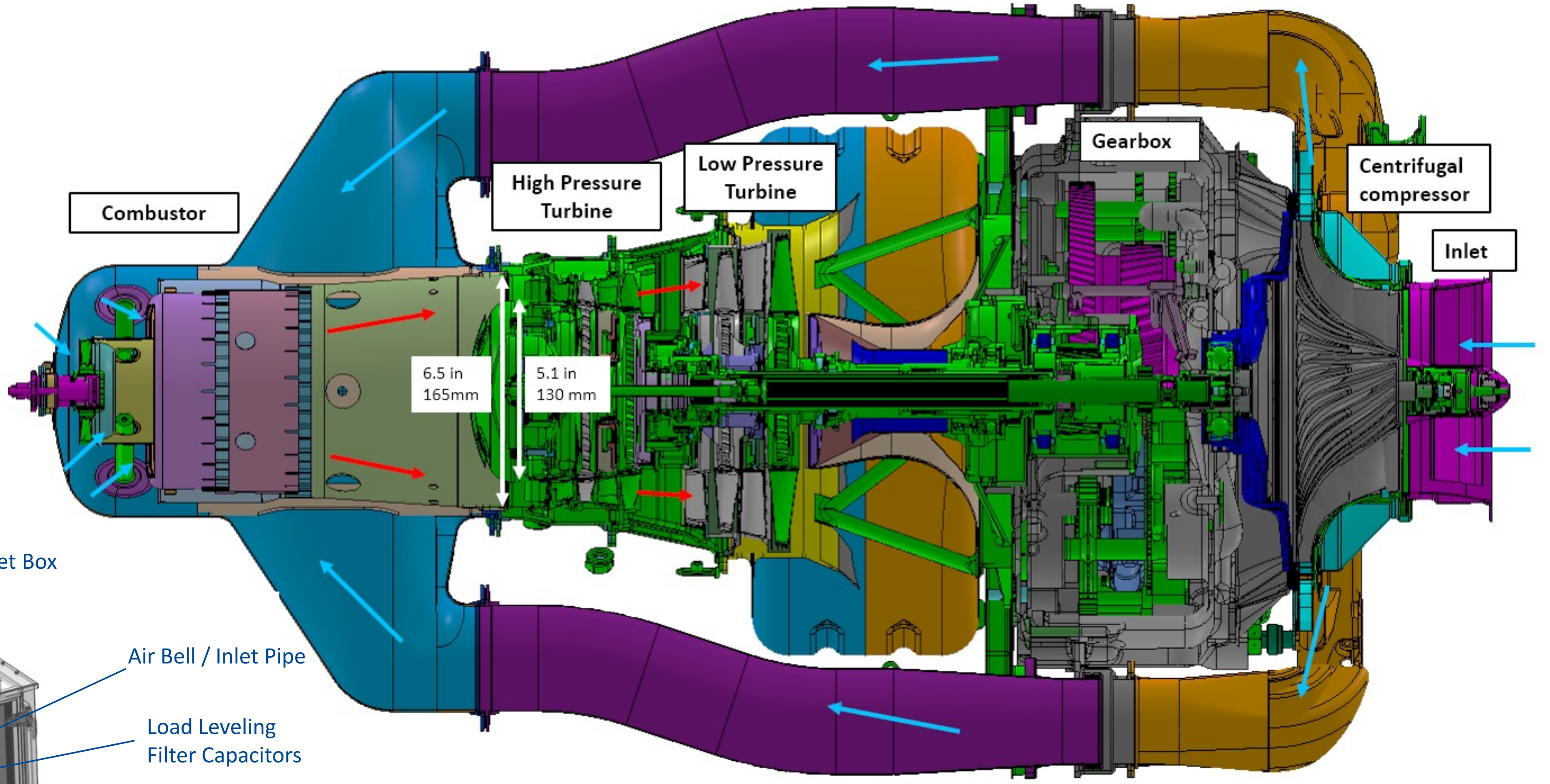


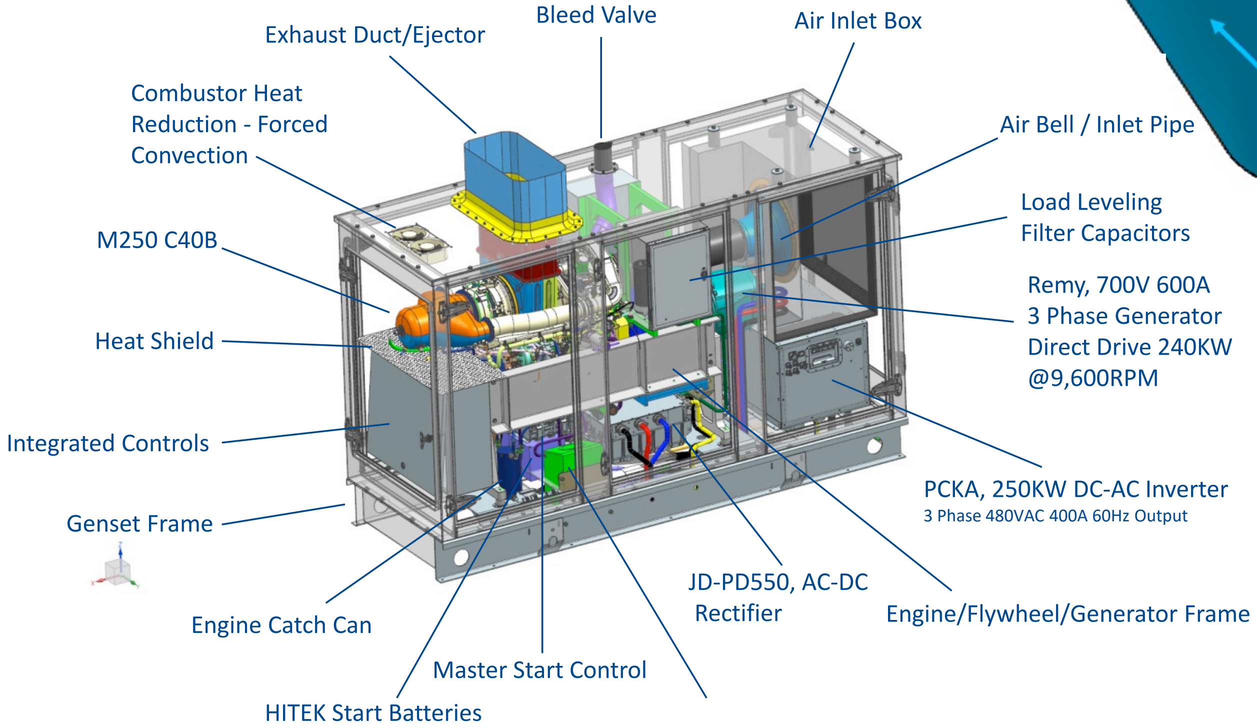
- Detailed characterization of NGV flow field
  - Instrumentation: pressure taps, Kiel & 5H probe traverses, turbulence intensity & oil visualization
- Extensive testing envelope
  - Inlet Mach number [0.6 - 1.0]; Reynolds [$7.5*10^5$ - $2*10^6$]



Subtask 3.4 Experimental demonstration of RDC + turbine

RR M250 C40B





Subtask 3.4 Experimental demonstration of RDC + turbine

Overview of modifications: Cooled RDC Integration with M250

- Fresh mixture injected from tanks not from compressor discharge (engine loop not closed)
- Compressor acts as HPT brake (compressor outlet is throttled)
- LPT connected to generator + load bank for power dissipation