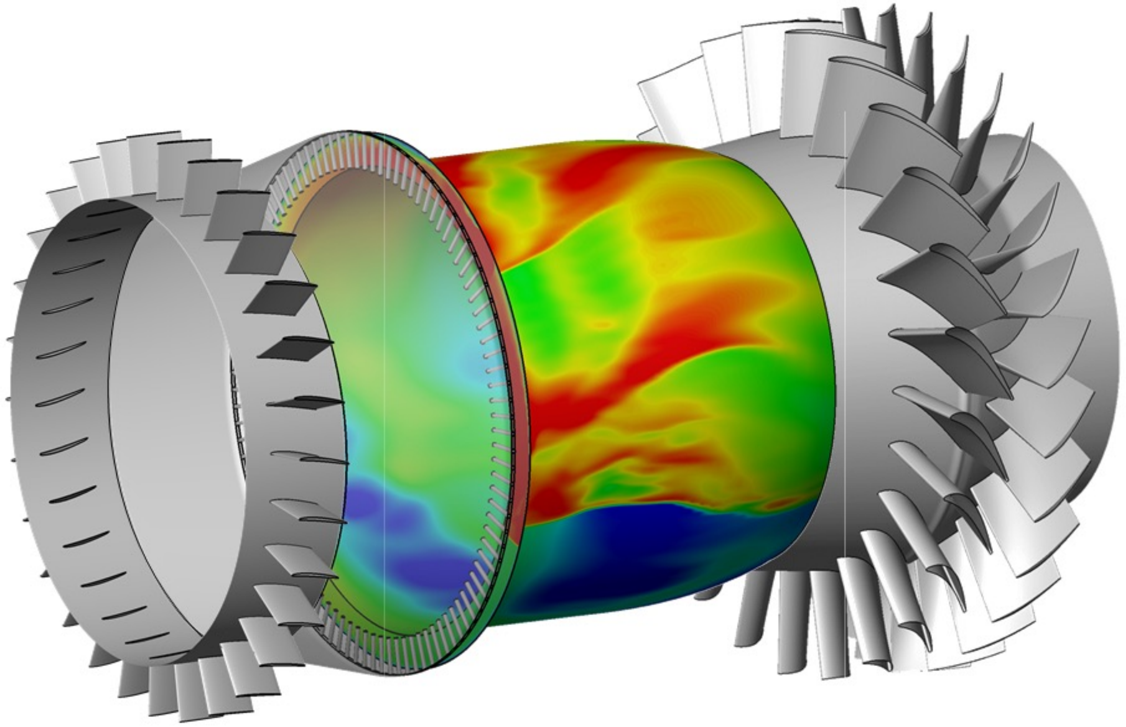
Physics-based Integration of H2-Air Rotating Detonation into Gas Turbine Power Plant (HydrogenGT)



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Overall aim: develop a high-speed diffuser-turbine from rotating detonation combustors (RDC) to industrial turbines

Project objectives

(1) improve turbine overall work extraction with a diffuser-turbine efficiency of 90%
(2) air dilution of 100% or less
(3) minimize heat fluxes
(4) ensure adequate damping to the rotating blades

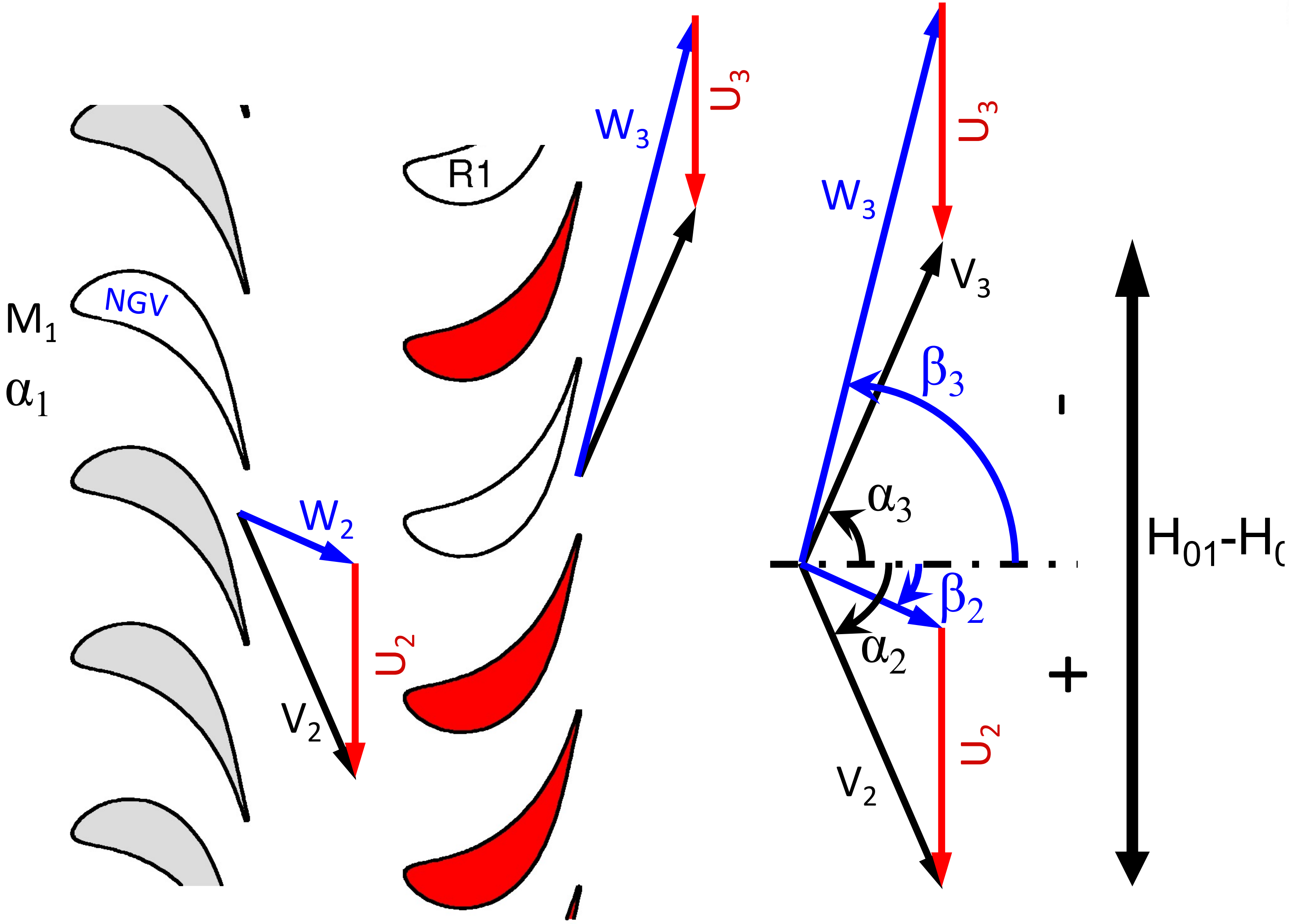
SCOPE OF WORK

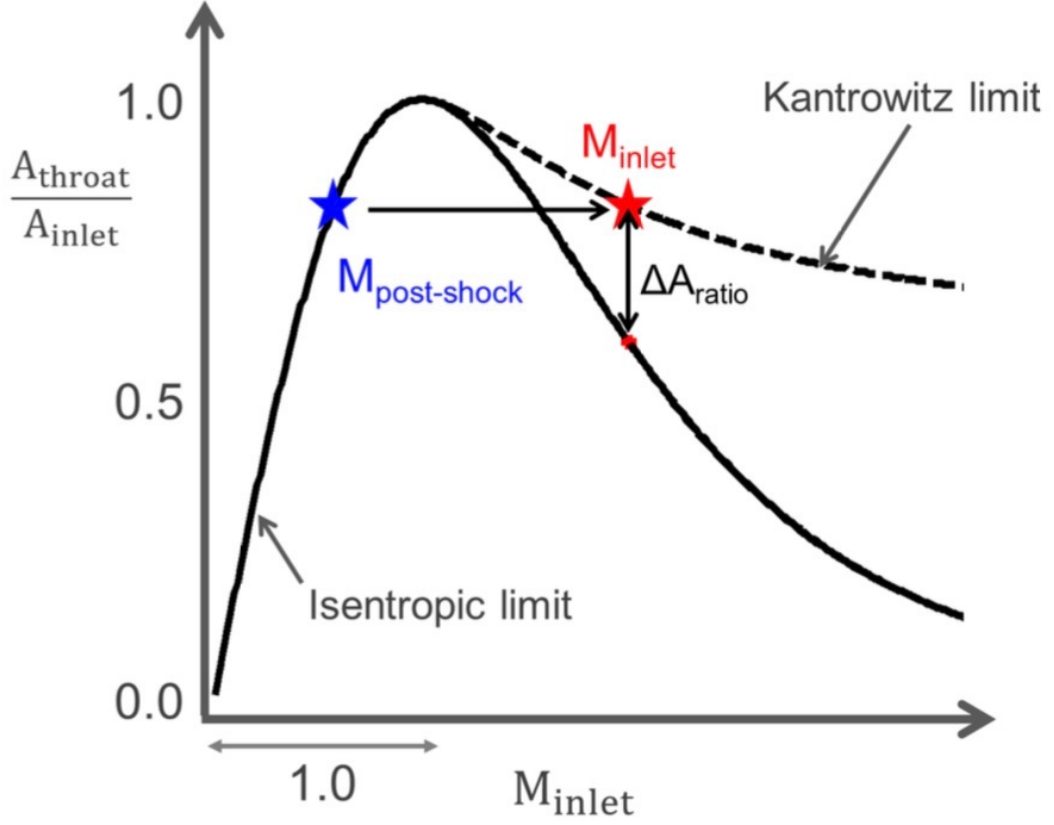
1. Identify the scaling parameters that emulate the RDC outlet conditions to enable TRL2/TRL3 testing
2. Design and assessment of an optimized axisymmetric diffuser under pulsating flow
3. Optimization and assessment of an industrial turbine vane under pulsating differ exit flow

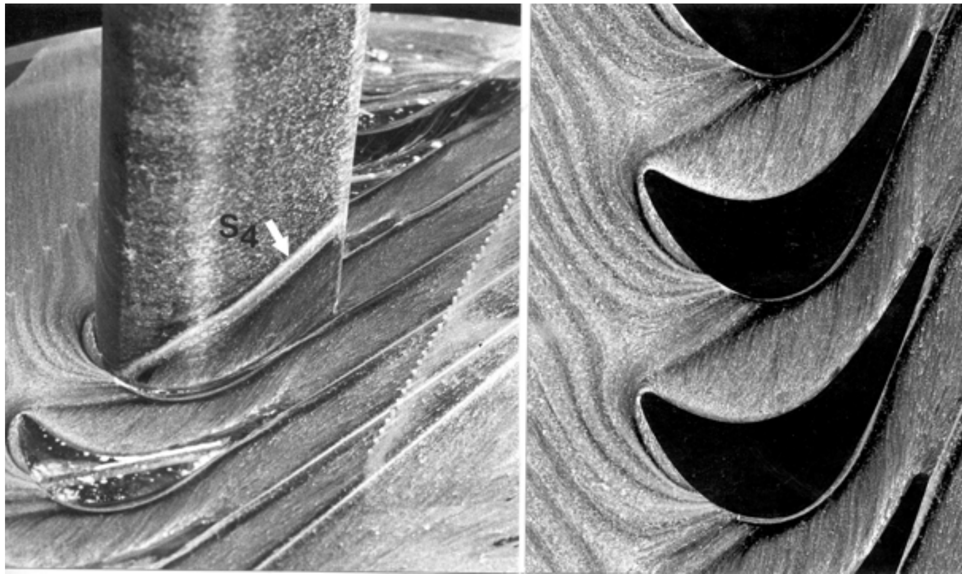
TASKS

1. Project Management and planning (management plan & technology maturation plan)
2. Loss budgeting in a combustor & transition element & turbine 1st stator (nozzle guide vane - NGV)
3. Demonstration RDC-transition-NGV coupling towards work production
4. Scale exp. & comp. studies to F-class and aero-derivative RDE gas turbine integrated system

Turbomachinery II - ME533







Sousa J., Paniagua G., 2015, http://doi.org/10.3390/e17085593

2: Loss budgeting in a combustor + diffuser + NGV (turbine 1st stator)

2.1 Identification of loss mechanisms for the combustor with turbine NGV

Initial work will focus on an existing combustor/diffuser/NGV geometry, followed by tests using optimized geometries (Task 3)
computational model validation, then predict the combustor losses of the larger-scale RDE combustor/diffuser/NGV
computational model will be used to minimize combustor losses in the final RDE-turbine geometry in Task 3

2.2 Quantification of the combustor/ turbine NGV performance metrics

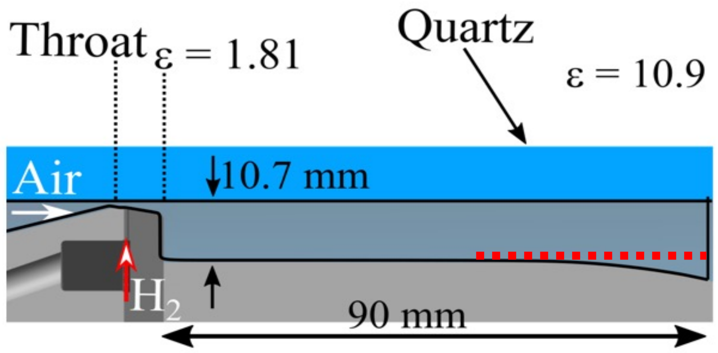
single representative metric of combustor/diffuser/NGV performance will then be utilized
a new scheme leveraging the high-speed particle image velocimetry (PIV)
CARS & PIV data will be used to validate this approach

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

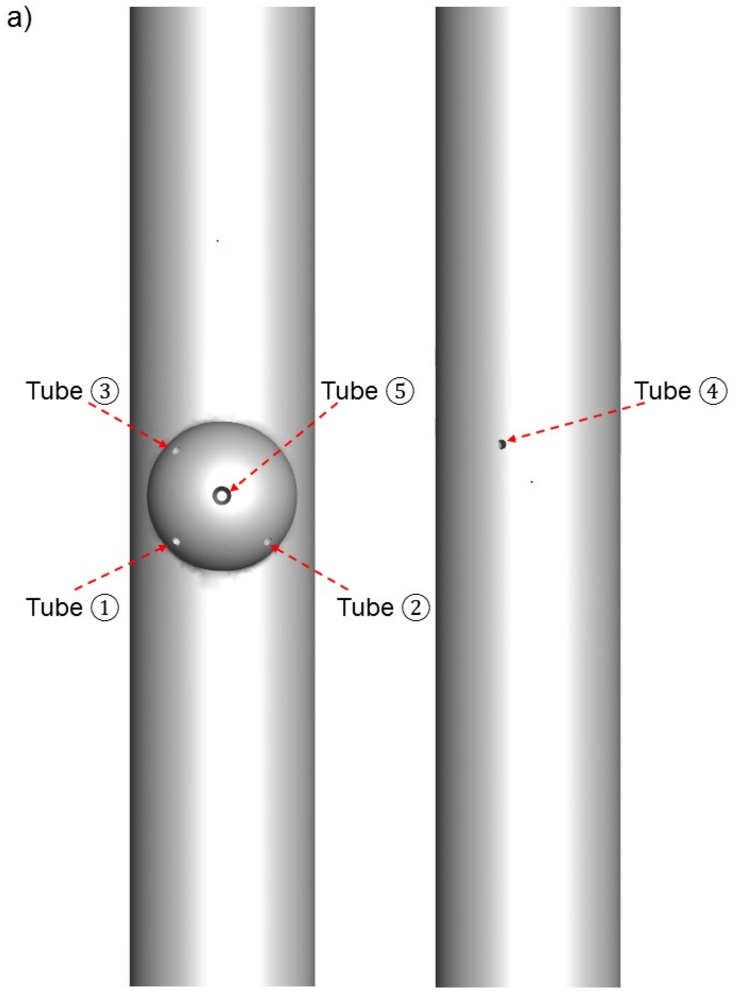
Subtask 2.1 Identification of loss mechanisms for the combustor with NGV (turbine 1st stator)

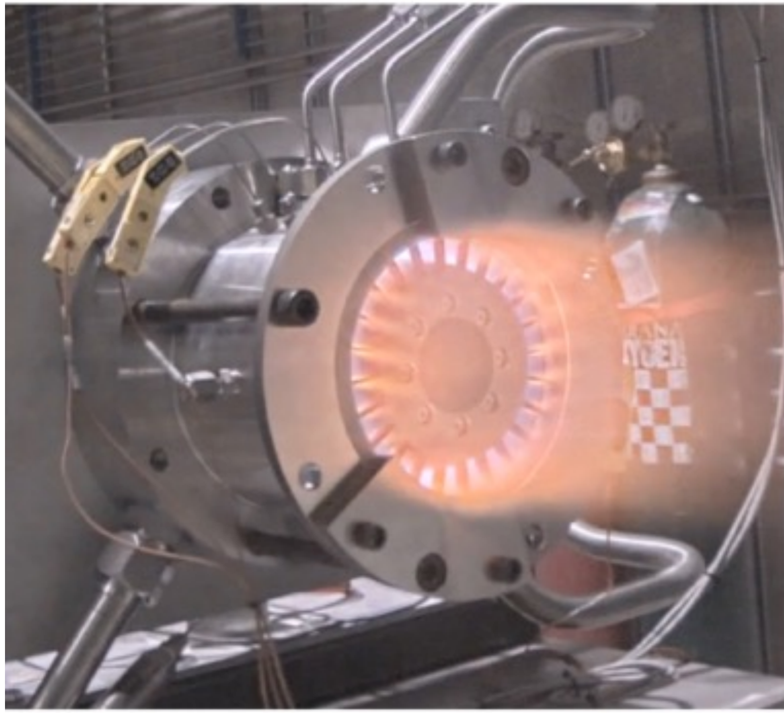
M_1, α_1 , T_{01}, P_{01}



Additional experimental goals:

- Study detonative dynamics with and without downstream element
- characterize detonation performance





Tools

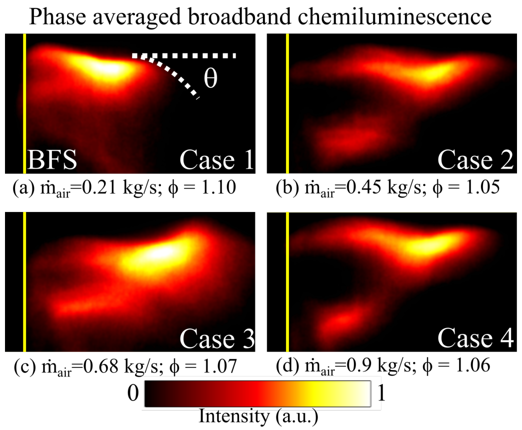
- High frequency directional probe: P_0, angle, Mach
- PIV: yaw, pitch, velocity
- Chemiluminescence: detonation height, shock wave

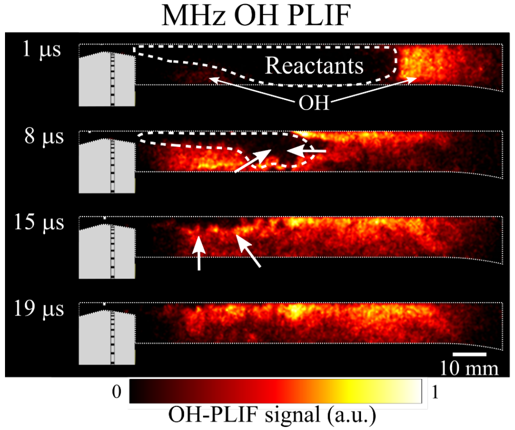
Liu Z., Paniagua G., 2018, https://doi.org/10.1115/1.4037640

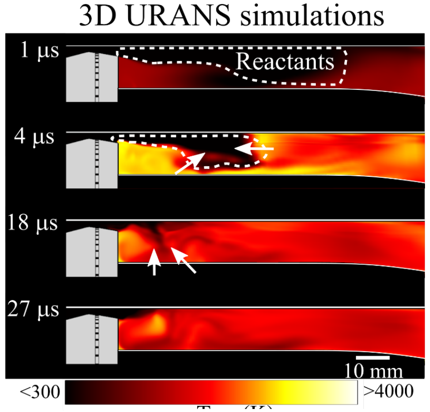
Braun J.,….. Paniagua G., Athmanathan V., Meyer T., 2019, https://doi.org/10.2514/6.2019-3873

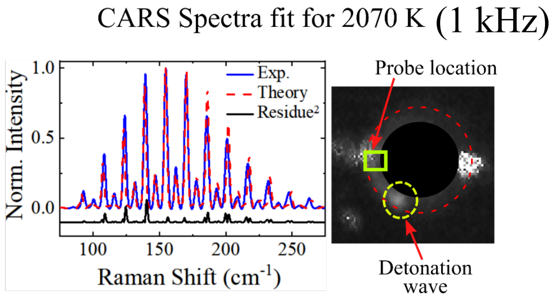
Subtask 2.1 Identification of loss mechanisms for the combustor with NGV (turbine 1st stator)

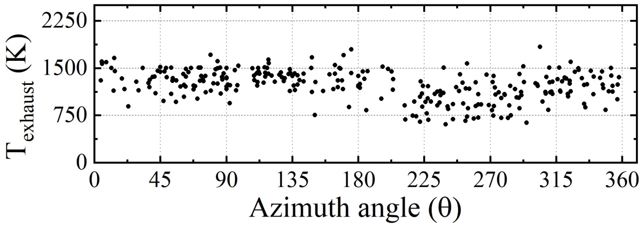
- Use orthogonal simultaneous high-repetition rate MHz OH-PLIF [1] and OH* chemiluminescence [2]
  - Refill length
  - Wave height
  - Trailing shock angles
  - SPOD analysis for non-ideal detonation wave structure.
- Quantitative two-color OH-PLIF to understand spatial distribution of temperature and detonation wave structure.
- Quantify detonation global performance using
  - 1 – 100 kHz rate Coherent anti-Stoke Raman Scattering for thermometry [3]
  - MHz velocity measurement using FLASH velocimetry (OH tracking)
- Compare the metrics to LES/URANS simulation[2]

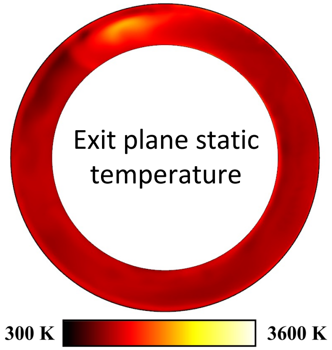




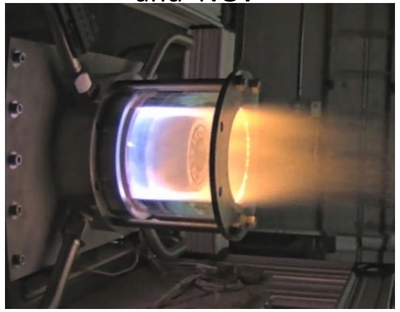




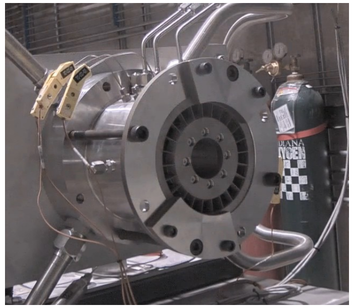




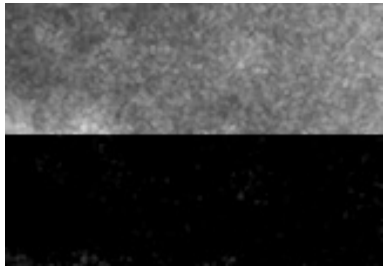
Without transition element and NGV



Transition element + NGV



MHz rate velocity measurement



[1] Hsu, P., Slipchenko, et. al (2020). Megahertz-rate OH planar laser-induced fluorescence imaging in a rotating detonation combustor. Optics Letters, 45(20), 5776–5779.

[2]Athmanathan, V., Braun, J., Ayers, Z., et. Al (2020). Detonation structure evolution in an optically-accessible non-premixed H2-Air RDC using MHz rate imaging. In AIAA SciTech 2020 Forum

[3]Athmanathan, V., Rahman, K., Lauriola, D., Braun, J., Paniagua, G., Slipchenko, M., Roy, S., & Meyer, T. (2021). Femtosecond/picosecond rotational coherent anti-Stokes Raman scattering thermometry in the exhaust of a rotating detonation combustor. Combust. Flame, 231, 111504.

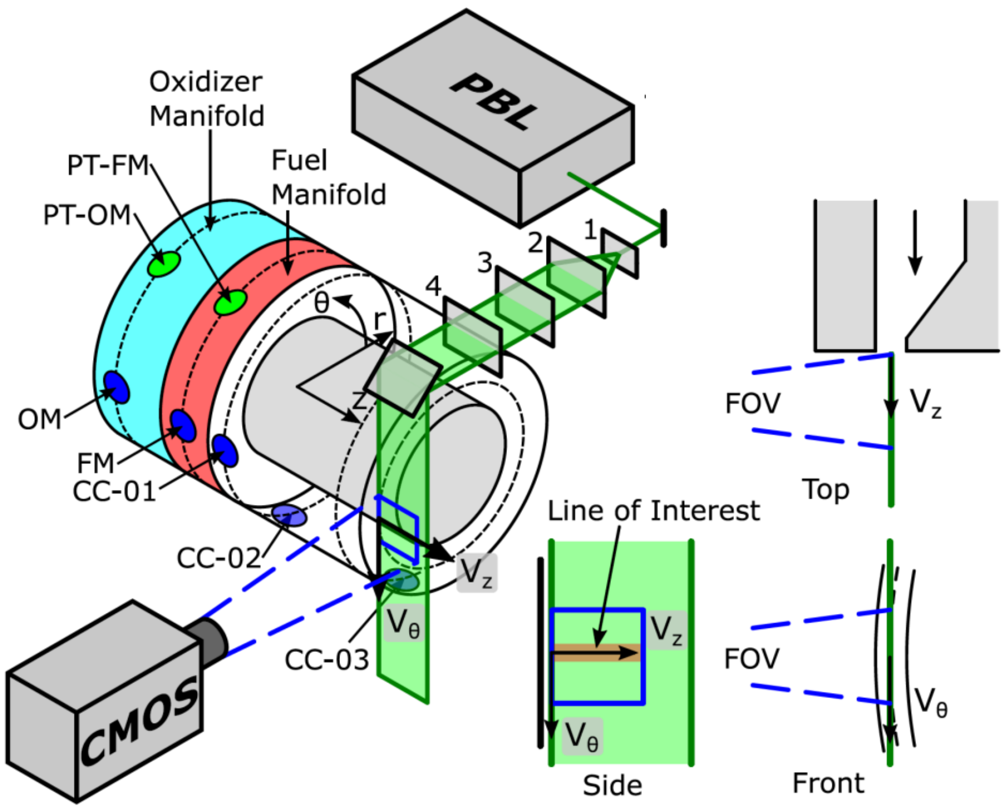
Subtask 2.2 Quantification of the combustor & NGV (turbine 1st stator) performance metrics

- Compute steady thermodynamic state from which work is extracted
- Analogous to EAP, but eliminates *M = 1* assumption at exit
- Assumptions of thermodynamic state at exit remain
  - Averaged values for CJ detonation and CP combustion from NASA CEA used in current approach
  - ***Combine current model and proposed measurements in Tasks 2.1-2.3 for accurate performance characterization of THOR***

$$p_0 = \frac{R_u T_0 \dot{m}}{A_e MW}\left(\int_0^1\int_0^1 V_z\left(\frac{T_e}{T_0}\right)^{\frac{1}{\gamma-1}}\partial\vartheta\partial\tau\right)^{-1}$$

$$F = p_0 A_e \int_0^1\int_0^1\left(\frac{MW}{R_u T_0}V_z^2\left(\frac{T_e}{T_0}\right)^{\frac{1}{\gamma-1}} + \left(\frac{T_e}{T_0}\right)^{\frac{\gamma}{\gamma-1}}\right)\partial\vartheta\partial\tau - p_\infty A_e$$

$$\frac{T_e}{T_0} = 1 - \frac{MW\cdot(\gamma-1)}{\gamma R_u T_0}\cdot\frac{V_z^2+V_\theta^2}{2}$$

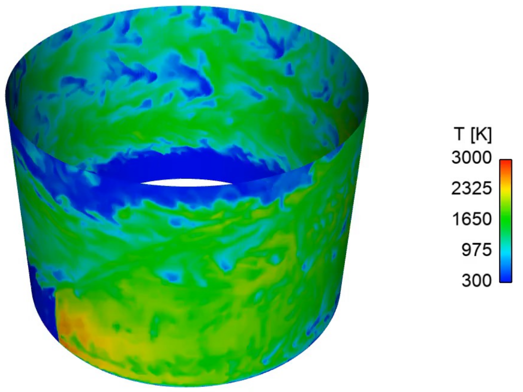


	V_{Wave}/V_{CJ}	p_3 [MPa]	EAP [MPa]	p_0 [MPa]	T_0 [K]	Swirl Number
Single Wave	58%	2.33	0.81 ±0.012	0.86 ±0.013	1900 ±65	0.072 ±0.009
Slapping Mode	59%	2.34	0.84 ±0.012	0.91 ±0.011	2050 ±55	-0.028 ±0.001

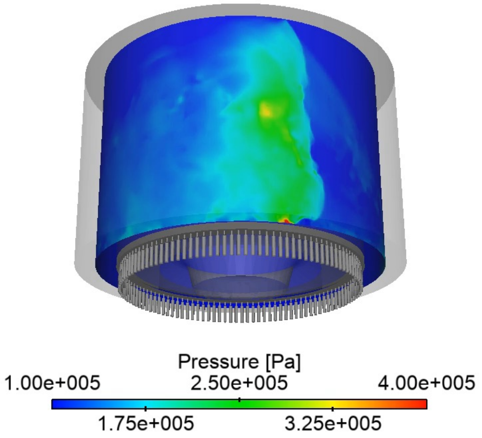
Walters, et al. AIAA JPP 2020, https://doi.org/10.2514/1.B38087
Walters, et al. Combustion and Flame 2021, https://doi.org/10.1016/j.combustflame.2021.111549

Subtask 2.3 Uncertainty quantification of loss mechanisms

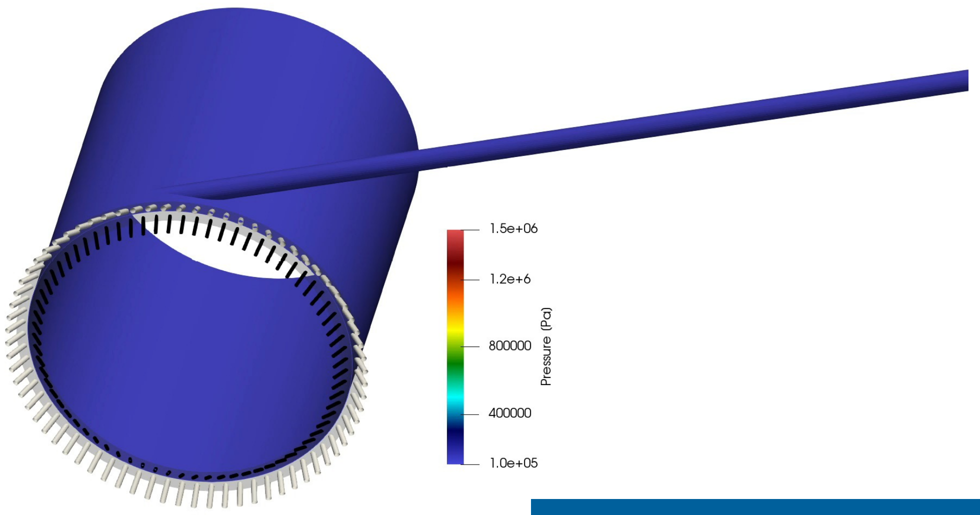
- Argonne has developed a **predictive** and **computationally efficient** high-fidelity large-eddy simulation (LES) modeling approach to capture supersonic combustion in **full-scale RDCs**
- The LES modeling framework uses **adaptive mesh refinement (AMR)** to achieve good trade-off between computational cost and accuracy
- The CFD approach has been demonstrated for full-scale air-breathing and rocket RDCs, and a variety of fuels (hydrogen, ethylene, methane)
- Argonne's CFD model and HPC resources will be leveraged to perform high-fidelity LES of the Purdue H_2/air optical RDC under varying operating conditions
- Model validation will be performed against experimental data from Purdue (wave speed, wave number, fill height, axial pressure, etc.)
- Argonne's computational combustion diagnostic tool based on **chemical explosive mode analysis (CEMA)** will be utilized to **quantify non-ideal losses in the RDC**, in conjunction with experimental diagnostics



Hydrogen-Air RDE
AIAA SciTech 2020-2161



Ethylene-Air RDE
AIAA P&E 2020-3876



Methane-Oxygen Rocket RDE
AIAA P&E 2021-3642

3: Demonstration RDC - transition element - NGV coupling towards work production

3.1 Overall transition element optimization

definition of the inlet conditions

Multi-objective optimization using genetic algorithms of the 16 param that defines the geometry

full unsteady simulations with 3 different combustor wave modes will be used to assess the diffuser performance

3.2 Computational multi-objective optimization of the NGV for integration with the rotor

multi-objective differential evolutionary optimization strategy

objective 1 - Abate tonal noise & harmful structural vibrations

objective 2– Increase efficiency

optimization run first on the vane alone, then performance assessed with a full turbine stage unsteady simulation

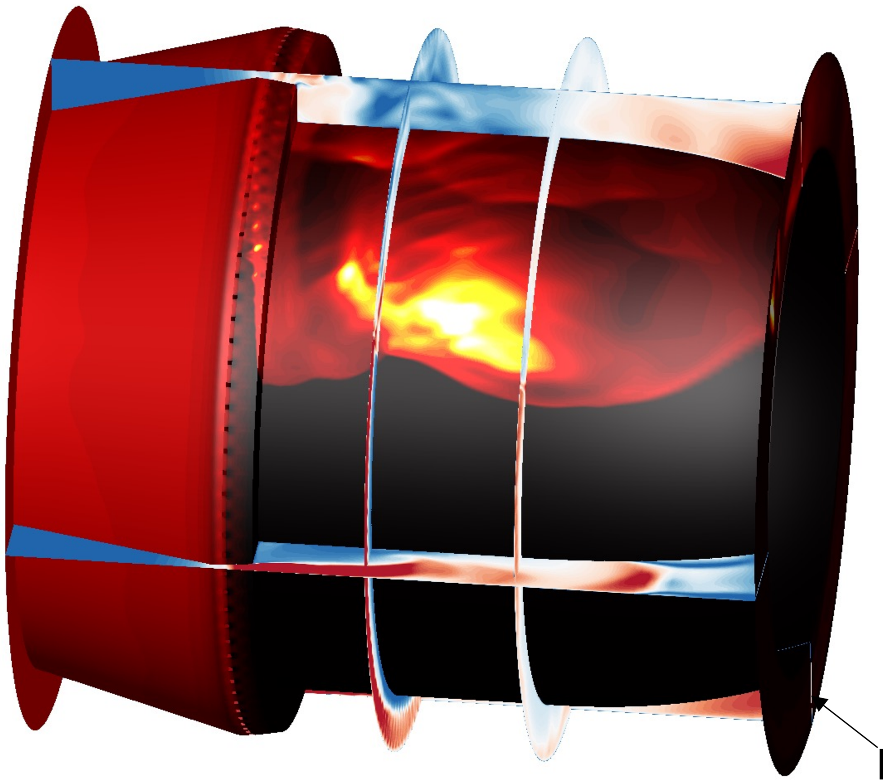
3.3 Experimental demonstration of the transition element + NGV @warm conditions (500K)

aerothermal testing in the Big Rig of Aerothermal Stationary Turbine Analysis

3.4 Experimental demonstration of the optimal combustor + transition + NGV @hot conditions (1,700K)

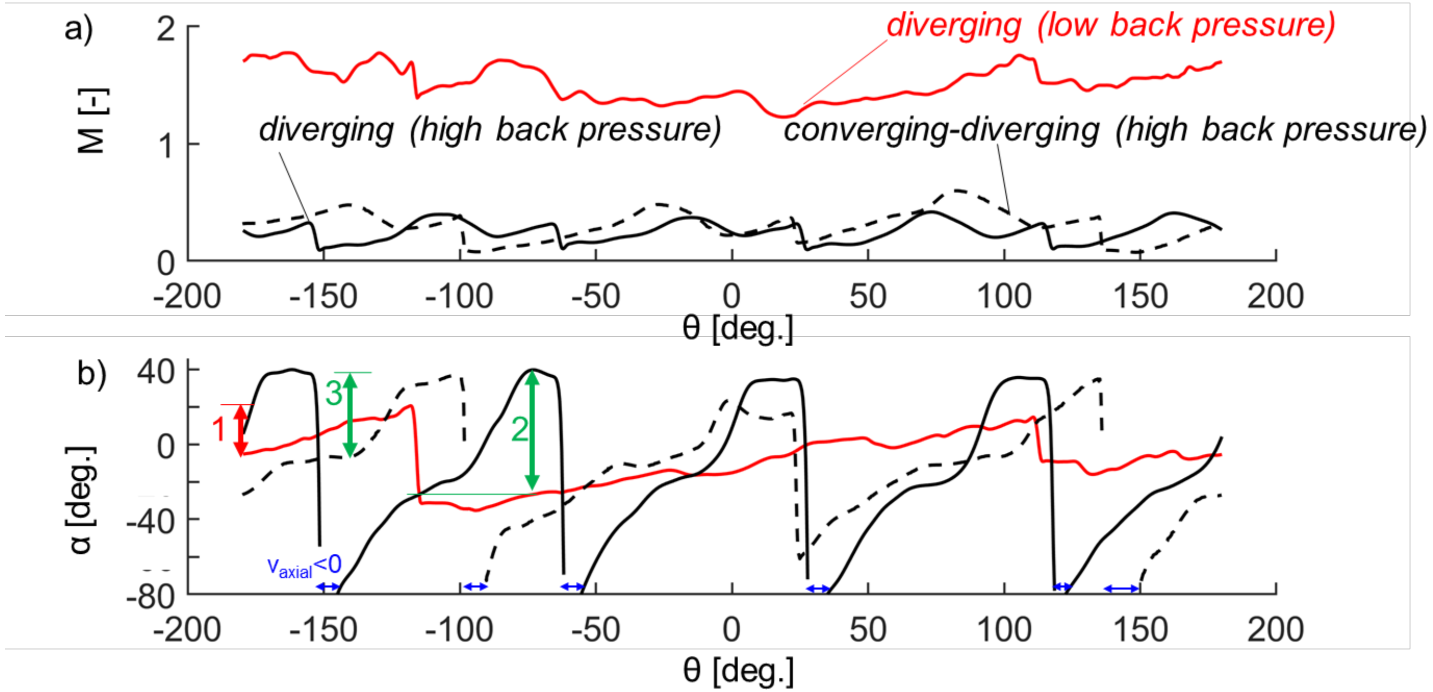
aerothermal testing in RDC+M250 (RR engine)

Subtask 3.1 Overall transition element optimization



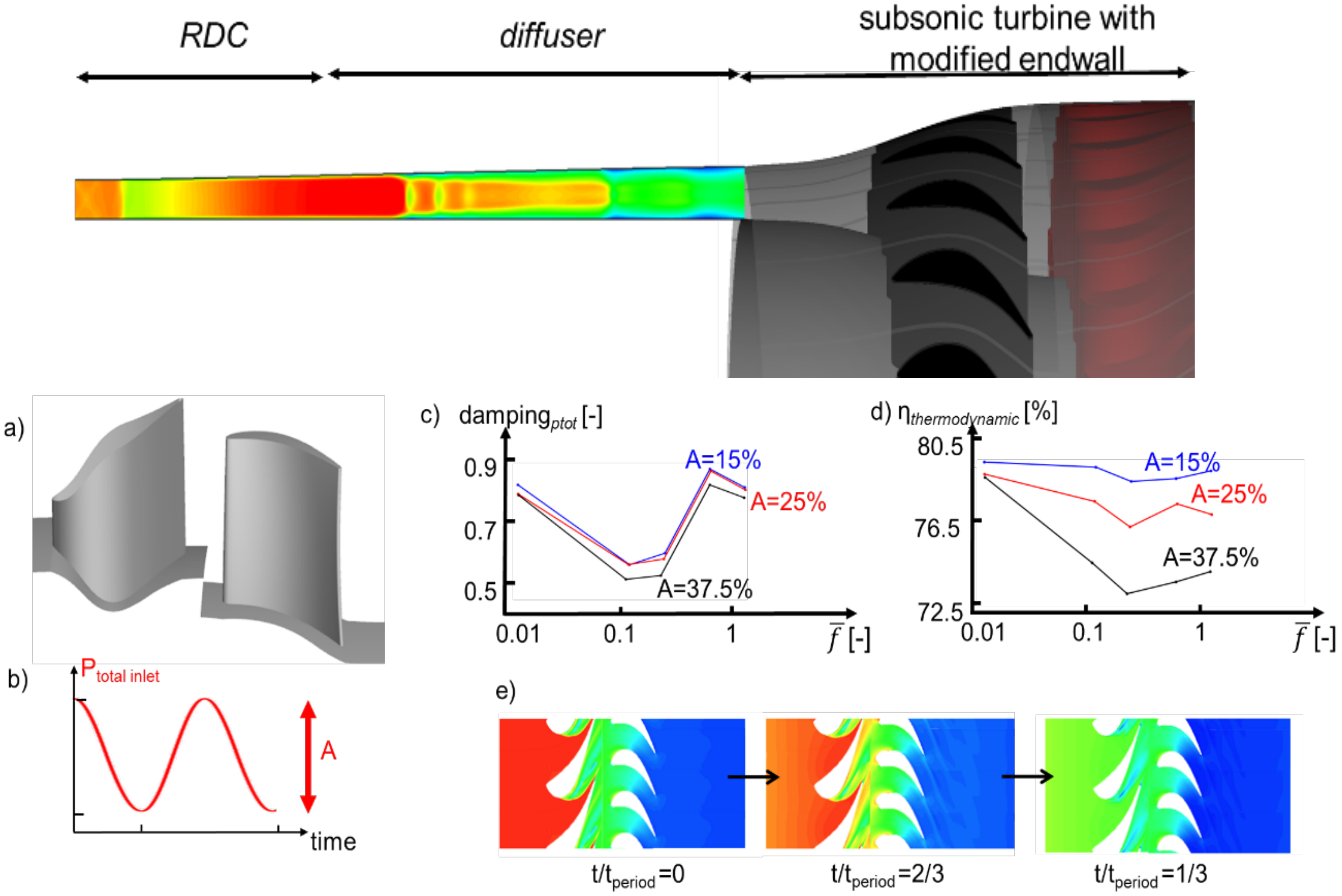
inlet:
$P_{total} T_{total}$

$P_{static,\ outlet}$=1.56 bar



Braun J., Paniagua G., Ferguson D., 2021, "RDC Downstream transition …". Proceedings of the Active Flow Control Conference, Berlin

Subtask 3.2 Computational multi-objective optimization of the NGV



Liu Z, Braun J., Paniagua G., 2020, https://doi.org/10.1515/tjeng-2020-0016

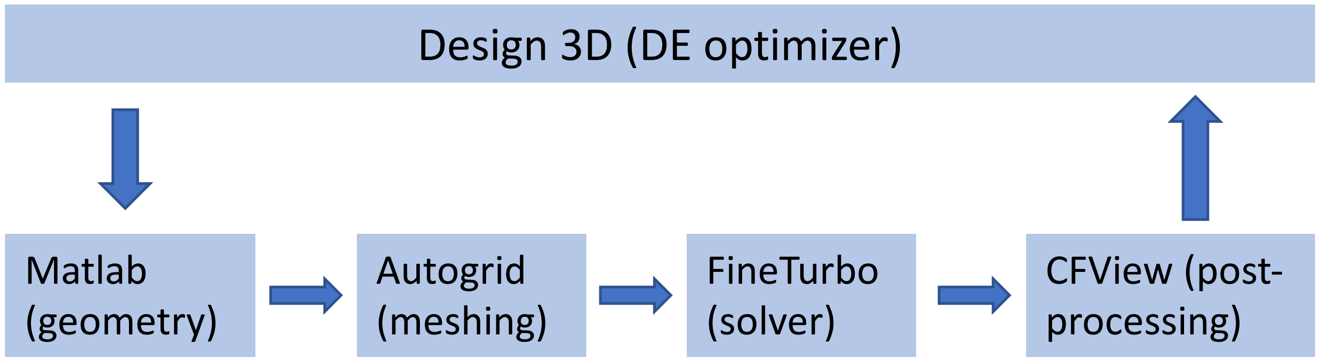
Subtask 3.2 Computational multi-objective optimization of the turbine 1st stator (NGV)

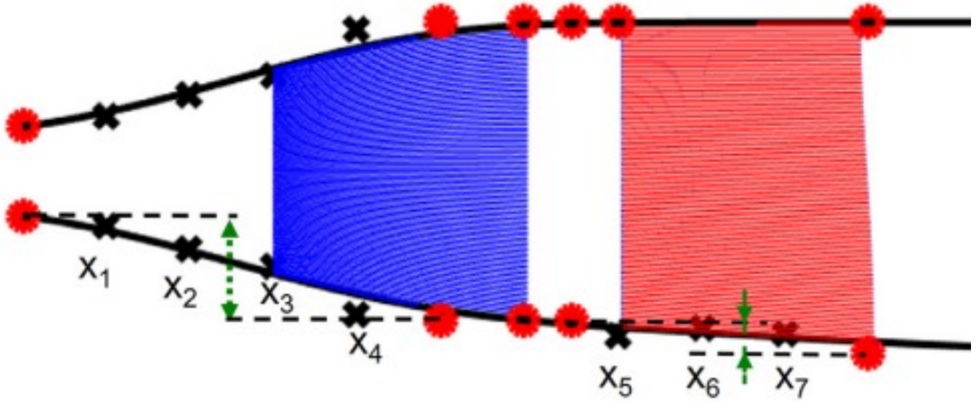
- Software: Design 3D

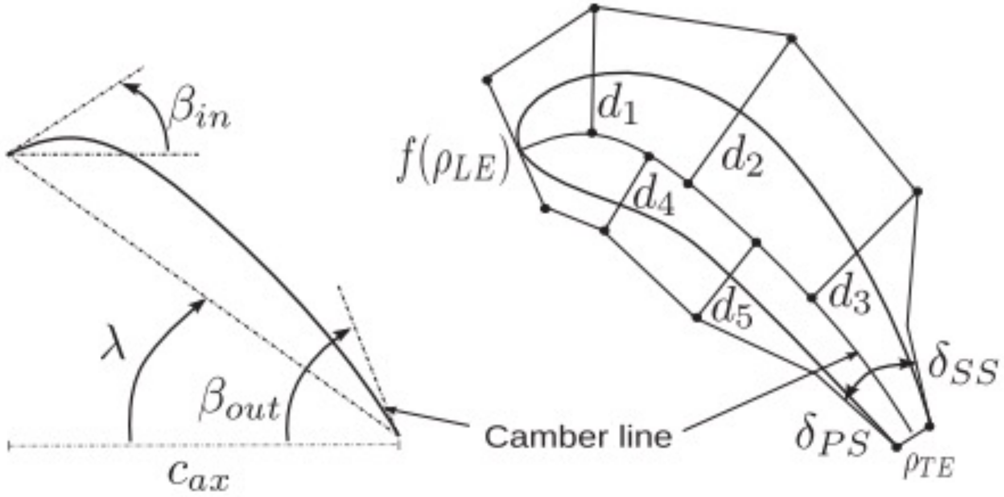
- Differential Evolution Optimizer based on Genetic Algorithms

- Objectives
  - Efficiency
  - Tonal noise
  - Structural vibrations

- Define number of design parameters

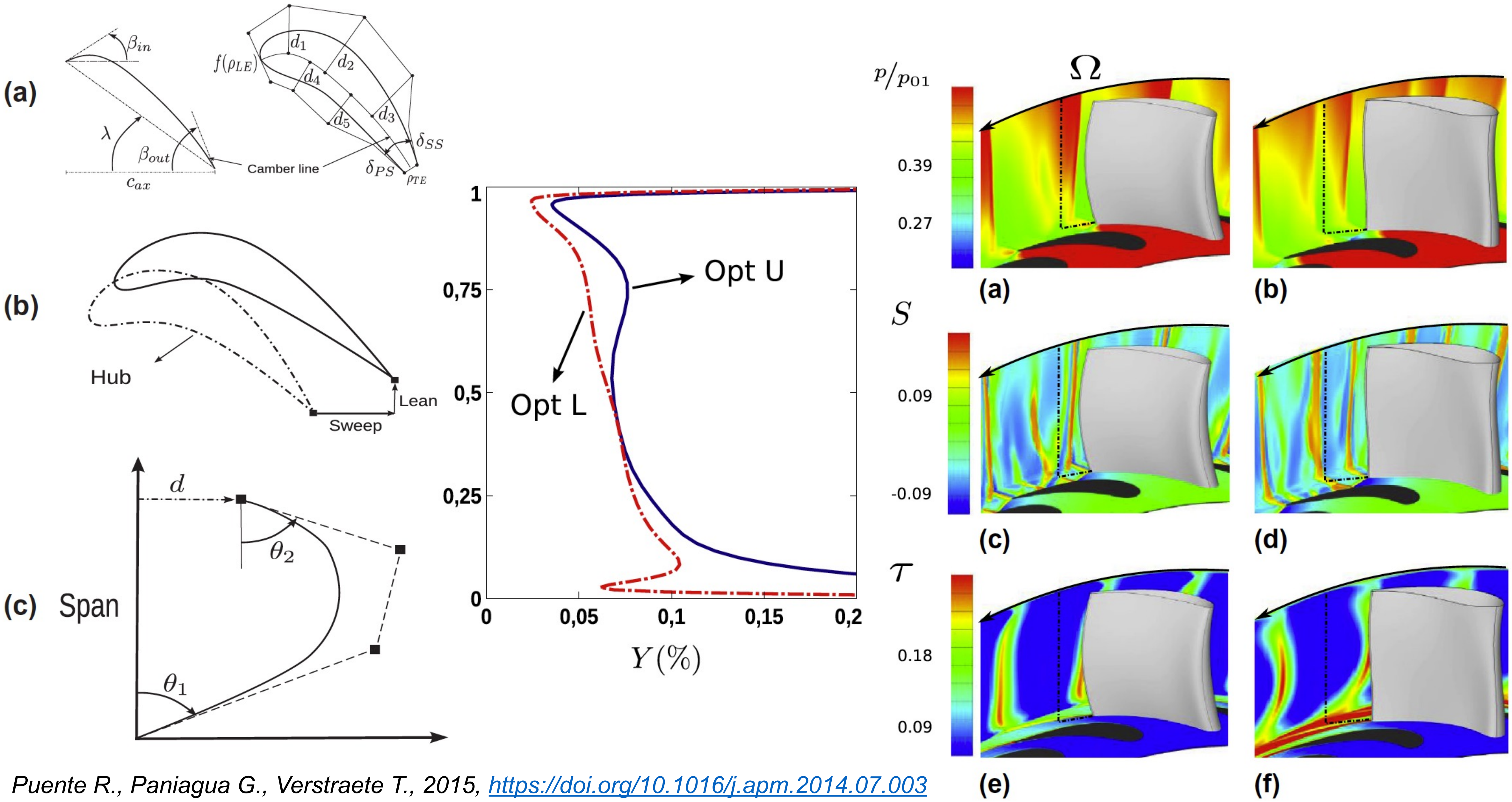






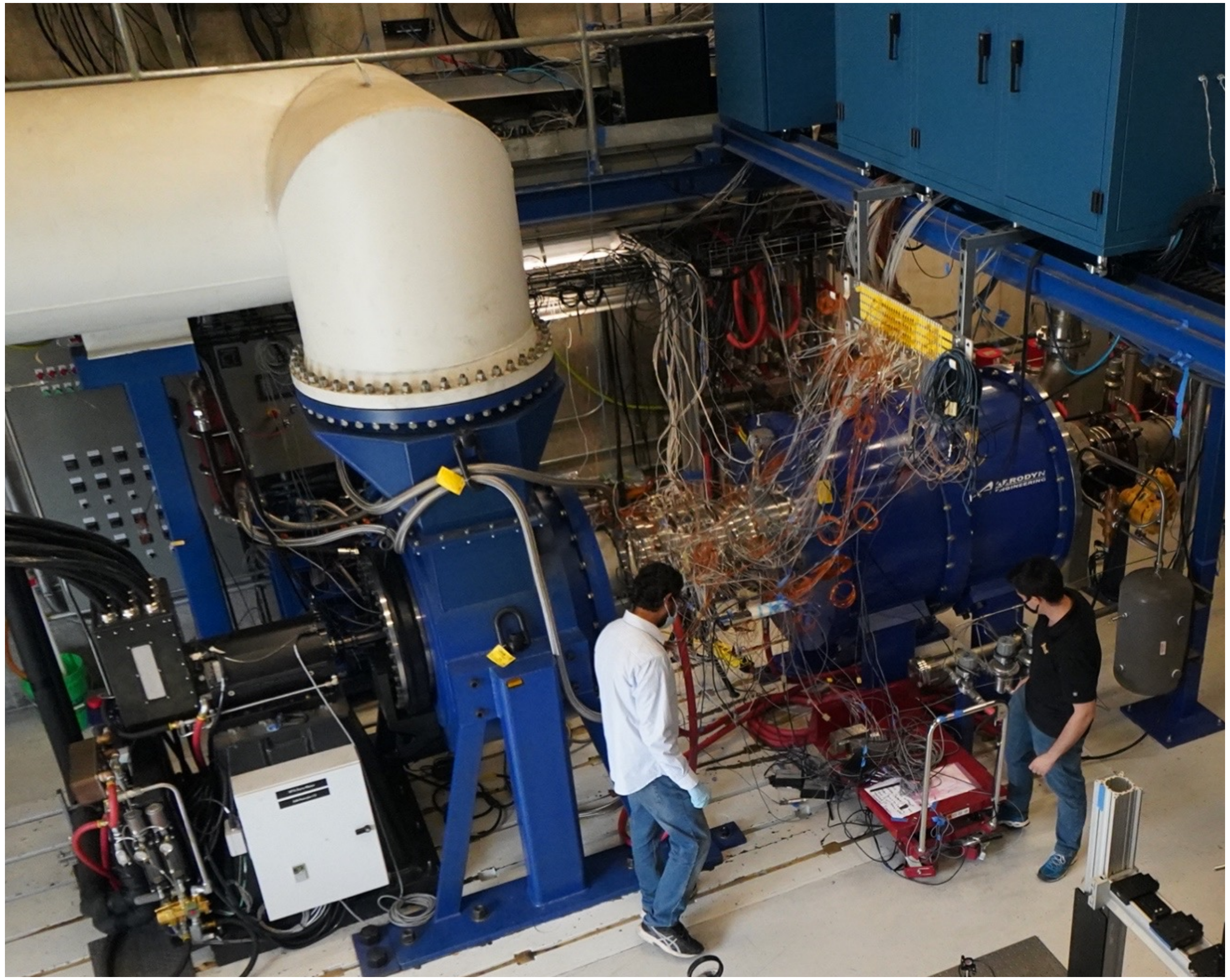
Liu Z, Braun J., Paniagua G., 2020, https://doi.org/10.1016/j.ijmecsci.2020.105918

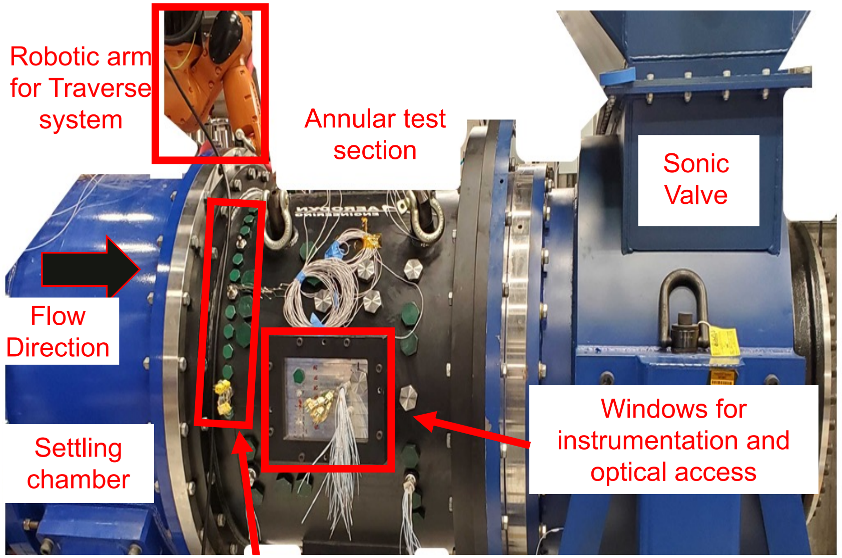
Subtask 3.2 Computational multi-objective optimization of the turbine 1st stator (NGV)

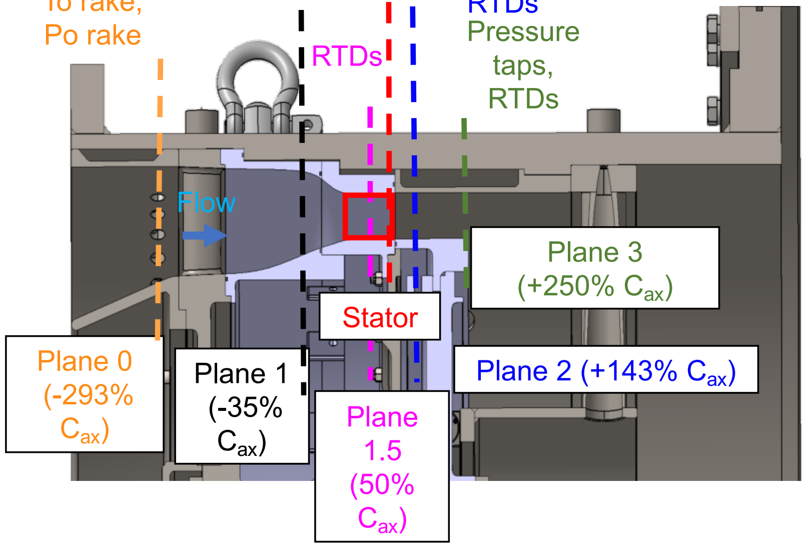


Puente R., Paniagua G., Verstraete T., 2015, https://doi.org/10.1016/j.apm.2014.07.003

Subtask 3.3 Experimental demonstration of the transition element + NGV @warm conditions (700K)







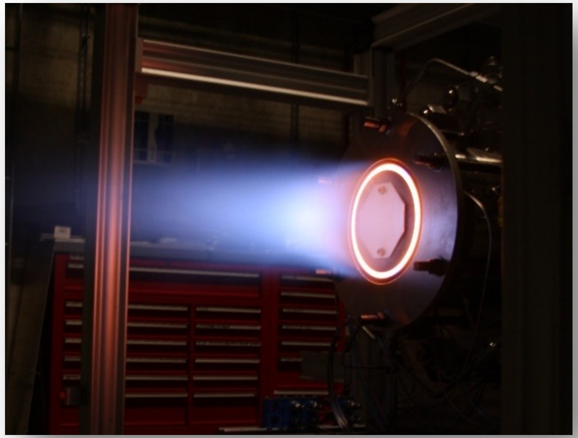
Paniagua G., et al., 2019, http://dx.doi.org/10.1115/1.4040683

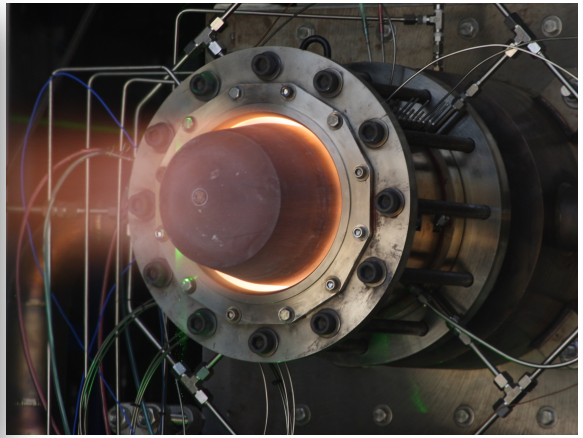
Bhatnagar L., Paniagua G., Gonzalez-Cuadrado D., Aye-Addo P.A.N., Castillo A., Lozano F., Bloxham M., 2021, https://doi.org/10.1115/1.4052385

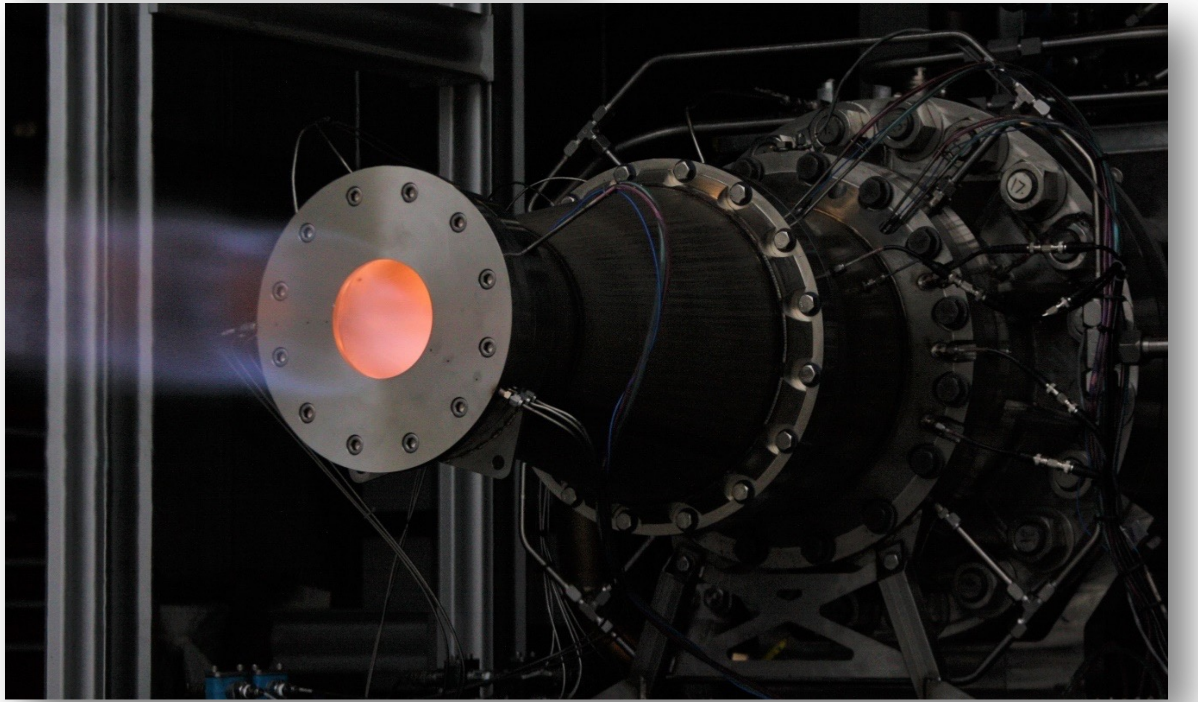
Subtask 3.4 Experimental demonstration of the optimal combustor + transition + NGV @hot conditions (1,700K)

- Developed for RDE operation and characterization at application relevant scale and operating conditions
- 600+ hot-fire tests between three test articles
- ***Purdue UTSR combustor to be adapted for H2-Air***

Air Flow Rate	≤ 11 kg/s (25 lbm/s)
Air Temperature	≤1050 K
Air Pressure	5.8 MPa (800 psia)
Reactants	NG, H2, CH_4, gO_2 (ox- enrichment)
Cooling/ Purge	High-pressure water (10 MPa) and gN_2
(Axial) Thrust	44.5 kN (10,000 lbf)
Diagnostics	CTAP, Ps (up to 2 MHz), PIV, Chem







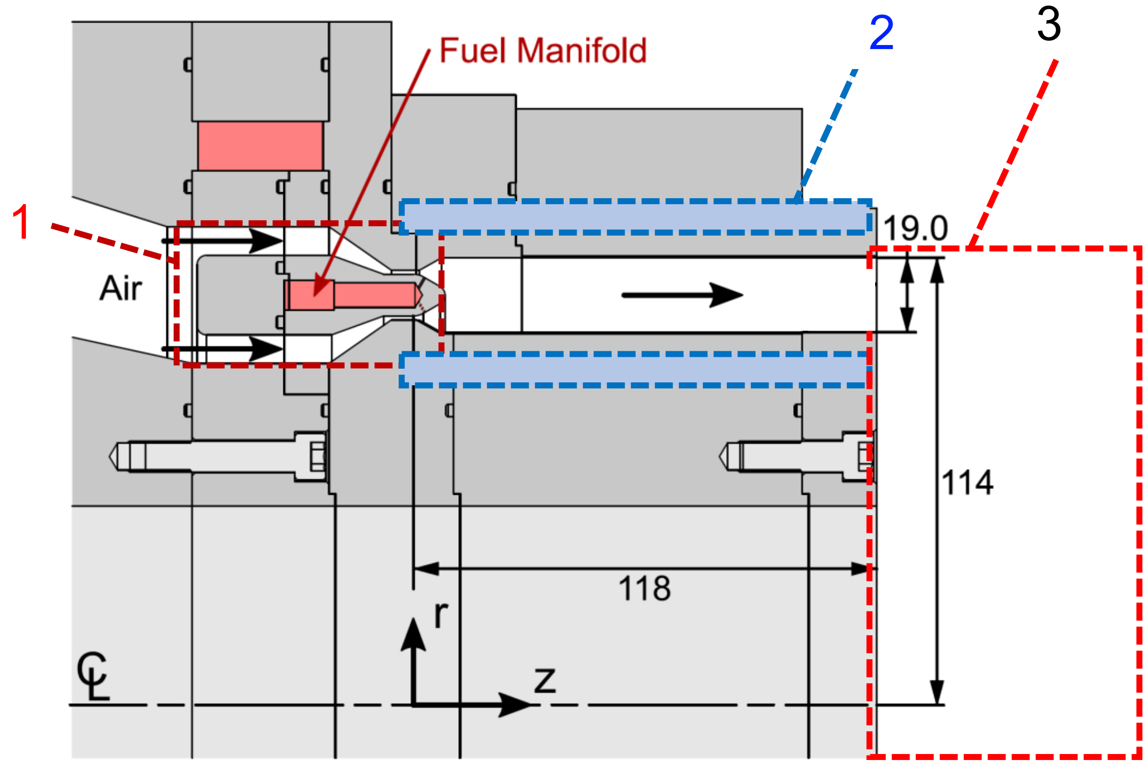
Walters, et al. AIAA JPP 2020, *https://doi.org/10.2514/1.B37735*
Journell, et al. AIAA JPP 2019, *https://doi.org/10.2514/1.B37740*

Subtask 3.4 Experimental demonstration of the optimal combustor + transition + NGV @hot conditions (1,700K)

- Purdue UTSR combustor to be adapted for H2-Air use for the current project
  1. New injector for H2
  2. Cooling strategies
  3. Transition and Turbine Nozzle guide vane

- The APEX platform includes hot gas valves (1500 F at 800 psia) for supplying air to and around the experiment

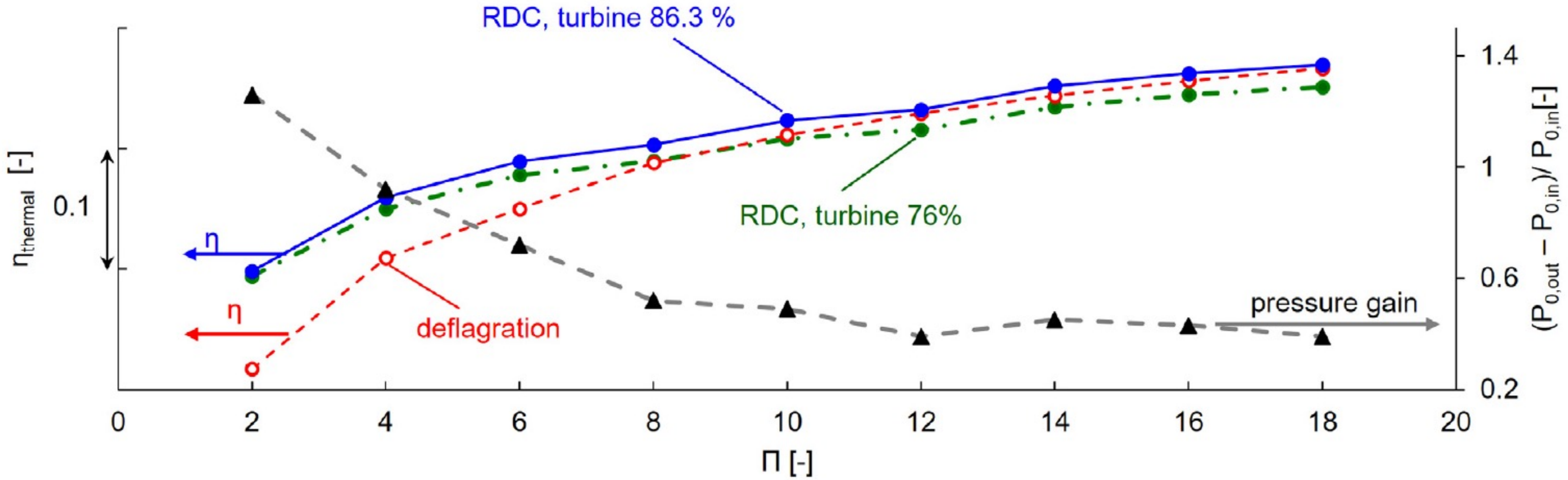
- Prior to the test we will flow warm flows to set the right M250 engine clearances



Proposed APEX Modifications for Task 3.4

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

4.1 Cycle analysis to predict the performance 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

Sousa J., Braun J., Paniagua G., 2017, https://doi.org/10.1016/j.apm.2017.07.019
Liu Z, Braun J., Paniagua G., 2020, https://doi.org/10.1016/j.ijmecsci.2020.105918

PETAL
Zucrow Labs

Calibration and testing at building ZL5
38 ft × 48 ft

ZL3 Offices CS, JB, GP

Turbine testing test cell (nr1)
30 ft × 35 ft

RDC is located in test cell (nr2)

RDC located in test cell (nr4)