PhD Program 2019-2020

Fluid meeting 14th October 2019

Performance and Stability Analysis of a Highly-Loaded Low-Pressure Compressor Under Distorted Inflow Conditions

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LIÈGE université

von KARMAN INSTITUTE FOR FLUID DYNAMICS

Context

Reasons:

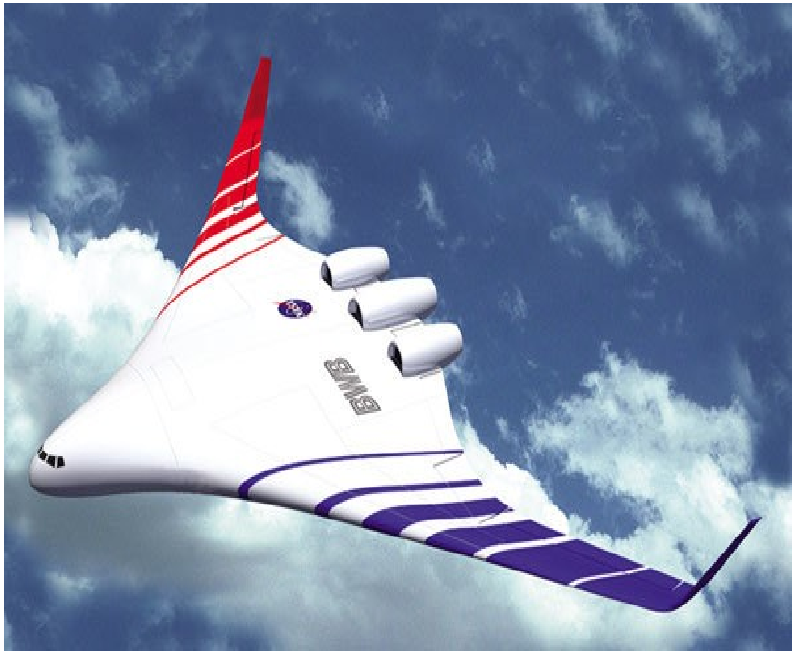
- Stringent environmental legislation
- Growth of the aviation sector

Community objective:

- Reduction of CO2 and NOx emissions

Geared high-bypass turbofans

Boundary Layer Ingestion (BLI)



Credit: https://www.flickr.com/photos/ramis-photos/44852983645

Leiffson L.T. *"Multidisciplinary Design Optimization of Low-Noise Transport Aircraft"* PhD thesis, Virginia Polytechnic and State University, 2005

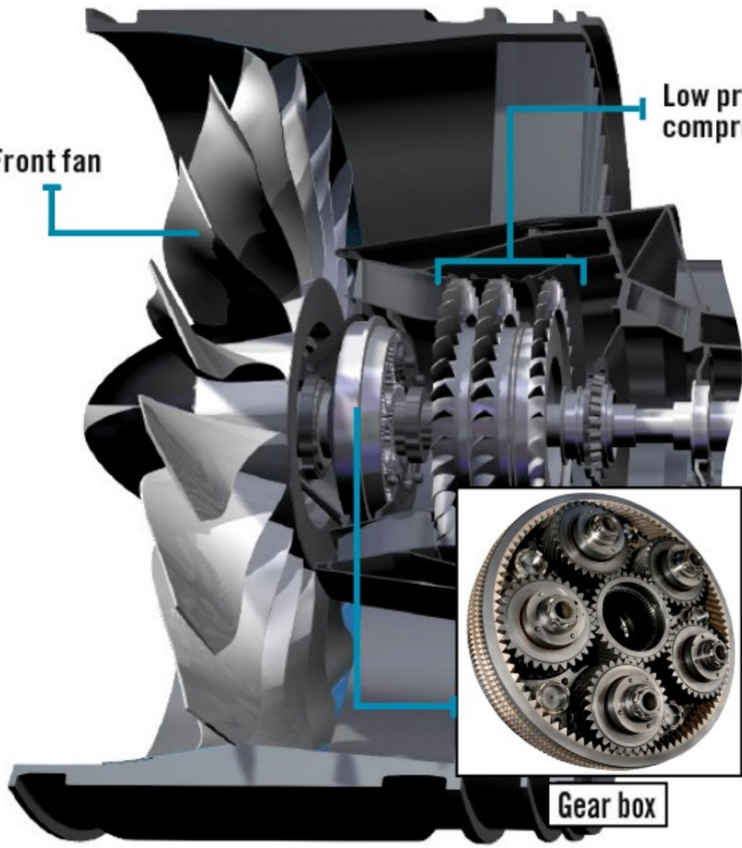
Geared high-bypass turbofans

✓ Improvement of the efficiency

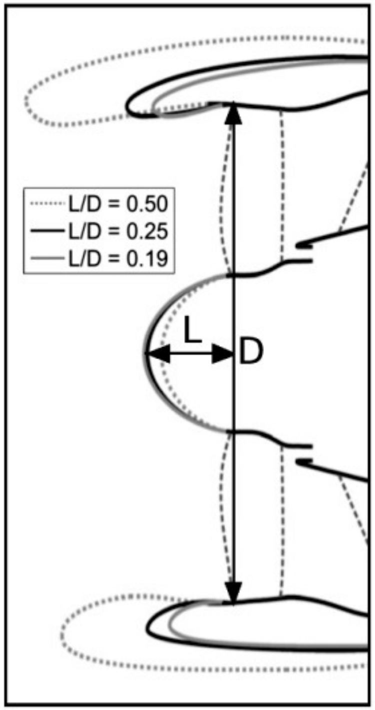
✗ Increase of engine weight

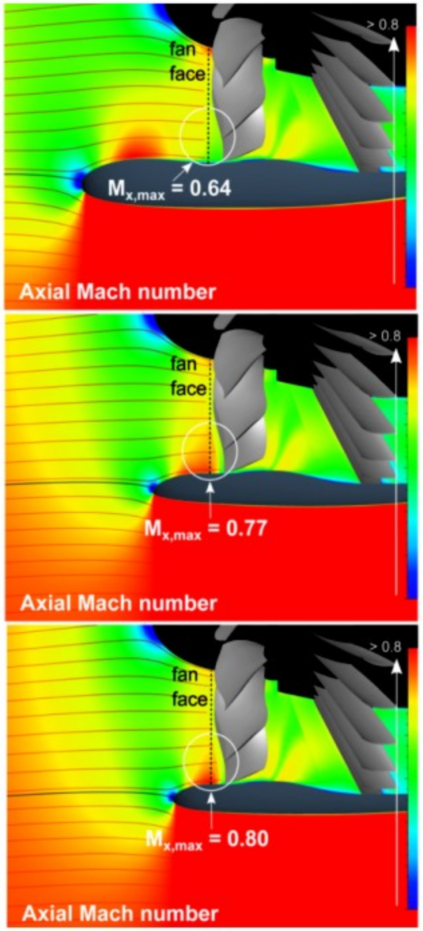
✓ Use of shorter nacelles

✗ **Generation of inlet distortions!**



Short-nacelles



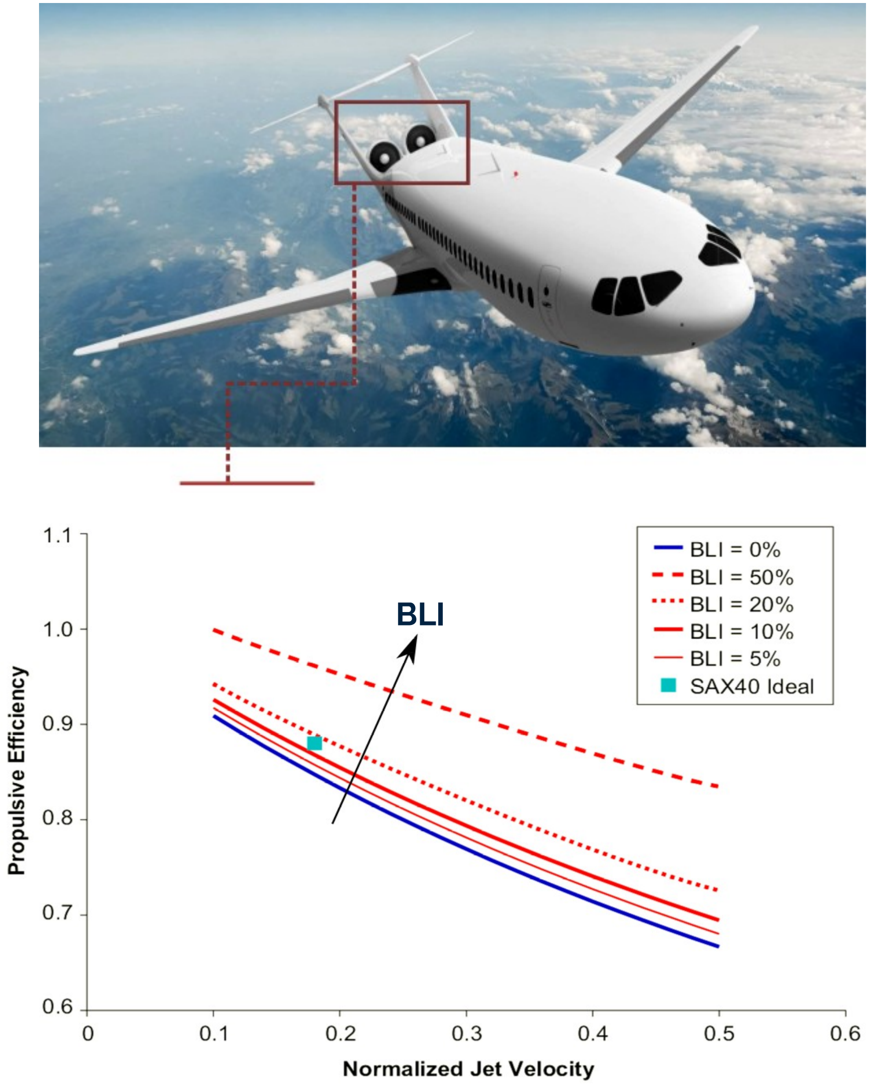


Shorter

Credit: https://aerospaceamerica.aiaa.org/features/high-gear/

Peters A. et al. *"Ultrashort Nacelles for Low Fan Pressure Ratio Propulsors"* Journal of Turbomachinery 2014

Boundary layer ingestion



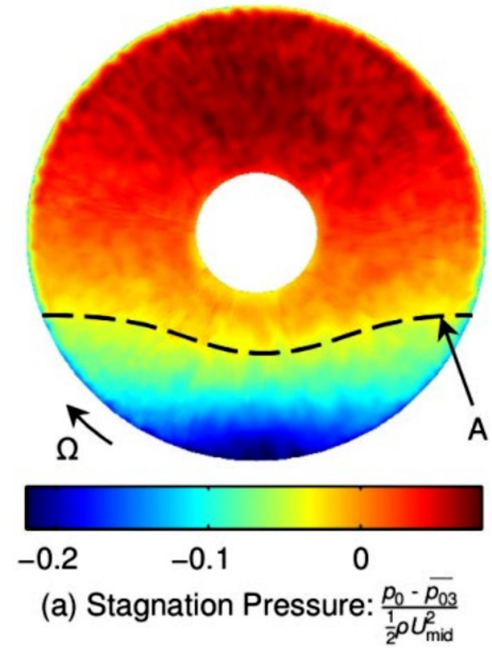
✓ Improvement of the propulsive efficiency:

$$\eta_p = \frac{2}{1 + \frac{v_9}{v_0}}$$

Exit velocity (v_9)

Inlet velocity (v_0)

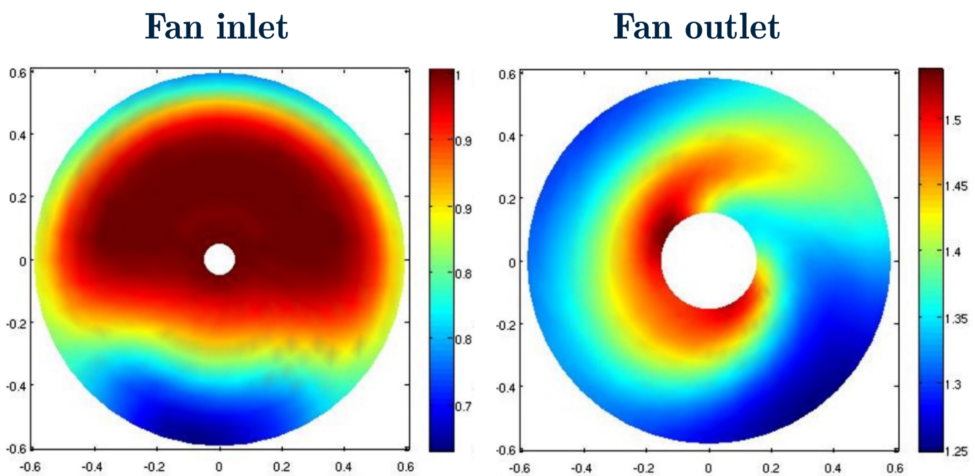
✗ **Generation of inlet distortions!**



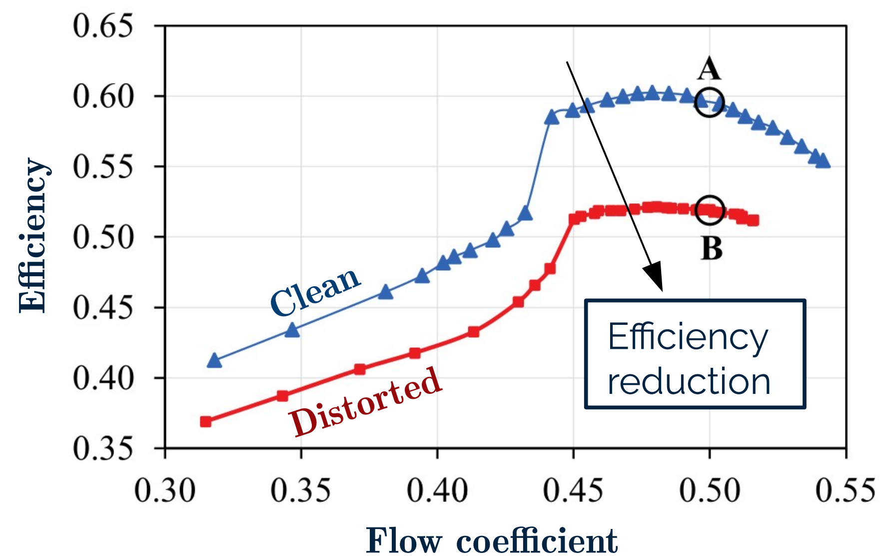
Credit: https://www.paramountbusinessjets.com/blog/nasa-double-bubble-d8-aircraft/
Plas A.P. et al. *"Performance of a Boundary Layer Ingesting (BLI) Propulsion System"* 45 th AIAA Aerospace Sciences Meeting and Exhibit 2007
Gunn et al. *"Aerodynamics of Boundary Layer Ingesting Fans"* ASME Turbo Expo 2014

The fan

Given its crucial role on the overall propulsive efficiency, the fan has been in the focus of research on distortion effects



Distortion evolution in the Fan



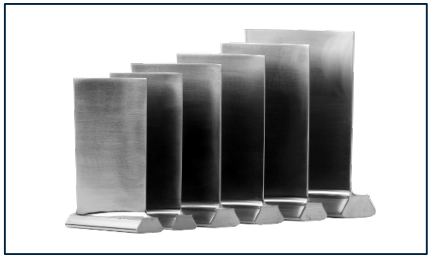
The distortion reduces the efficiency of the fan!

Plas A.P. et al. *"Performance of a Boundary Layer Ingesting (BLI) Propulsion System"* 45 th AIAA Aerospace Sciences Meeting and Exhibit 2007
Gunn E.J. et al. *"An Experimental Study of Loss Sources in a Fan Operating With Continuous Inlet Stagnation Pressure Distortion"* Journal of Turbomachinery 2013

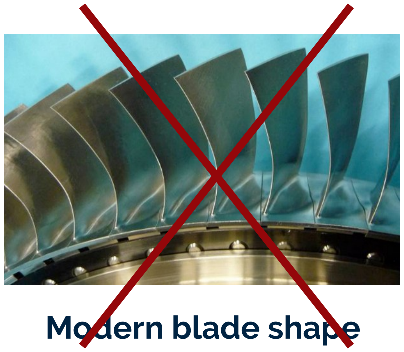
Low-pressure compressor

A performance and stability reduction occurs also in the LPC

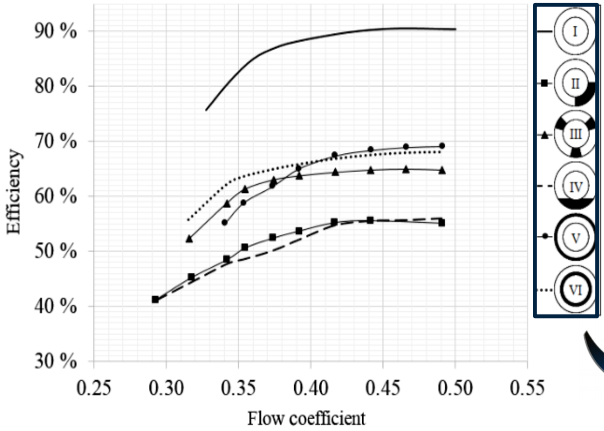
- ✘ No representative geometries for LPC
- ✘ No representative distortions for LPC

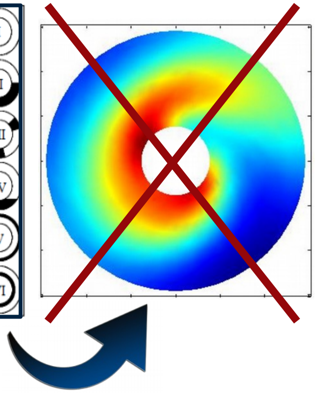


Old blade shape



Modern blade shape





There is a lack of information on the LPC!

Sans J., Brouckaert J. F. *"DREAM project: Experimental study of two highly loaded low pressure compressors"* 2011-2012
Taghavi Zenouz R. et al. *"Performance of a Low Speed Axial Compressor Rotor Blade Row Under Different Inlet Distortions"* Mechanical Sciences 2017
Plas A.P. et al. *"Performance of a Boundary Layer Ingesting (BLI) Propulsion System"* 45 th AIAA Aerospace Sciences Meeting and Exhibit 2007

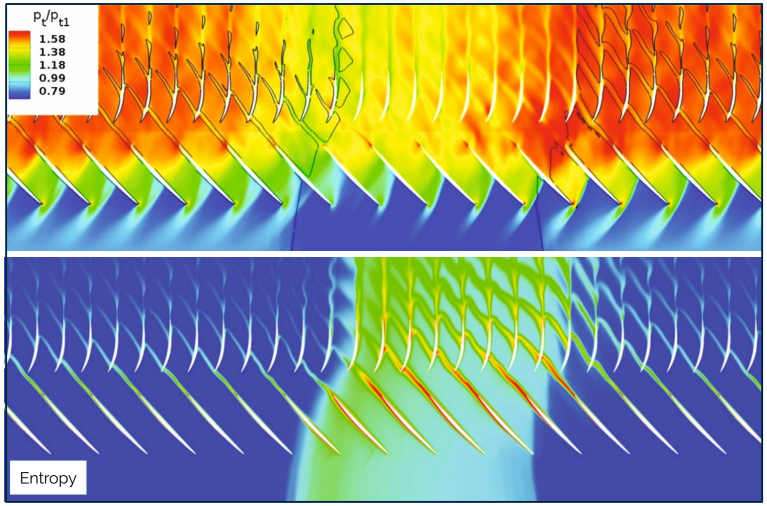
Research objective

Assessment of the global performance reduction and the dynamic behavior of modern LPC under "real" distortions

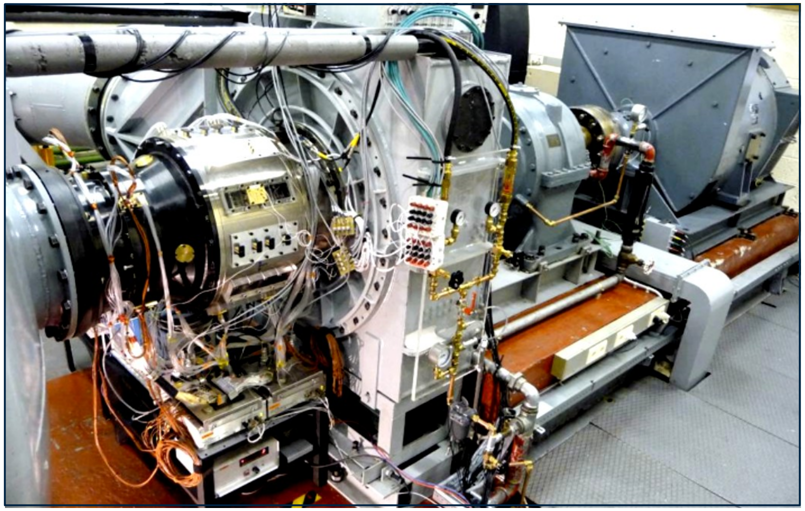
How? **Description of the involved flow physics!**

Methodology

Numerical activity



Experimental activity



Sebastian B. et al. *"Unsteady CFD simulation of transonic axial compressor stages with distorted inflows"* 2016
Sans J., Brouckaert J. F. *"DREAM project: Experimental study of two highly loaded low pressure compressors"* 2011-2012

Challenges

Scientific challenges

- ✓ **Characterize** steady and unsteady phenomena
- ✓ Link the **flow phenomena with performance and stability reduction**
- ✓ Identify the **flow mechanisms inducing stall**
- ✓ Describe the **post-stall behavior**

Industrial challenges

- ✓ **Provide new designs** to reduce the performance and stability loss
- ✓ Allow the **development of distortion tolerant LPC** for geared and BLI aircraft
- ✓ Support the **development of modern engine technologies**

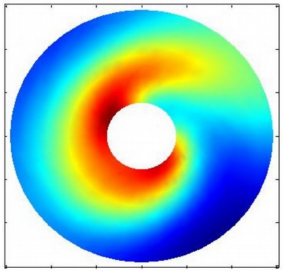
Innovation

- ✓ **Fully characterize the flow physics** under real distortions
- ✓ **Quantify the performance and stability reduction** induced by distortions
- ✓ **Describe the stable and unstable operating conditions**

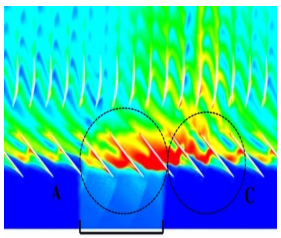
Research activity

Steps of the research activity:

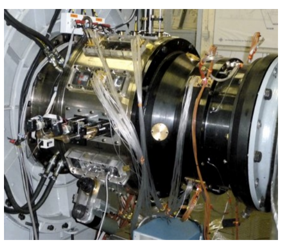
Timeline



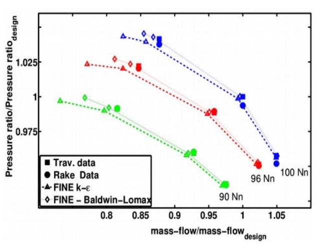
Step 1: **Bibliographic research** to define in detail the research methodology



Step 2: URANS simulations to **describe the flow topology** and **drive the design of experiments**



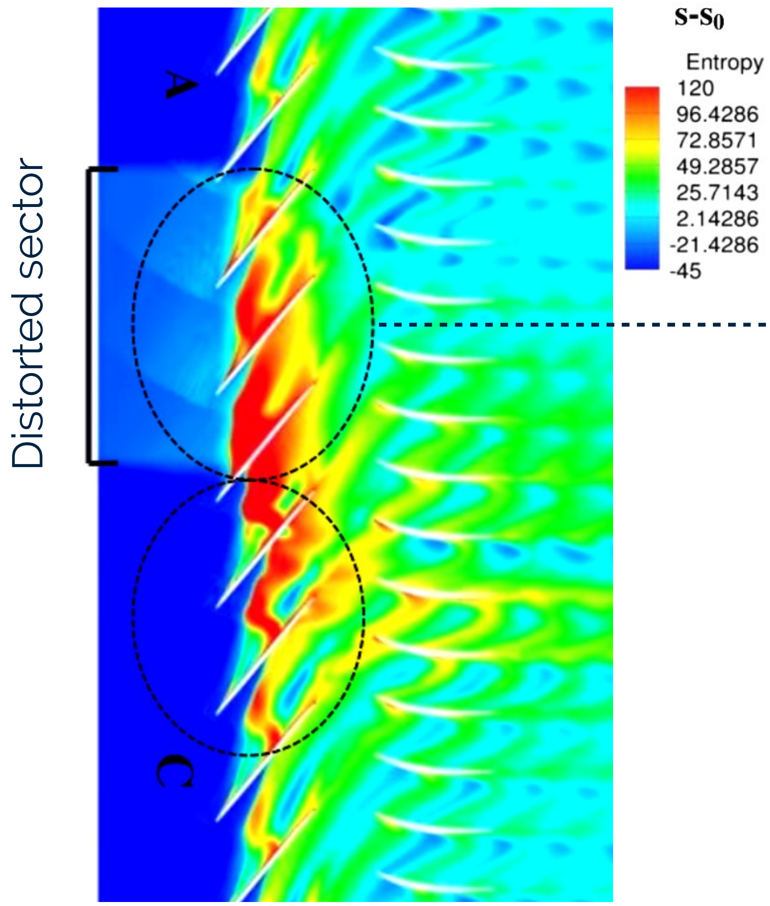
Step 3: Steady and unsteady **experimental characterization**



Step 4: **Interpretation of the** numerical and experimental **results**

Step 1 & 2: URANS simulations

Numerical characterization of the flow under distorted conditions



The bibliographic research aims at characterizing the **most critical distortions** for the LPC!

Design of experiments

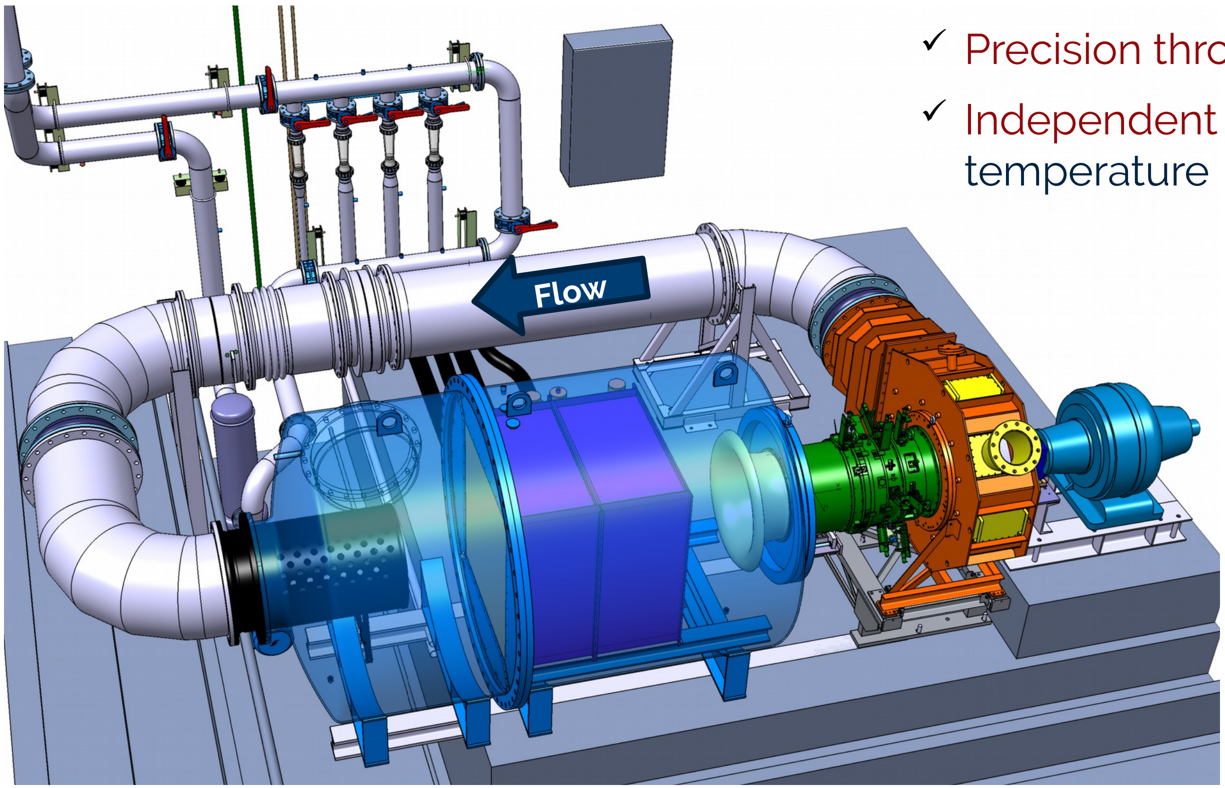
- ✓ Increased spatial and temporal resolution in secondary flows and gradient regions
- ✓ Right bandwidth for the instrumentation
- ✓ Probes location optimization

Lesser A., Niehuis R. *"Transonic Axial Compressors With Total Pressure Inlet Flow Field Distortions"* ASME Turbo Expo 2014 (GT2014-26627, pp. V01AT01A036)

Step 3: Experiments

VKI R4 closed-loop compressor rig

- ✓ 750 [kW] installed power
- ✓ Up to 25000 rpm
- ✓ Controlled inlet temperature for stabilized conditions
- ✓ Precision throttling
- ✓ Independent variation of pressure and temperature

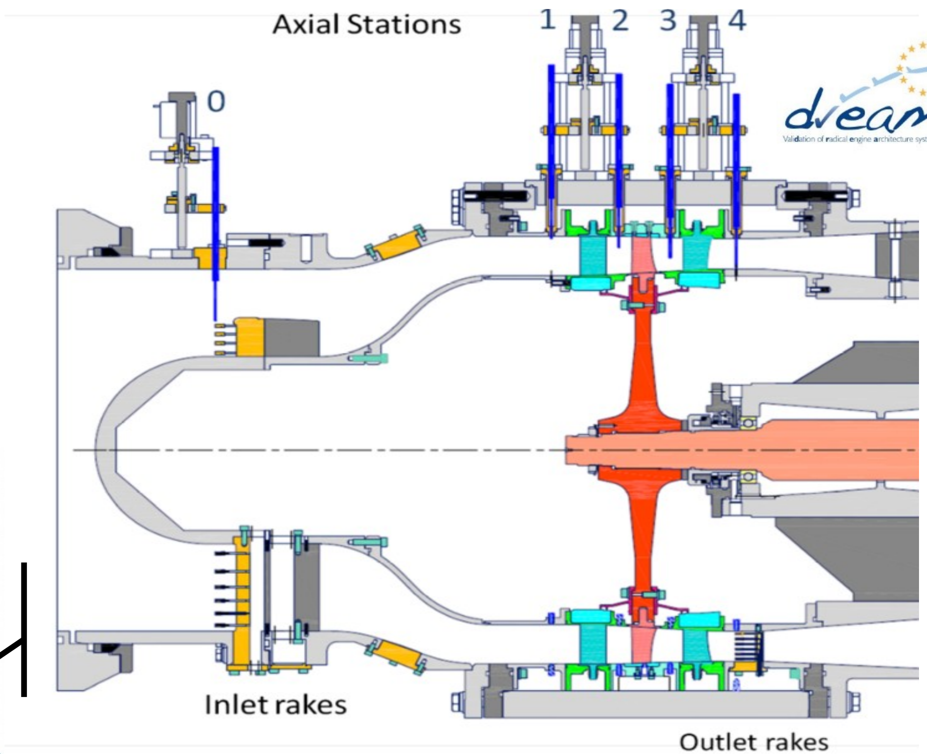


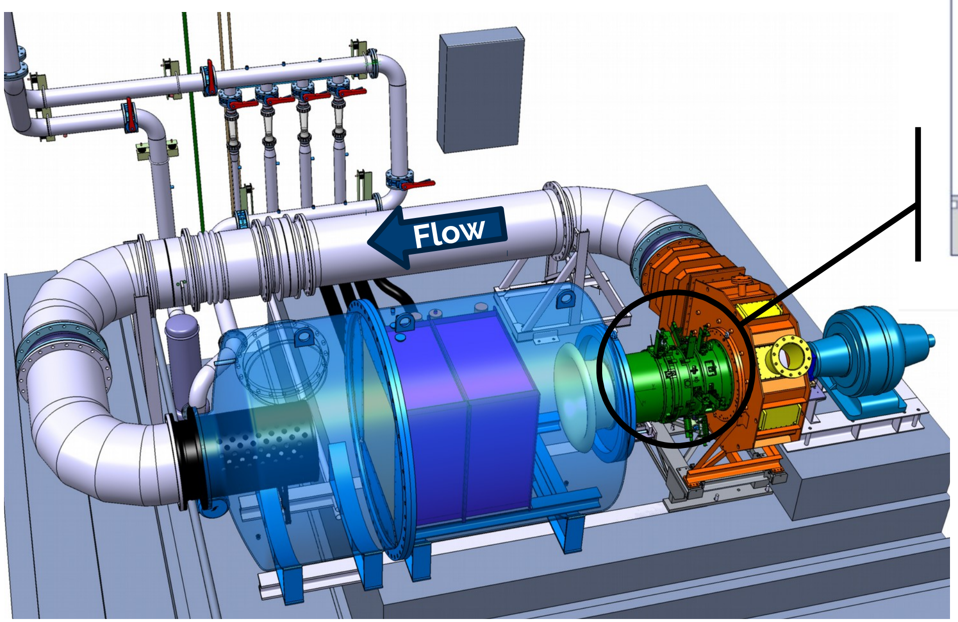
Different operating conditions (take-off, cruise) can be tested!

Sans J., Brouckaert J. F. *"DREAM project: Experimental study of two highly loaded low pressure compressors"* 2011-2012

DREAM test section

- ✓ Representative of a geared engine LPC
- ✓ Fully characterized in clean conditions (previous EU FP7 DREAM project)
- ✓ Fully instrumented

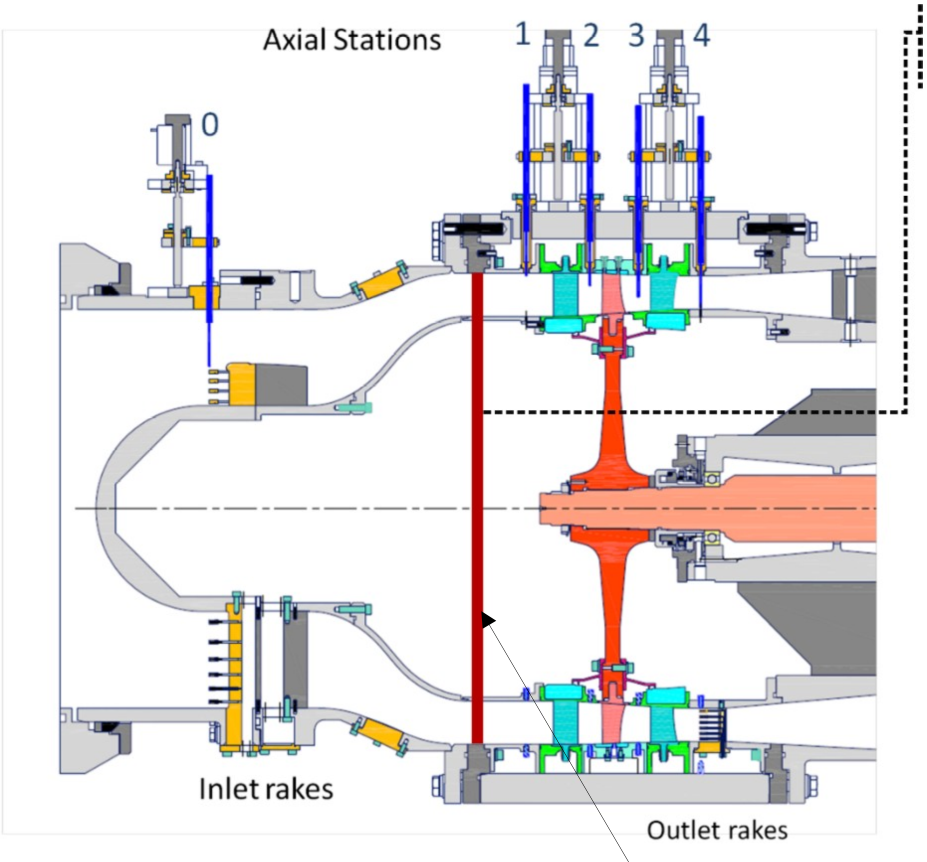




Sans J., Brouckaert J. F. *"DREAM project: Experimental study of two highly loaded low pressure compressors"* 2011-2012

Step 3: Experiments

DREAM test section



Distortion screen location!

Clean Sky 2

ASTORIA project

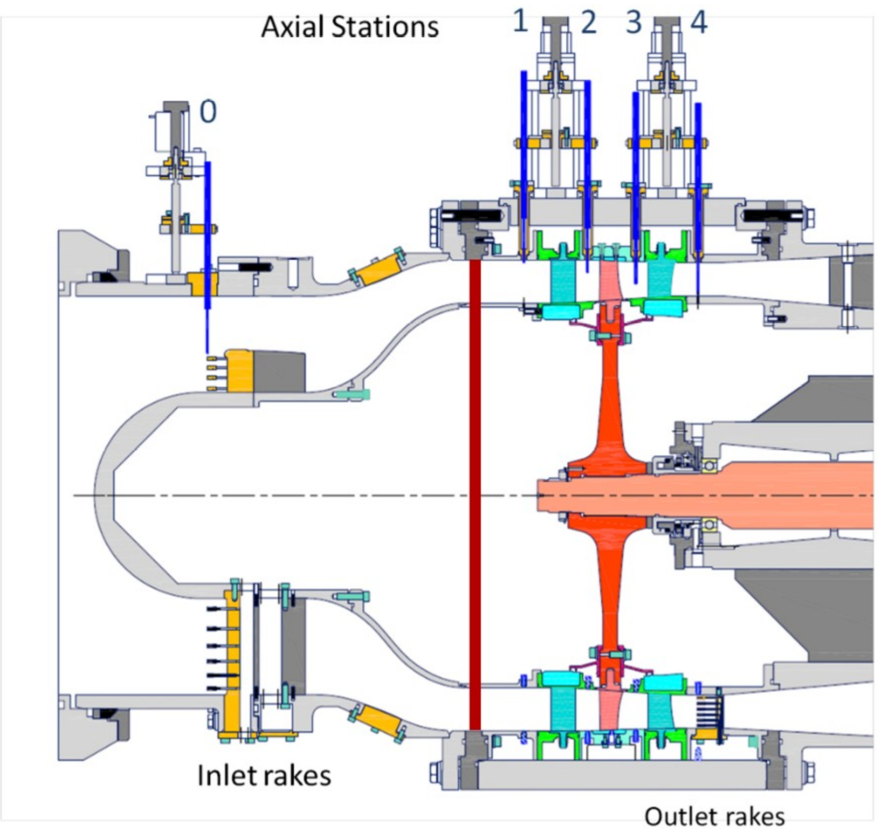
✓ Installation of a screen to reproduce the desired **swirl** and **total pressure** distortion

Thanks to Astoria!

Sans J., Brouckaert J. F. *"DREAM project: Experimental study of two highly loaded low pressure compressors"* 2011-2012
Stephens J.E., Celestina M., Hughes C. *"Swirl Distortion Using Stream Vanes for Boundary Layer Ingestion Research"* ASME Turbo Expo 2019 (GT2019-92073).

Step 3: Experiments

DREAM test section



Measurements

✓ Steady measurements:

- Global performance
- 2D maps of total quantities and flow angles

✓ Unsteady measurements:

- Total pressure 2D maps
- Static pressure (rotor casing)
- Operating conditions:
  - Stable operation
  - Stall inception
  - Post-stall

✓ Measurement planes: 1 to 4

Sans J., Brouckaert J. F. *"DREAM project: Experimental study of two highly loaded low pressure compressors"* 2011-2012

Step 4: Physical interpretation

Simulations & experiments become complementary → Detailed analysis of the results

- ✓ **Performance and stability reduction** with respect to the clean case
- ✓ **Identification of the flow phenomena** linked with the performance and stability loss
- ✓ **Understand the role of unsteady effects**, as secondary flows, shock-BL interactions and BL separations
- ✓ Identification of **stall inception mechanisms and type of stall cells**
- ✓ **Design considerations** for distorted operation

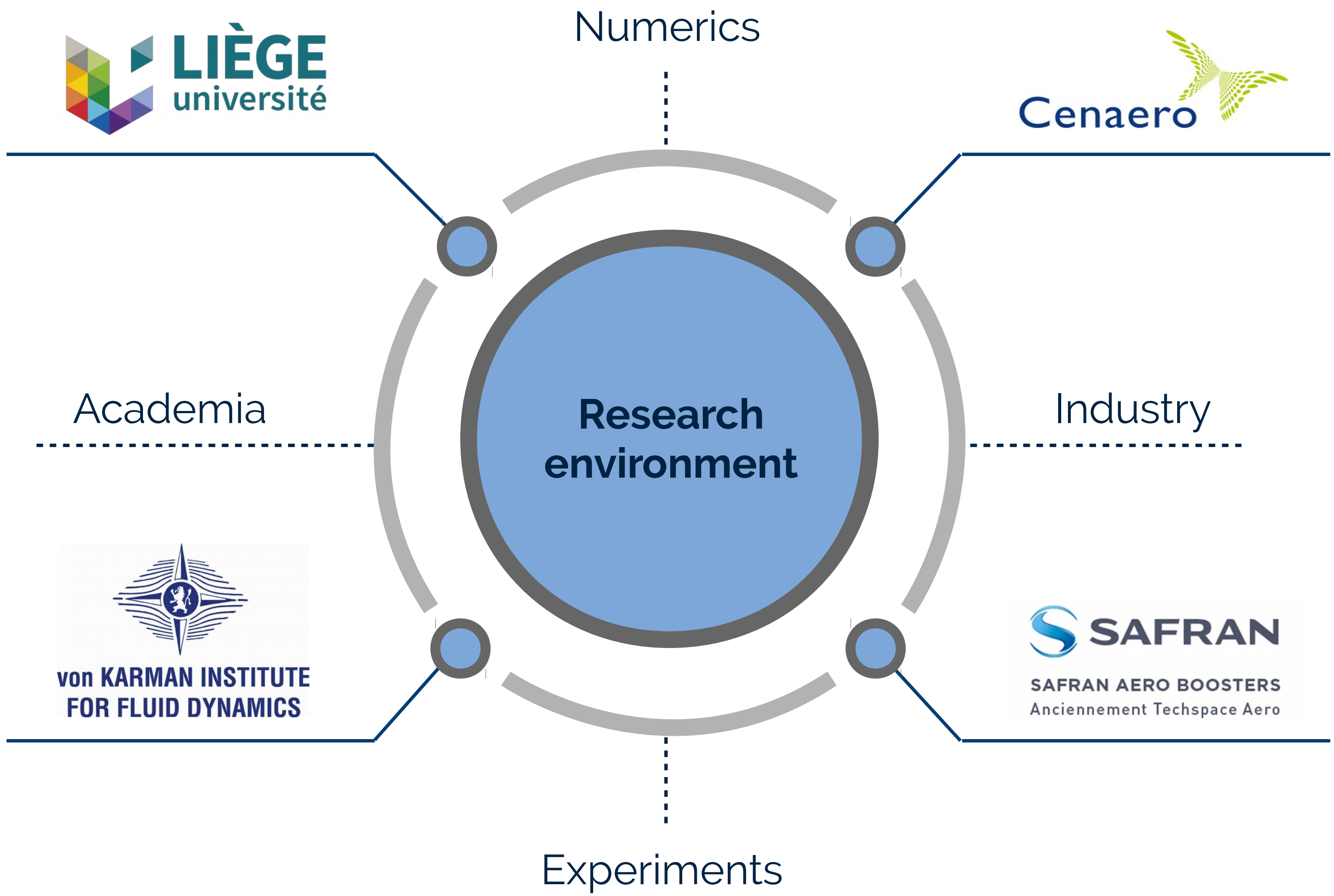
Perspective

This project will provide unprecedented numerical and experimental outcomes to support the development and design of LPC for geared aircraft and BLI engines

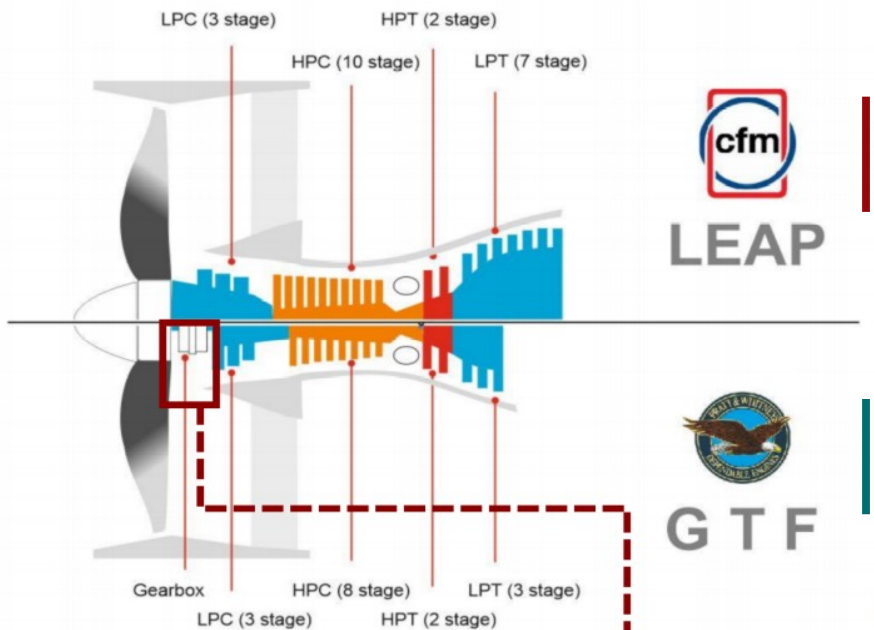
Thank you a lot for the attention

Backup slides

Environment



Geared Turbofan - Layout



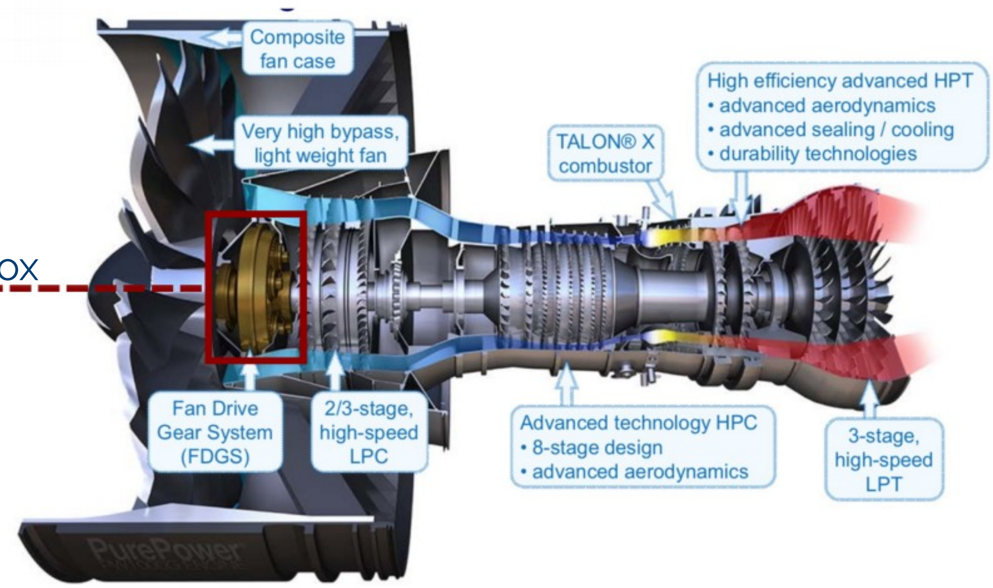
LEAP

✘ Large number of engine stages

GTF

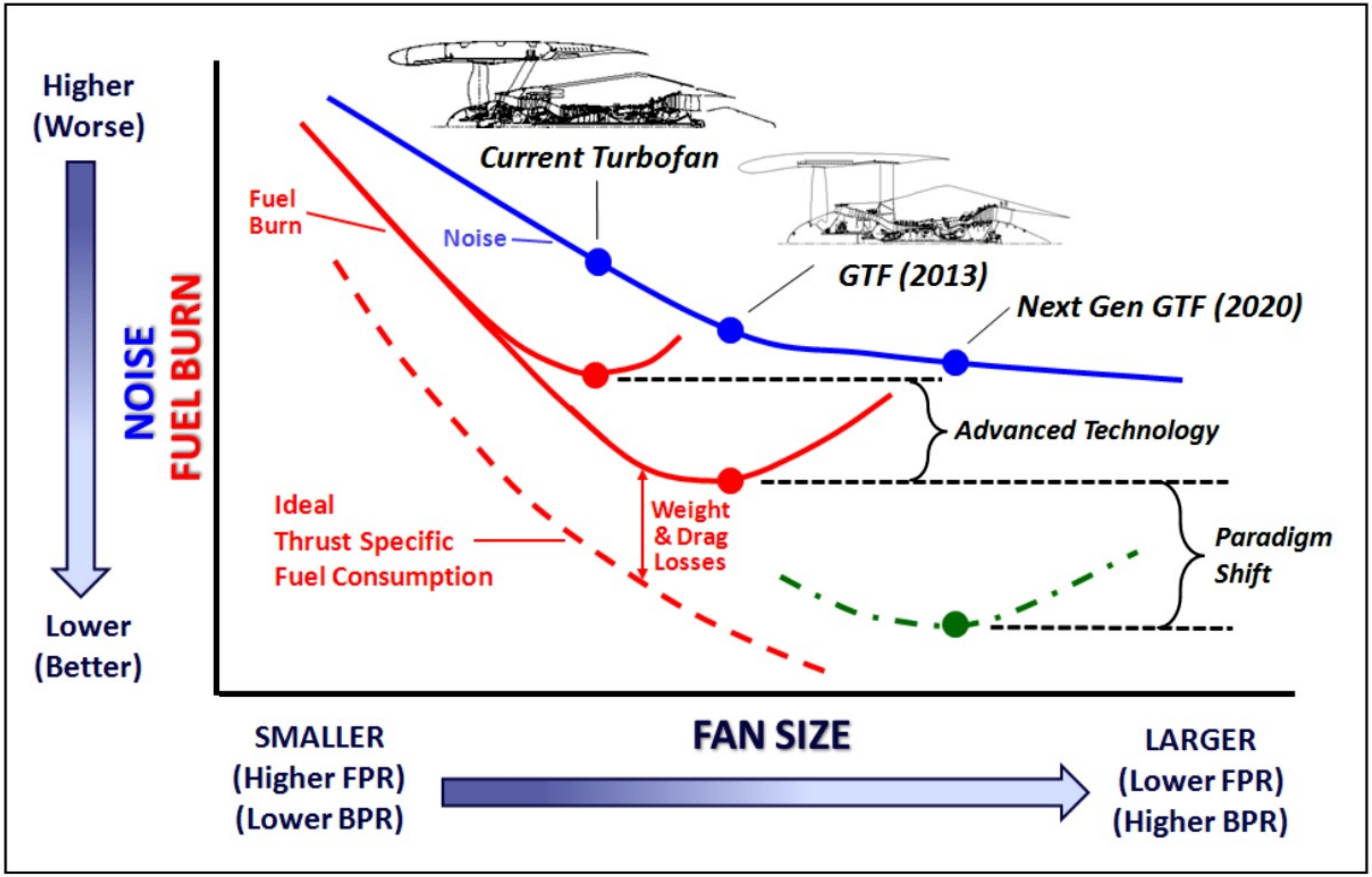
✓ Small number of engine stages

Gear box



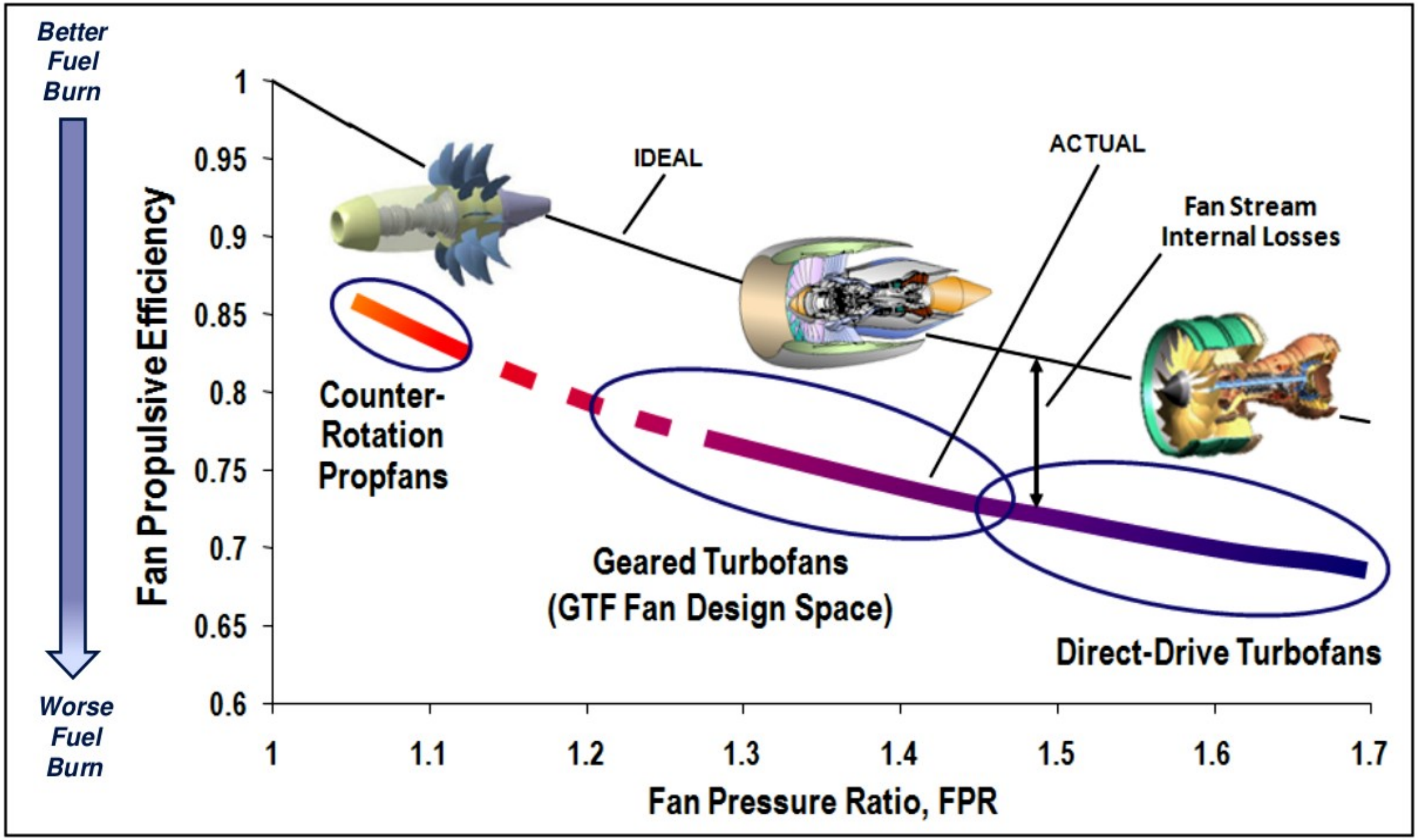
Credit: https://www.willisasset.com/application/files/3815/2594/2691/A320_NEO_.pdf
Credit: http://newsinflight.com/2019/02/19/pratt-whitney-gtf-pw1900g-engines-for-the-first-e195-e2-aircraft-arrived-in-brazil/

Range of application



Christopher E. Huges *"Aircraft Engine Technology for Green Aviation to Reduce Fuel Burn"* 3rd AIAA Atmospheric Space Environments Conference, 2011.

Range of application



Christopher E. Huges *"Aircraft Engine Technology for Green Aviation to Reduce Fuel Burn"* 3rd AIAA Atmospheric Space Environments Conference, 2011.

HBP turbofan advantages

Why does the propulsive efficiency improve by increasing the by-pass ratio?

$$\dot{m} = \dot{m}_e \approx \dot{m}_i$$

$$F = \dot{m}_e V_e - \dot{m}_i V_i + (p_e - p_i)A_e \approx \dot{m}(V_e - V_i) + (p_e - p_i)A_e$$

Increase of thrust by : Increasing the mass flow or Increasing the kinetic energy variation

However:

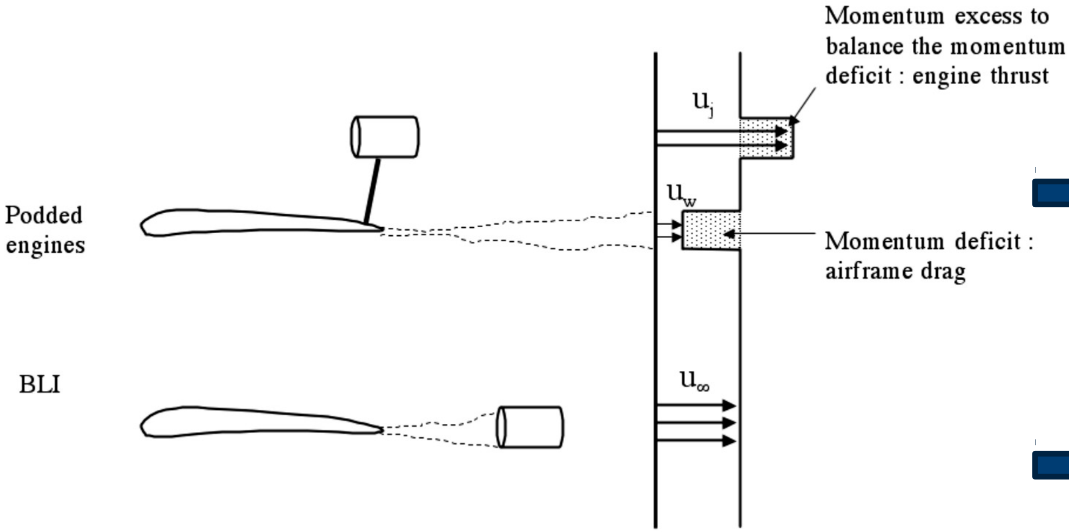
$$\eta_p = \frac{2}{1 + \frac{v_9}{v_0}}$$

The increase of exit kinetic energy would reduce the propulsive efficiency!

The best way is to increase the mass flow!

Use of large high-bypass ratios!

BLI advantages



$$F = \dot{m}(u_j - u_\infty)$$

$$P_{noBLI} = \frac{\dot{m}}{2}(u_j^2 - u_\infty^2) = \frac{F}{2}(u_j + u_\infty)$$

$$F = \dot{m}(u_\infty - u_w)$$

$$P_{BLI} = \frac{\dot{m}}{2}(u_\infty^2 - u_w^2) = \frac{F}{2}(u_w + u_\infty)$$

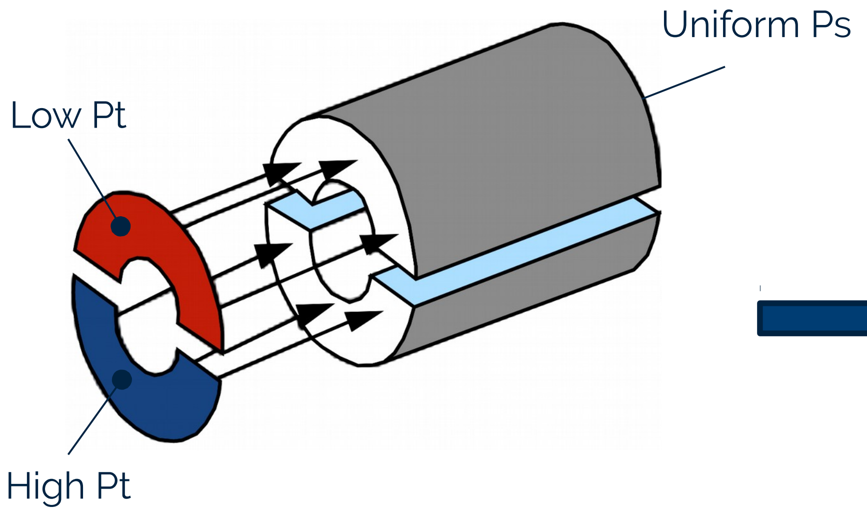
Since: $u_j > u_w$ → $P_{noBLI} > P_{BLI}$

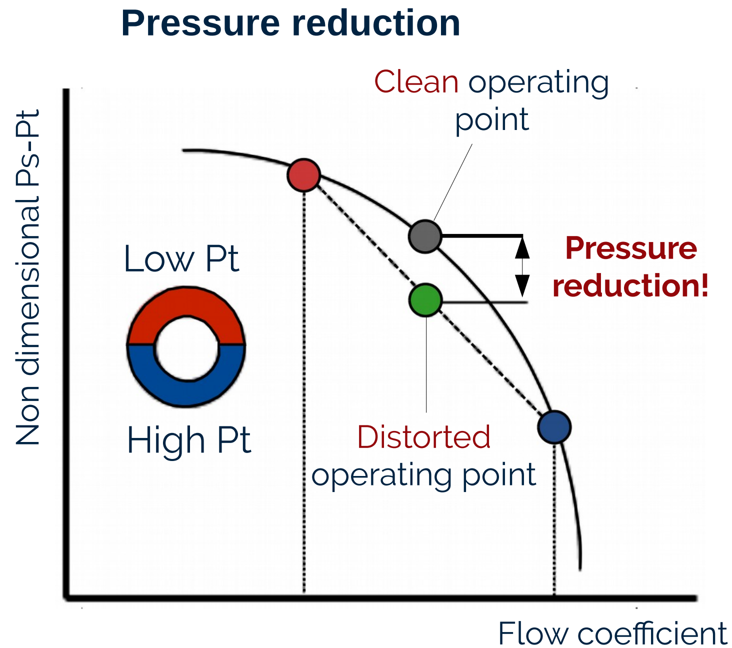
The power needed for the podded engine is larger than that for the BLI

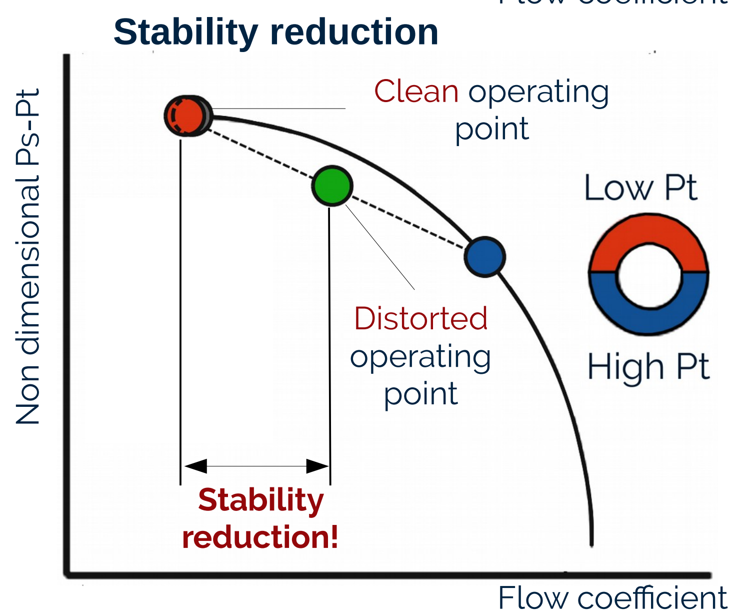
Plas A.P. et al."Performance of a Boundary Layer Ingesting (BLI) Propulsion System" 45 th AIAA Aerospace Sciences Meeting and Exhibit 2007

Distortion effects

Parallel compressor model







Assumption of the model: The distorted stability limit is reached when the operating point for the low total pressure stream reaches the flow stability limit!

Numerical simulations

Full annulus URANS

To describe flow phenomena with larger periodicity!

~~**Mixing Plane**~~ ~~**Frozen rotor**~~

Possible alternative methods?

Bibliographic research will provide feasibility and possible techniques to adopt!

HPC facilities

Clusters **+** **Workstations** → **Not enough?**

1) 1792 cores – 7 TB cluster

2) 288 cores - 9 TB AMD EPYC 7551 based cluster

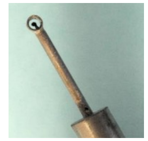
two AMD EPYC 7551 32-Core of 252 GB and 1 TB of RAM

Cenaero clusters!

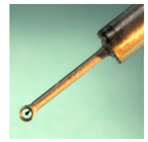
The available computational power will be in any case able to manage the planned numerical activity!

Measurements

Steady measurements

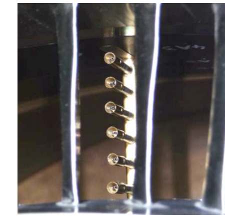


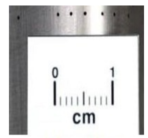
Total pressure
(Kiel probe)



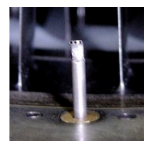
Total temperature
(Shielded thermocouple)

Inlet and outlet **rakes**





Static pressure
(Pressure taps)

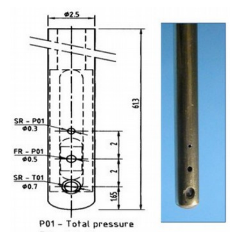


Flow direction
(3-hole probes)

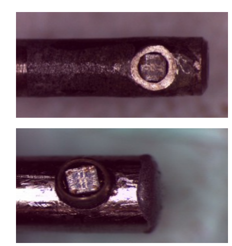
Hot-wire measurements

Hot-wire anemometer
(hub and tip turbulence intensity)

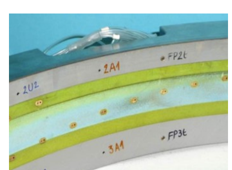
Unsteady measurements



Total and static pressure, total temperature
(AP1-C25 probe)

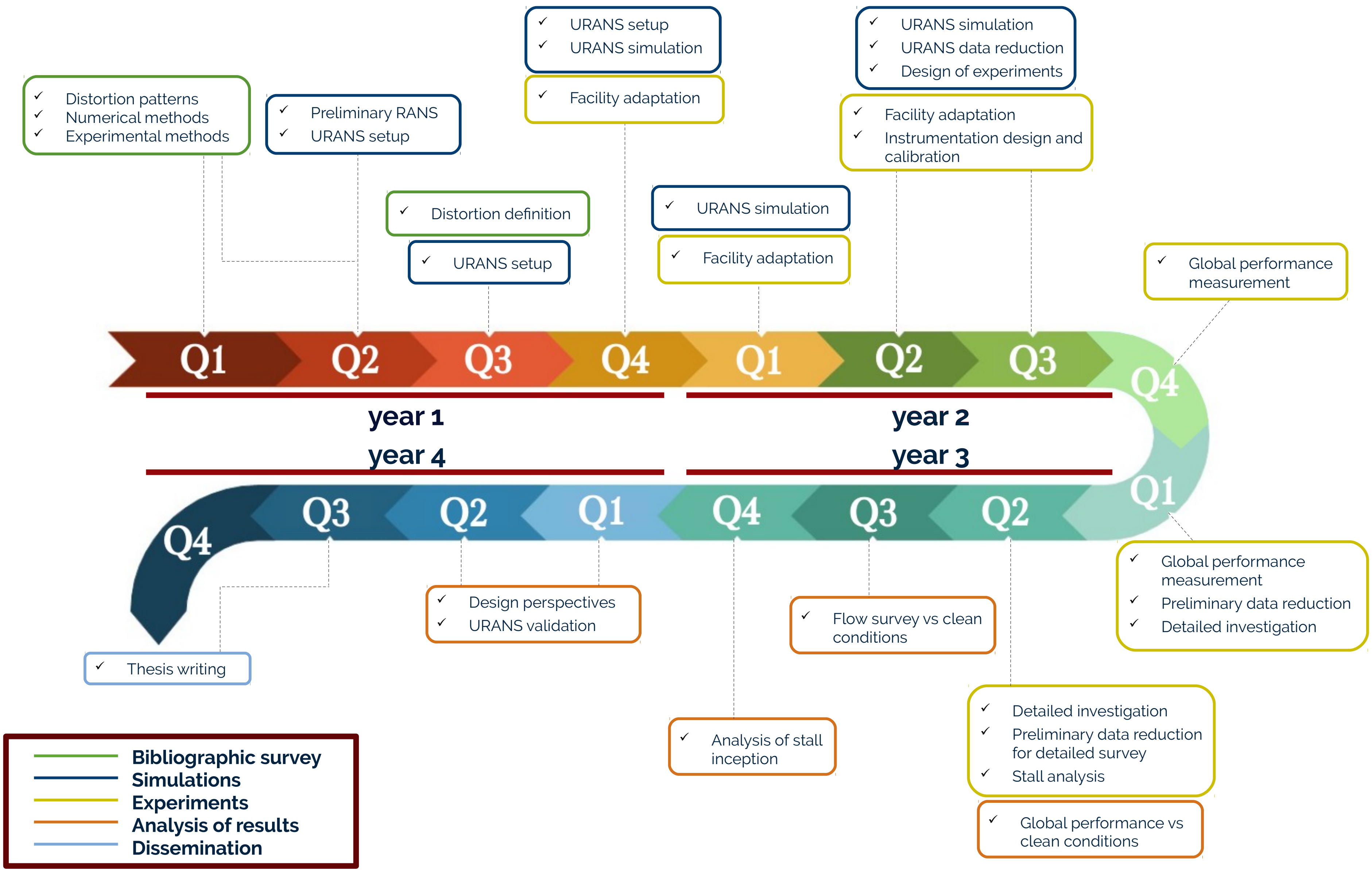


Total pressure
(FP2, FP3)



Static pressure
(Fast response pressure taps)

Work plan



Distortion patterns
Numerical methods
Experimental methods
Preliminary RANS
URANS setup
Distortion definition
URANS setup
URANS setup
URANS simulation
Facility adaptation
URANS simulation
Facility adaptation
URANS simulation
URANS data reduction
Design of experiments
Facility adaptation
Instrumentation design and calibration
Global performance measurement
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
year 1
year 2
year 4
year 3
Q4
Q3
Q2
Q1
Q4
Q3
Q2
Q1
Thesis writing
Design perspectives
URANS validation
Analysis of stall inception
Flow survey vs clean conditions
Detailed investigation
Preliminary data reduction for detailed survey
Stall analysis
Global performance vs clean conditions
Global performance measurement
Preliminary data reduction
Detailed investigation
Bibliographic survey
Simulations
Experiments
Analysis of results
Dissemination