Forum TERATEC 2018
Atelier 1 - Mercredi 20 juin - de 09h00 à 12h30

CERFACS
CENTRE EUROPÉEN DE RECHERCHE ET DE FORMATION AVANCÉE EN CALCUL SCIENTIFIQUE

Machine learning for **A**dvanced **G**as Turbine **I**njection **S**ystems to **E**nhance Combustor pe**R**formance **(MAGISTER)**

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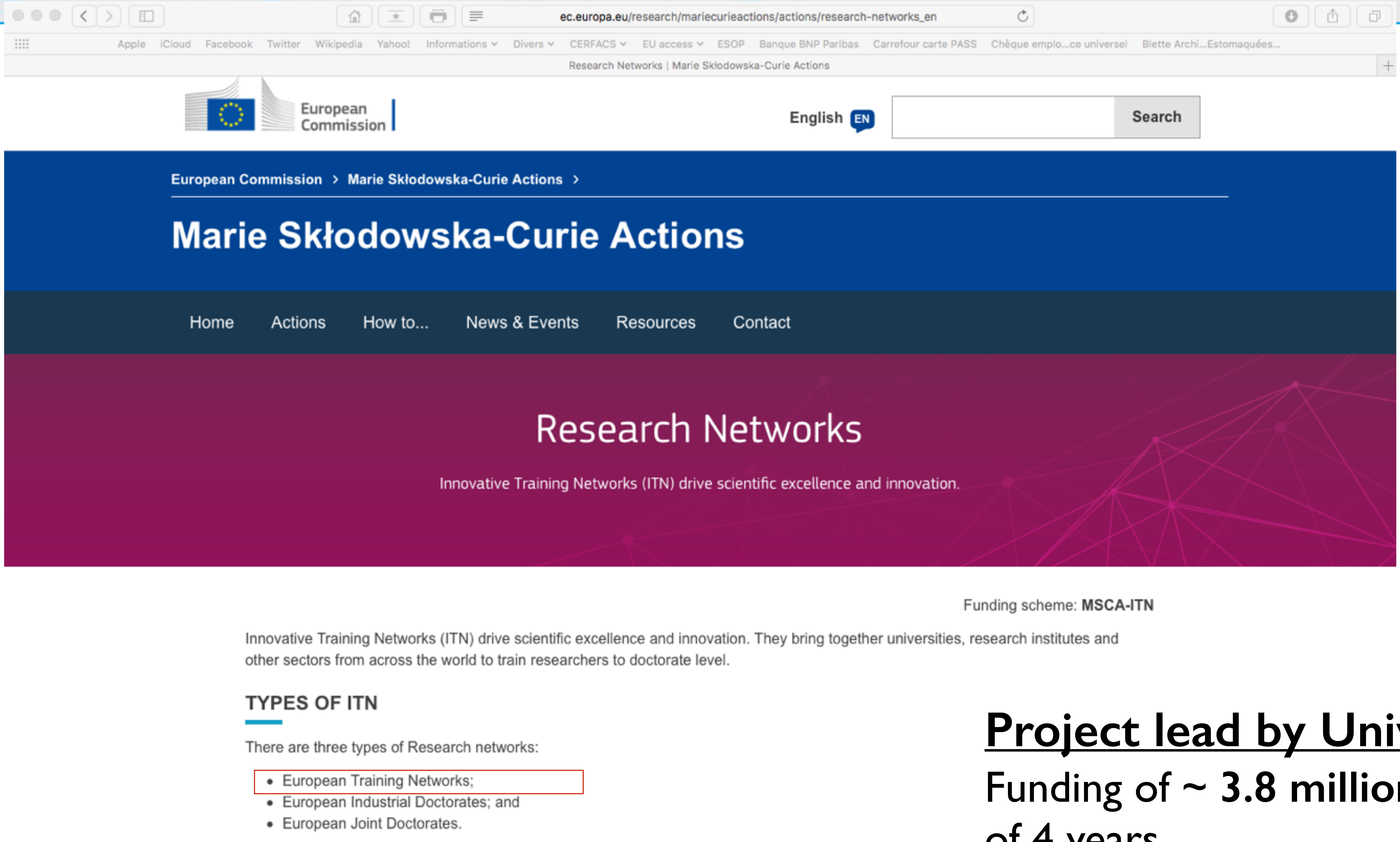
European
Commission

MAGISTER: ITN Marie-Curie European Training Network

Coordination: Prof. Jim Kok



Marie Skłodowska-Curie Actions

Research Networks

Innovative Training Networks (ITN) drive scientific excellence and innovation.

Funding scheme: **MSCA-ITN**

Innovative Training Networks (ITN) drive scientific excellence and innovation. They bring together universities, research institutes and other sectors from across the world to train researchers to doctorate level.

TYPES OF ITN

There are three types of Research networks:

- European Training Networks;
- European Industrial Doctorates; and
- European Joint Doctorates.

Project lead by University of Twente (NL):

Funding of ~ **3.8 millions €** or **540 MM** over a period of 4 years

Context of work and link with the project MAGISTER

Combustion: An engineering science at the cross-road between *chemistry & fluid mechanics* with strong *technological / industrial and societal* implications

From ICAO Environmental Report, Chapter 2, 2010.

CFM 56
- Dual Annular Combustor
- 2-nozzle lean burn mode

GEnx
- Twin Annular Pre-mixing Swirler (TAPS)

CFM LEAP
- Next gen TAPS

Potential evolution ...

RQL concept

LPP concept

Annular chamber MICCA-Spray
Combustion instability

EM2C Lab - Prieur, Durox, Schuller, Candel
CNRS - CentraleSupélec - Safran

MAGISTER

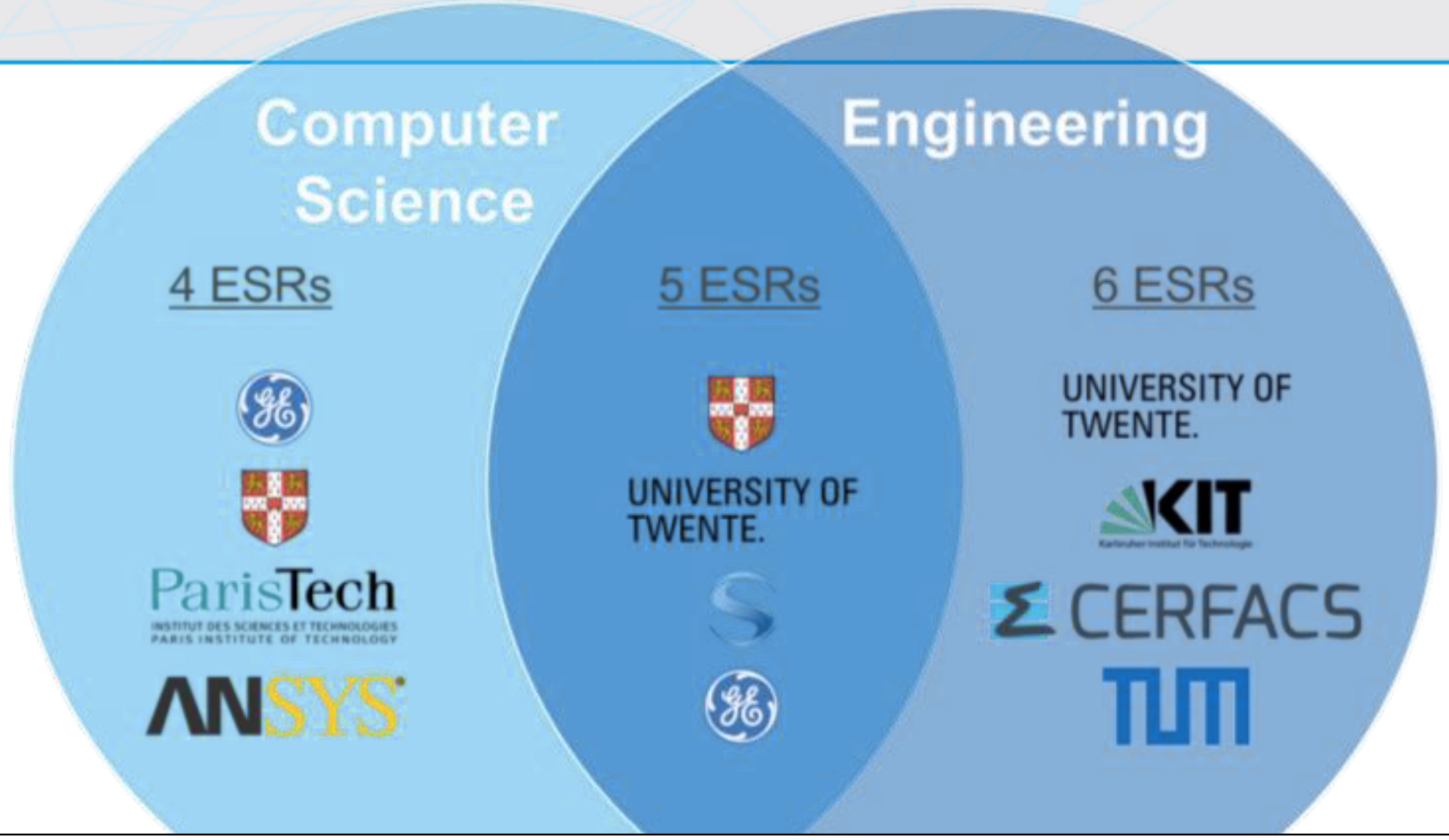
Machine learning for **A**dvanced **G**as Turbine **I**njection **S**ystems to **E**nhance Combustor pe**R**formance

- Partenaires and project layout
- Existing methods, tools and strategies to predict thermo acoustic instabilities in real engines
- Project side actions

MAGISTER

Build on existing engineering / research tools around thermo acoustic instabilities and adapt / transfer them to obtain a digital twin of the real engine

MAGISTER consortium



Partners

1. UNIVERSITEIT TWENTE (Netherlands)
2. GENERAL ELECTRIC DEUTSCHLAND HOLDING GMBH (Germany)
3. TECHNISCHE UNIVERSITÄT MÜNCHEN (Germany)
4. KARLSRUHER INSTITUT FÜR TECHNOLOGIE (Germany)
5. THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE (United Kingdom)
6. CENTRE EUROPEEN DE RECHERCHE ET DE FORMATION AVANCEE EN CALCUL SCIENTIFIQUE (France)
7. ASSOCIATION POUR LA RECHERCHE ET LE DEVELOPPEMENT DES METHODES ET PROCESSUS INDUSTRIELS (France)
8. SAFRAN SA (France)
9. SAFRAN HELICOPTER ENGINES (France)
10. ANSYS FRANCE SAS (France)

Associated partners

1. Rolls-Royce Power Engineering United Kingdom)
2. General Electric Switzerland(Switzerland)
3. Shell Research Limited(United Kingdom)
4. KLM Koninlijke Luchtvaart Maatschappij (Netherlands)
5. FDX Fluid Dynamix GmbH (Germany)
6. Stanford University (United States)
7. Georgia Institute of Technology (United States)

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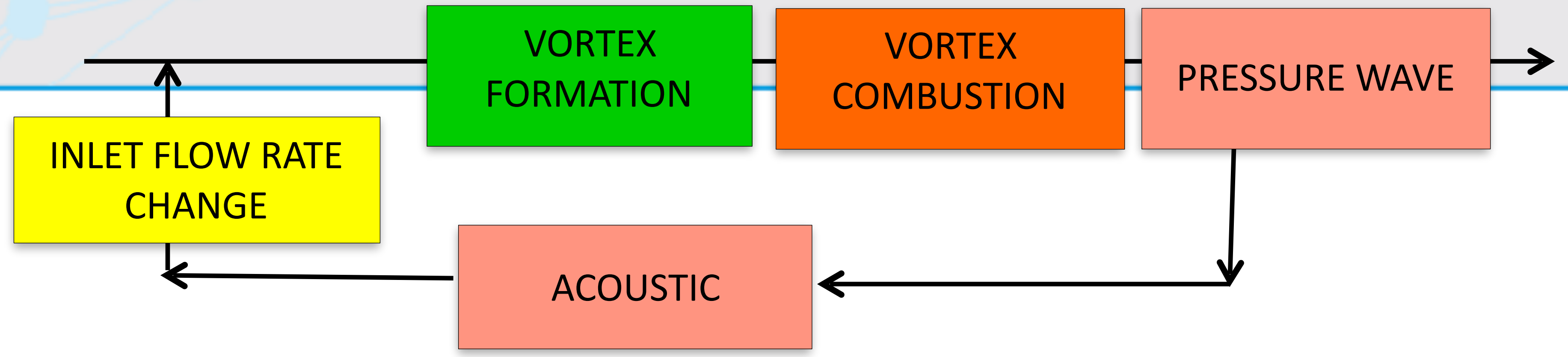
Thermo acoustic's NUMERICAL TWIN

Identify the risk of entering in the loop:



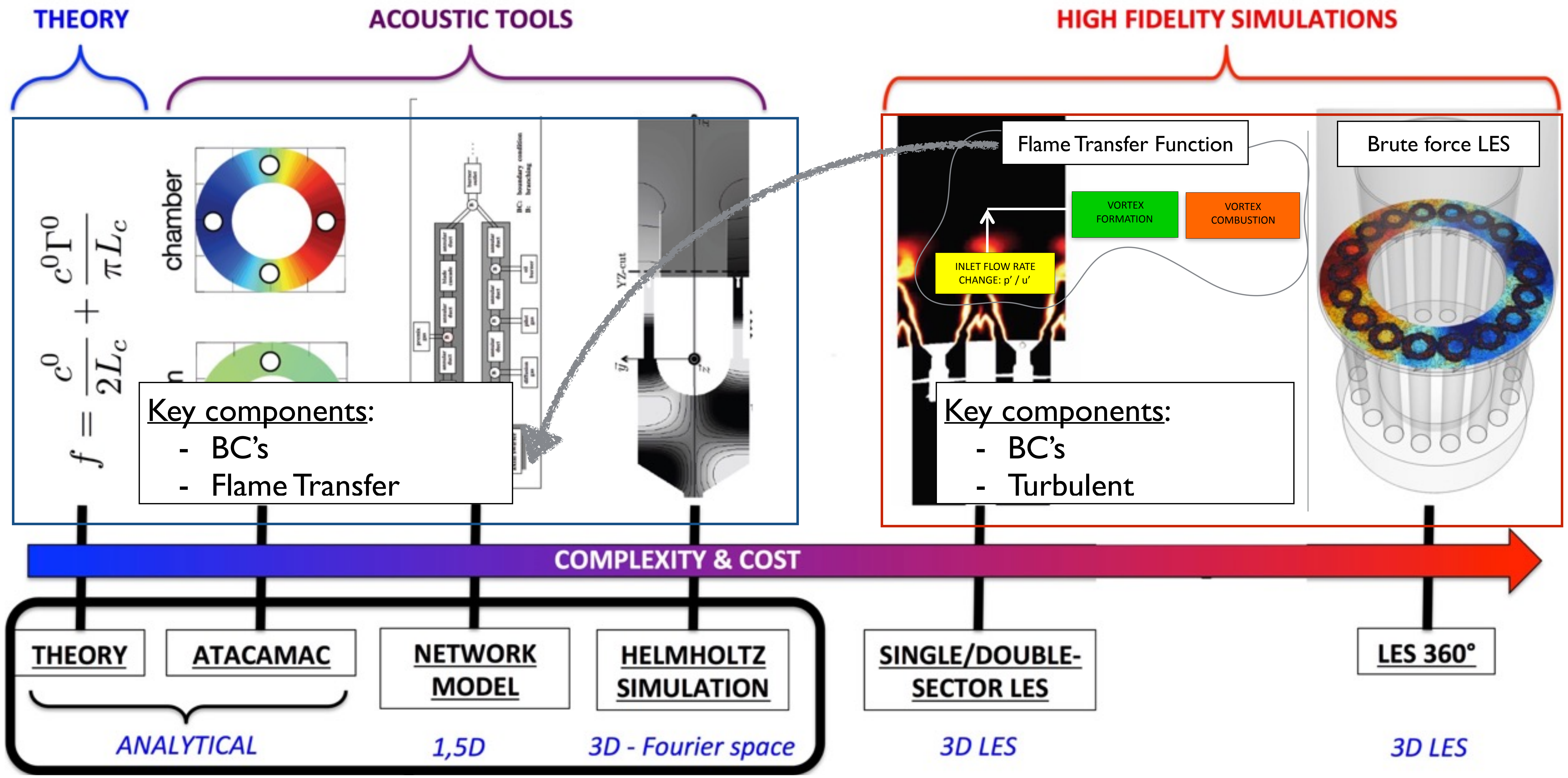
INLET FLOW RATE CHANGE

VORTEX FORMATION

VORTEX COMBUSTION

PRESSURE WAVE

ACOUSTIC



THEORY

ACOUSTIC TOOLS

HIGH FIDELITY SIMULATIONS

$$f = \frac{c^0}{2L_c} + \frac{c^0\Gamma^0}{\pi L_c}$$

Key components:

- BC's
- Flame Transfer

Flame Transfer Function

Brute force LES

Key components:

- BC's
- Turbulent

COMPLEXITY & COST

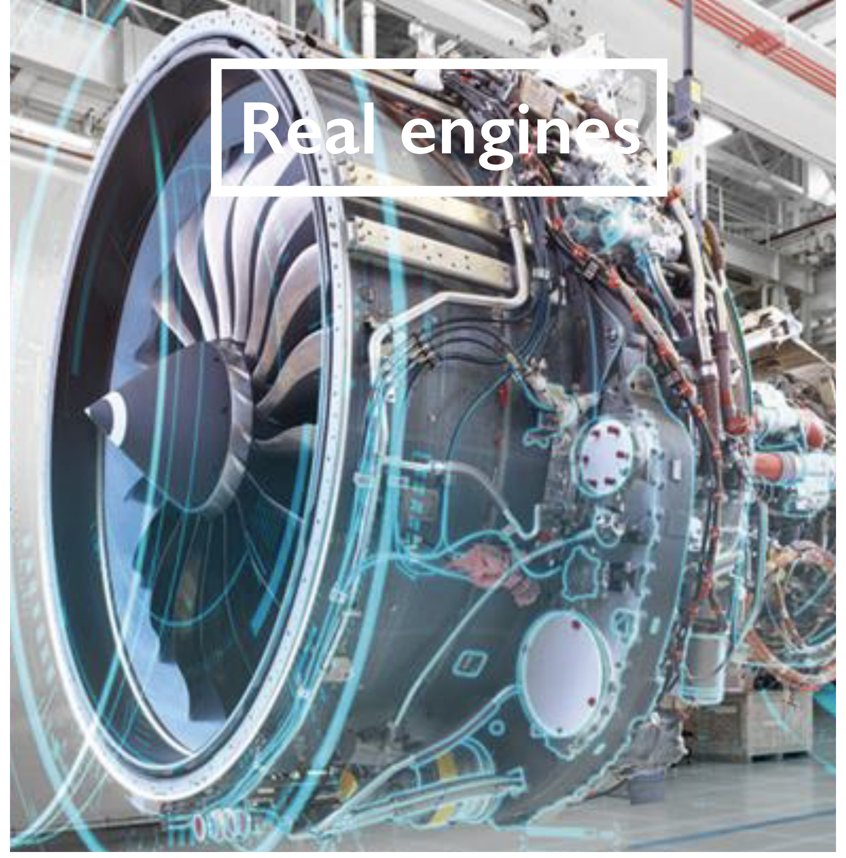
THEORY | **ATACAMAC** | **NETWORK MODEL** | **HELMHOLTZ SIMULATION** | **SINGLE/DOUBLE-SECTOR LES** | **LES 360°**

ANALYTICAL | *1,5D* | *3D - Fourier space* | *3D LES* | *3D LES*

Model validation verification…

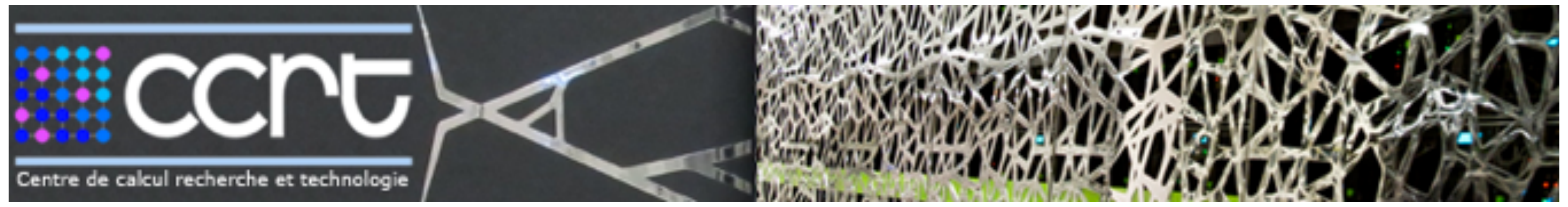
Transfer & adaptation…

Experimental test benches

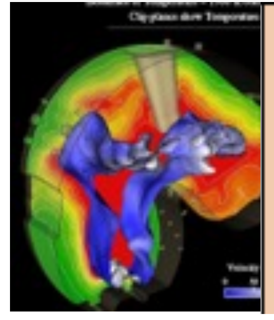


Real engines

Computing facilities



Prediction

WP	*Current state of the art*	*Beyond State of the Art in MAGISTER*
1. Machine Learning	Multiple input/single output model (MISO) with fixed parameters for acoustic oscillations.[4] Feedback control of thermos-acoustics on basis of a fixed algorithm.[5] Manual optimization of chemical kinetics parameters.	System characterization of thermoacoustics by means of probabilistic (Bayesian) prior-reward methods. Use of both data-based and physics-based machine learning tools and seamless joining of the two. Scale up from laboratory rigs to full engine tests. Feedback control by unsupervised learning methods to find the optimal path towards thermoacoustic stability.
2. Modelling: Dynamics of Fuel sprays + combustion	Standard second order finite volume schemes[6] Large amount of artificial dissipation and prohibitively fine grids	Fourth and higher order finite element discretization schemes: Discontinuous Galerkin (DG) discretization. High order time accurate local time stepping. Negligible amount of artificial dissipation and very small dispersion errors
	LES using equilibrium, mono-component evaporation models LES of spray with no acoustic excitation[7]	Detailed LES of spray using non-equilibrium, multi-component evaporation models with 4-way coupling under high-frequency excitation Extension of LES to account for acoustic effects

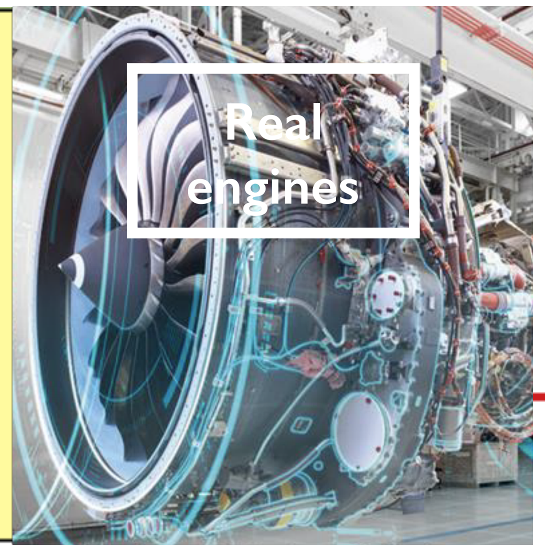
Experiment

4. Measurements and Numerical Experiments in sprays	Time averaged steady state cold spray evolution Time averaged steady state spray combustion Data collection on basis of spectra	Transient and trigger averaged response of cold sprays on acoustic forcing Transient and trigger averaged response of spray combustion on acoustic forcing Machine learning data collection on basis of prior response	 Experiment

Mitigation

3. Acoustic characterization of	Acoustic models for combustor liners with empirical settings of wall model parameters.[8] Acoustic models neglecting acoustic damping by dilution holes and turbulent flow	Adjoint sensitivity analysis of the parameters of the wall models defining an optimal combustor design for controlling combustion dynamics. Damping and cross over effect of liner dilution holes, burner inlet and turbine nozzles implemented in acoustic models

End application

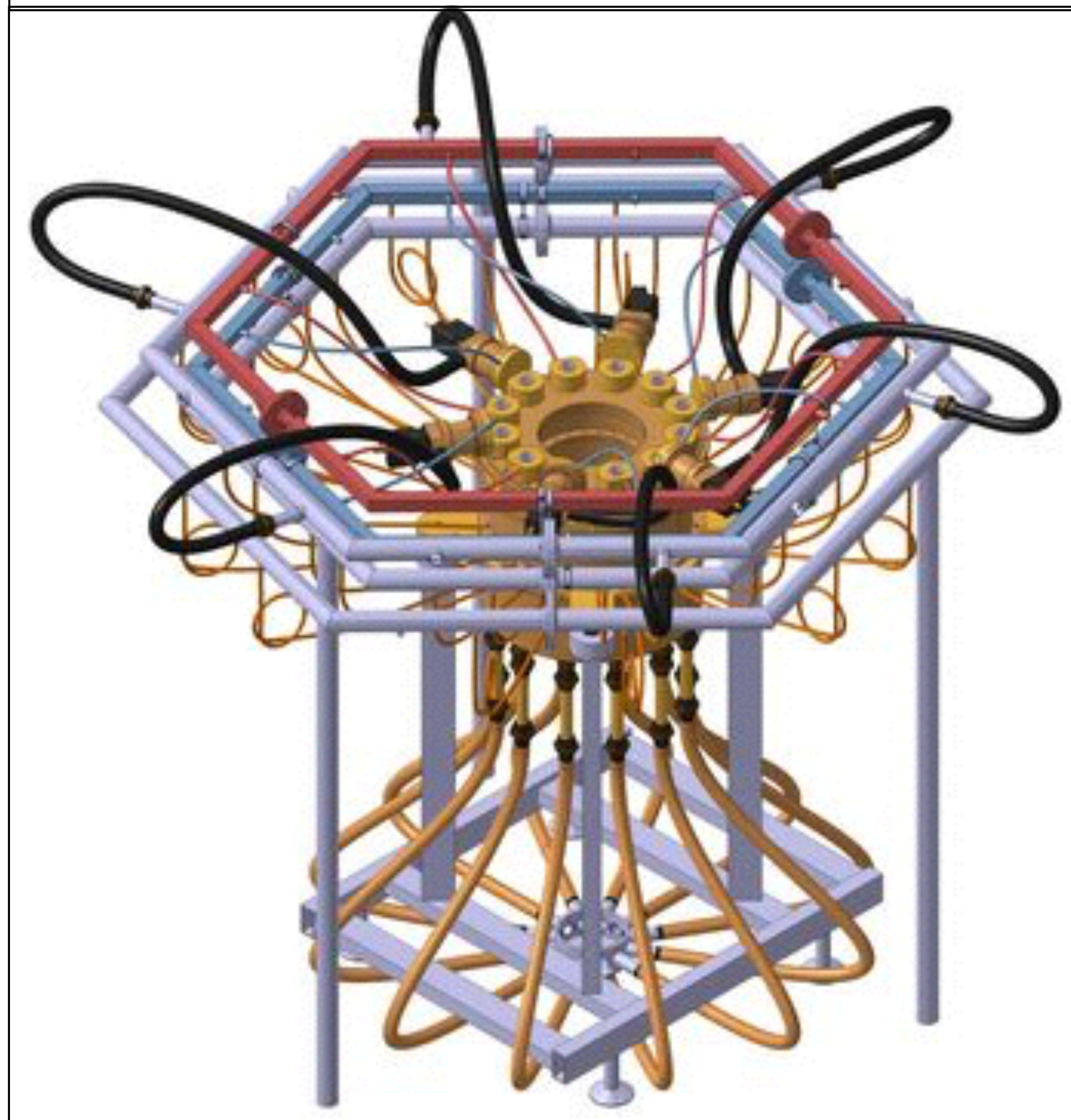
5 Aircraft engine simulations	Thermoacoustics models based on lab scale tests Low reliability of engine simulations due to highly uncertain parameters Physics based models for thermoacoustics based on simplifying assumptions	Machine learning enhanced models which adapt automatically as the development cycle matures. Uncertainty quantification and parameter estimation based on supervised learning algorithms Deep learning approach to generate data based models for clustering and design recommendations	 Real engines

Experimental devices

Twente single burner test facility

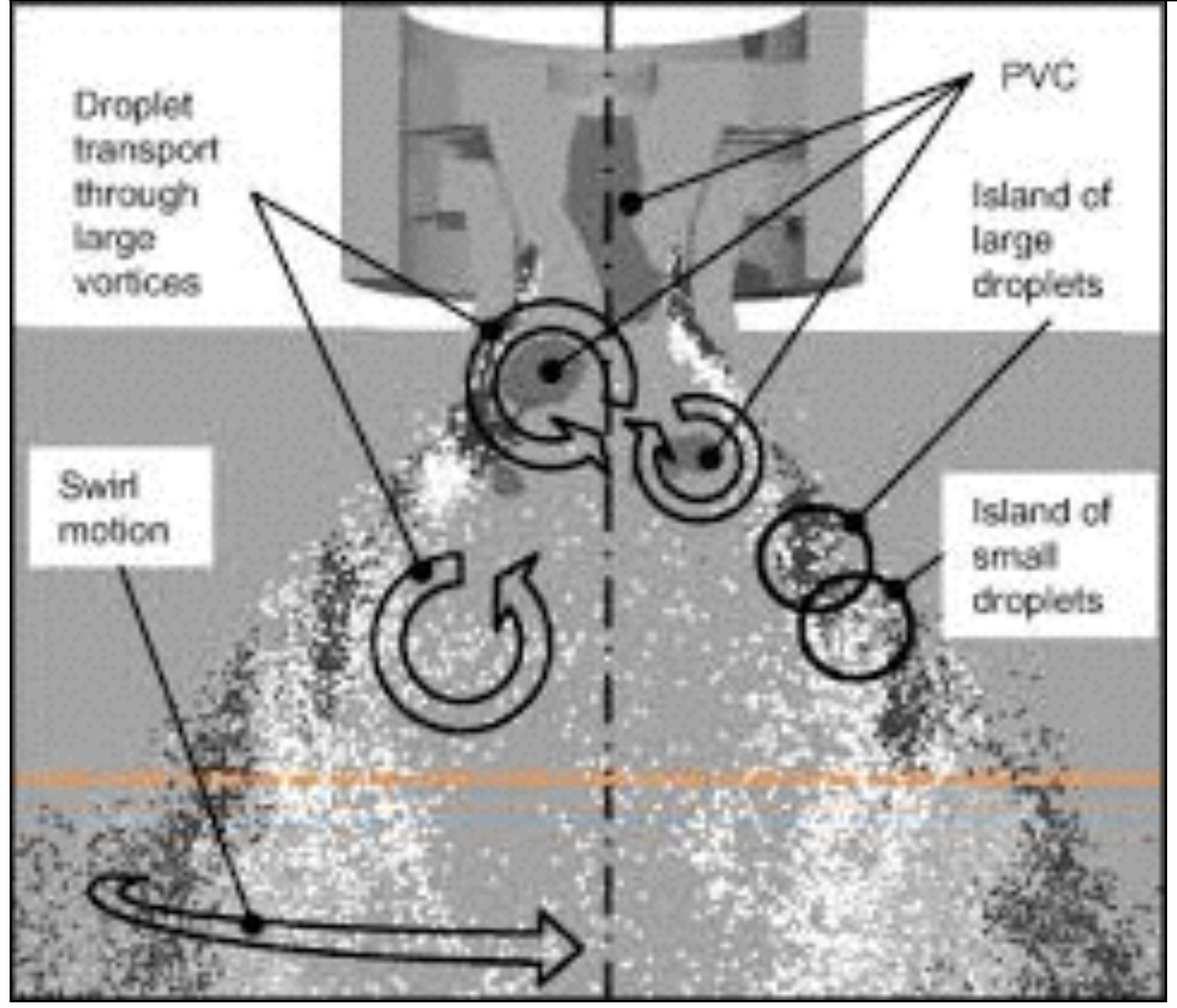
=> thermal effect

TUM Annular multi-burner test facility



=> group effect / damping

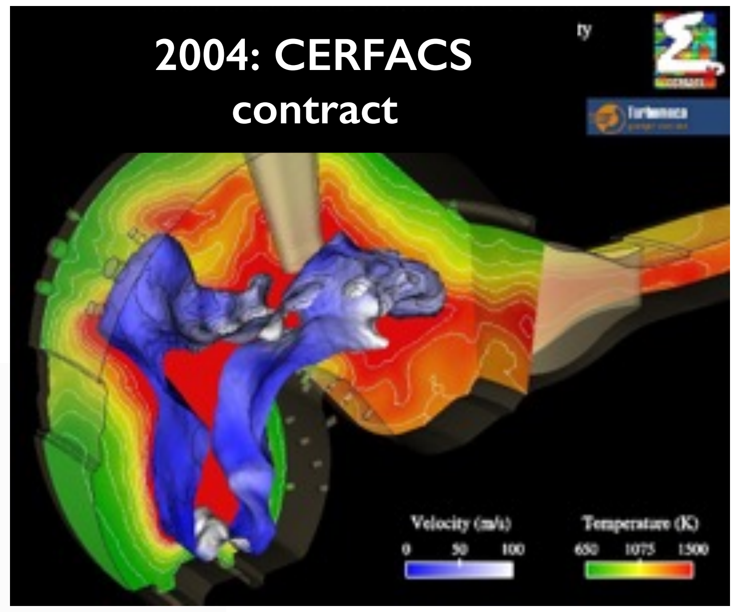
KIT two phase flow characterization



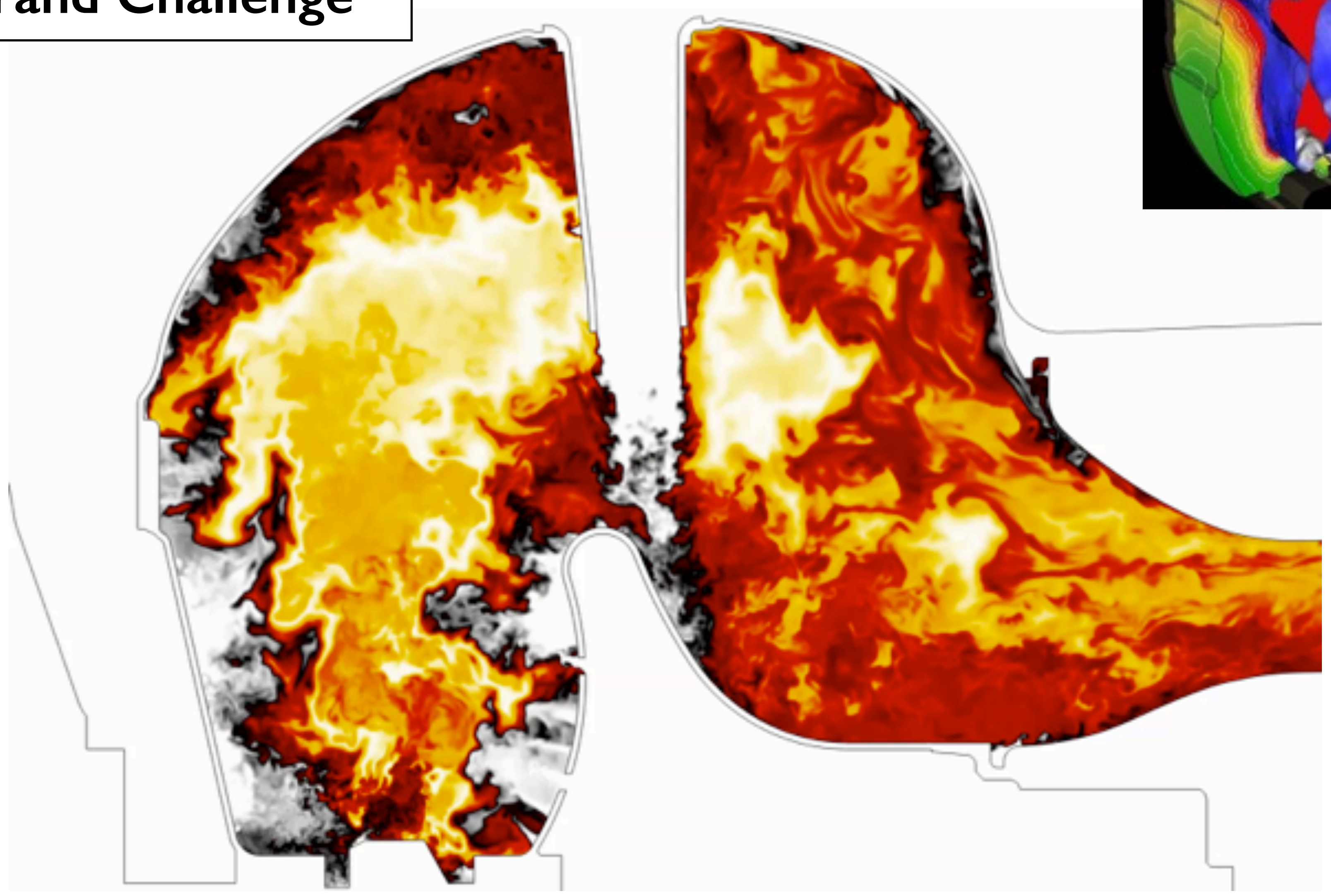
=> liquid fuel effect / atomization

CFD tools

AVBP - CERFACS


2004: CERFACS contract

2016: SAFRAN SHE Grand Challenge

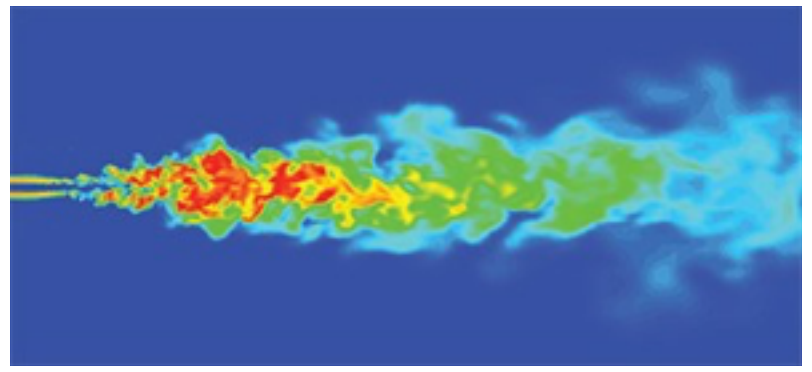
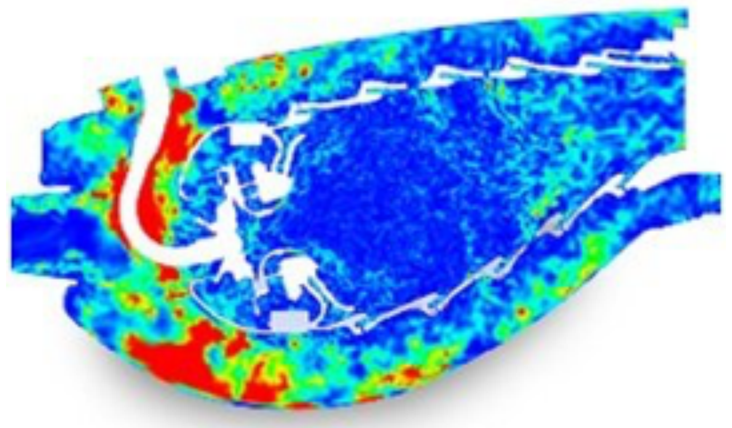


Twelve years to do:

- ~1 500 times on the number of cells and ~250 times on the number of procs
- improved reduced chemistry model *PLUS* NOx and CO (crude models)
- homogeneous vs heterogeneous multi perforated plate model
- full transfer to the industry

=> Flame transfer function evaluation / analysis

Fluent - Ansys


=> Reduced model generation

SU2
The Open-Source CFD Code

What is SU2?

SU2 is an open-source collection of software tools written in C++ and Python for the analysis of partial differential equations (PDEs) and PDE-constrained optimization problems on unstructured meshes with state-of-the-art numerical methods. SU2 is a leading technology for adjoint-based optimization. Through the initiative of users and developers around the world, SU2 is now a well established tool in the computational sciences with wide applicability to aeronautical, automotive, naval, and renewable energy industries, to name a few.

Find a detailed description of the code philosophy, components, and implementations in the SU2 AIAA Journal article. Whether it's discrete adjoints, non-ideal compressible CFD, or high-performance computing, SU2 has something for you.

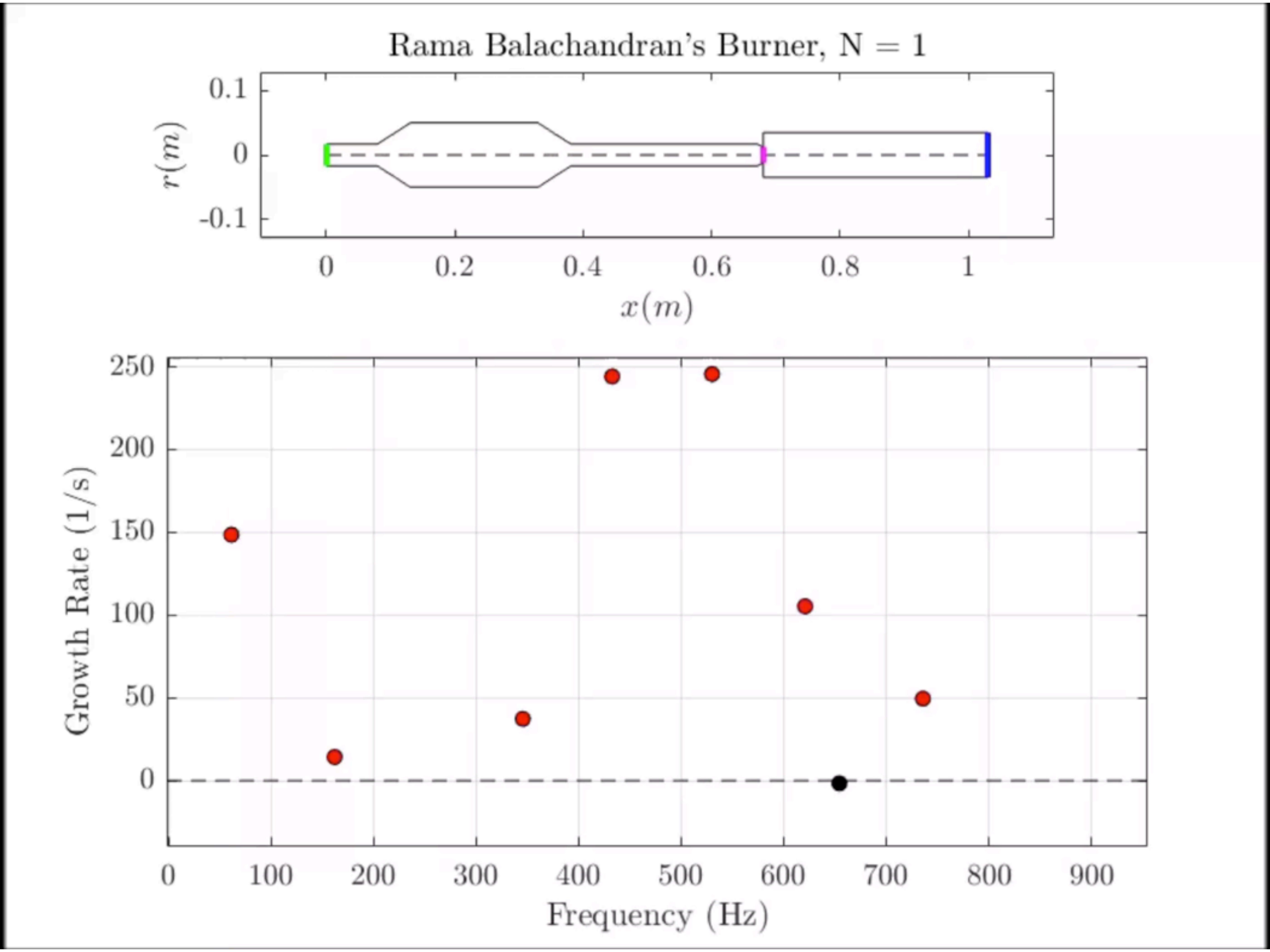
=> Numerics and modeling

Reduced order models

Physics based models:

- usually constructed on the basis of the planar wave hypothesis (1D acoustics)
- required inputs from more detailed analyses: Flame Transfer Function / Damping…
- very versatile and fast
- strong mathematical background giving access to optimization

=> How to make such tools *engine relevant* and *adaptive*



Courtesy of Prof. M. Juniper (Cambridge University - head of Energy group)

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MAGISTER - https://www.utwente.nl/en/et/magister/

Formation workshops (every 6 months) and summer schools - open to all

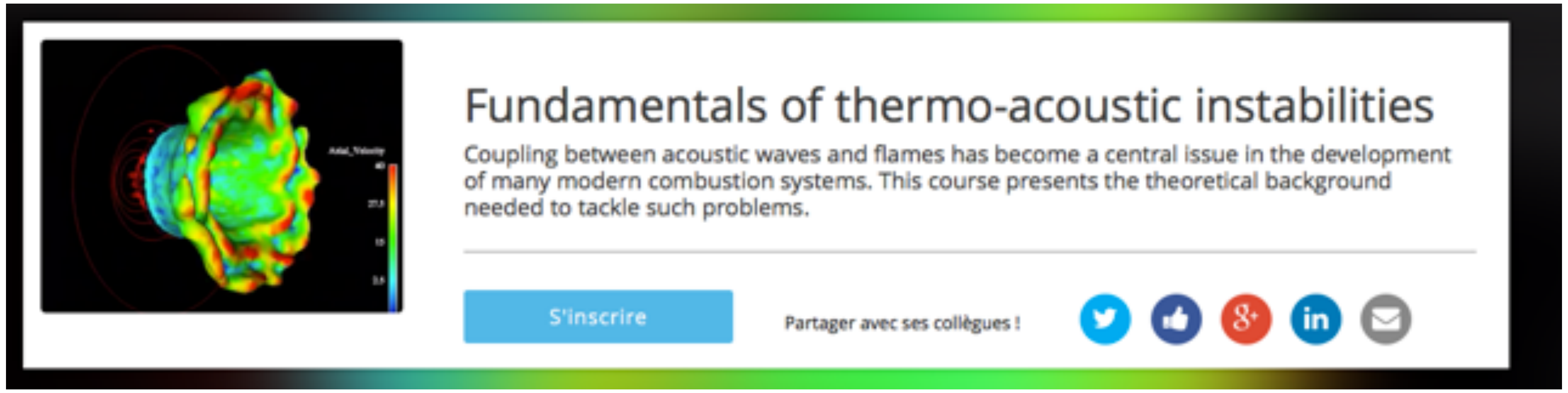
- ***Wednesday 19th - Friday 21st September***
  Workshop A on Machine Learning, Combustion and Acoustics in aero engine combustors
  - Prof Carl Rasmussen, Cambridge University

- ***Monday 24th September – Wednesday 26th September***
  Summer School on Thermo-acoustics and combustion dynamics in aero gas turbine engines
  - Prof Wolfgang Polifke – TUM
  - Prof Tim Lieuwen – Georgia Tech
  - Prof Aimee Morgan - ICL

Thursday 27th September
Rolls Royce visit

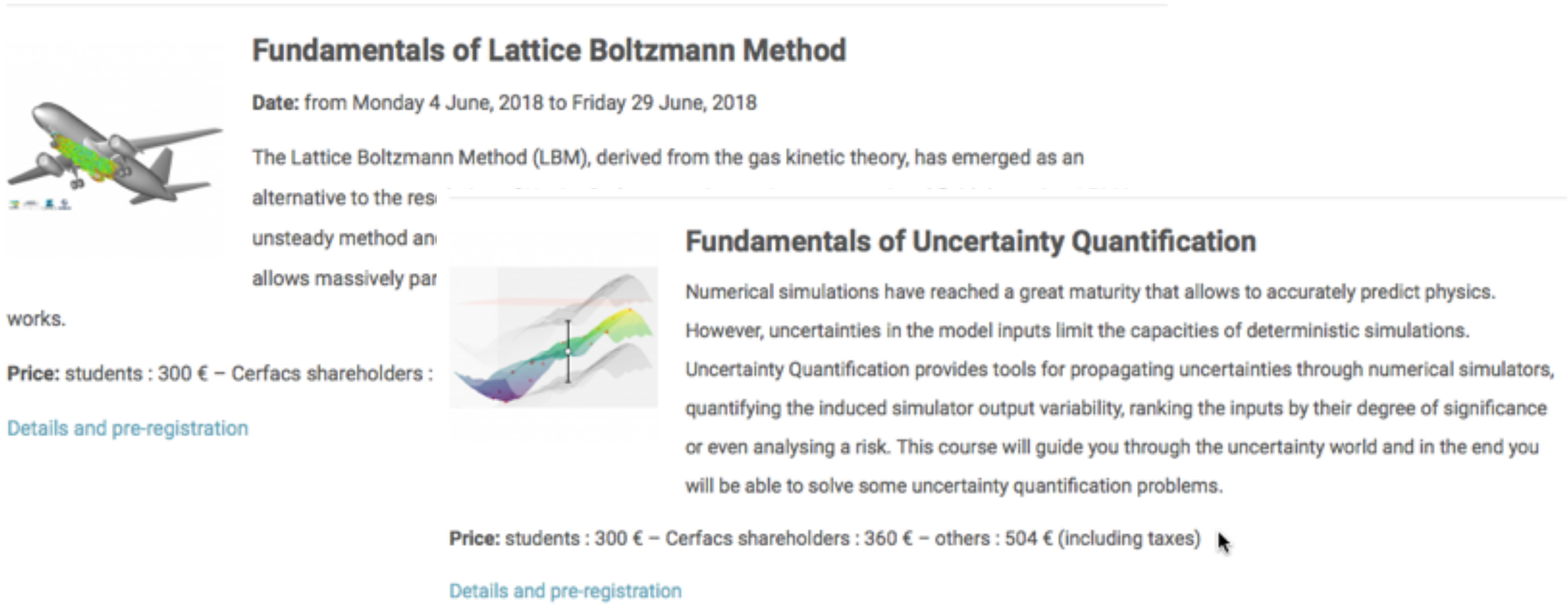
SPOC

https://cerfacs.fr/en/online-training/



Fundamentals of thermo-acoustic instabilities

Coupling between acoustic waves and flames has become a central issue in the development of many modern combustion systems. This course presents the theoretical background needed to tackle such problems.



Fundamentals of Lattice Boltzmann Method

Date: from Monday 4 June, 2018 to Friday 29 June, 2018

The Lattice Boltzmann Method (LBM), derived from the gas kinetic theory, has emerged as an alternative to the res unsteady method an allows massively par works.

Price: students : 300 € – Cerfacs shareholders :

Details and pre-registration

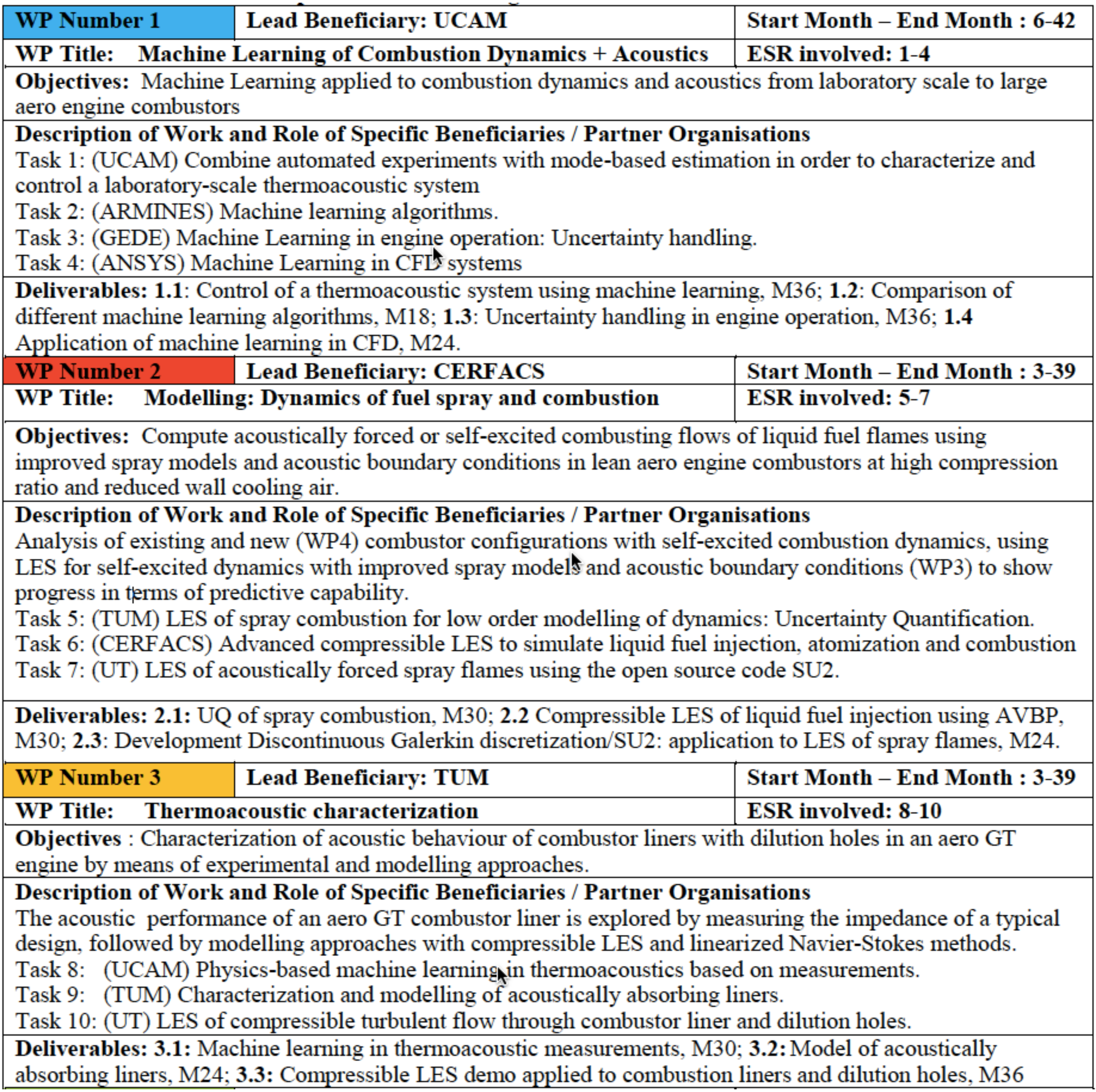
Fundamentals of Uncertainty Quantification

Numerical simulations have reached a great maturity that allows to accurately predict physics. However, uncertainties in the model inputs limit the capacities of deterministic simulations. Uncertainty Quantification provides tools for propagating uncertainties through numerical simulators, quantifying the induced simulator output variability, ranking the inputs by their degree of significance or even analysing a risk. This course will guide you through the uncertainty world and in the end you will be able to solve some uncertainty quantification problems.

Price: students : 300 € – Cerfacs shareholders : 360 € – others : 504 € (including taxes)

Details and pre-registration

List of work packages - <u>5 WP</u>



WP Number 1	**Lead Beneficiary: UCAM**	**Start Month – End Month : 6-42**
WP Title: Machine Learning of Combustion Dynamics + Acoustics		**ESR involved: 1-4**

Objectives: Machine Learning applied to combustion dynamics and acoustics from laboratory scale to large aero engine combustors

Description of Work and Role of Specific Beneficiaries / Partner Organisations
Task 1: (UCAM) Combine automated experiments with mode-based estimation in order to characterize and control a laboratory-scale thermoacoustic system
Task 2: (ARMINES) Machine learning algorithms.
Task 3: (GEDE) Machine Learning in engine operation: Uncertainty handling.
Task 4: (ANSYS) Machine Learning in CFD systems

Deliverables: 1.1: Control of a thermoacoustic system using machine learning, M36; **1.2**: Comparison of different machine learning algorithms, M18; **1.3**: Uncertainty handling in engine operation, M36; **1.4** Application of machine learning in CFD, M24.

WP Number 2	**Lead Beneficiary: CERFACS**	**Start Month – End Month : 3-39**
WP Title: Modelling: Dynamics of fuel spray and combustion		**ESR involved: 5-7**

Objectives: Compute acoustically forced or self-excited combusting flows of liquid fuel flames using improved spray models and acoustic boundary conditions in lean aero engine combustors at high compression ratio and reduced wall cooling air.

Description of Work and Role of Specific Beneficiaries / Partner Organisations
Analysis of existing and new (WP4) combustor configurations with self-excited combustion dynamics, using LES for self-excited dynamics with improved spray models and acoustic boundary conditions (WP3) to show progress in terms of predictive capability.
Task 5: (TUM) LES of spray combustion for low order modelling of dynamics: Uncertainty Quantification.
Task 6: (CERFACS) Advanced compressible LES to simulate liquid fuel injection, atomization and combustion
Task 7: (UT) LES of acoustically forced spray flames using the open source code SU2.

Deliverables: 2.1: UQ of spray combustion, M30; **2.2** Compressible LES of liquid fuel injection using AVBP, M30; **2.3**: Development Discontinuous Galerkin discretization/SU2: application to LES of spray flames, M24.

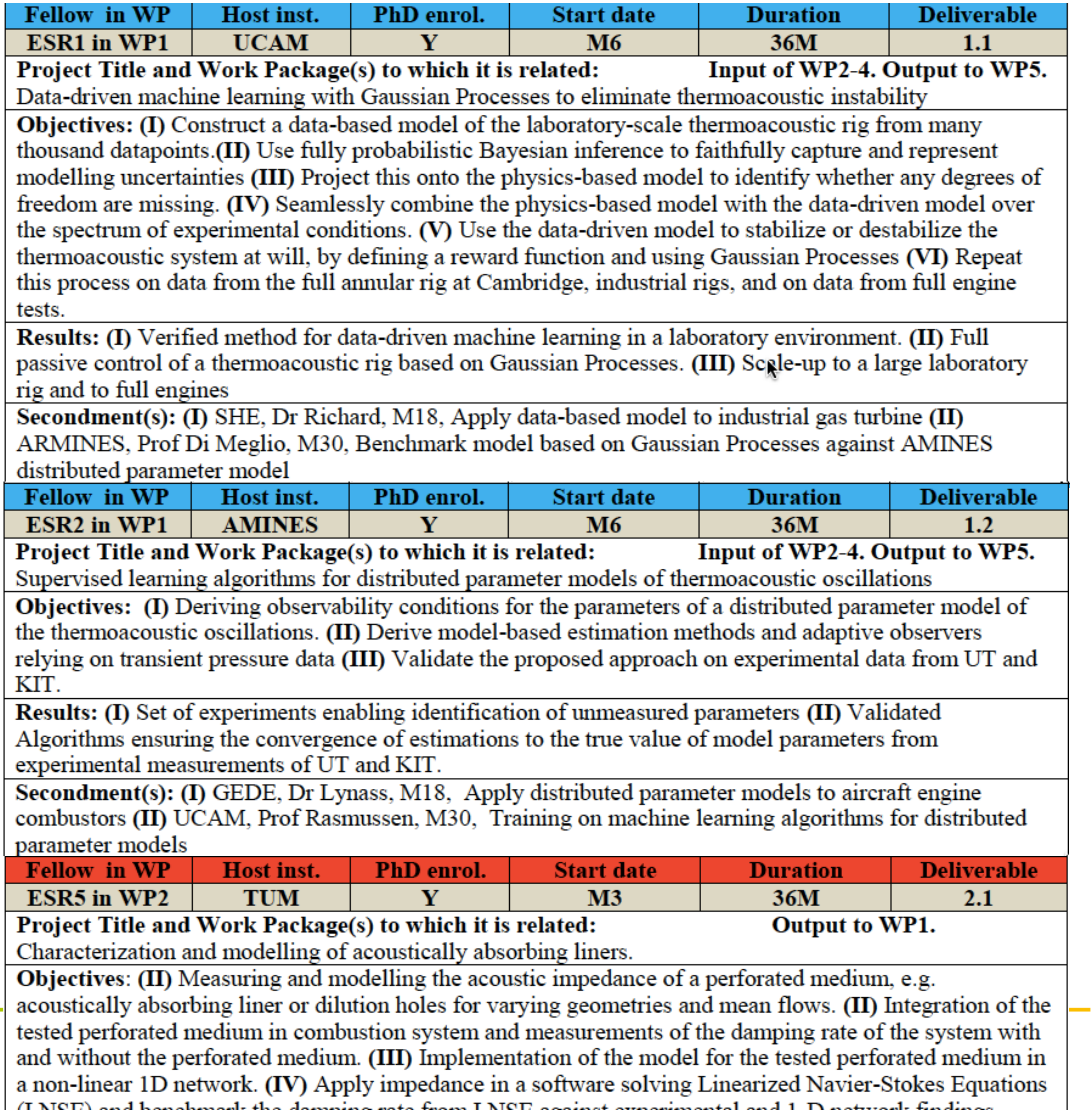
WP Number 3	**Lead Beneficiary: TUM**	**Start Month – End Month : 3-39**
WP Title: Thermoacoustic characterization		**ESR involved: 8-10**

Objectives : Characterization of acoustic behaviour of combustor liners with dilution holes in an aero GT engine by means of experimental and modelling approaches.

Description of Work and Role of Specific Beneficiaries / Partner Organisations
The acoustic performance of an aero GT combustor liner is explored by measuring the impedance of a typical design, followed by modelling approaches with compressible LES and linearized Navier-Stokes methods.
Task 8: (UCAM) Physics-based machine learning in thermoacoustics based on measurements.
Task 9: (TUM) Characterization and modelling of acoustically absorbing liners.
Task 10: (UT) LES of compressible turbulent flow through combustor liner and dilution holes.

Deliverables: 3.1: Machine learning in thermoacoustic measurements, M30; **3.2:** Model of acoustically absorbing liners, M24; **3.3:** Compressible LES demo applied to combustion liners and dilution holes, M36

Individual Fellow programs - <u>15 ESR</u>



Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR1 in WP1	UCAM	Y	M6	36M	1.1

Project Title and Work Package(s) to which it is related: **Input of WP2-4. Output to WP5.**
Data-driven machine learning with Gaussian Processes to eliminate thermoacoustic instability

Objectives: (I) Construct a data-based model of the laboratory-scale thermoacoustic rig from many thousand datapoints.**(II)** Use fully probabilistic Bayesian inference to faithfully capture and represent modelling uncertainties **(III)** Project this onto the physics-based model to identify whether any degrees of freedom are missing. **(IV)** Seamlessly combine the physics-based model with the data-driven model over the spectrum of experimental conditions. **(V)** Use the data-driven model to stabilize or destabilize the thermoacoustic system at will, by defining a reward function and using Gaussian Processes **(VI)** Repeat this process on data from the full annular rig at Cambridge, industrial rigs, and on data from full engine tests.

Results: (I) Verified method for data-driven machine learning in a laboratory environment. **(II)** Full passive control of a thermoacoustic rig based on Gaussian Processes. **(III)** Scale-up to a large laboratory rig and to full engines

Secondment(s): (I) SHE, Dr Richard, M18, Apply data-based model to industrial gas turbine **(II)** ARMINES, Prof Di Meglio, M30, Benchmark model based on Gaussian Processes against AMINES distributed parameter model

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR2 in WP1	AMINES	Y	M6	36M	1.2

Project Title and Work Package(s) to which it is related: **Input of WP2-4. Output to WP5.**
Supervised learning algorithms for distributed parameter models of thermoacoustic oscillations

Objectives: (I) Deriving observability conditions for the parameters of a distributed parameter model of the thermoacoustic oscillations. **(II)** Derive model-based estimation methods and adaptive observers relying on transient pressure data **(III)** Validate the proposed approach on experimental data from UT and KIT.

Results: (I) Set of experiments enabling identification of unmeasured parameters **(II)** Validated Algorithms ensuring the convergence of estimations to the true value of model parameters from experimental measurements of UT and KIT.

Secondment(s): (I) GEDE, Dr Lynass, M18, Apply distributed parameter models to aircraft engine combustors **(II)** UCAM, Prof Rasmussen, M30, Training on machine learning algorithms for distributed parameter models

Fellow in WP	Host inst.	PhD enrol.	Start date	Duration	Deliverable
ESR5 in WP2	TUM	Y	M3	36M	2.1

Project Title and Work Package(s) to which it is related: **Output to WP1.**
Characterization and modelling of acoustically absorbing liners.

Objectives: **(II)** Measuring and modelling the acoustic impedance of a perforated medium, e.g. acoustically absorbing liner or dilution holes for varying geometries and mean flows. **(II)** Integration of the tested perforated medium in combustion system and measurements of the damping rate of the system with and without the perforated medium. **(III)** Implementation of the model for the tested perforated medium in a non-linear 1D network. **(IV)** Apply impedance in a software solving Linearized Navier-Stokes Equations (LNSE) and benchmark the damping rate from LNSE against experimental and 1-D network findings

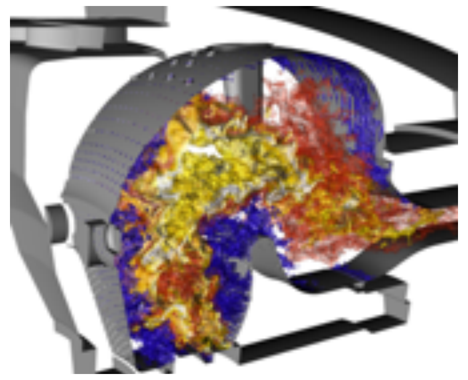
Conclusions & Perspectives

Clearly brings opportunities but the difficulty is today to incorporate such tools into an existing framework where data is not necessarily accessible and as large or even as specific as for the GAFA….

=> let's see how smart we can get - see you in 4 years

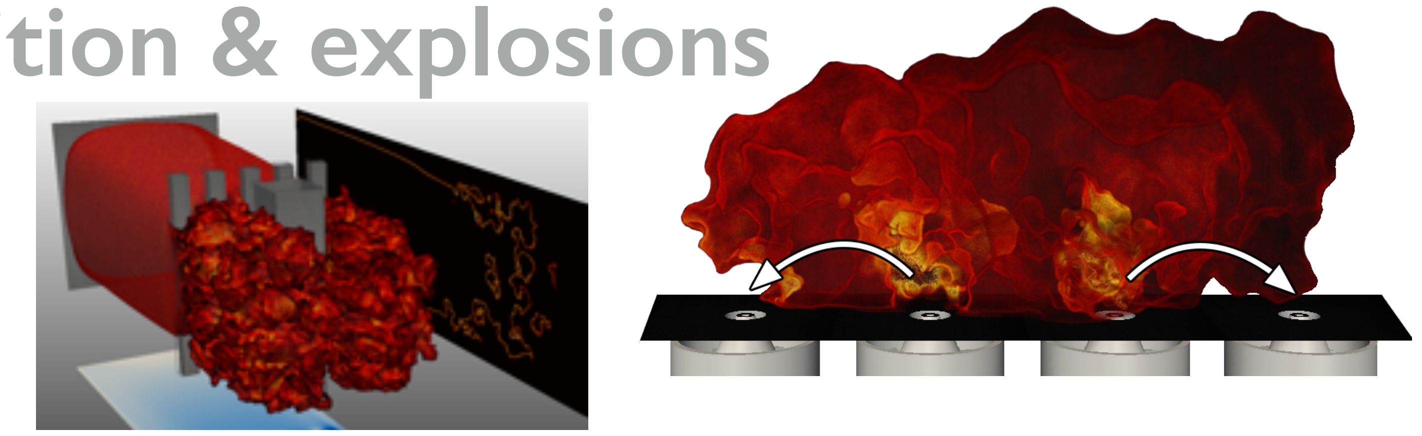
Transfer to industry of the CERFACS LES based solution is now *acquired* but the new challenge and request from the partners is to provide a ***multipurpose LES modeling context***:

- Industrial design

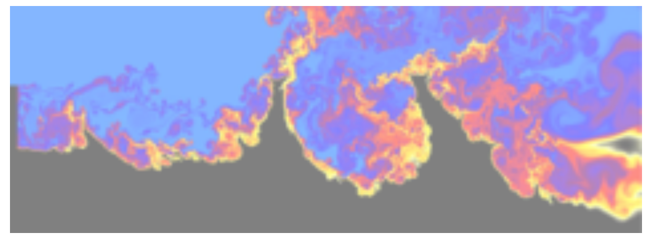


=> to be pursued

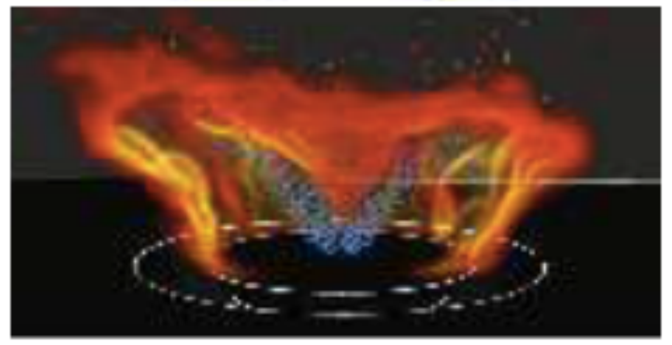
- Ignition & explosions



- Real gas applications



- **Two-phase flows**

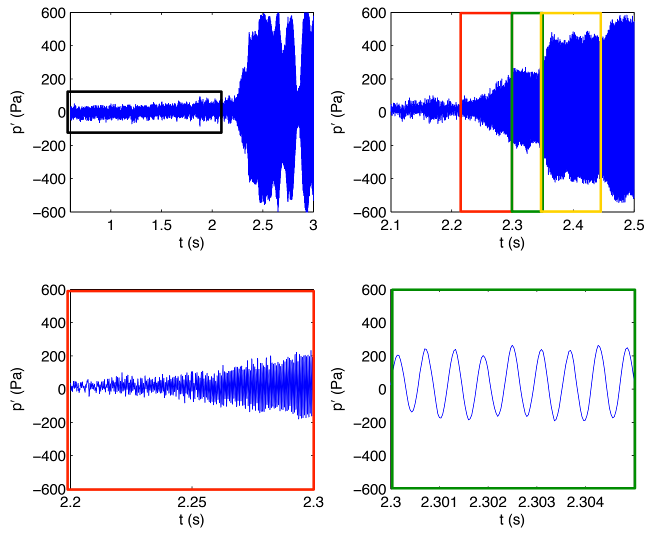


=> to be pursued

- etc…

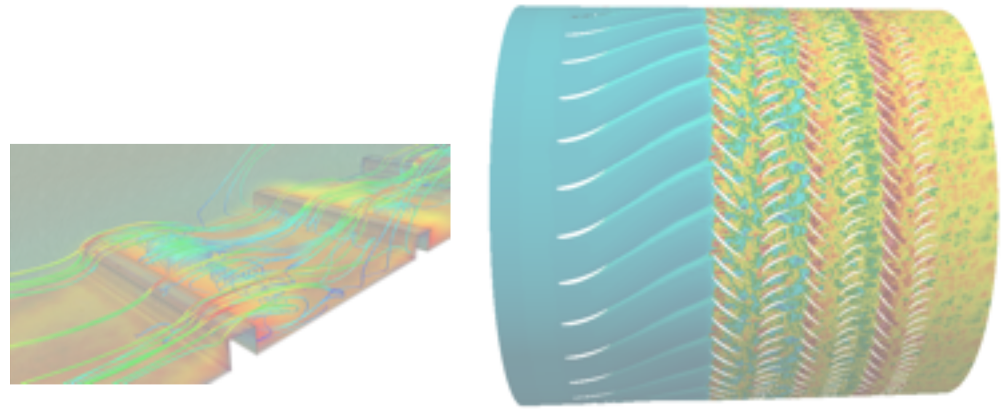
- **Thermo acoustic instabilities**

=> to be pursued



Courtesy of Worth and Dawson (private communication)

-Turbomachinery & heat transfer



- Improved chemistry: *pollutants*