



HPC for combustion instabilities

The ERC INTECOCIS projet in Toulouse

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Avancée en Calcul Scientifique)

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INTECOCIS: ERC (European Research Council) advanced grant (intecocis.inp-toulouse.fr)

- ERC advanced grant coordinated by IMF Toulouse and CERFACS (CNRS : adm. coord.). Started in Feb. 2013
- CERFACS provides codes and IMF provides tools as well as experiments in simple cases. 10 new scientists hired, working with those who were already here
- Multiple collaborations already established: EM2C, NTNU, Cambridge, TU Munich, Karlsruhe Inst. Tech., ETH Zurich





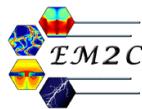
Acknowledgements

- Research is a team effort. Specially when dealing with CFD and HPC
- 10 Phd students a year , 5 permanent staff
- Lots of collaborators around the world.

A. Urbano, L. Selle, T. Poinsot (IMFT)

G. Staffelbach, B. Cuenot, L. Gicquel, O. Vermorel, E. Riber, A. Dauptain, J. Dombard, F. Duchaine, M. Bauerheim, P. Wolf, I. Hernandez, C. Lapeyre, JF Parmentier (CERFACS)

T. Schmitt, S. Ducruix, S. Candel (EM2C)



Context

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





Context

→ Pollution and climate change definitely will ...





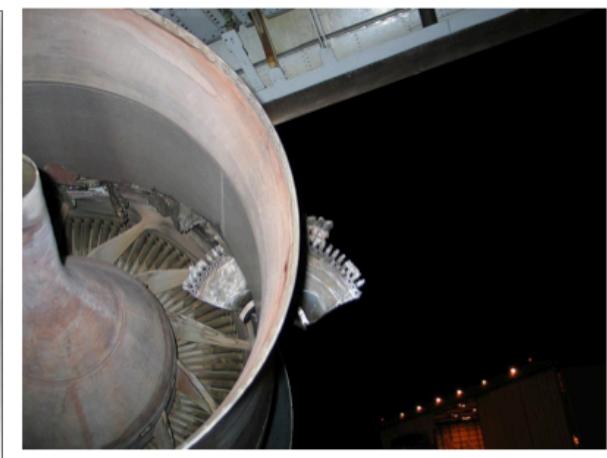
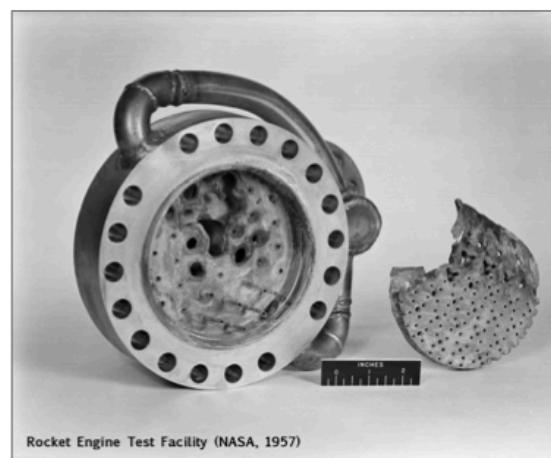
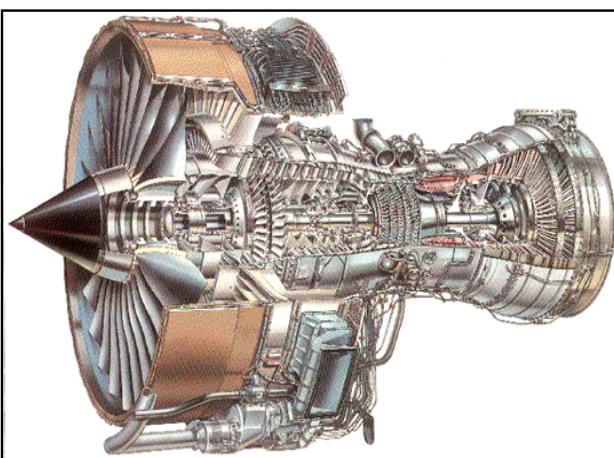
Context

- Definite need to optimise combustion processes
- Via new technologies:
 - New fuels ?
 - New materials ?
 - New operating conditions ?



Context

- Optimizing combustion is a priority but ..
- New conditions can lead to new problems ...
- ◆ One of the usual problems encountered during optimization of combustion systems is combustion ***instabilities*** (« thermoacoustics » in combustion)





What is a combustion instability ?

→ Very simple experiment (40\$)

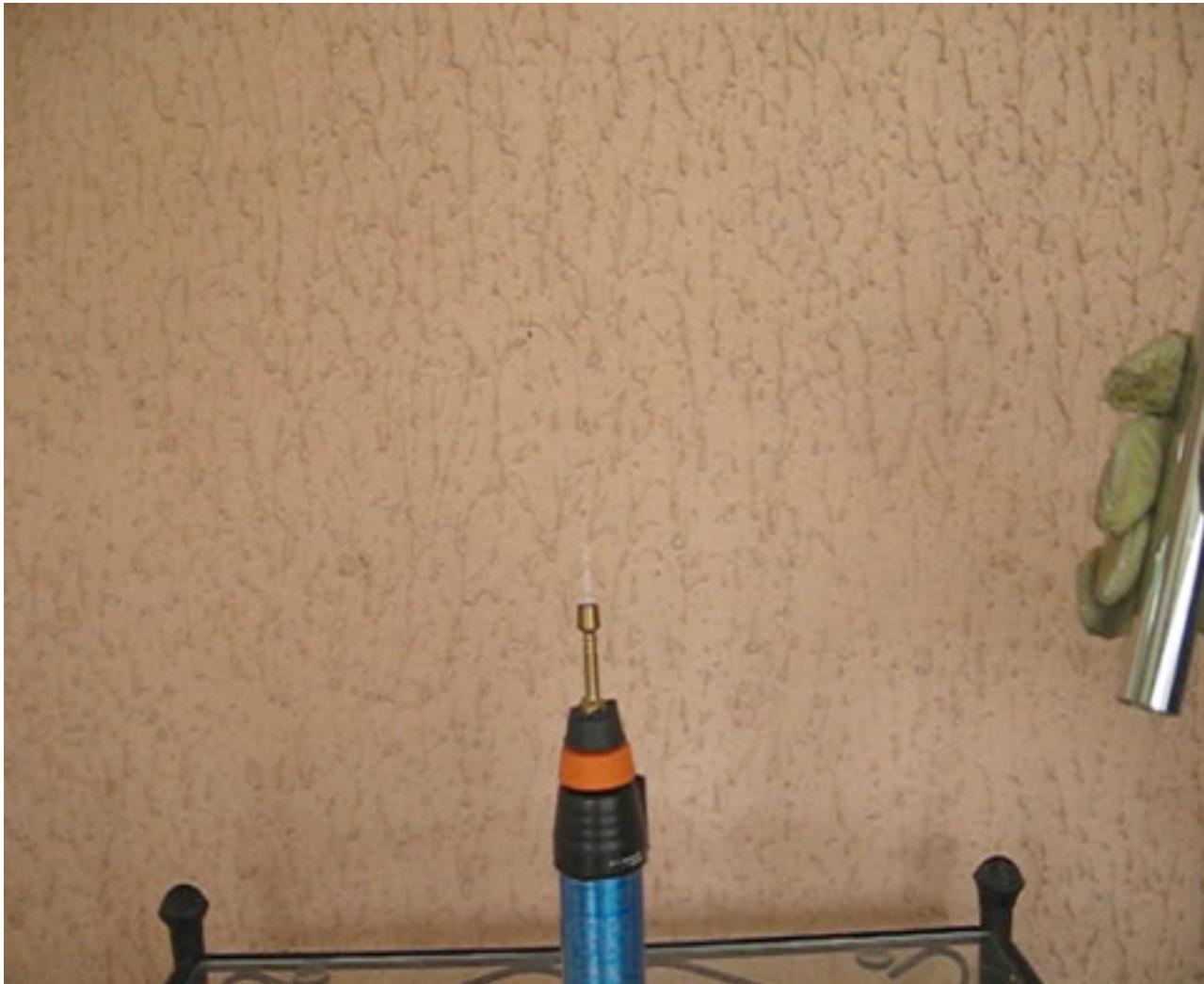


+





What is a combustion instability ?





What is a combustion instability ?





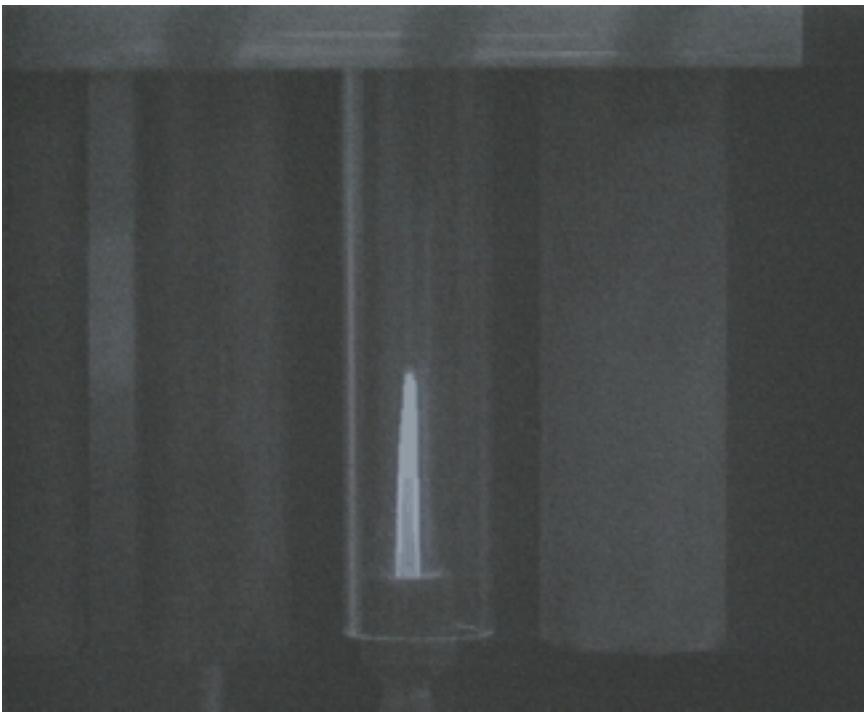
What is a combustion instability ?



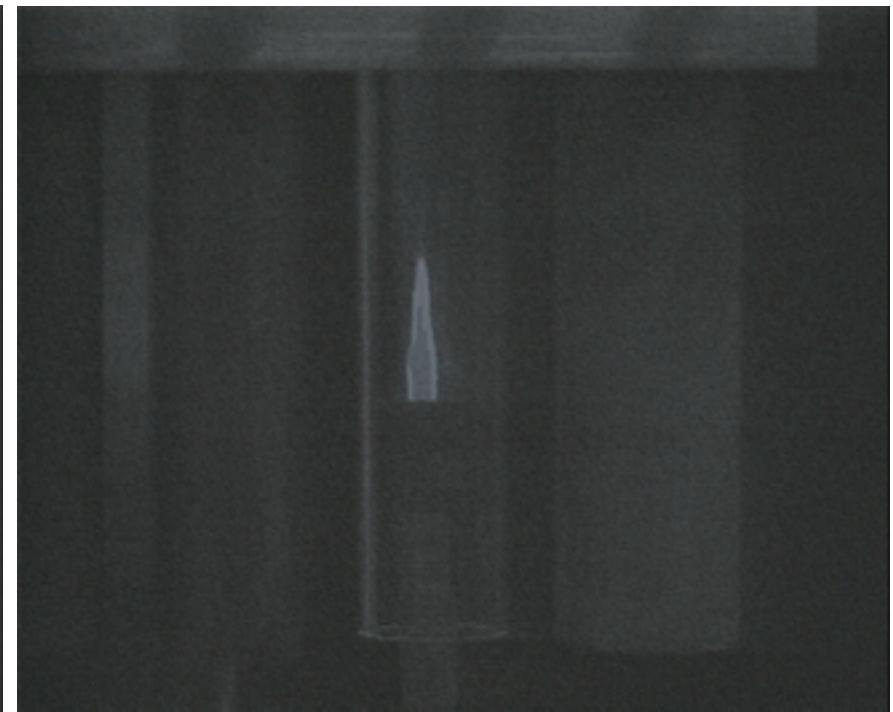


What is a combustion instability ?

- Same experiment with glass walls (Dr Durox, EM2C Paris): 2000 \$ experiment (quartz)



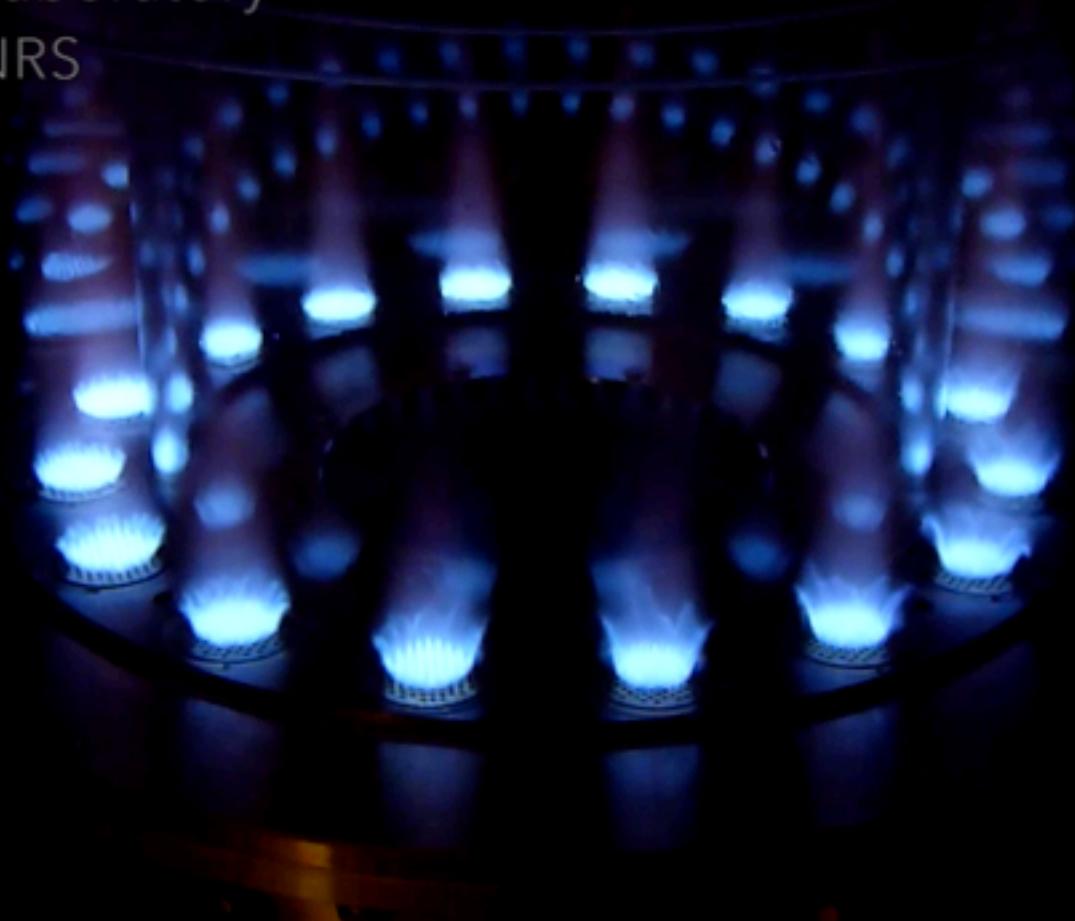
STABLE



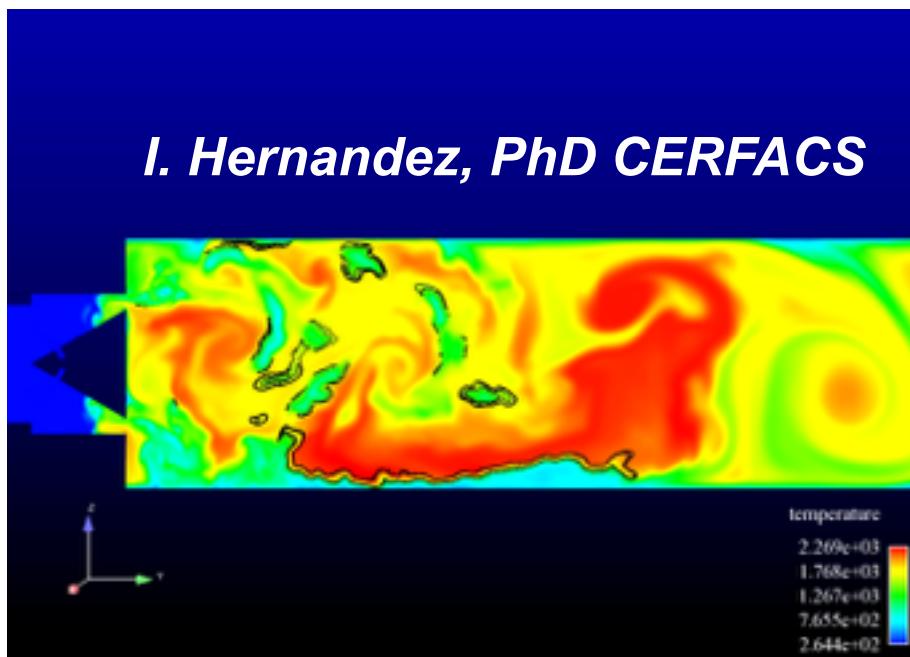
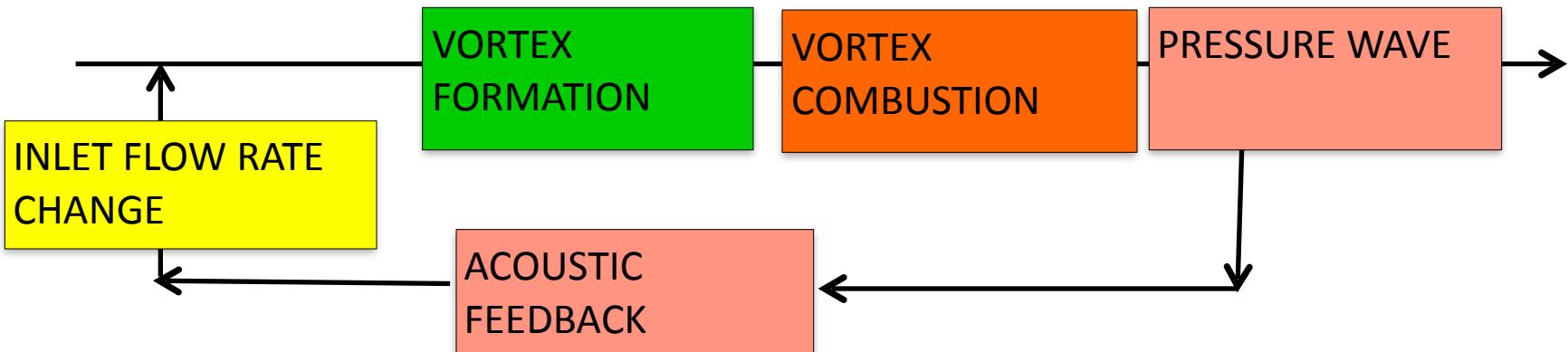
UNSTABLE



EM2C Laboratory
ECP/CNRS



Numerical approaches for thermoacoustic instabilities studies

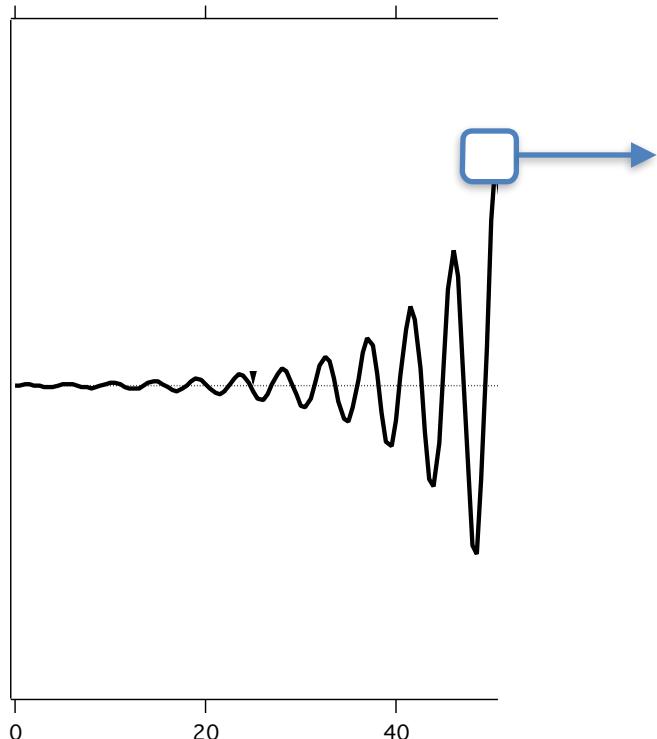


- Pressure, velocity and combustion rate oscillate simultaneously.
- Range: 100 - 3000 Hz.
- Amplitude: a few Pascal to a few bars.
- Most thermoacoustic instabilities are linearly unstable

Numerical approaches for thermoacoustic instabilities studies

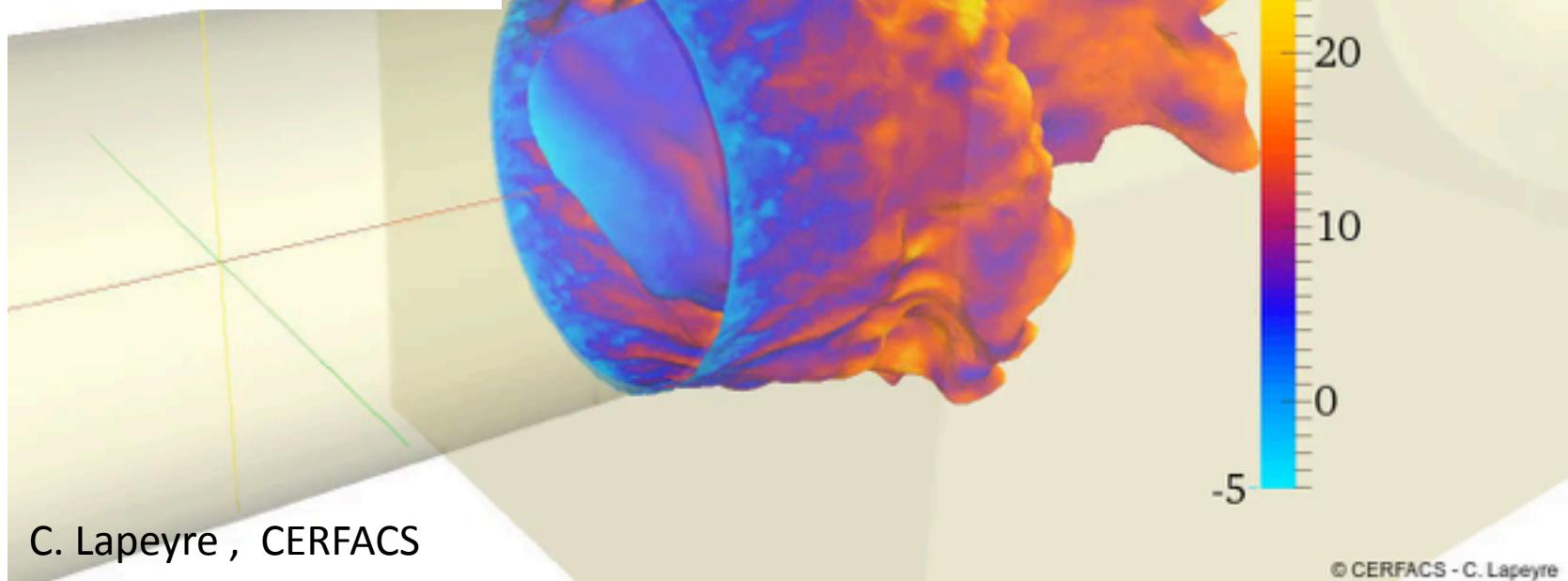
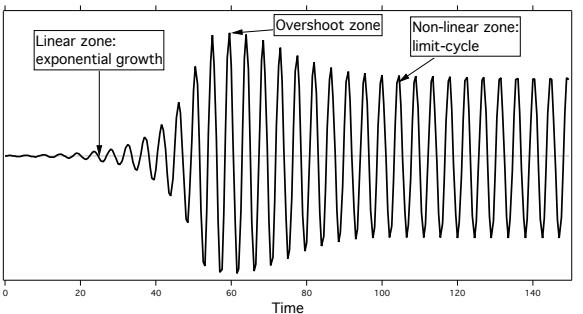
- If oscillation attain a high enough level ...

Pressure or heat release



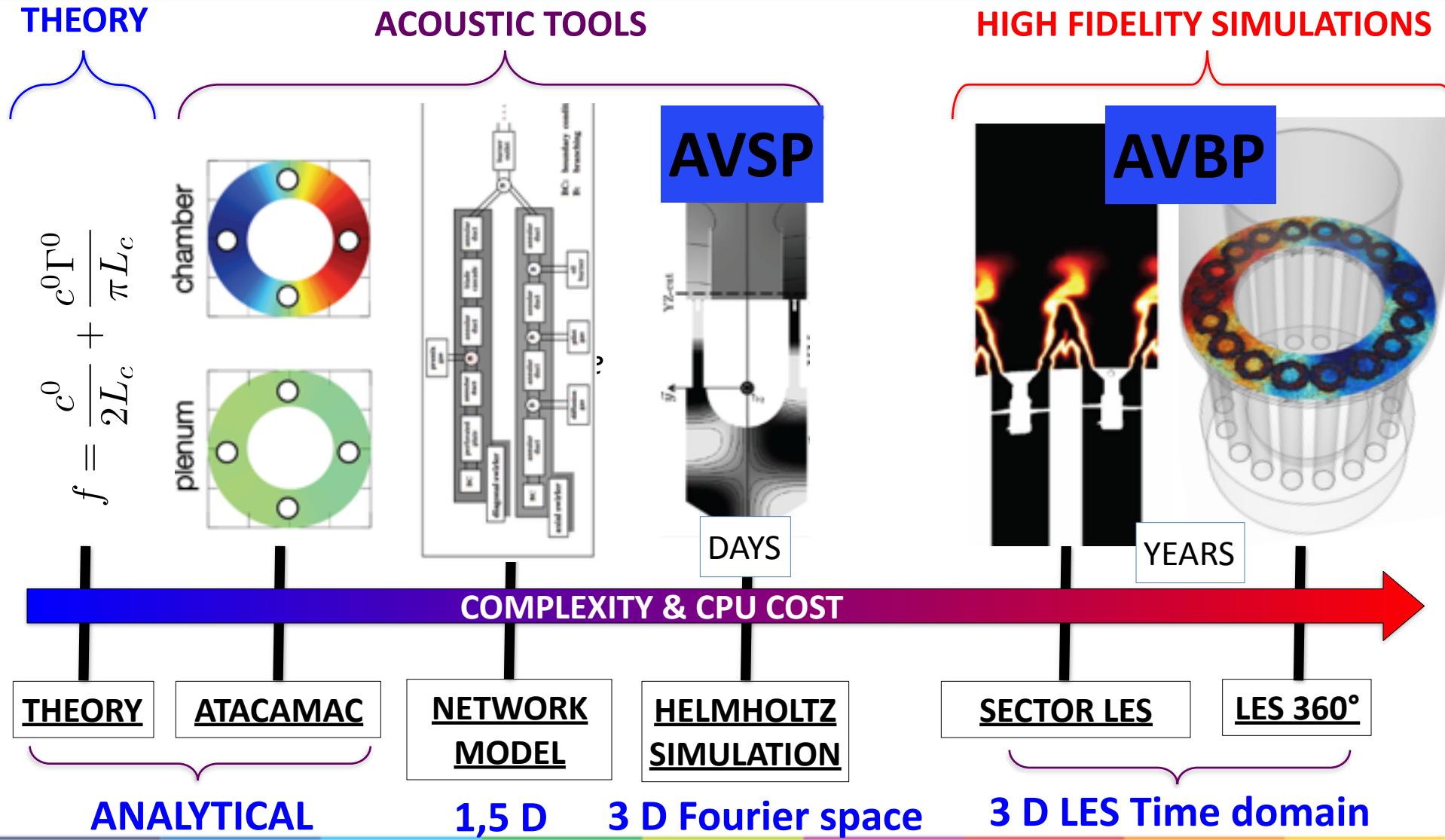
Numerical approaches for thermoacoustic instabilities studies

→ If oscillation attain a high enough level ...



C. Lapeyre , CERFACS

CERFACS/ERC Tools for thermoacoustics

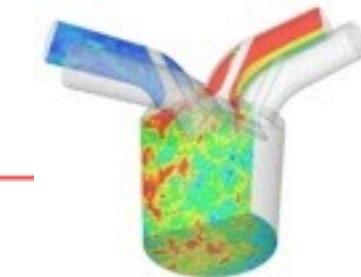
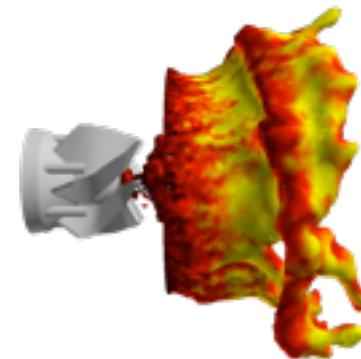
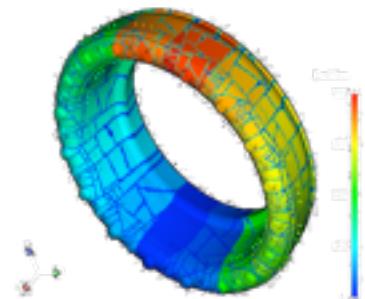
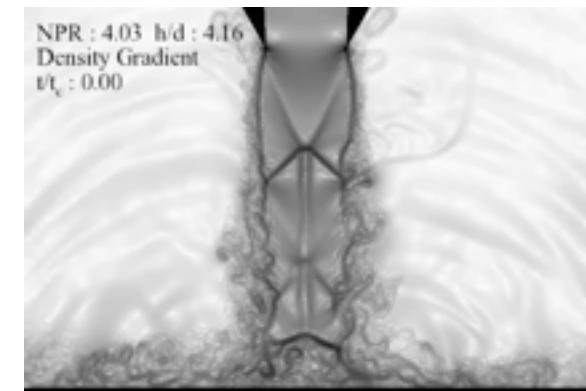
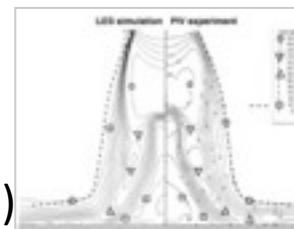
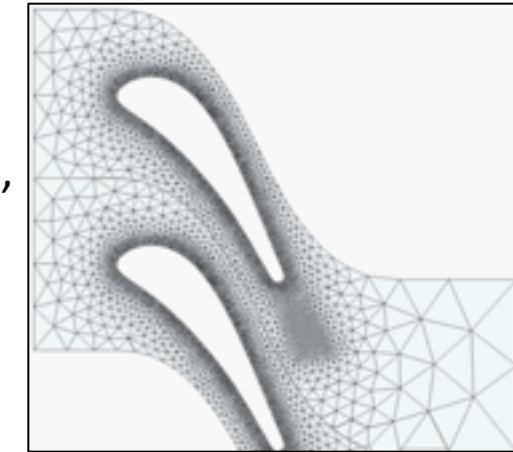




The AVBP code

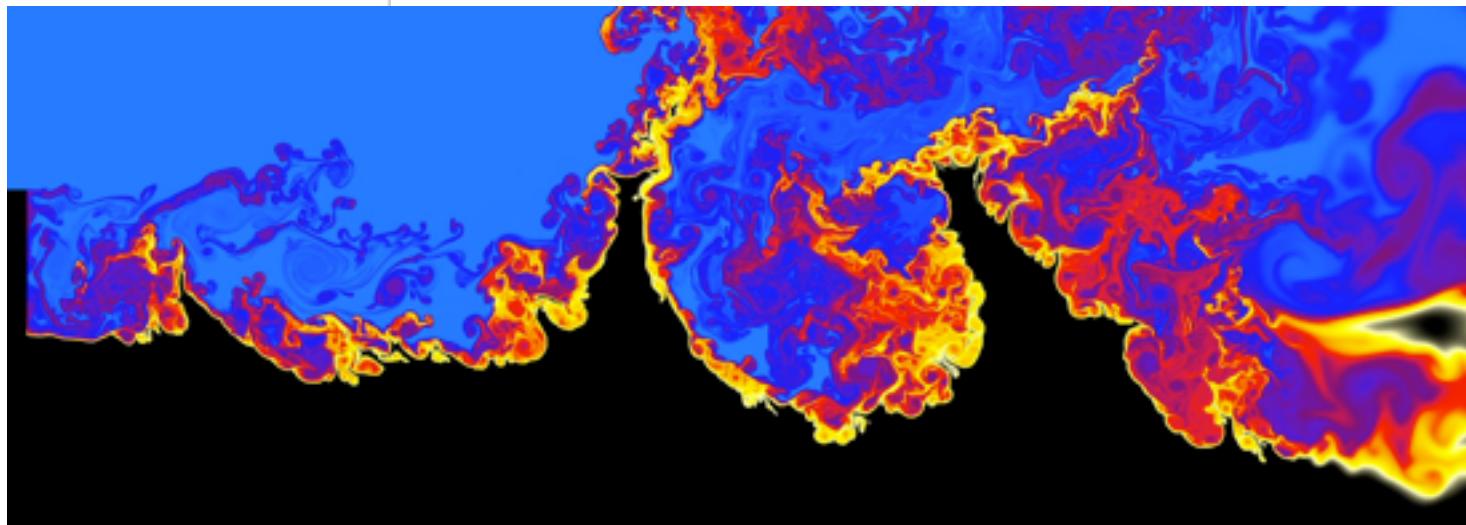
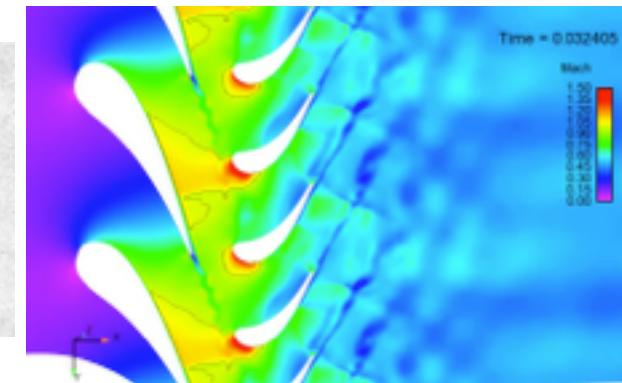
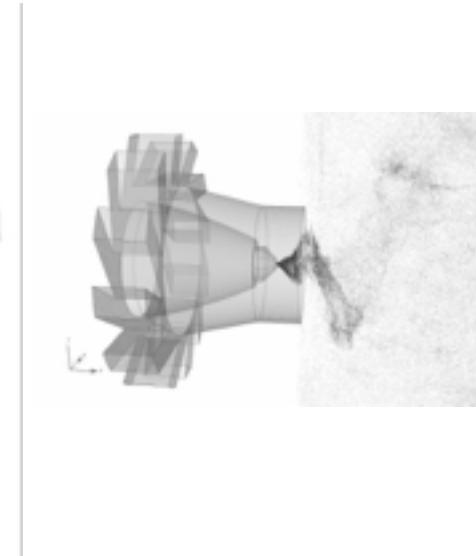
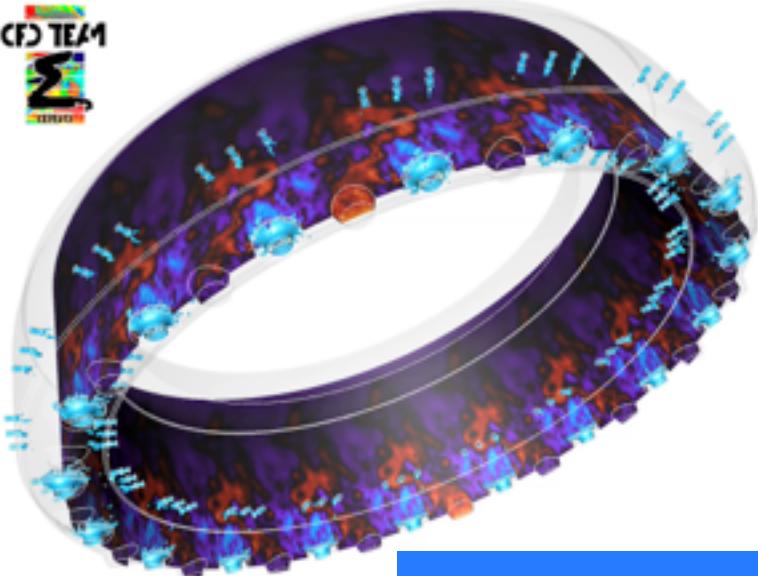


- ▶ Developed by CERFACS and IFP-EN,
- ▶ External/internal flows,
- ▶ Fully compressible turbulent reacting flows (ideal & real gases),
- ▶ DNS/LES approaches,
- ▶ Unstructured hexahedral, tetrahedral, prisms & hybrid meshes,
- ▶ Massively parallel,
- ▶ C/Fortran languages,
- ▶ SPMD approach.
- ▶ Multi-phase solvers (Lagrangian & Eulerian)



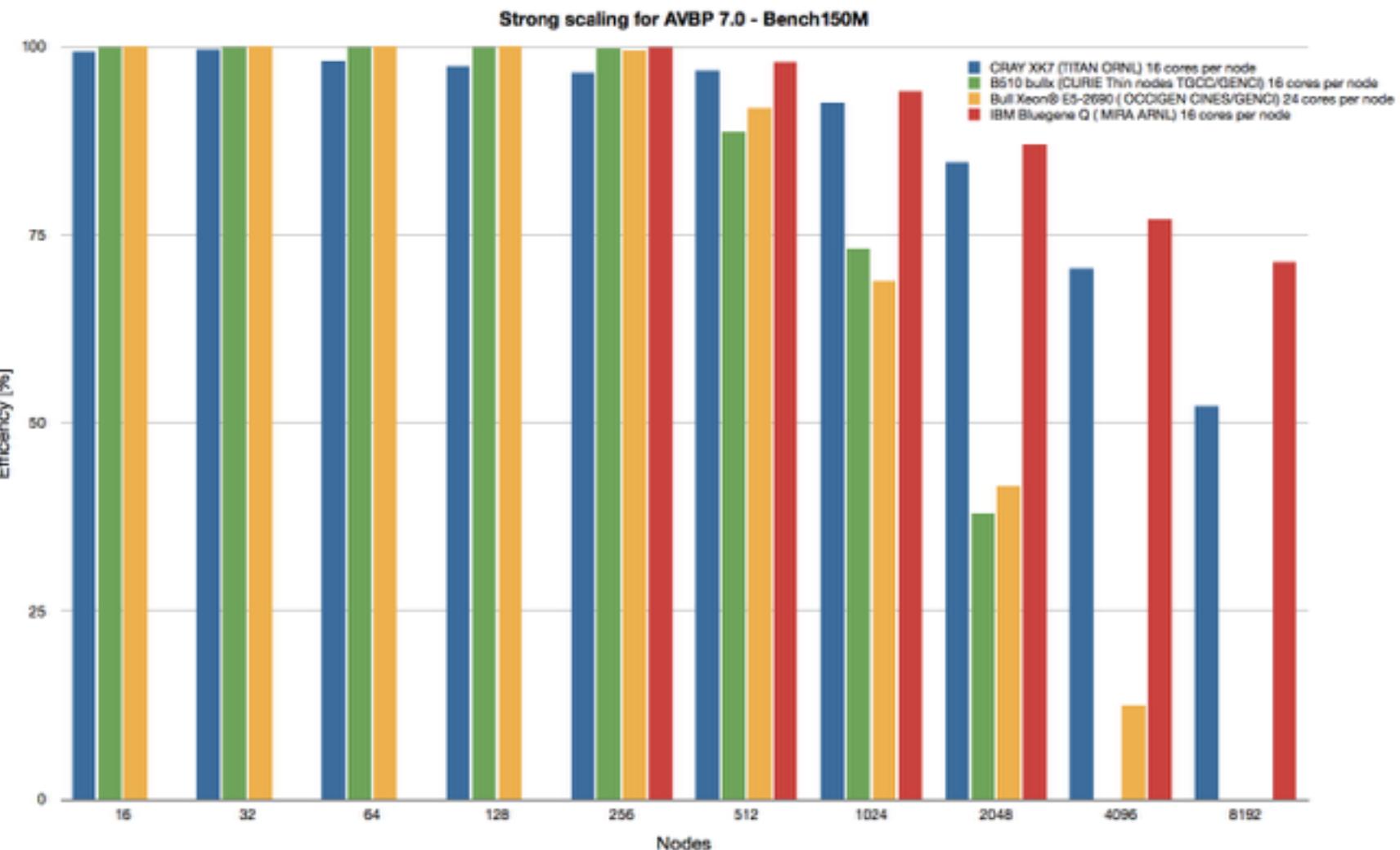


AVBP applications



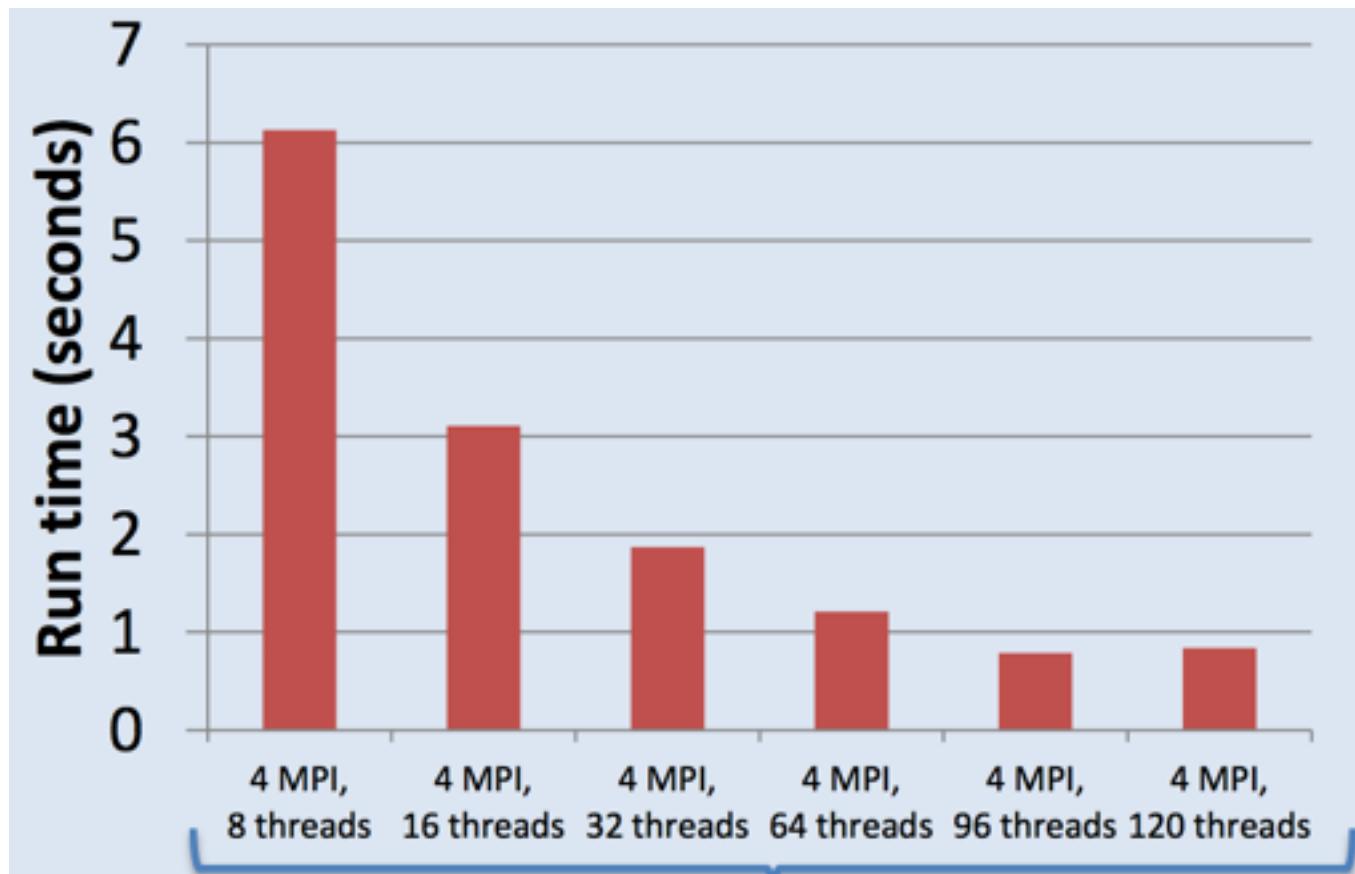


Parallel performance



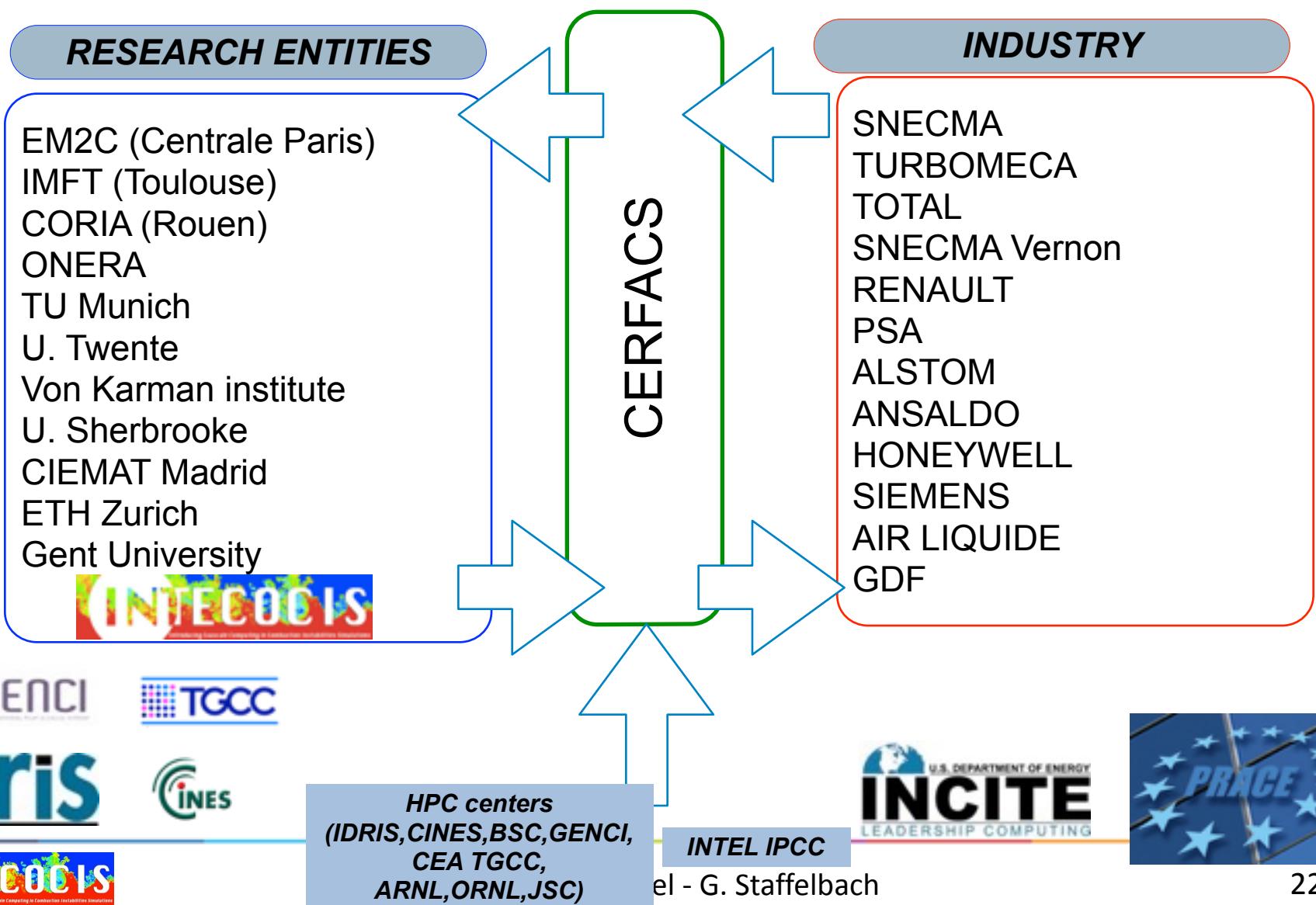


Parallel performance





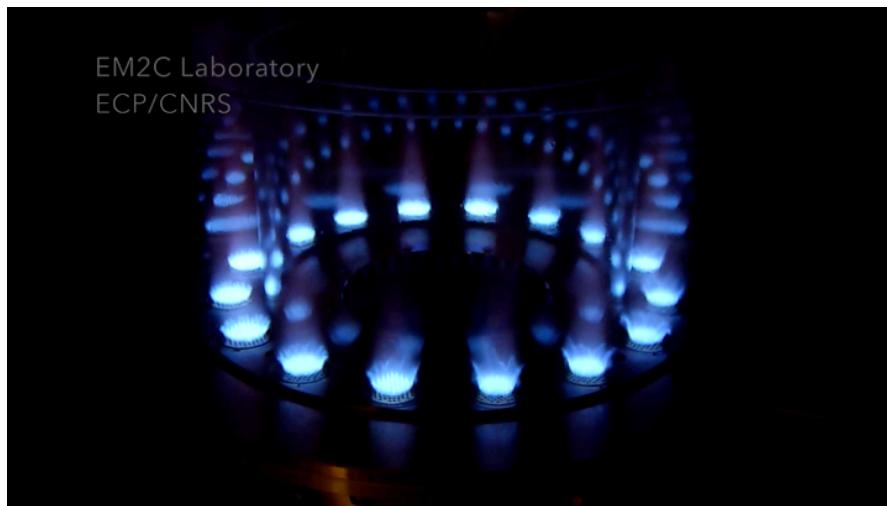
An open science project





Combustion instabilities in Gas turbines

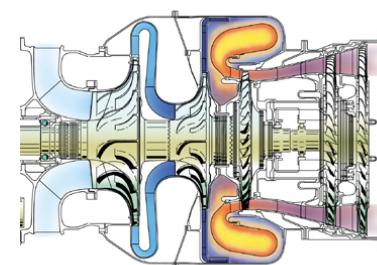
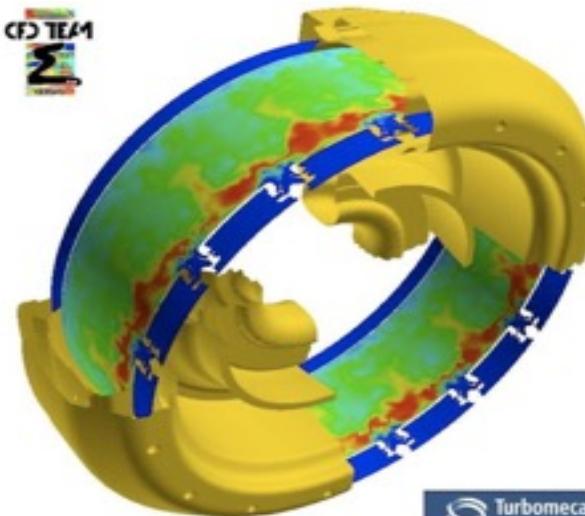
- From experiment to real turbines
- Use LES to ‘predict’ instabilities



Wolf et al Comb. Flame, 159: 3398-3413, 2012

Gicquel et al Progress in Energy and Combustion Science.
38, 782-817. 2012.

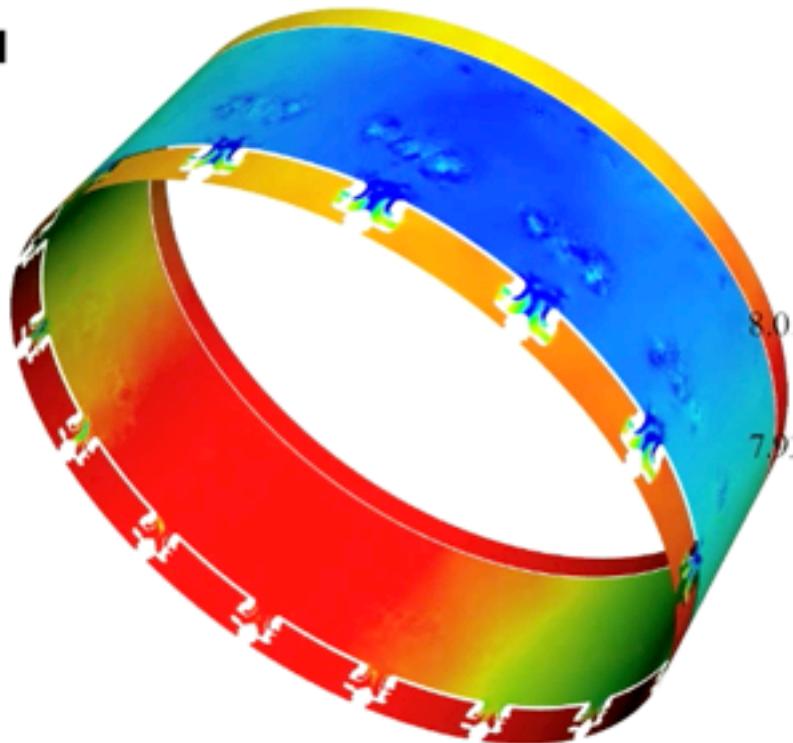
Parmentier et al Combustion and Flame 159, 7, July 2012,
2374-2387.



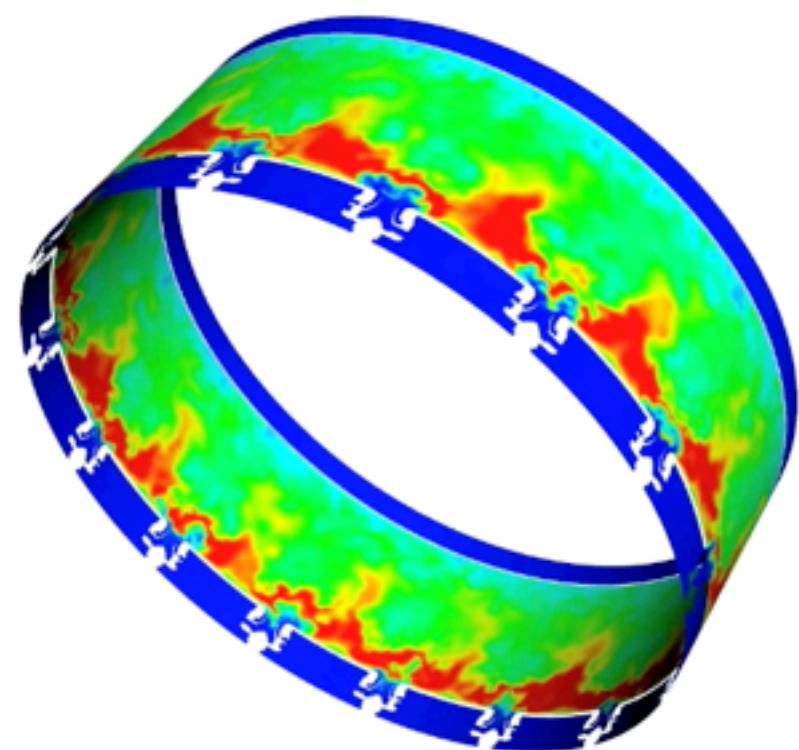


LES of full 360 Gas Turbine

- LES of a gas turbine is able to predict the azimuthal combustion instability



Pressure



Temperature

G. Staffelbach, L. Gicquel, G. Boudier, and T. Poinsot. Large Eddy Simulation of self excited azimuthal modes in annular combustors. Proc. of the Combustion Institute, 32:2909-2916, 2009.

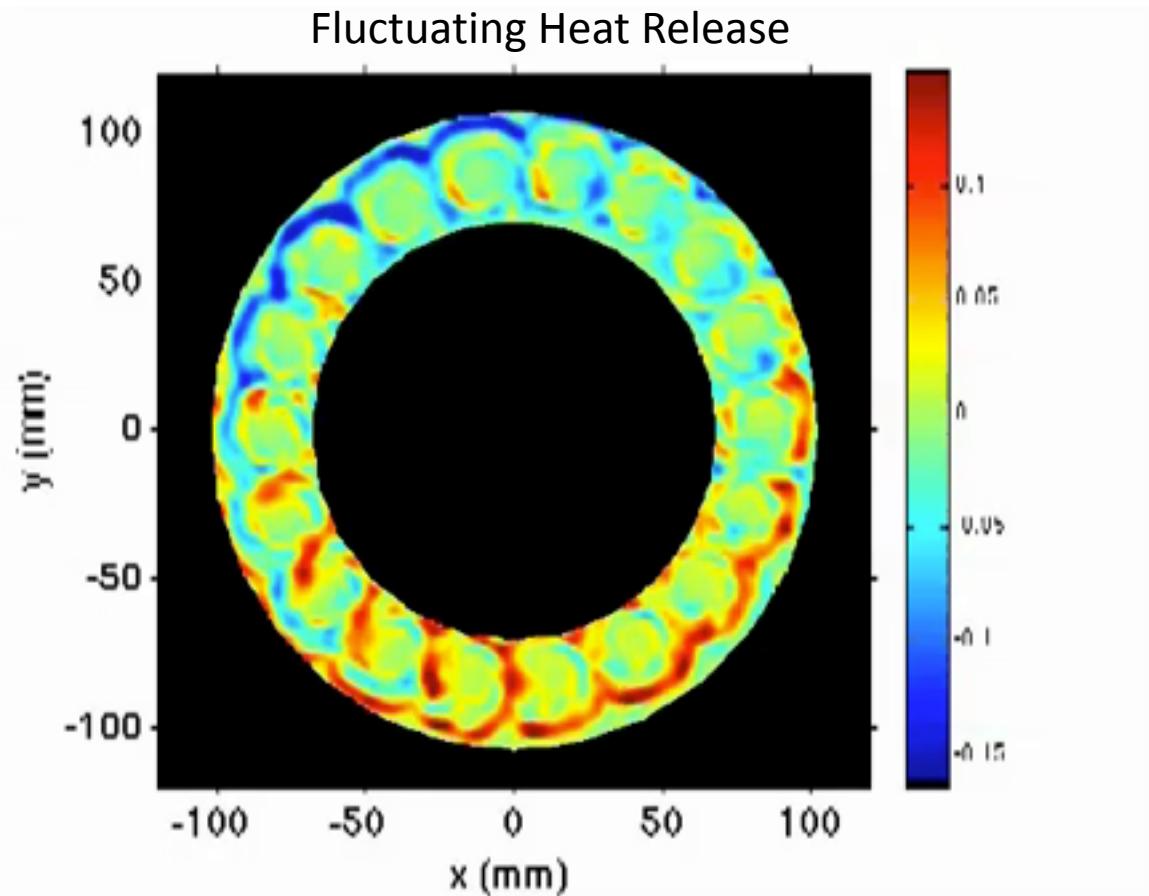
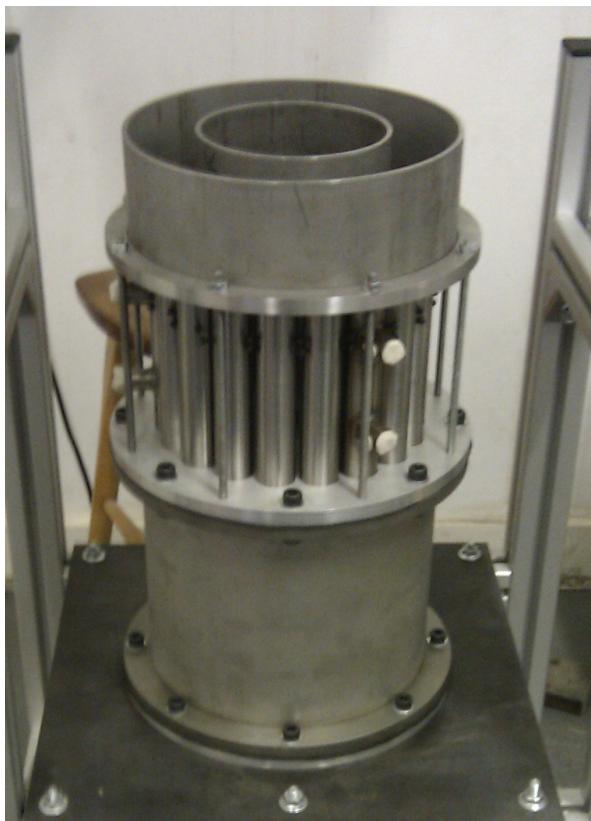
P. Wolf, R. Balakrishnan, G. Staffelbach, L. Gicquel and T. Poinsot "Using LES to study reacting flows and instabilities in annular combustion chambers", Flow, Turbulence and Combustion, 88(1-2):191-206, 2012.

P. Wolf, G. Staffelbach, L.Y.M. Gicquel, J.-D. Mueller, and T. Poinsot. Acoustic and Large Eddy Simulation studies of azimuthal modes in annular combustion chambers. Comb. Flame, 159: 3398-3413, 2012



Illustration in the lab

→ DAWSON Experiment (Cambridge 2011)

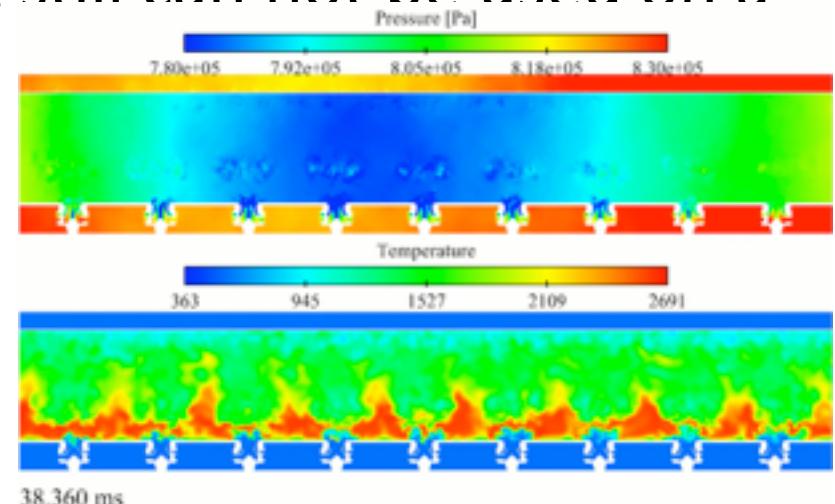


N.A. Worth, J.R. Dawson, Proc. Combust. Inst. (2012), <http://dx.doi.org/10.1016/j.proci.2012.05.061>



Combustion instabilities

- Large Eddy Simulation (with AVBP) is able to predict the combustion instability, however the computing cost is high and even though HPC is bridging the gap between costs and results it still can not be used on a parametric study basis ..
- Need cheaper/simpler tools



M. Bauerheim, J.F. Parmentier, P. Salas, F. Nicoud, T. Poinsot. An analytical model for azimuthal thermoacoustic modes in an annular chamber fed by an annular plenum, Comb. Flame, 161, 5, 2013, 1374-1389.

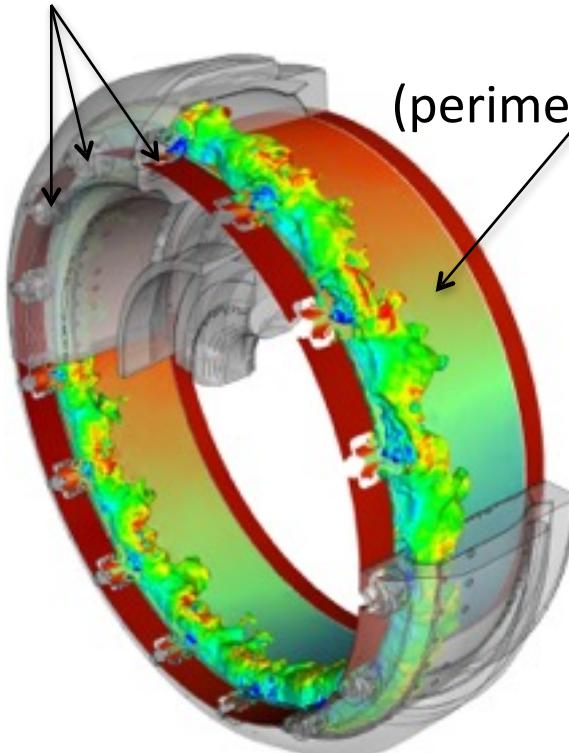
J.F. Parmentier, P. Salas, P. Wolf, G. Staffelbach, F. Nicoud and T. Poinsot, "A simple analytical model to study and control azimuthal instabilities in annular combustion chambers", Comb. Flame 159, 7, 2012, 2374-2387.

M. Bauerheim, M. Cazalens and T. Poinsot. A theoretical study of mean azimuthal flow and asymmetry effects on thermo-acoustic modes in annular combustors. Proc. Comb. Inst. 35, in press, 2015.

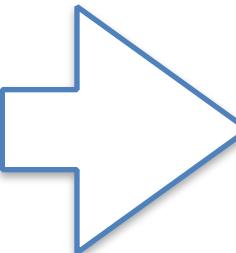
ATACAMAC: Analytical Tool to Analyze and Control Azimuthal Modes in Annular Combustors

- If we assume acoustics are the 1st order phenomena controlling the problem we can include everything in a acoustic formulation

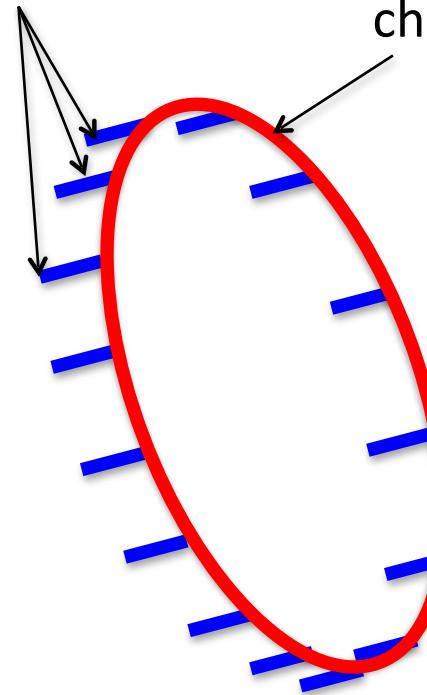
3D Burners



3D Annular chamber
(perimeter = $2L_c$)



1D Burners

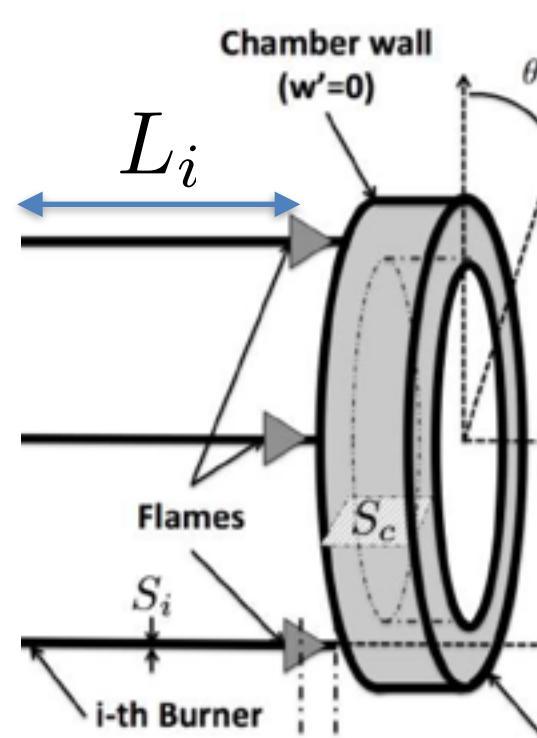


1D Annular chamber

1,5D ACOUSTIC NETWORK MODEL

3D CONFIGURATION

ATACAMAC: Analytical Tool to Analyze and Control Azimuthal Modes in Annular Combustors



$$\Gamma_i = -\frac{1}{2} \frac{S_i}{S_c} \frac{\rho_c c_c}{\rho_i c_i} \tan\left(\frac{\omega L_i}{c_i}\right) (1 + n e^{j\omega\tau_i})$$

Annotations point to the following components:

- Cross section of burner i** : Points to the term S_i / S_c .
- Length of burner i** : Points to the term $\omega L_i / c_i$.
- Flame response parameters (one set of n and tau for each burner)**: Points to the term $(1 + n e^{j\omega\tau_i})$.
- Cross section of annular chamber**: Points to the term $\rho_c c_c / \rho_i c_i$.

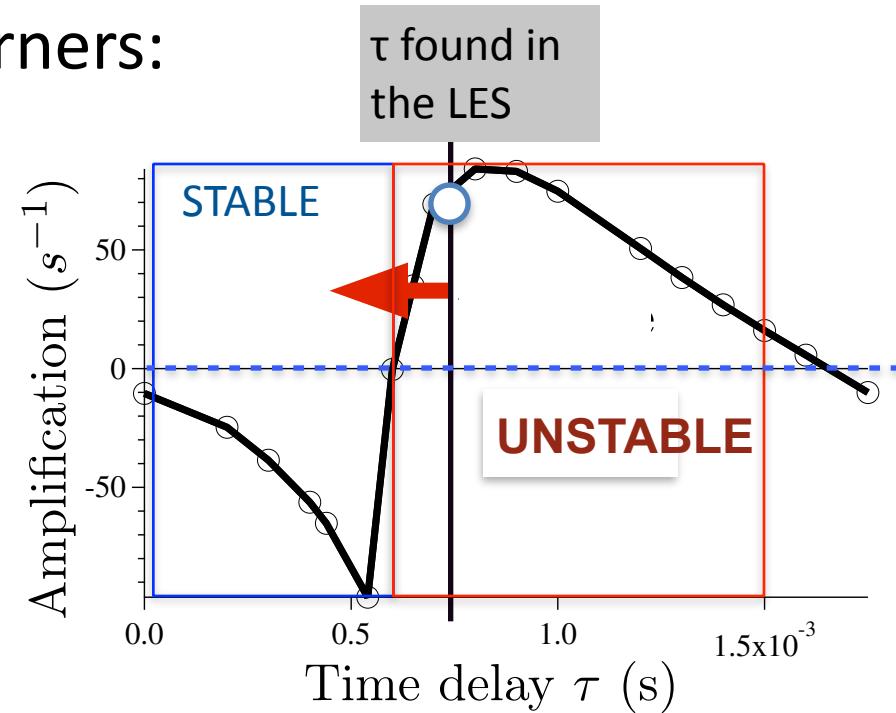
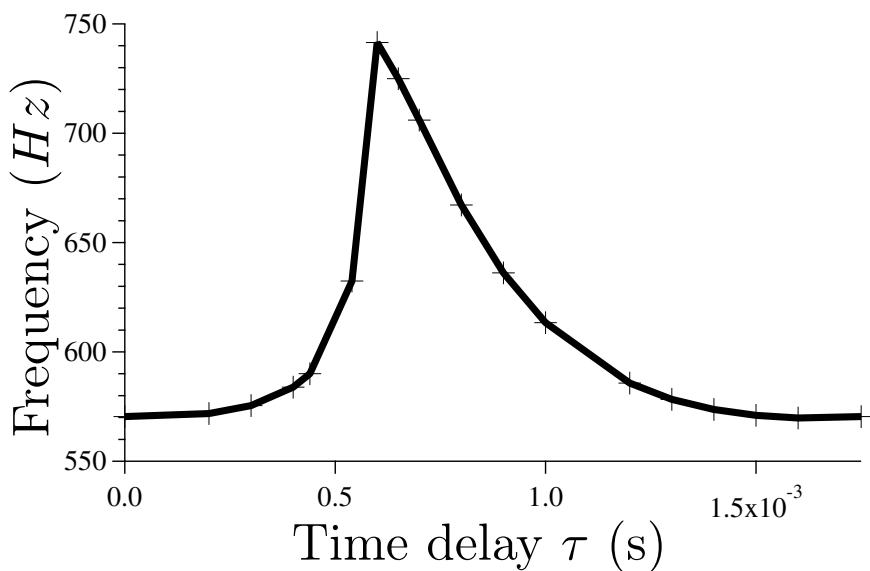
$$f = \frac{c_c}{2L_c} - \frac{c_c}{4\pi L_c} \sum \quad \sum = \sum_{i=1}^{i=N} \Gamma_i$$

[1] A.P. Dowling, Journal of Sound and Vibration 180 (4), 1995, 557-581

[2] M. Bauerheim, F. Nicoud and T. Poinsot, Combustion and Flame (in press, 2014)

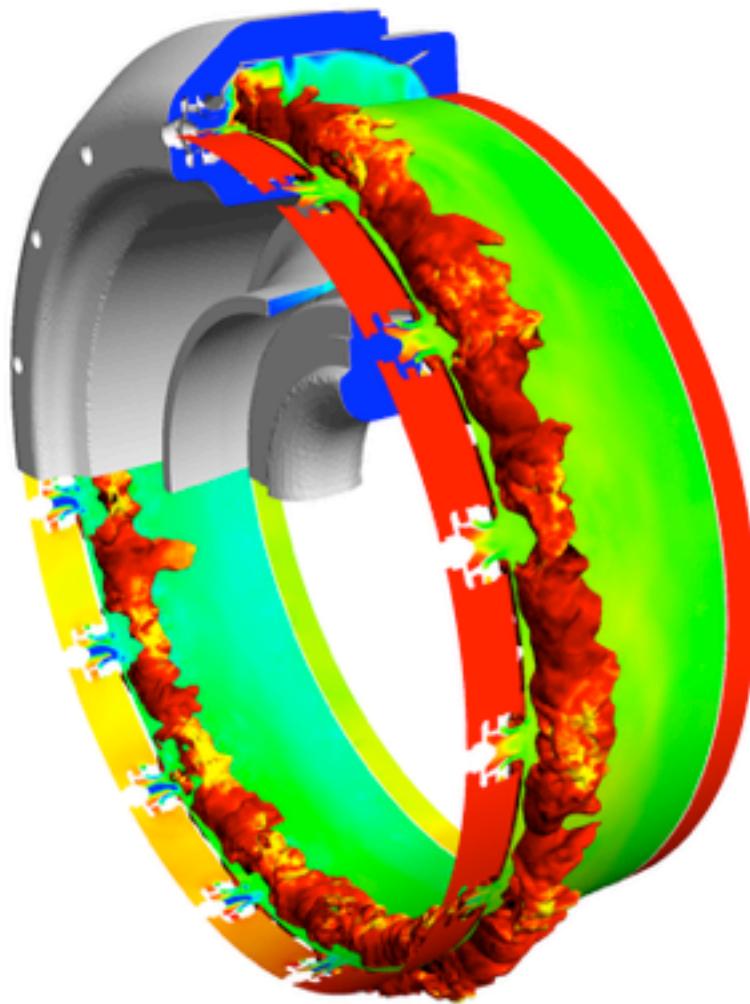
Stability prediction

- Frequency and growth rate of the azimuthal mode vs the flame delay τ of the burners:

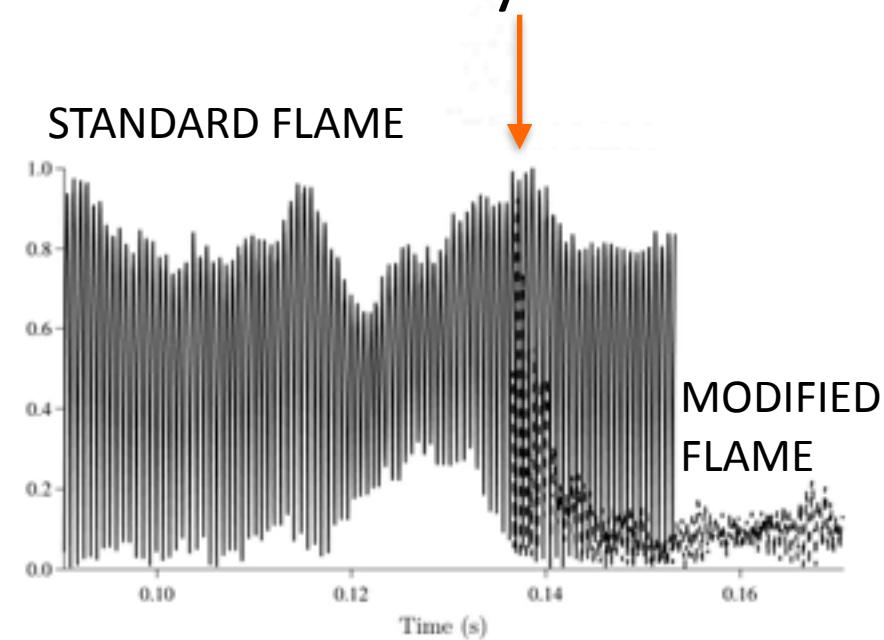


ATACAMAC suggests: 'decrease the delay τ and this combustor will become stable'

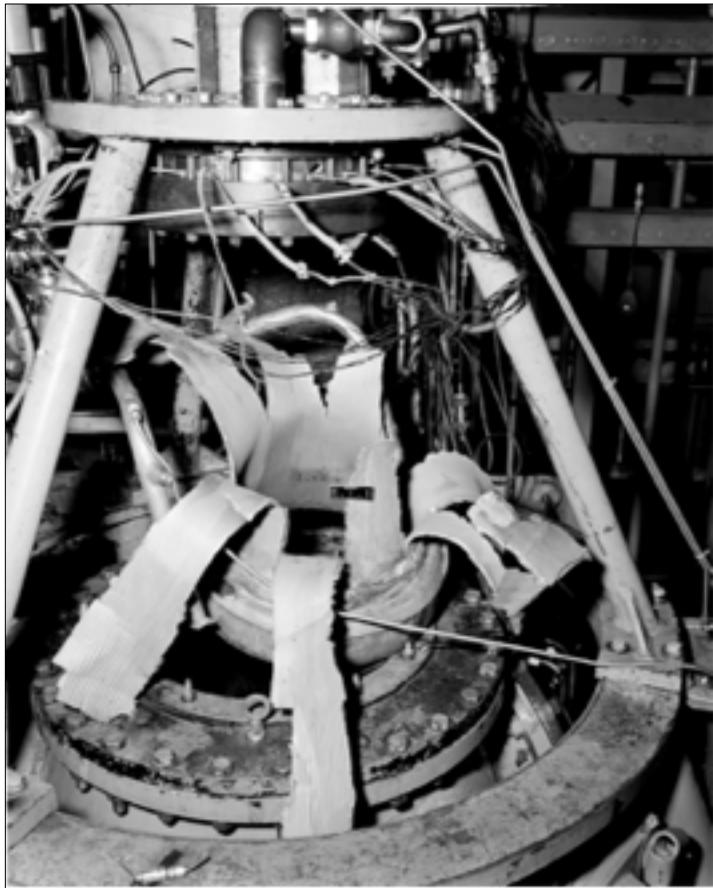
Stability prediction



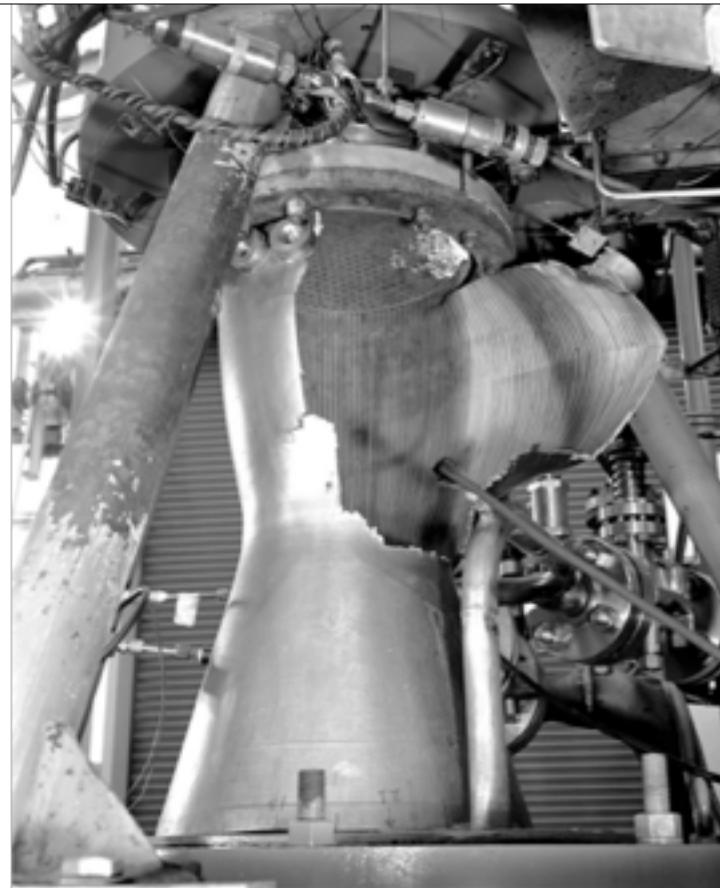
→ Increasing the fuel consumption rate reduces the delay and stabilised the system



Really bigger: the 10 M\$ failure(s)



Liquid rocket engine (NASA 1957)

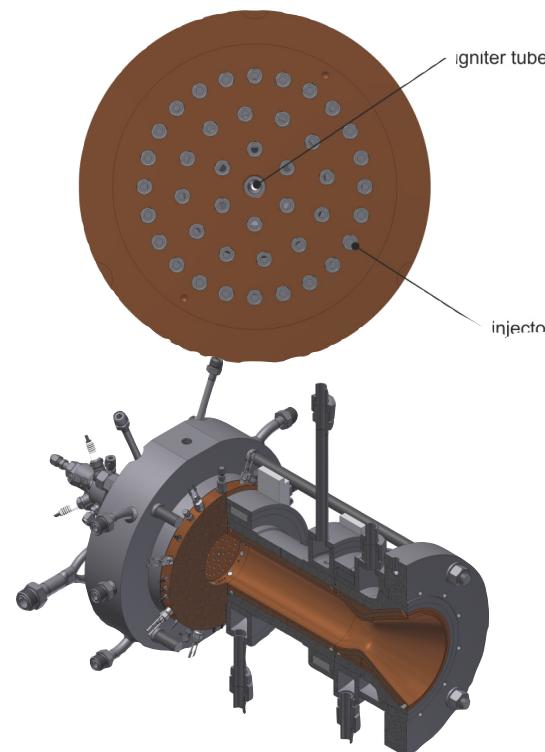
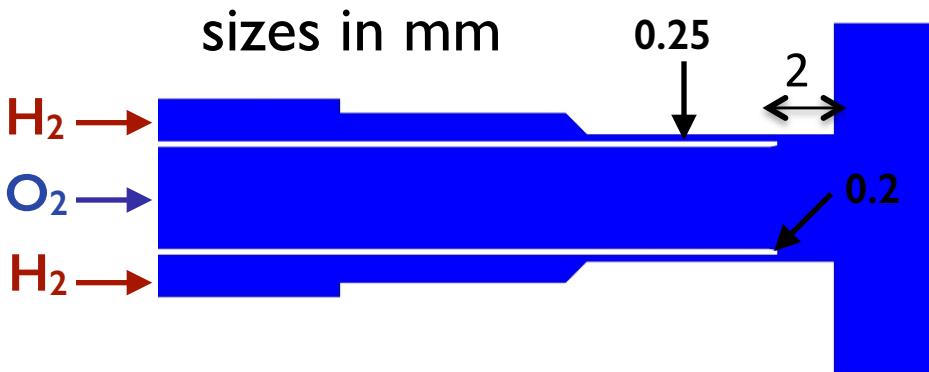
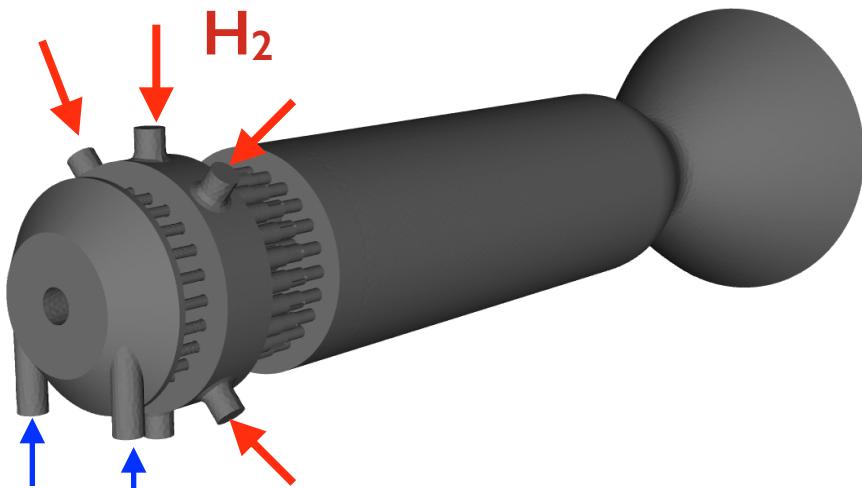


Liquid rocket engine (NASA 1963)

Combustion instabilities in Rocket engines

→ DLR LAMPOLDSHAUSEN HF7 BKD

Full engine: 42 coaxial injectors
Cryogenic O₂/H₂ propellants
Pressure range: 50-80 bar



power ~
100 MW

Combustion instabilities in Rocket engines

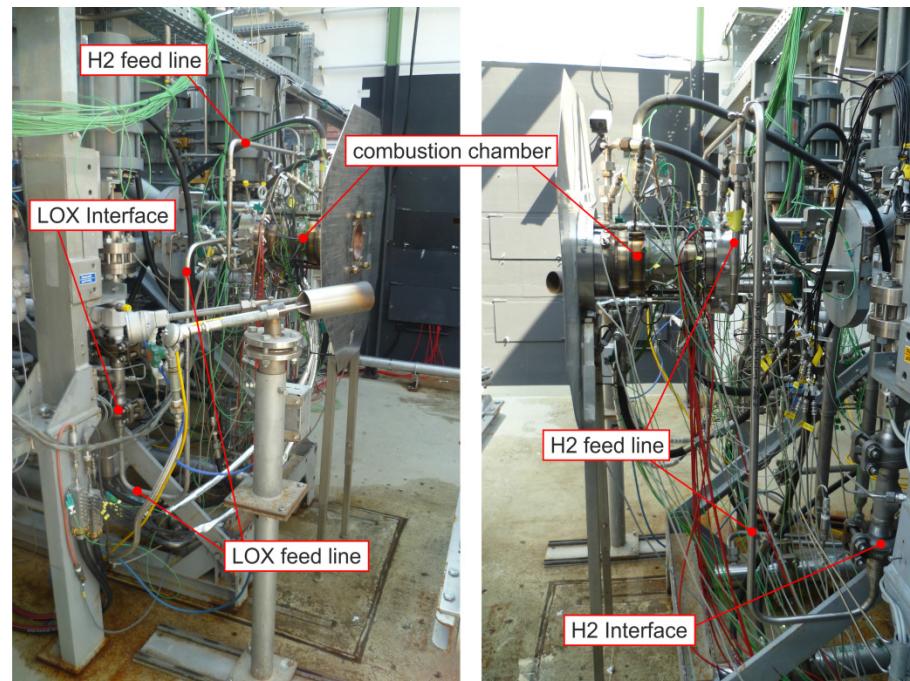
- Two operating conditions
- Two stabilities

conditions	LPI	LP4
p_c [bar]	70	80
ROF	4	6
m_{tot} [kg.s ⁻¹]	5.5	6.7

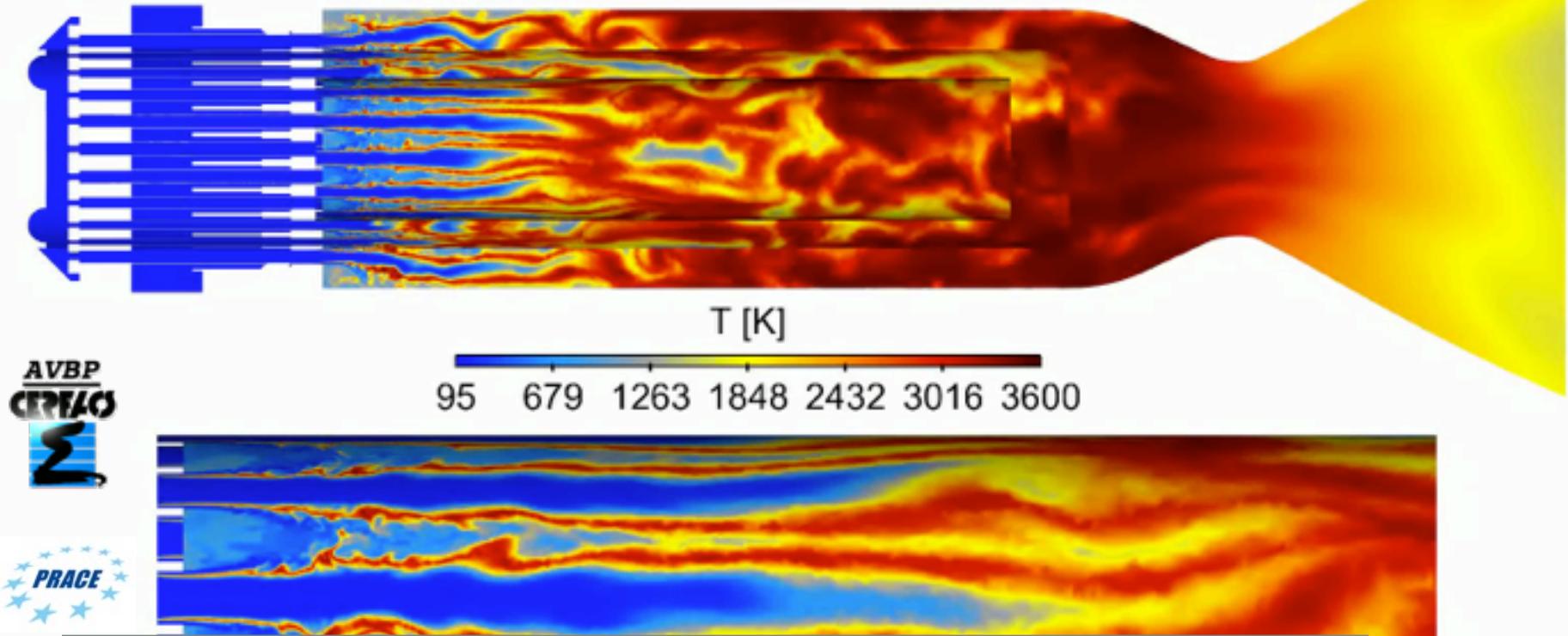
EXPE	stable	unstable
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Gröning, Suslov, Oschwald, Sattelmayer

“Stability behaviour of a cylindrical rocket engine combustion chamber operated with liquid hydrogen and liquid oxygen” EUCASS (2013).



80 M hours on FERMI (cineca IT) , 9th Prace CALL



World first full LRE simulation

Ongoing work ...

- steady state results: more than 40 ms ...
- 84M tets mesh exhibits no self triggered instability
- 500M tets mesh simulations on-going (ETA August)



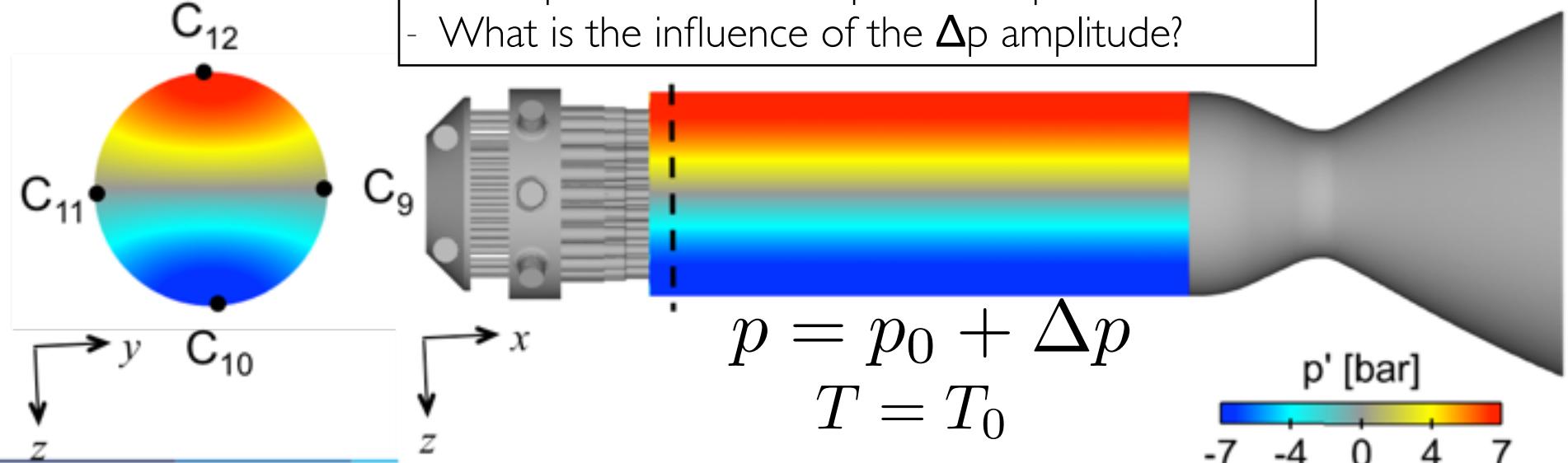
Instability triggering

- Self triggering instability not found (yet) ..
- Artificial induction of instability ...
 - Add a pressure perturbation to the flow field with the 1T mode shape and look at the amplification

...

Analysis of the response of the system:

- Is the perturbation damped or amplified?
- What is the influence of the Δp amplitude?

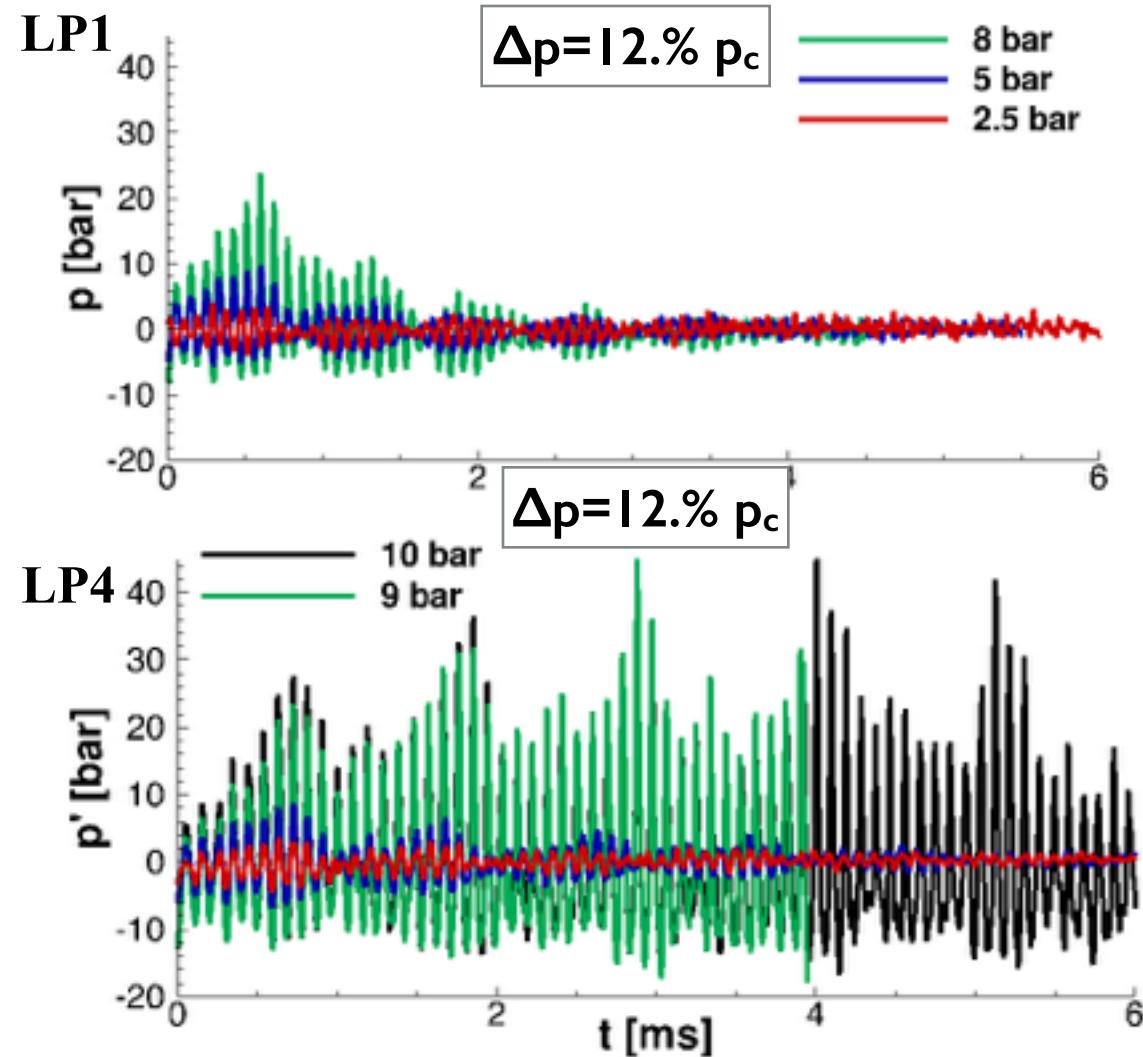




Instability triggering

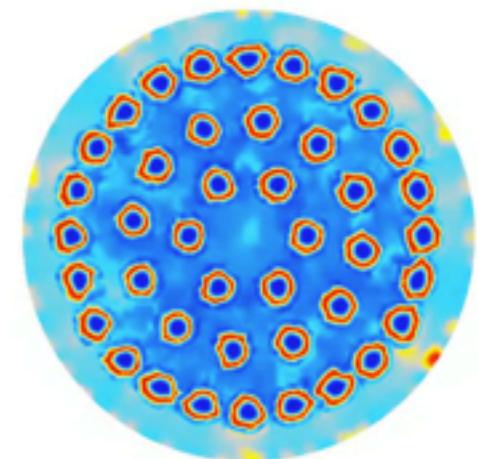
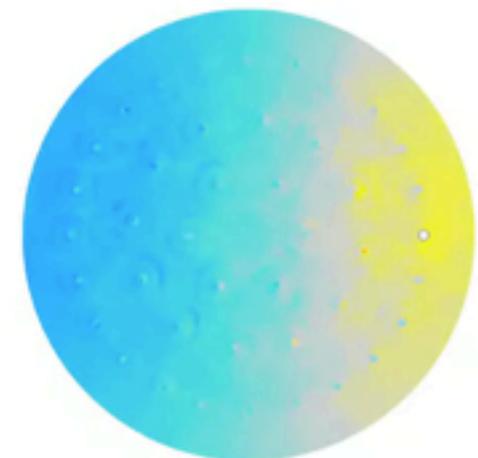
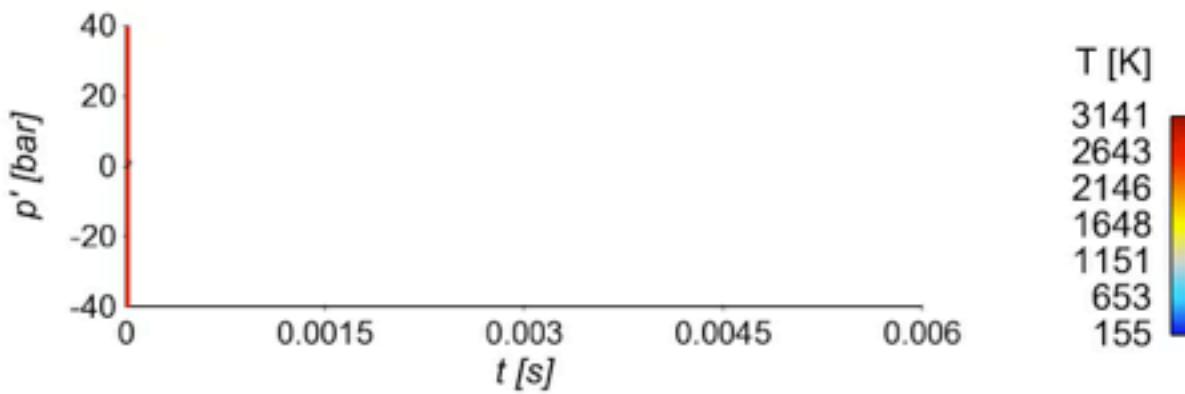
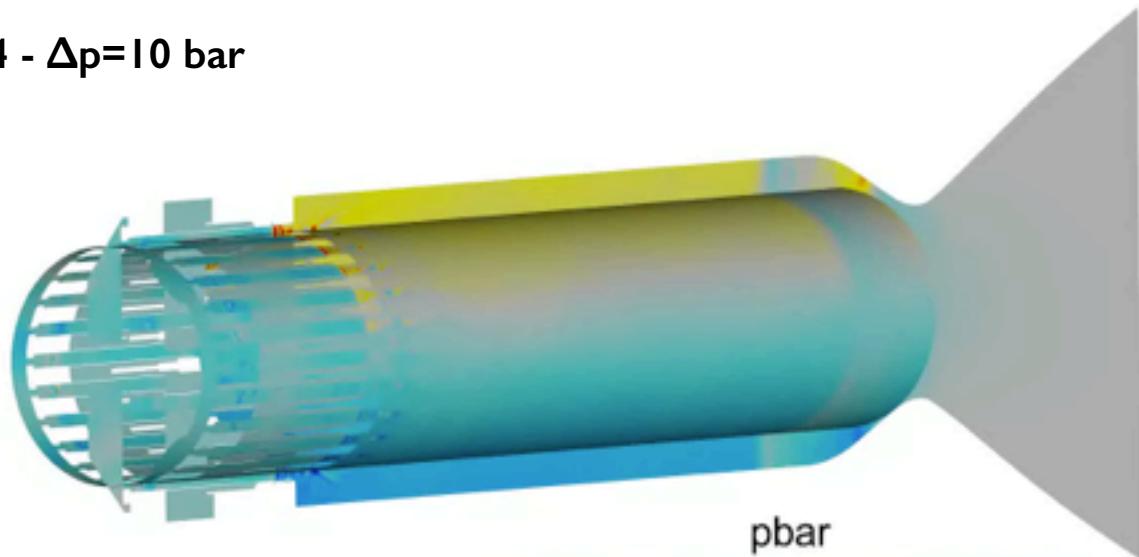
LP1: dissipated \rightarrow **stable**
LP4: small Δp dissipated,
high Δp limit cycle
non linearly
unstable

- With a high enough amplitude, LP4 attains a limit cycle
- LP1 dampens the perturbation

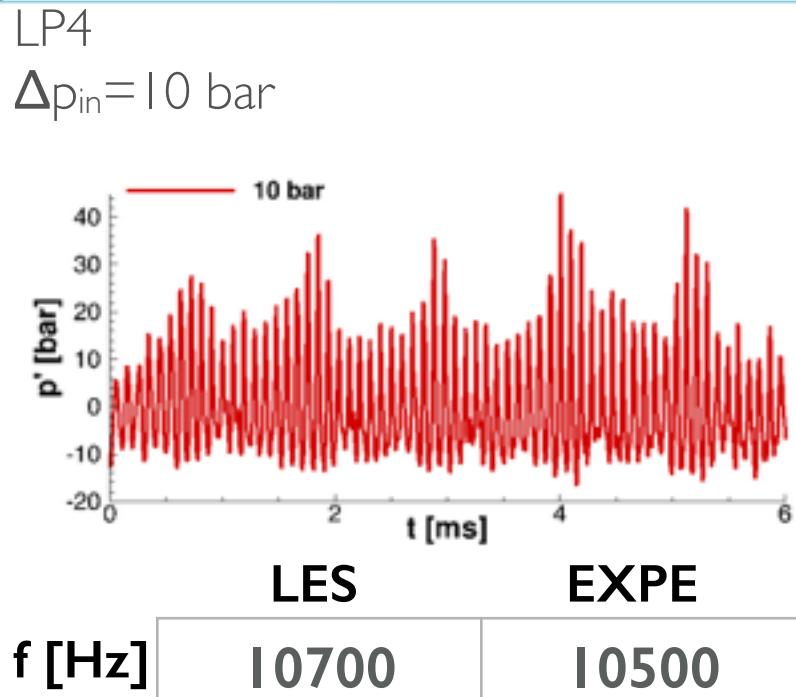


Flame dynamics

LP4 - $\Delta p = 10$ bar



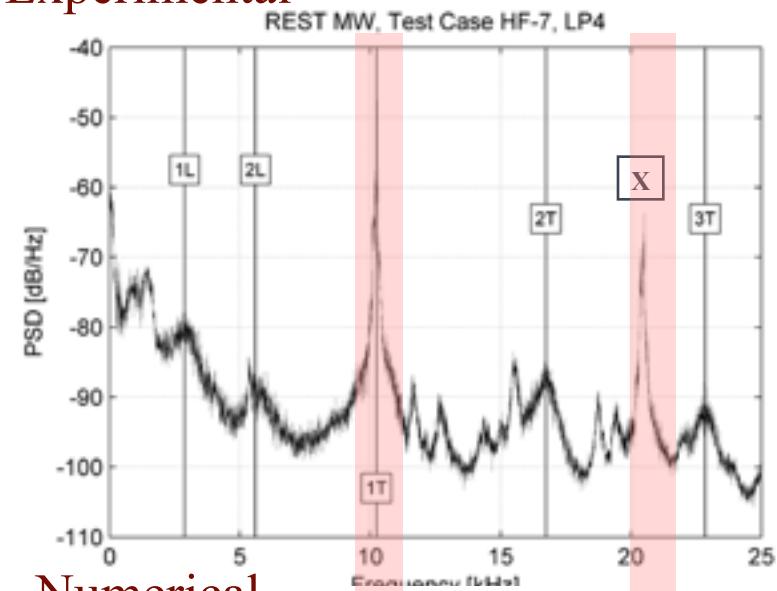
Experimental “validation”



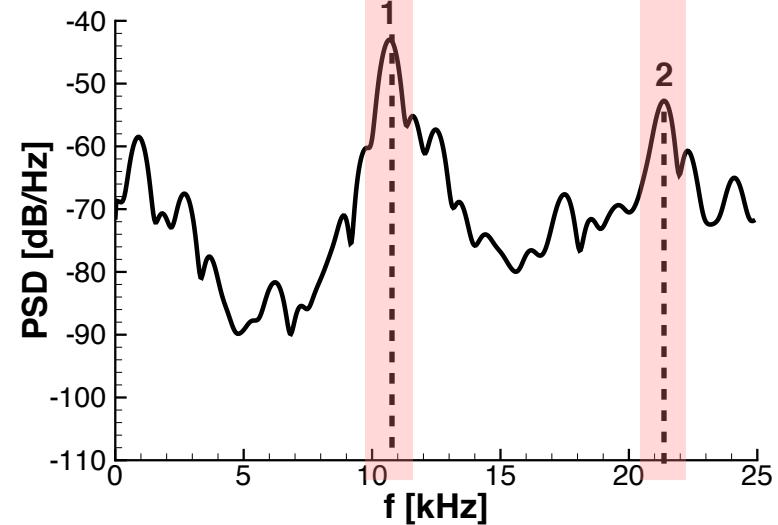
Spectra

Comparison with experimental data
 \Rightarrow same main peaks
 $\Rightarrow f_1$ looks like IT BUT what is f_2 ?

Experimental



Numerical

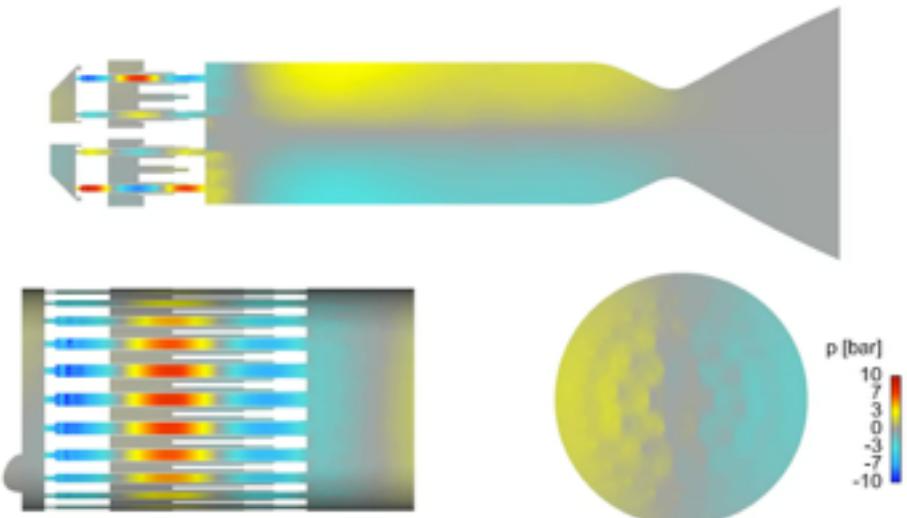




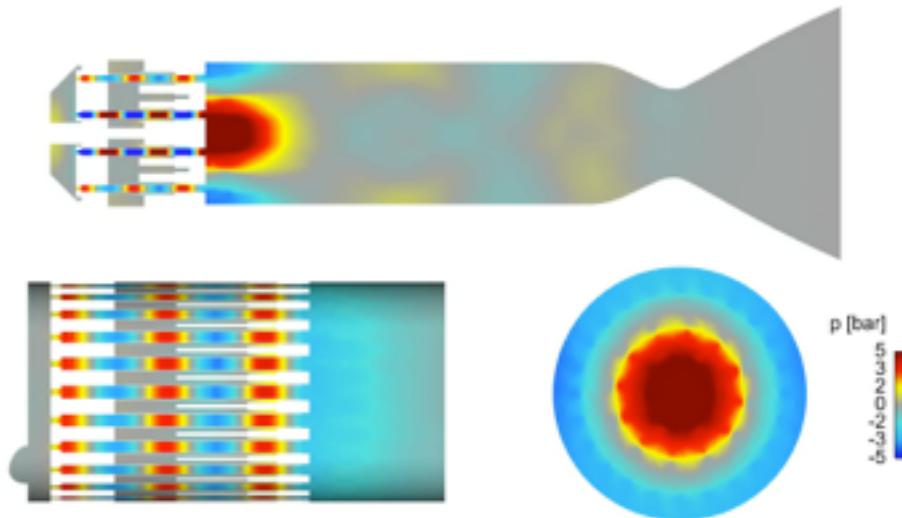
Acoustic analysis

- Power density spectra field of pressure allow to identify the structures reacting at the given frequency

$f_1 = 10700 \text{ Hz}$



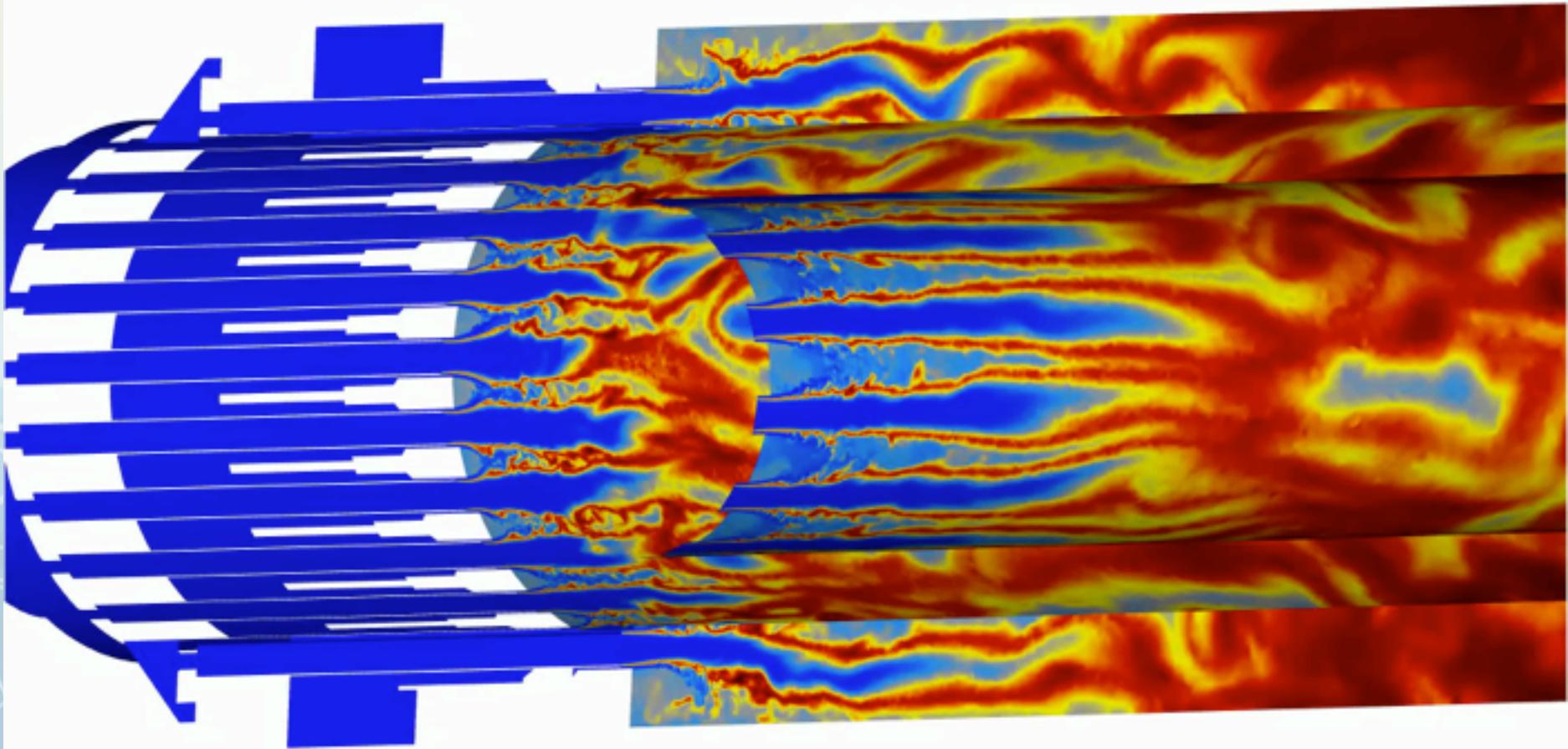
$f_2 = 21400 \text{ Hz}$





Conclusion

- The ERC INTECOCIS grant has allowed important advances on the comprehension of instabilities, how they are triggered and how to suppress them in gas turbines and rocket engines.
- New and old tools have been updated and enhanced to tackle exiting new physics benefitting the research community
- In particular the world first LES of a full LRE has already yielding impressive insights into the instability mechanisms in this systems
- Still 3 more years to go ...
- We would like to acknowledge the support from INTEL IPCC program, JSC, GENCI, PRACE and INCITE for the realisation of this research



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