ASPROM - « Calculs parallèles et Applications »
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Large Eddy Simulation of aeronautical combustion chambers: an efficient tool to address current technical challenges

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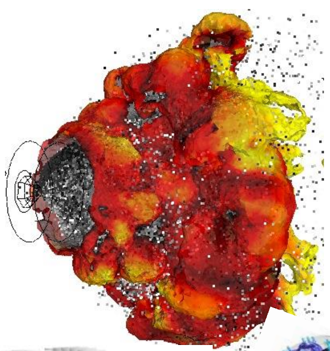
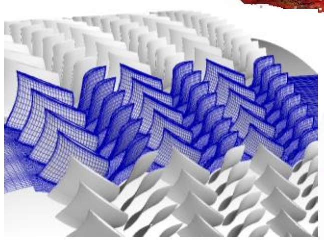




INTRODUCTION: The aeronautical context

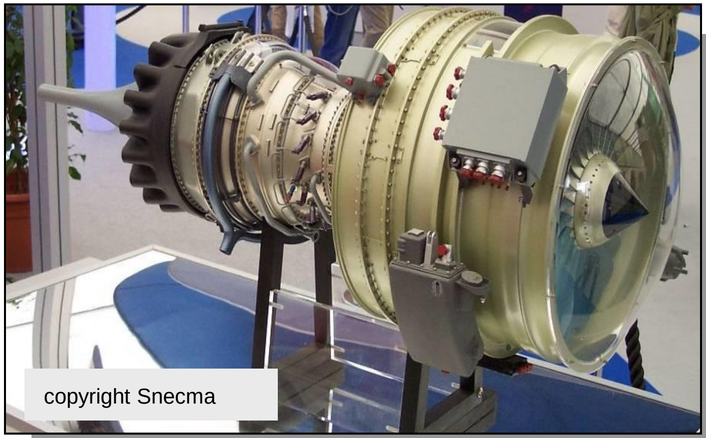
- CO_2 emissions from 1990 to 2025[a]: +100-600% (2008: 2.2% of the total).

- European objectives for 2020[b]:

  - ➢ reduce pollutant emissions (NO_x: -80%, CO_2: -50%),
  - ➢ reduce the noise emissions (-10dB).

- Economical constraints:
  - ➢ cut the engine costs (today it represents 30% of the aircraft cost).


copyright Airbus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Economical and environmental constraints impose technical and technological changes!

[a] *INRETS, 2004*

[b] *ACARE recommendations*

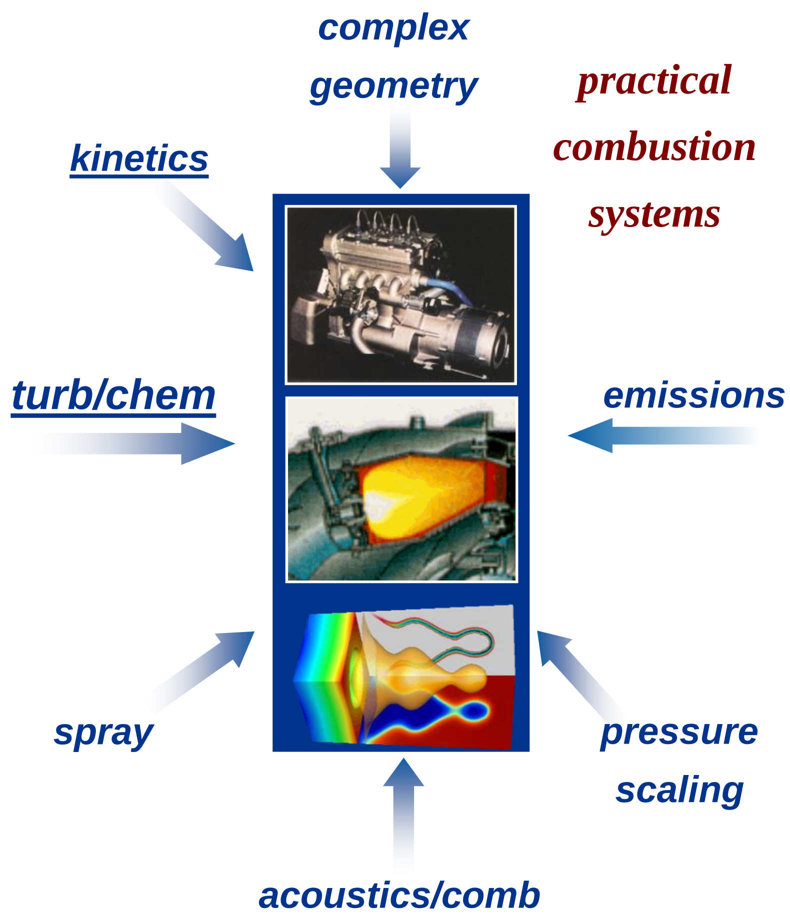
TECHNICAL CHALLENGES IN AERONAUTICAL BURNERS

Performances

- Temperature field ⟹ Turbine life cycle
- Efficiency & Emissions ⟹ NOx, CHx, CO2,CO
- Wall temperature ⟹ Chamber life cycle
- Stability & ignition

Technical challenges

- Aerodynamics & mixing
  ⟹ swirl, jets in cross-flow, multiperf.
- Turbulent combustion
  ⟹ kerosene kinetics, pollutants
- Two-phase flow
  ⟹ fuel flow physics & dynamics
- Heat transfer
  ⟹ cooling, thermal radiation



Advanced CFD and *Massively parallel* computer architectures offer a clear potential for time and cost reductions of the design chain while providing *more accurate predictions*

CFD research in Turbulent Combustion has massively transitioned to LES

Compressible Navier-Stokes equations in complex geometries

MODELS

Turbulence is solved via Large Eddy Simulation

Fuel composition is known or approximated via a surrogate

Chemical kinetics are based either on reduced schemes or tabulations (emissions)

Liquid phase is solved with eulerian or lagrangian solver

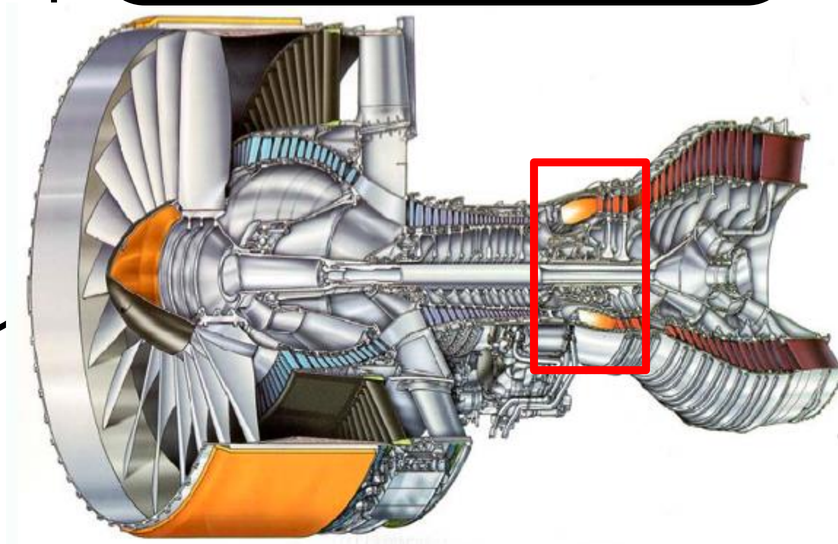
Turbulence-combustion interaction is modelled (thickened flame or pdf)

NUMERICS

-High order numerical schemes

-Unstructured grids

-HPC!

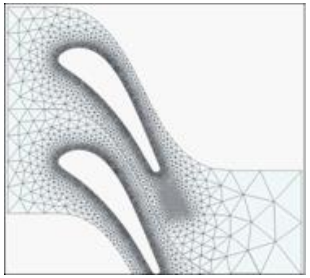


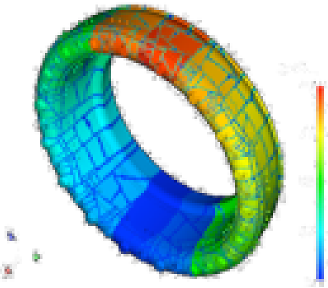
Boundary conditions are known or approximated (isothermal walls, acoustically abosrbing outlet, …) ⟹ Can be improved by using coupled simulations

AVBP – An unstructured LES solver

Jointly developed by IFP-EN and CERFACS

- External, internal flows
- Fully compressible turbulent reacting flows (ideal & real gas thermo.)
- DNS / LES approach



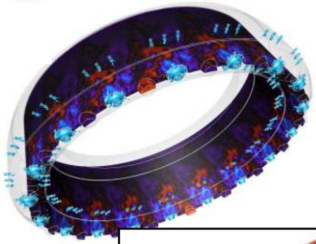


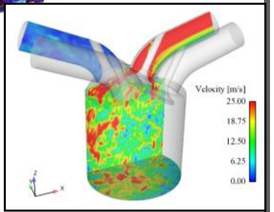
- Unstructured hexaedral, tetraedral, prisms & hybrid meshes
- Massively parallel, SPMD approach
- Explicit in time
- Centered schemes
  - Finite Volumes / Finite Elements ($2^{nd}/3^{rd}$ order[a])

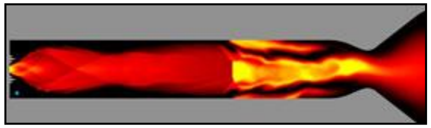
- SGS models : Smagorinsky(dynamic)/WALE[b]
- NSCBC[c] boundary cond. + wall laws
- Reduced[d] or tabulated[e] chemical kinetics
- Thickened flame turb. combustion model (TFLES)[f]
- Multi-phase solvers (Lagrangian & Eulerian)

Applications

- Gas turbines
- Aeronautical engines
- Piston engines
- Statoreactor
- Rocket engines
- Furnaces
- Heat exchangers

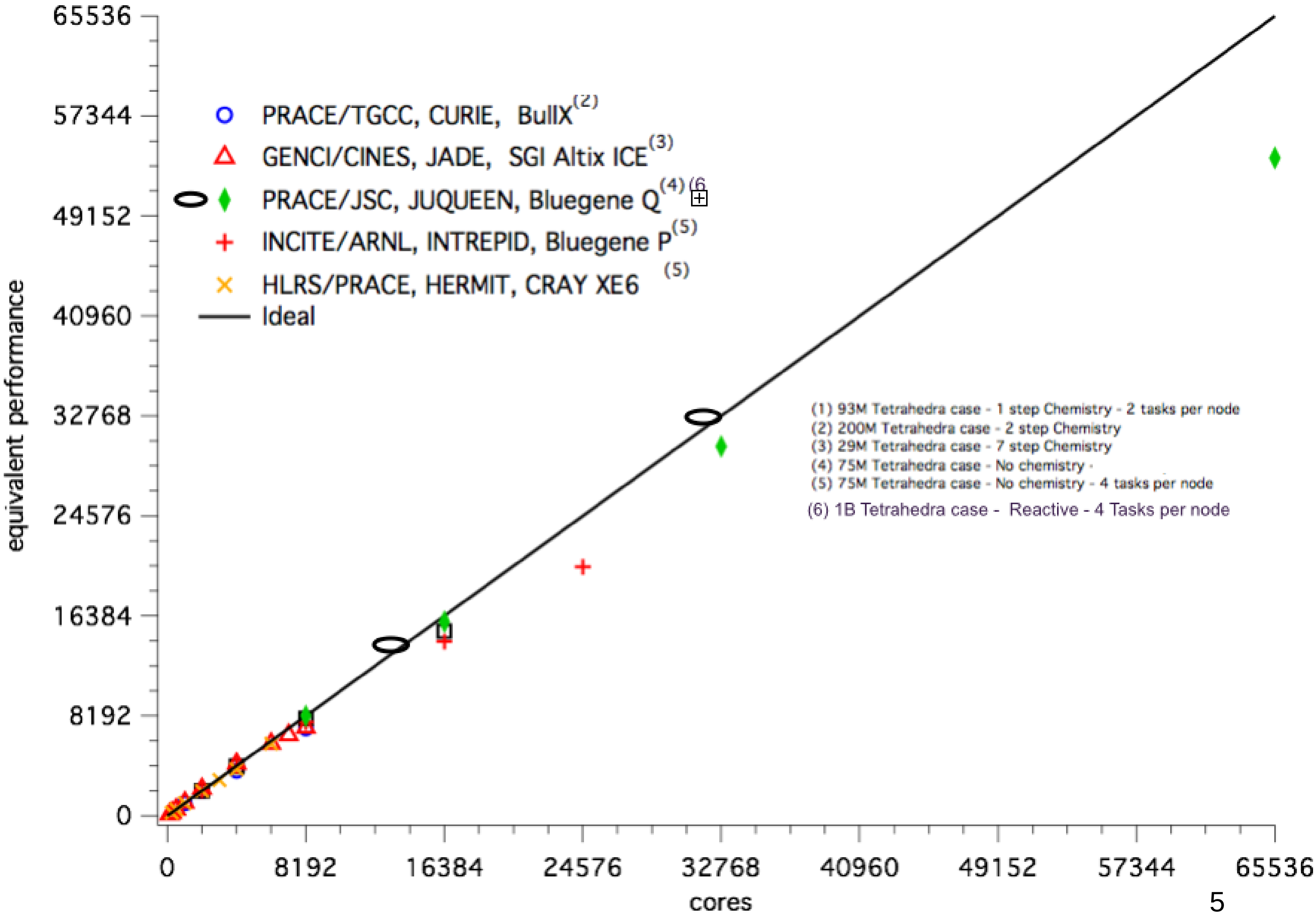




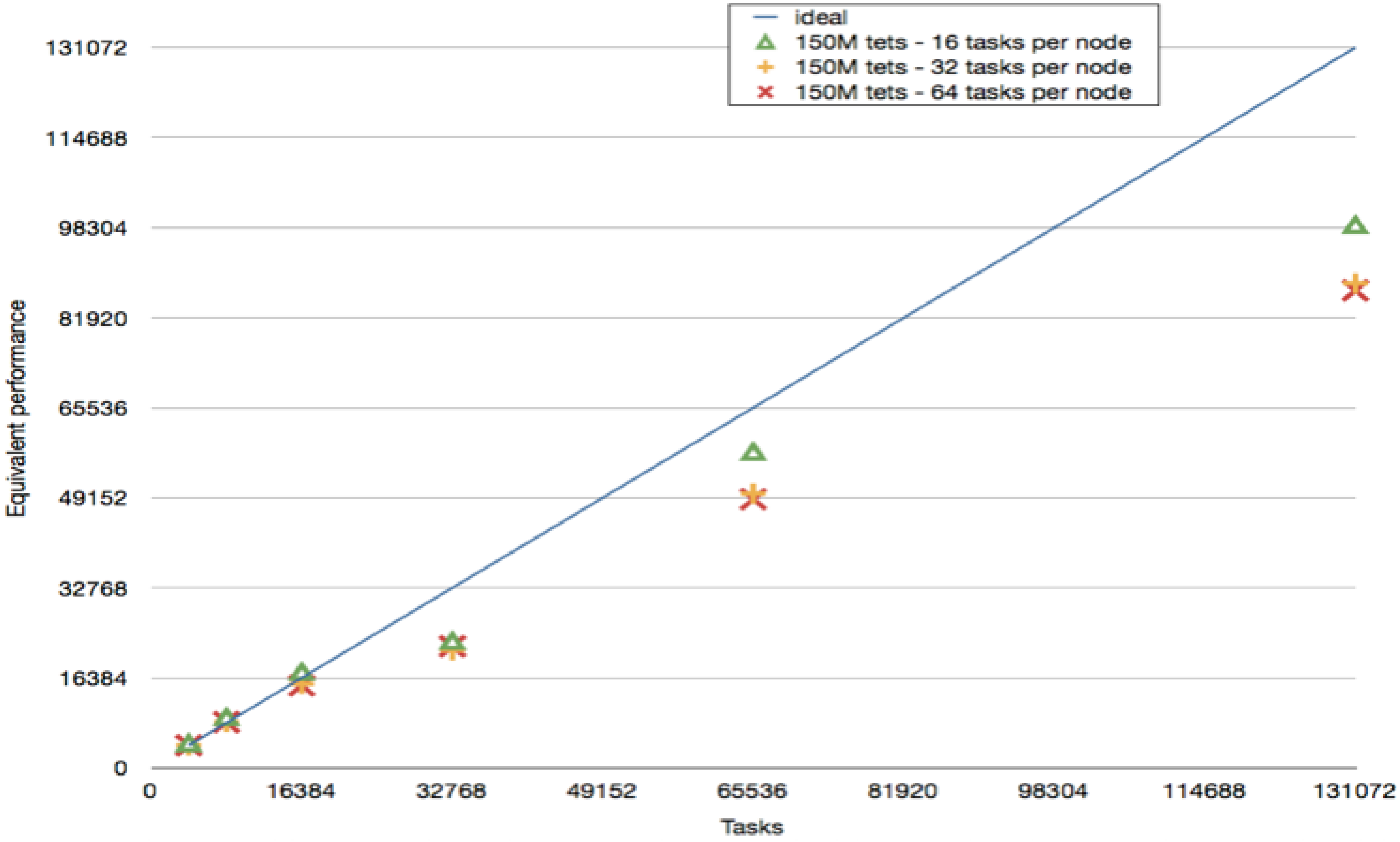


[a]Colin O. & Rudgyard M., Journal Comp. Physics, 2000
[b]Nicoud F. & Ducros F., Flow, Turb. Combustion, 1999
[c]Poinsot T. & Lele S., Journal Comp. Physics, 1992
[d]Franzelli B. et al., Combust. Flame, 2010
[e]Fiorina B. et al., Combust. Flame, 2010
[f]Colin O. et al. Physics of Fluids, 2000

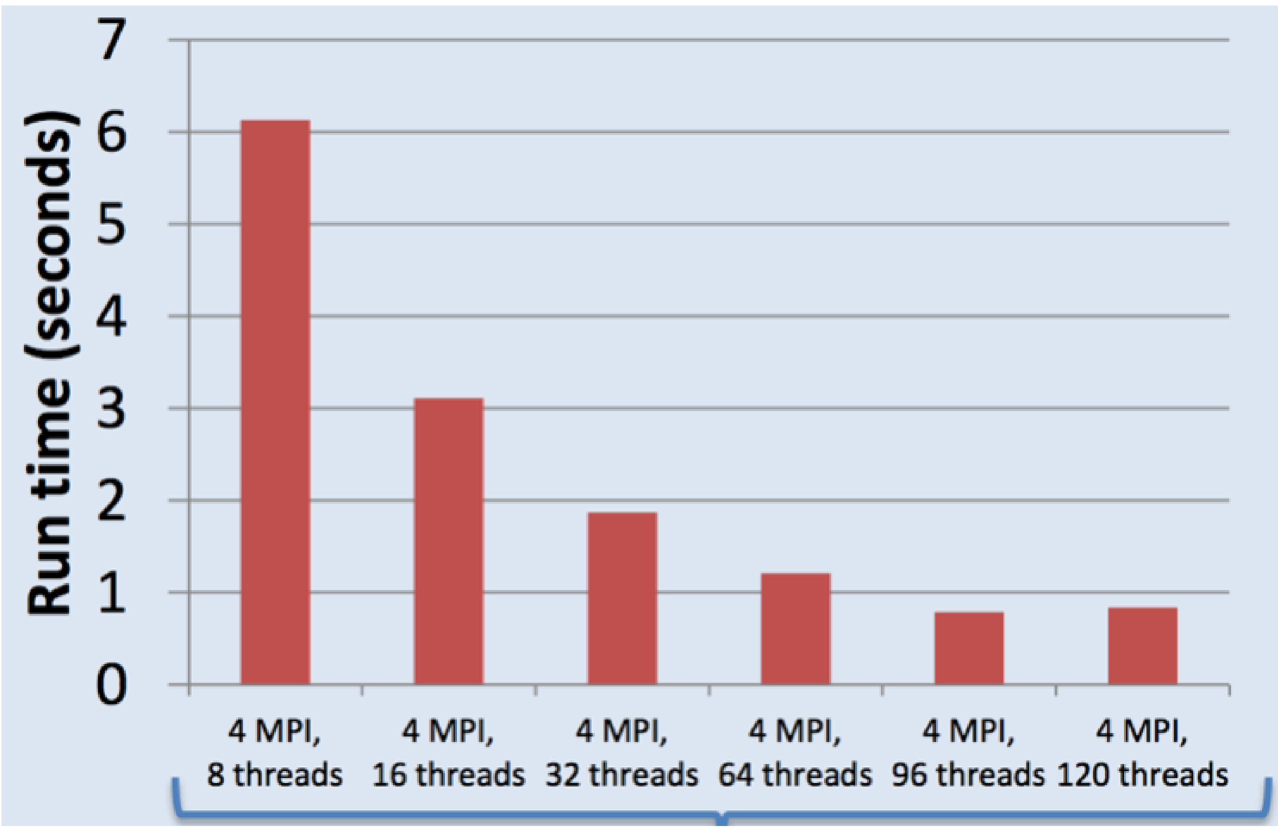
MPI strong scaling for REAL industry type configurations



Multi-threading



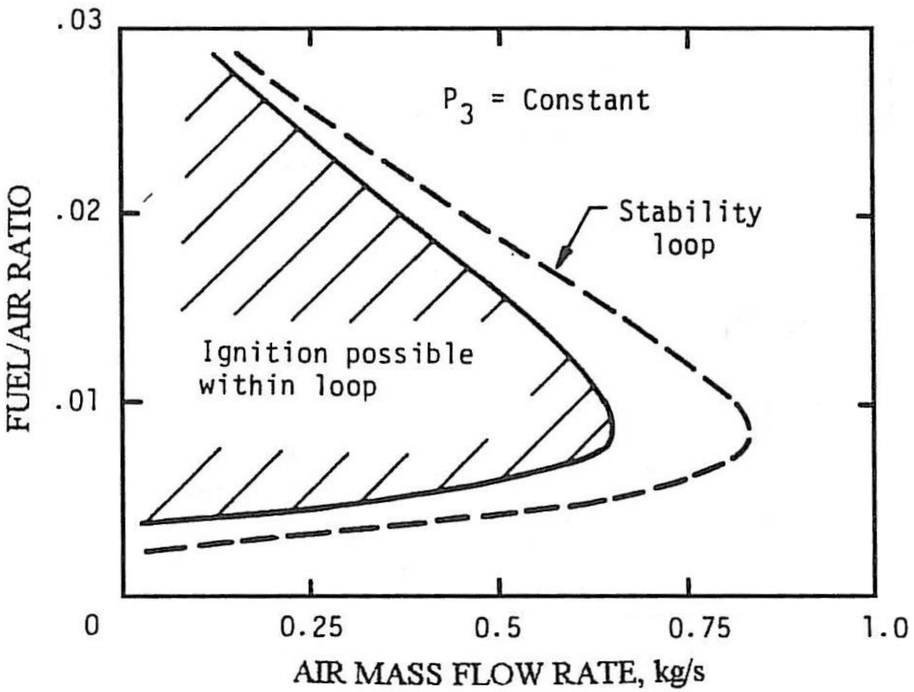
MPI + OmpSS strong scaling on Xeon Phi



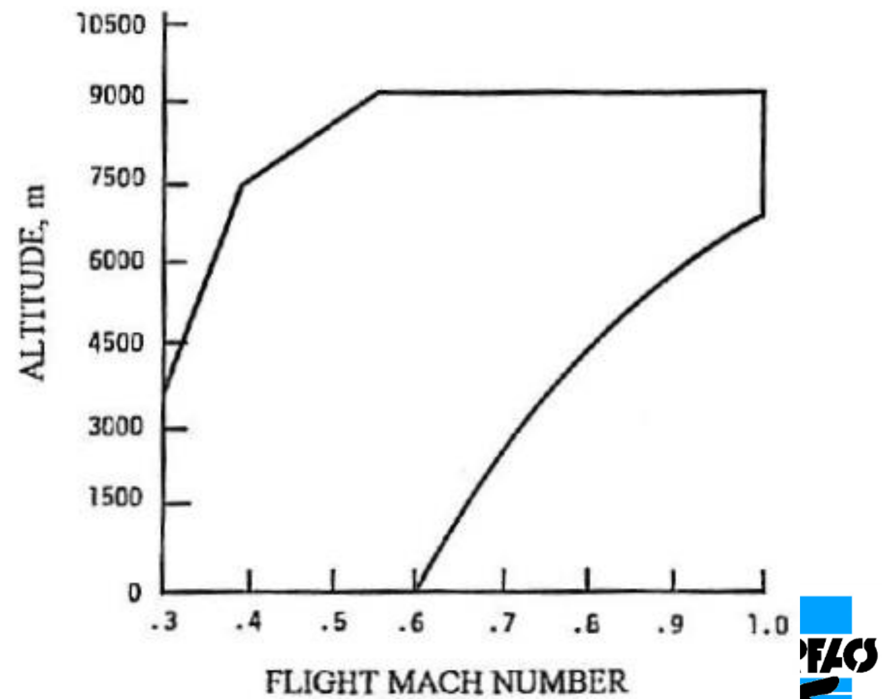
Using 2 Xeon Phi

Example 1: Ignition in annular gas turbines[a]

Ignition diagram



Re-ignition domain

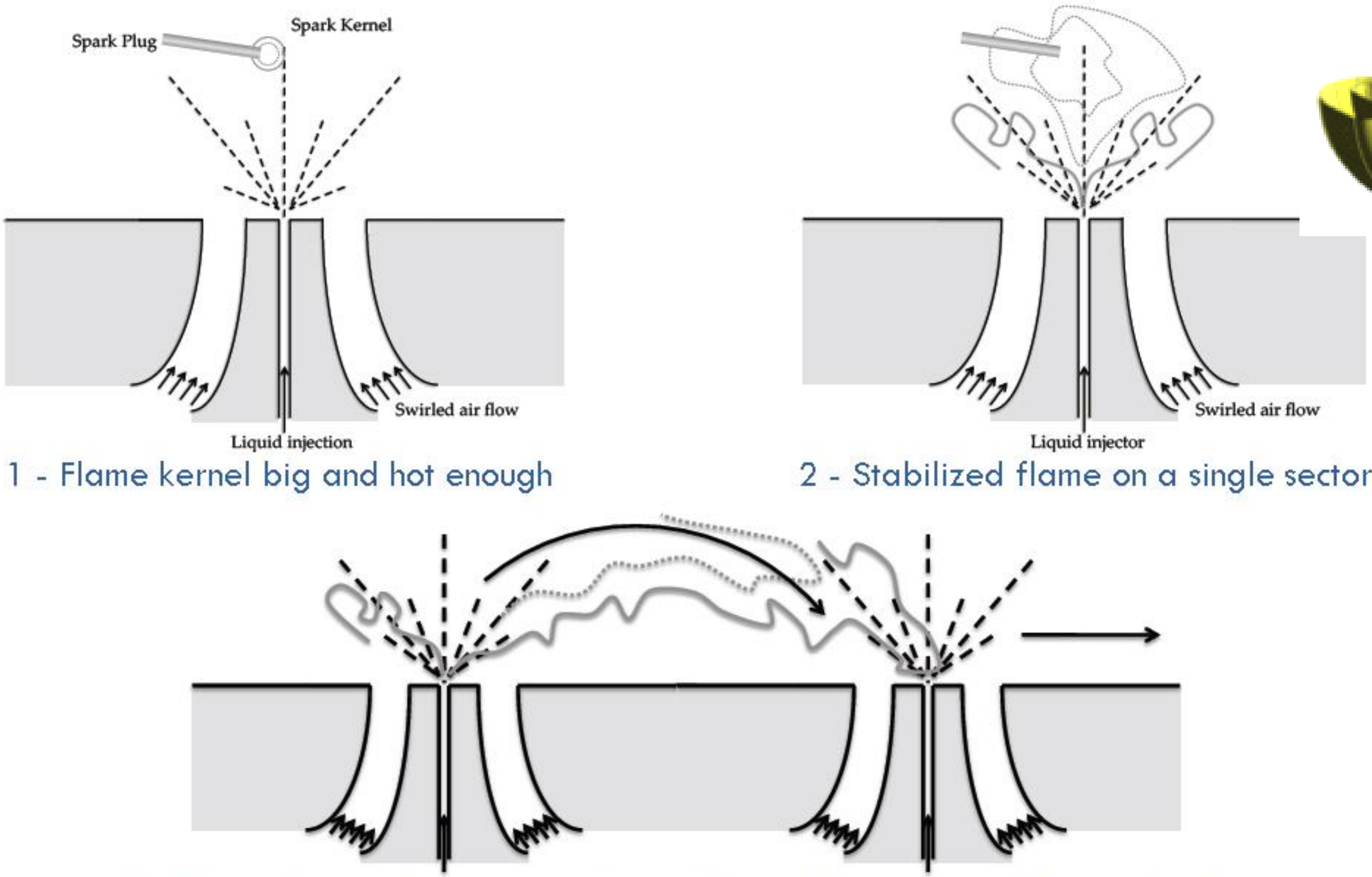


Need for reliable and efficient ignition system

[a]Lefebvre, Gas Turbine Comb. T&F, 1998

Ignition in annular gas turbines[a]

Ignition sequence has 3 phases



1 - Flame kernel big and hot enough

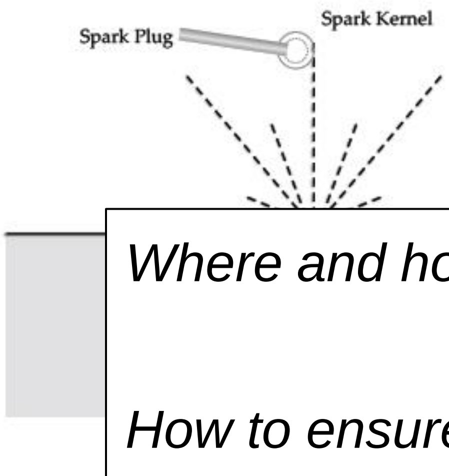
2 - Stabilized flame on a single sector

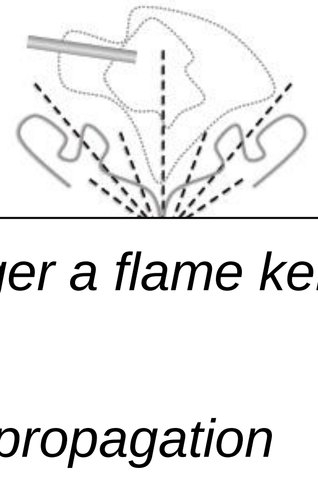
3 - Flame inter-sector propagation until complete ignition of the combustor

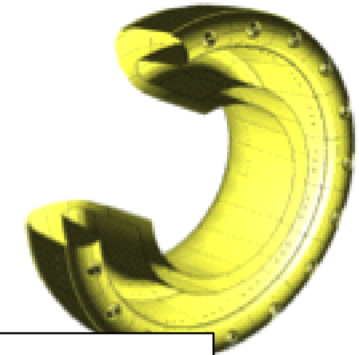
[a]Lefebvre, Gas Turbine Comb. T&F, 1998

Ignition in annular gas turbines[a]

Ignition sequence has 3 phases





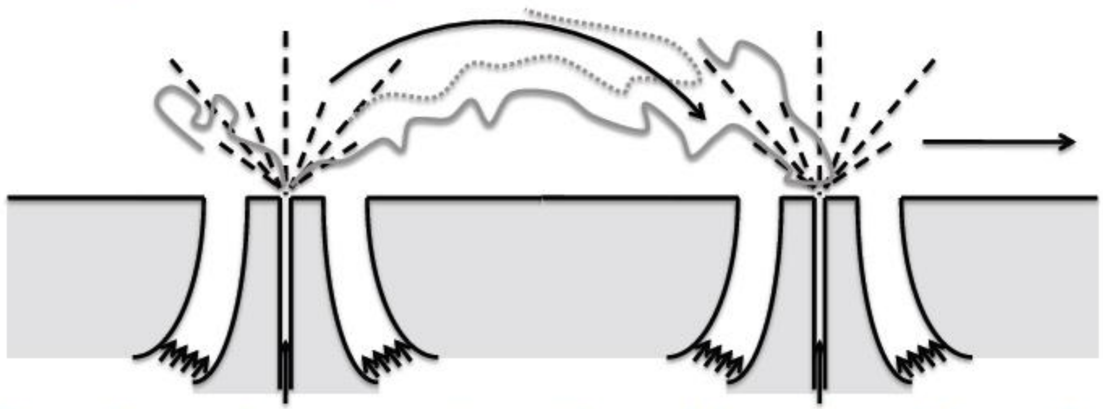


Where and how deposit energy to trigger a flame kernel?

How to ensure burner to burner flame propagation

1 - Flame kernel big and hot enough

2 - Stabilized flame on a single sector

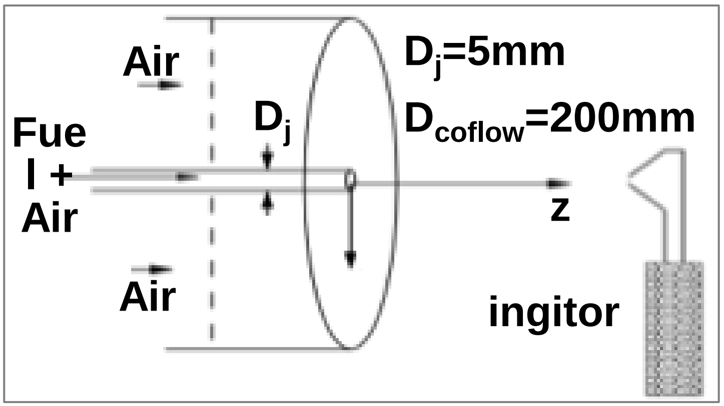


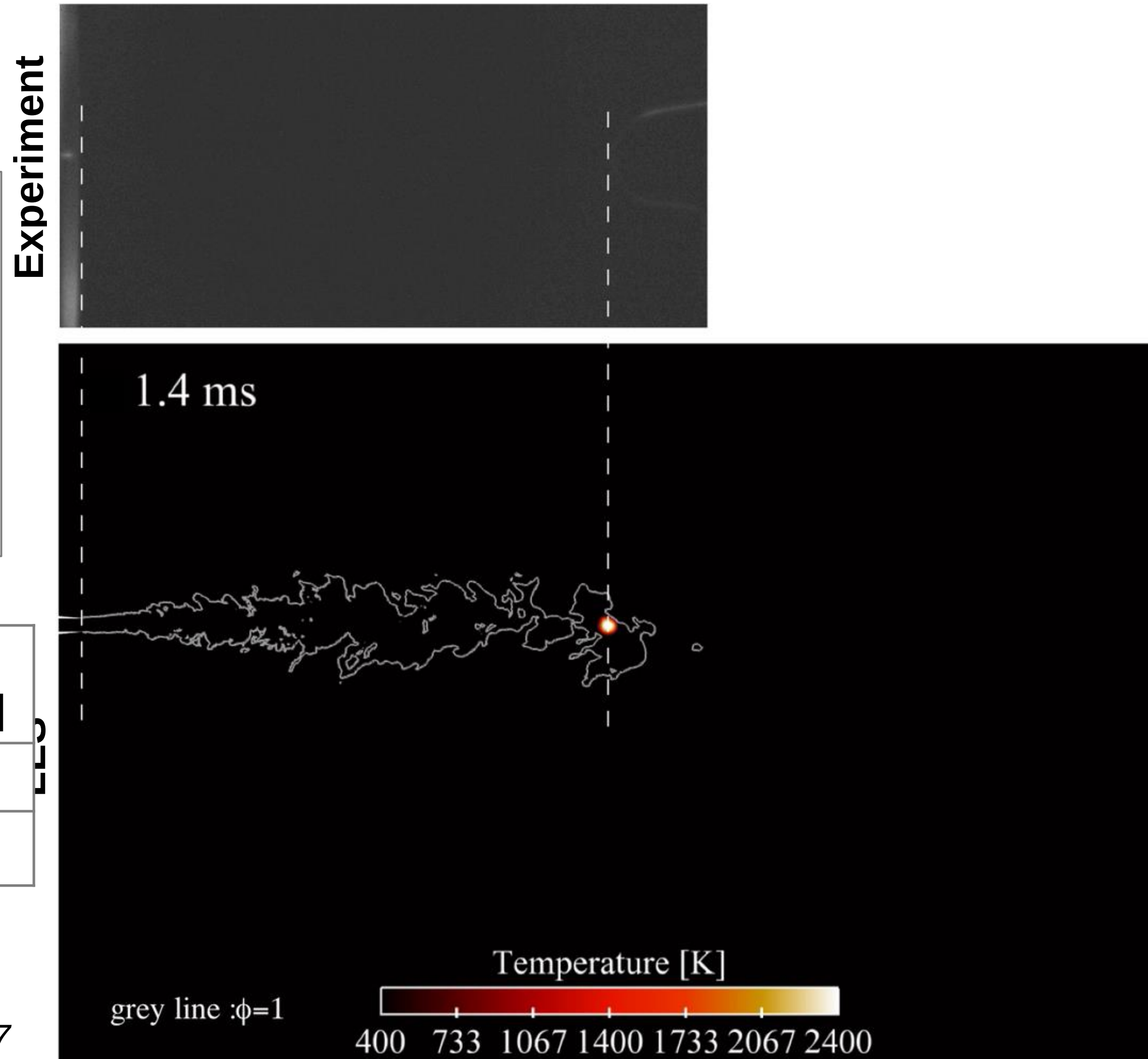
3 - Flame inter-sector propagation until complete ignition of the combustor

[a]Lefebvre, Gas Turbine Comb. T&F, 1998

LES of ignition

Validation in a non-premixed turbulent jet[a]





Spark	[mJ]	σ_t [µs]	σ_r [mm]
Exp	E_{tot}=100	400	1
LES	ε_i = 10	400	3

[a]*Ahmed S.F. Et al, Combust. Flame, 2007*

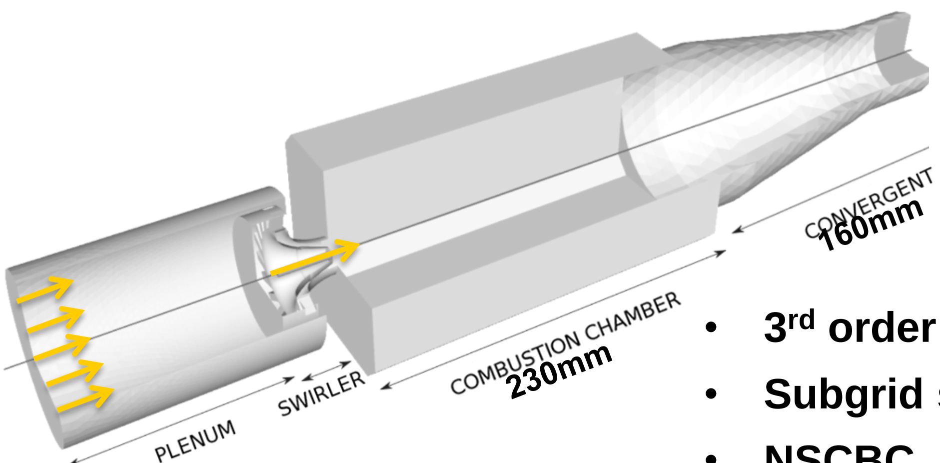
[b]*Lacaze et al., Combust. Flame, 2009*

Phase 2: Stabilisation in one sector[a]

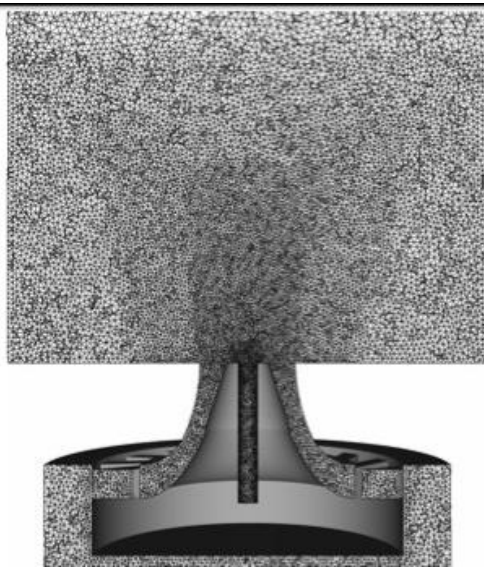
Laser ignition : 94 mJ

KIAI burner

	Swirler	Jet
Air flow rate	5.378 g/s	0.226 g/s
Methane flow rate	0.234 g/s	0.01 g/s
Equiv ratio	0.75	
Injection T°	298 K	
Pressure	1Atm	



6.7 million cells

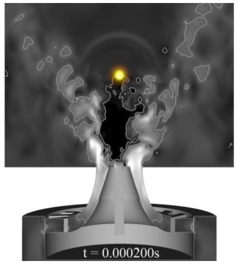


- **3rd order scheme (TTGC)**
- **Subgrid scale model WALE**
- **NSCBC**
- **2-steps chemistry**

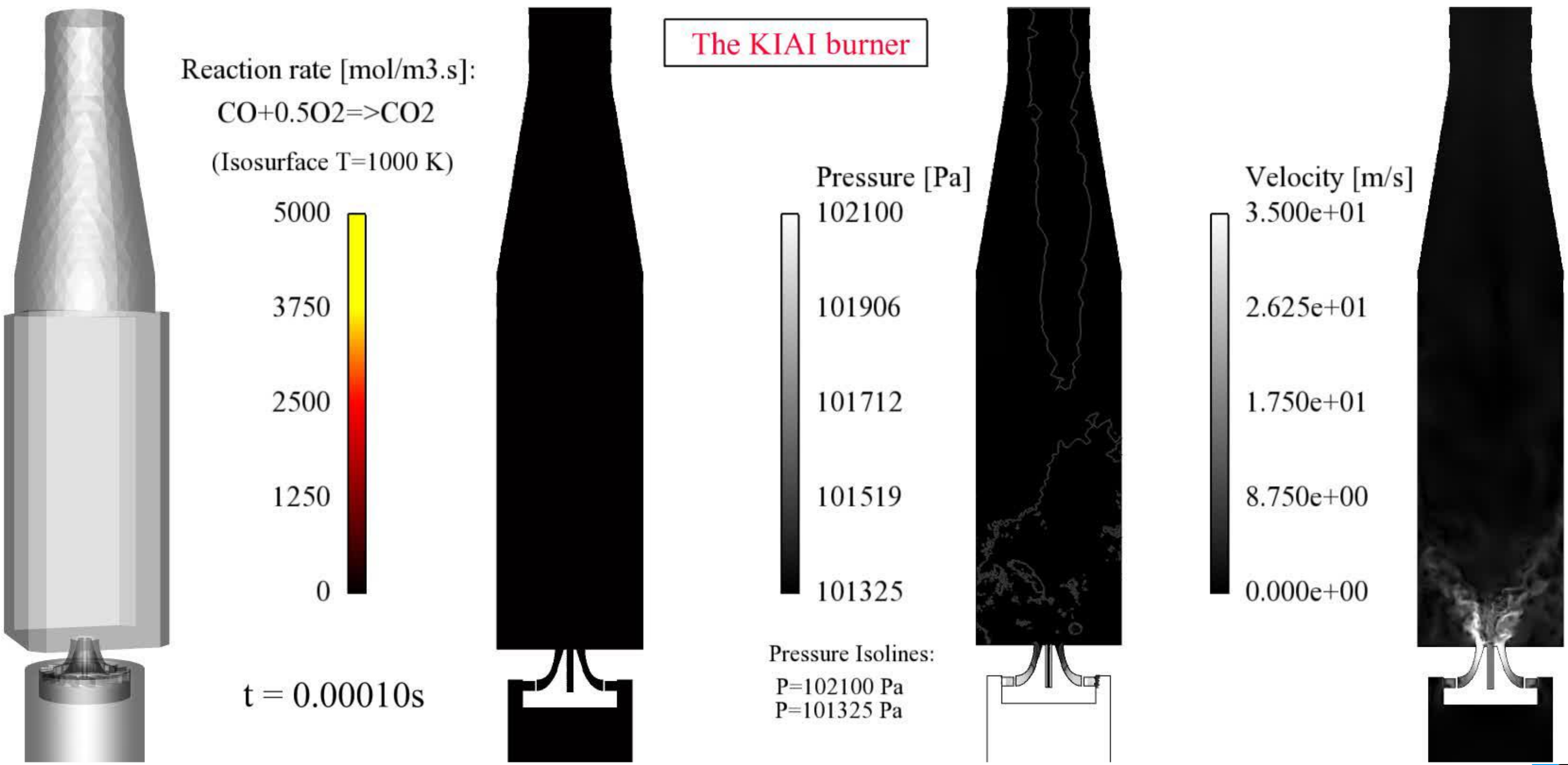
[a]*Barre et al, Combust. Flame, 2014*

LES of ignition

Spark in the IRZ (z/D=2)



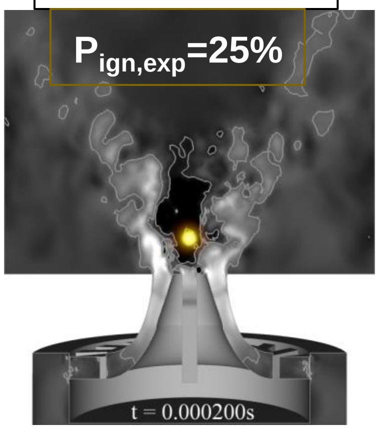
Phase 2: Successfull ignition



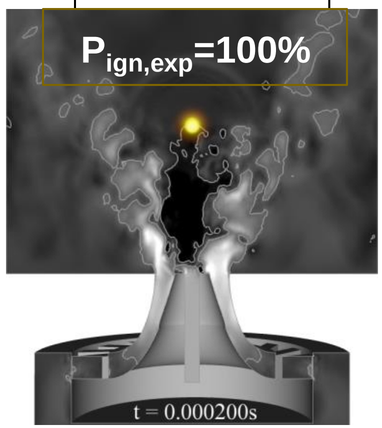
[a]*Barre et al, Combust. Flame, 2014*

Phase 2 : Impact of spark position: 4 tests

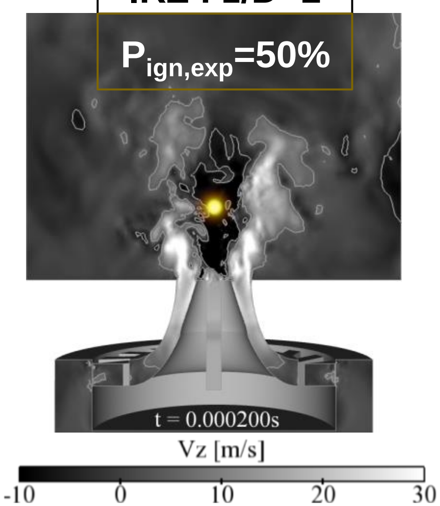
IRZ : z/D=0.5



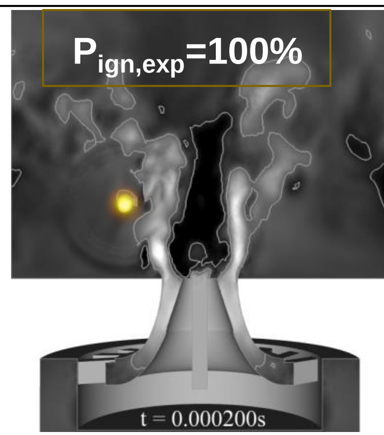
IRZ : z/D=2

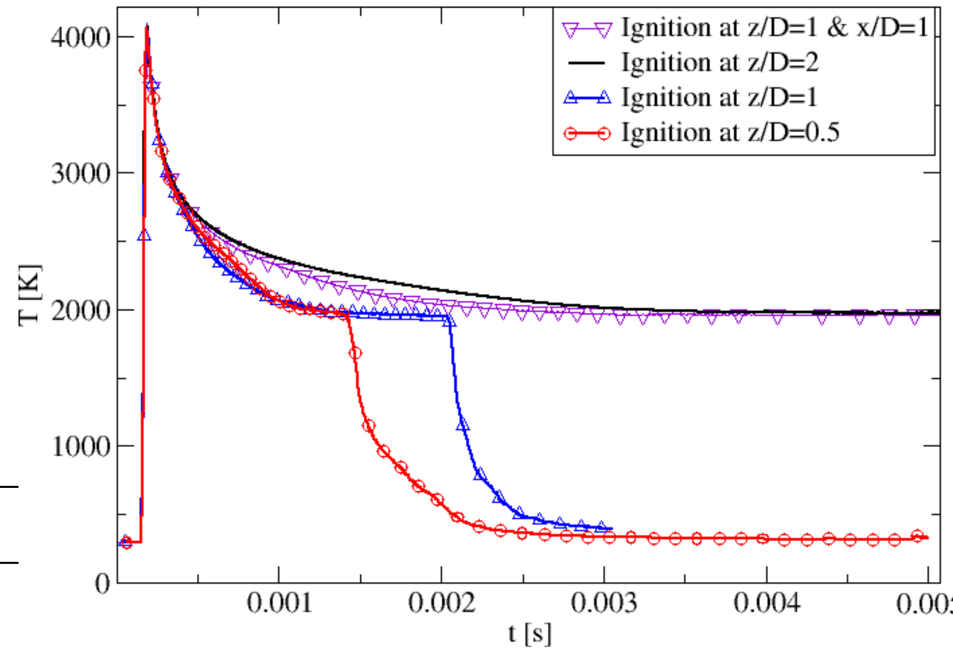


IRZ : z/D=1



CRZ : z/D=1 & x/D=1





Extinction occurs because of a too weak kernel

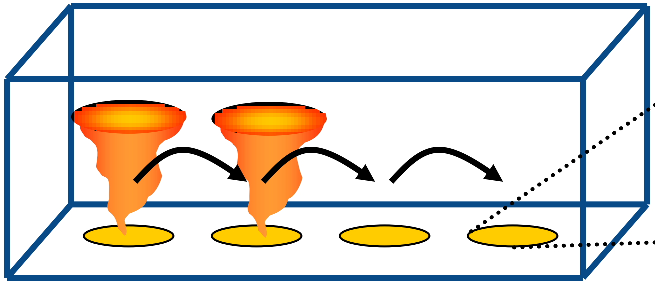
[a] *Barre et al, Combust. Flame, 2014*

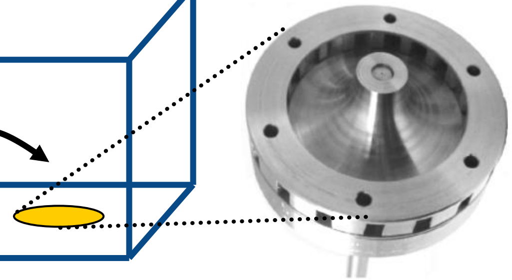
Phase 3: propagation to neighbouring injectors

CORIA multi-injector burner: partially premixed

Cordier et al. CST 2013

Gather data on the inter-injector spacing and its effect on the 'light-around' process

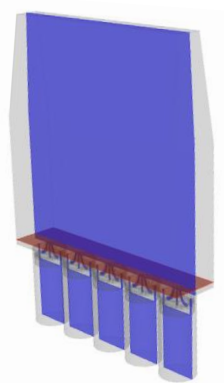




1/ Burner spacing: 9 cm (5 burners)

- Chamber spanwise length : 450 mm
- ~ 38 millions tetrahedra

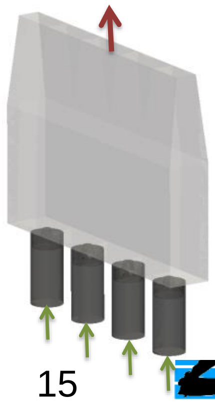
Experiments show radial ignition mode



2/ Burner spacing: 16 cm (4 burners)

- Chamber spanwise length : 650 mm
- ~ 43 millions tetrahedra

Experiments show radial and downstream ignition modes



Phase 3: propagation to neighbouring injectors: experiment[a]

[a]*Cordier et al, Combust. Sci. and Tech., 2013*

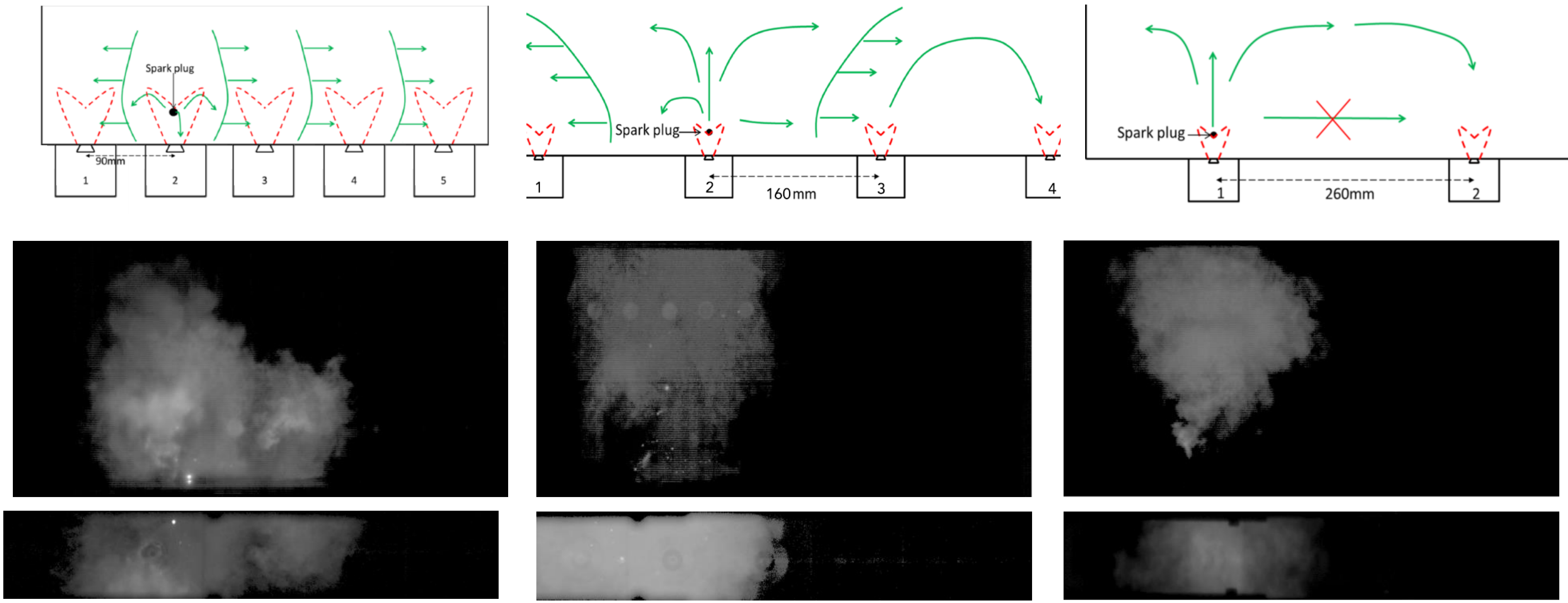
LES of ignition

Phase 3: propagation to neighbouring injectors: simulation[a]

[a]*Barre et al, Combust. Flame, 2014*

LES of ignition

Phase 3: propagation to neighbouring injectors: simulation



SP9: L = 90mm

SP16: L = 160mm

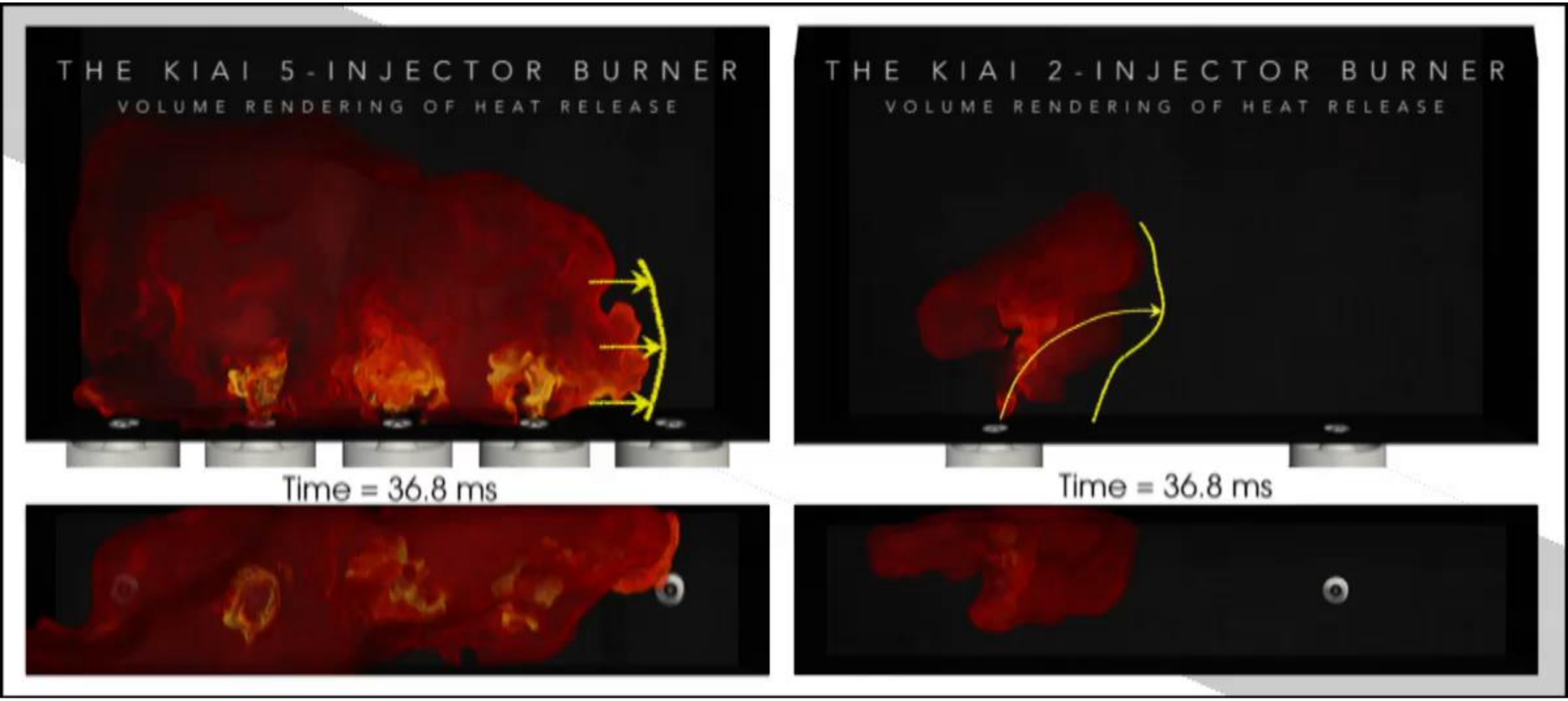
SP26: L = 260mm

[a]*Barre et al, Combust. Flame, 2014*

Phase 3: propagation to neighbouring injectors: simulation

SP9: L = 90mm

SP26: L = 260mm



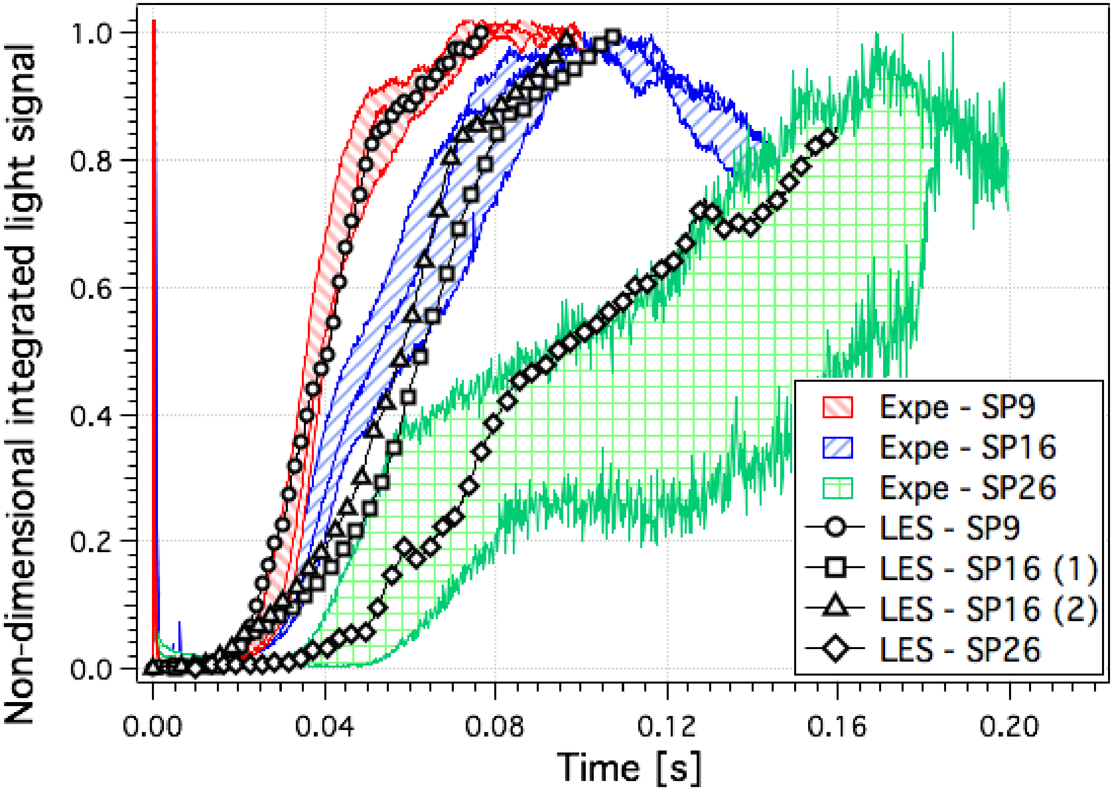
Radial flame propagation

Axial flame propagation

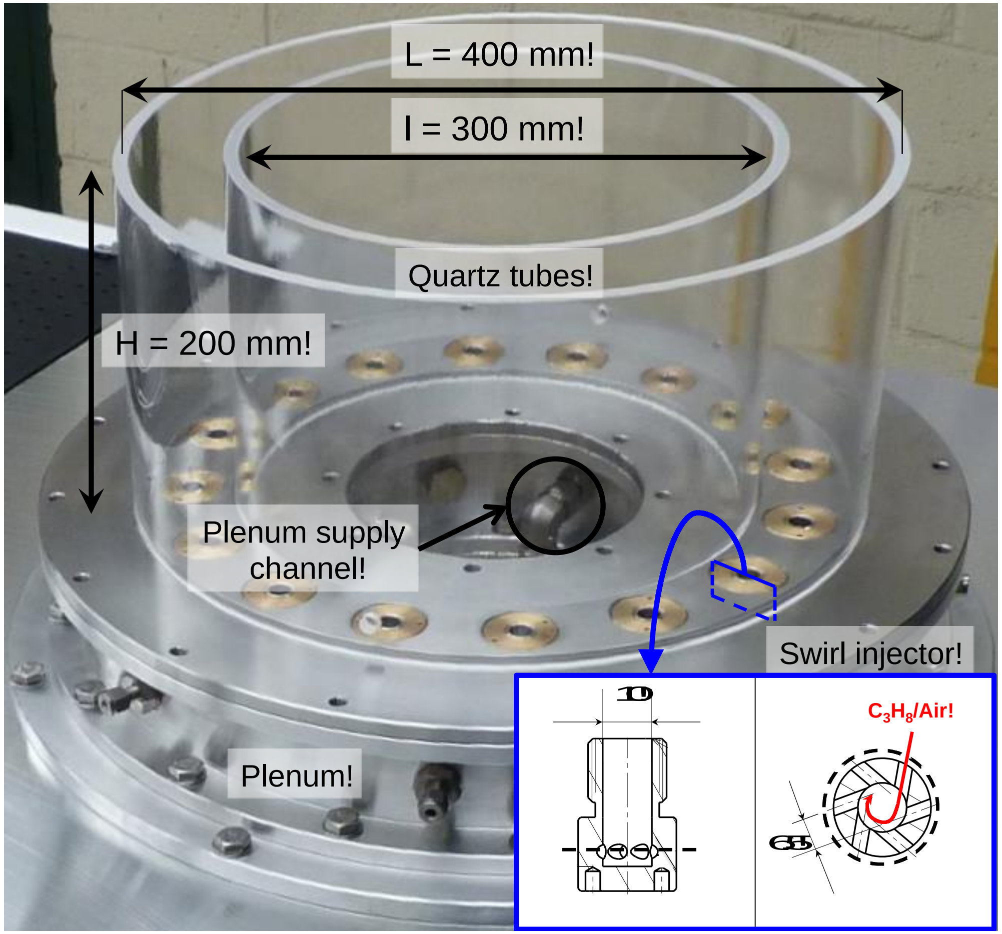
[a]*Barre et al, Combust. Flame, 2014*

Phase 3: propagation to neighbouring injectors: simulation

- Evolution of the luminous signal (CH emissions vs. Heat release images):

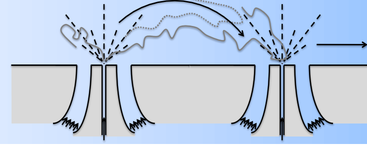


[a]*Barre et al, Combust. Flame, 2014*

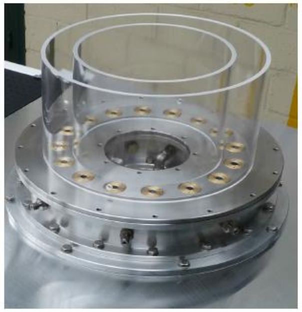


SIMAC (EM2C) (*Durox et al*)

- Annular chamber
- 16 swirled injectors
- propane
- transparent walls

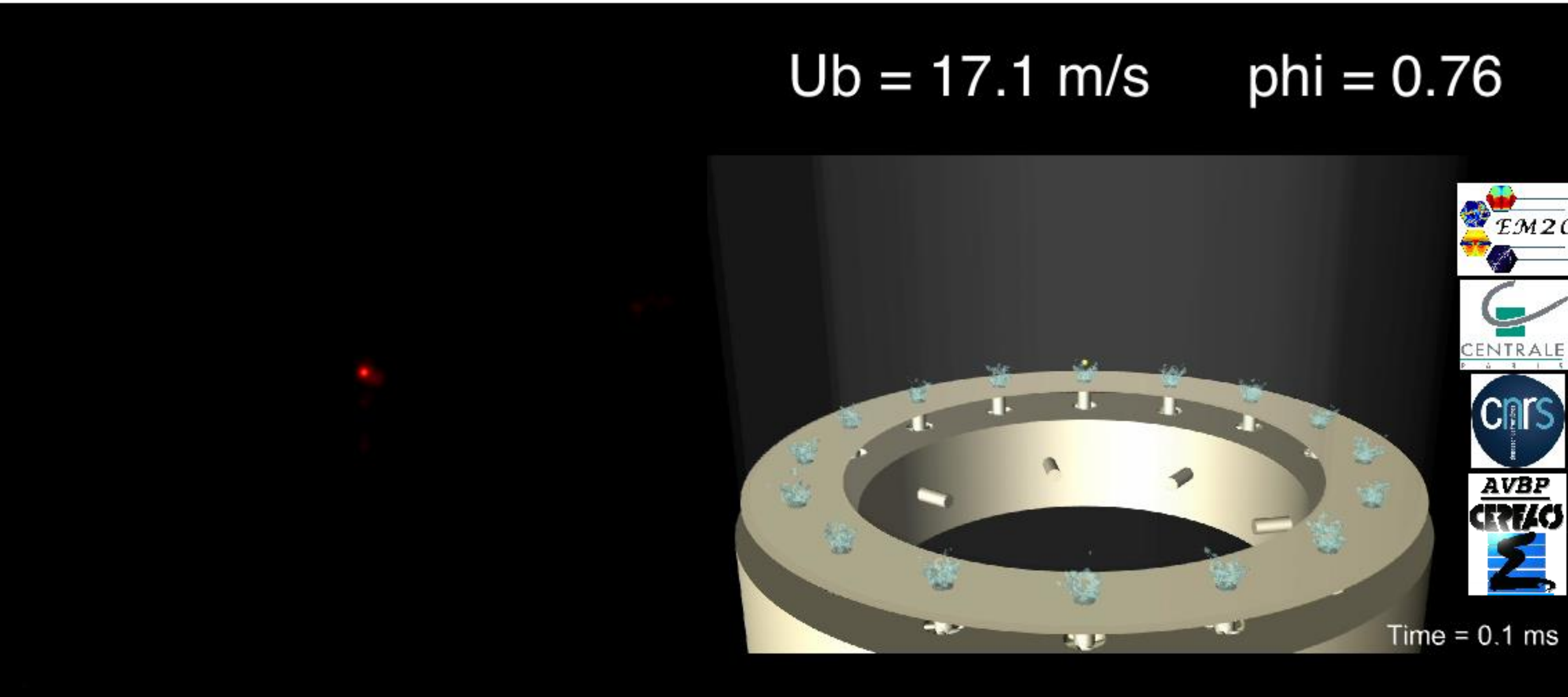


SIMAC : LES vs Experiment



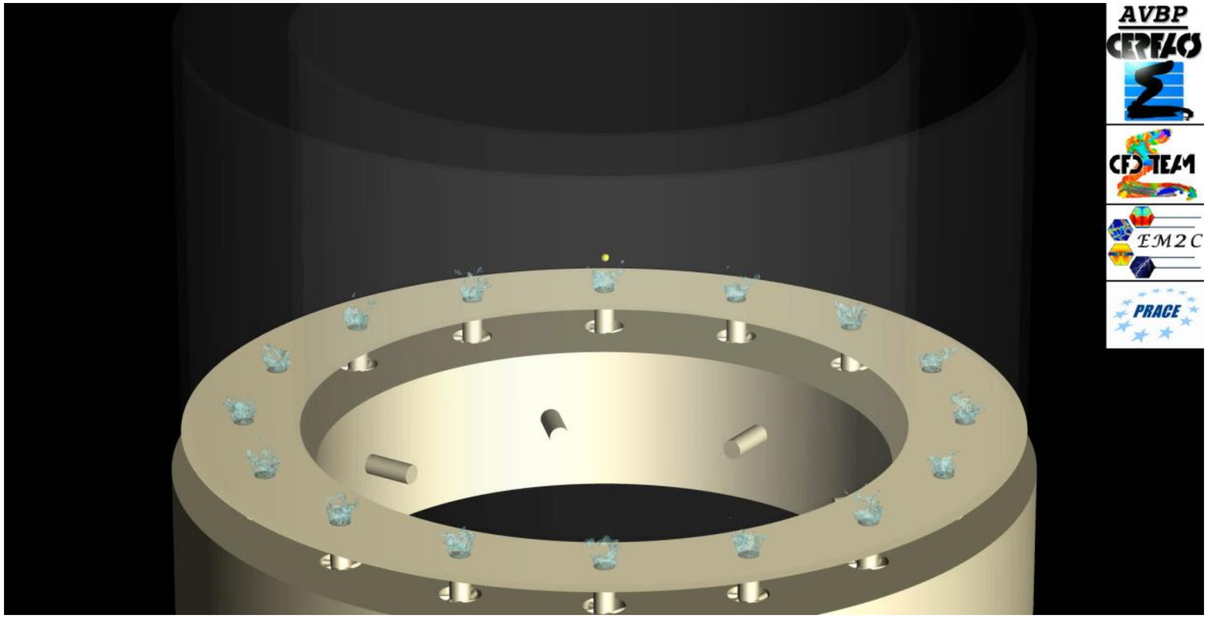
Philip et al, Proc. of the Comb Insititute

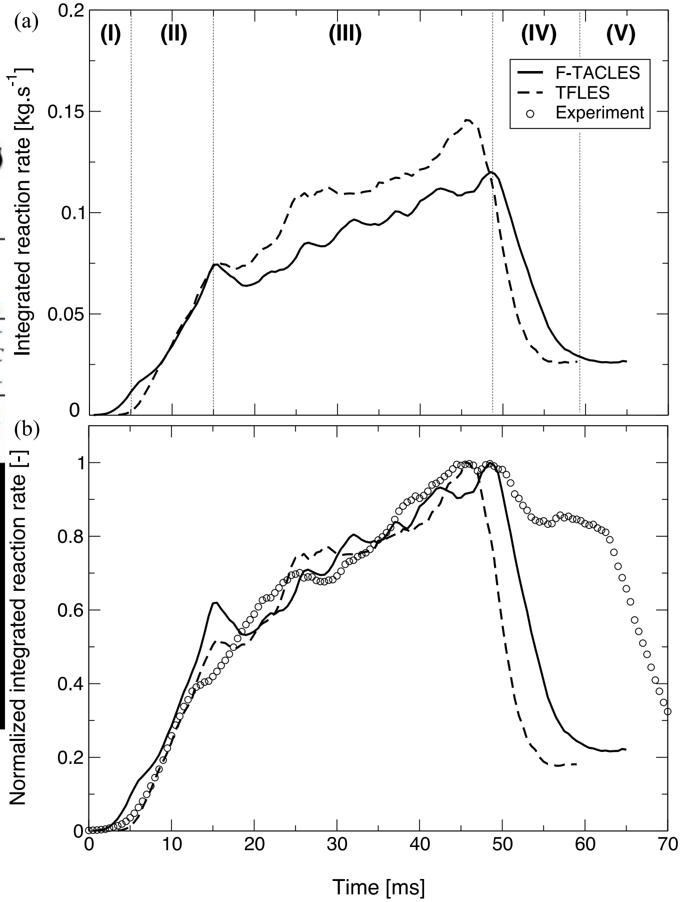
CURIE
6144 cores / run
15M CPU.h



SIMAC : F-TACLES vs TFLES

Philip et al, Proc. of the Comb Insititute





Example 2 : Acoustics / Combustion Interaction

Flames and acoustics are coupled

Acoustic energy equation:

$$\frac{\partial}{\partial t}\left[\frac{1}{2}\rho_0 u'^2 + \frac{1}{2}\frac{p'^2}{\rho_0 c^2}\right] + \frac{\partial}{\partial x}(u'p') = \frac{\gamma - 1}{\gamma P_0} p' \dot{\omega}'_T$$

Acoustic energy

Acoustic flux

Source term

(Rayleigh)

p' ~ 1000 to 20000 Pa for burners operating at P_a (ie .200 dB *)

ρc ~400 [uSI]

⇒ $u' = p'/\rho c$ ~ 2 to 20 m/s.

* dB = 20 log {*p'*/2 10^{-5}})

Example 2: Acoustics / Combustion Interaction

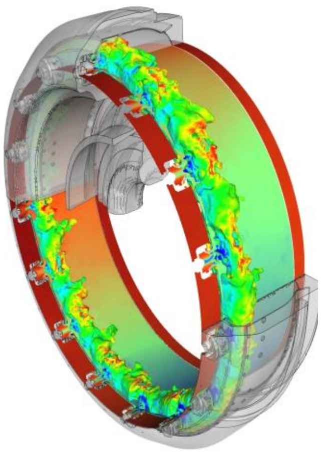
LES may be used in two ways:

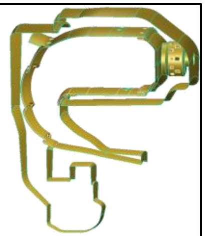
1/ Brute-force LES:

=> consider the full burner and compute

by compressible LES - stable or unstable?

- + Rely on LES modeling only (Stability maps?)
- − Effects of BC's and modeling
- − CPU intensive





[1] G. Boudier et al, Int. J. of Aroac., 8(1):69-94, 2009.
[2] G. Staffelbach et al., 32nd Symp., 2008.
[3] P. Wolf et al, CR Meca., 337(6-7):385-394, 2009.

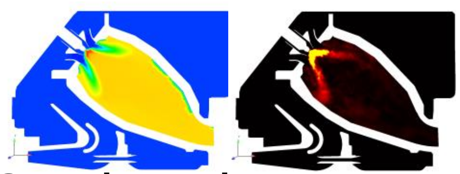
2/ Evaluate the Flame Transfer Function by LES:

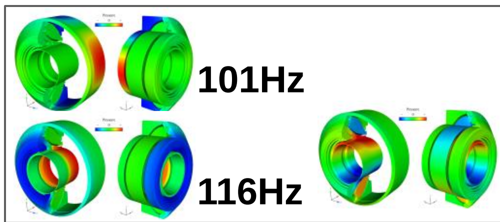
=> consider only one sector (acoustically open)

and its response to acoustic forcing

=> use the FTF with acoustic codes (Helmholtz solvers)

- + Reduced CPU cost (Stability maps accessible)
- − Model involved for FTF and estimation
- − Several code environment

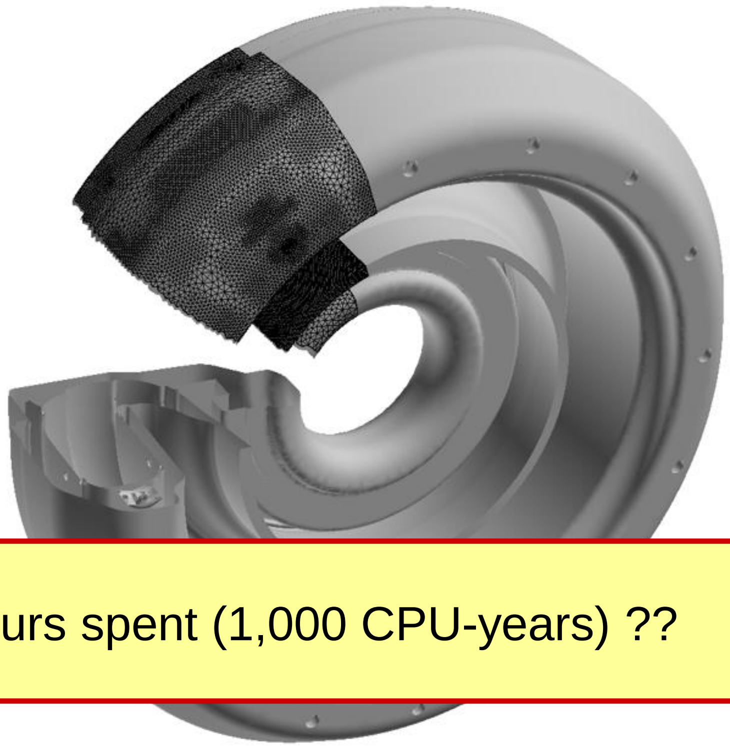




Example of brute-force LES: azimuthal thermo-acoustic instability

Full annular burner simulation

- Numerical aspects:
  - 3D compressible LES (AVBP),
  - reactive Navier-Stokes solver,
  - TTGC convective scheme (3rd order),
  - Smagorinsky model [1],
  - NSCBC boundary conditions [2],
  - Initial conditions from statistically converged mono-sector results.



What do you get out of the 8,000,000 CPU-hours spent (1,000 CPU-years) ??

- Chemical aspects:
  - JP10 1-step fitted mechanism (surrogate for kerosen [3])
  - Dynamic Flame Thickening [4].

G. Staffelbach et al., 2008

G. Boufier et al., IJ Aeroacoustic, 2007

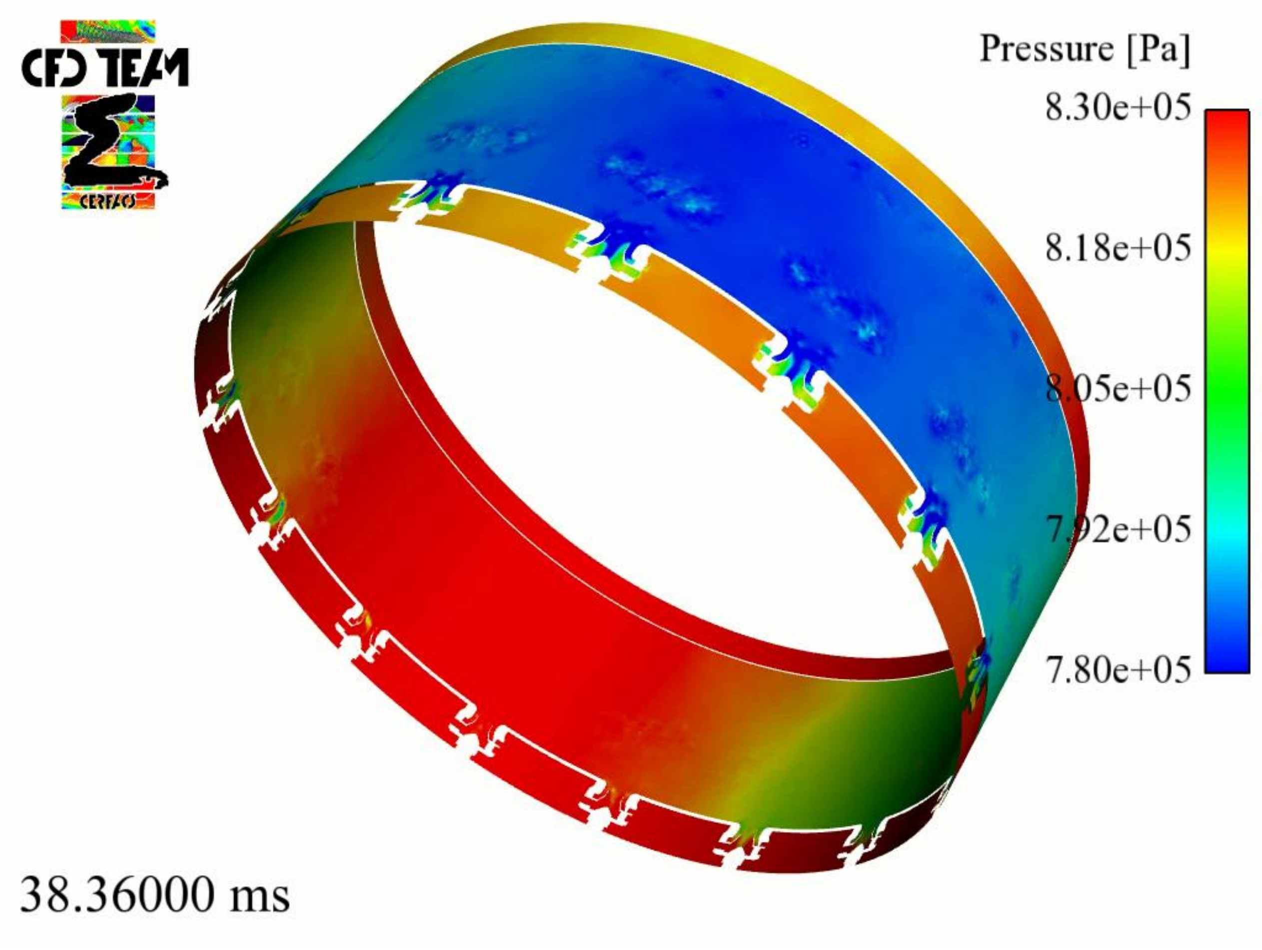
[1] Smagorinsky et al., 1963

[2] Poinsot et al., 1992

[3] Légier et al., 2001

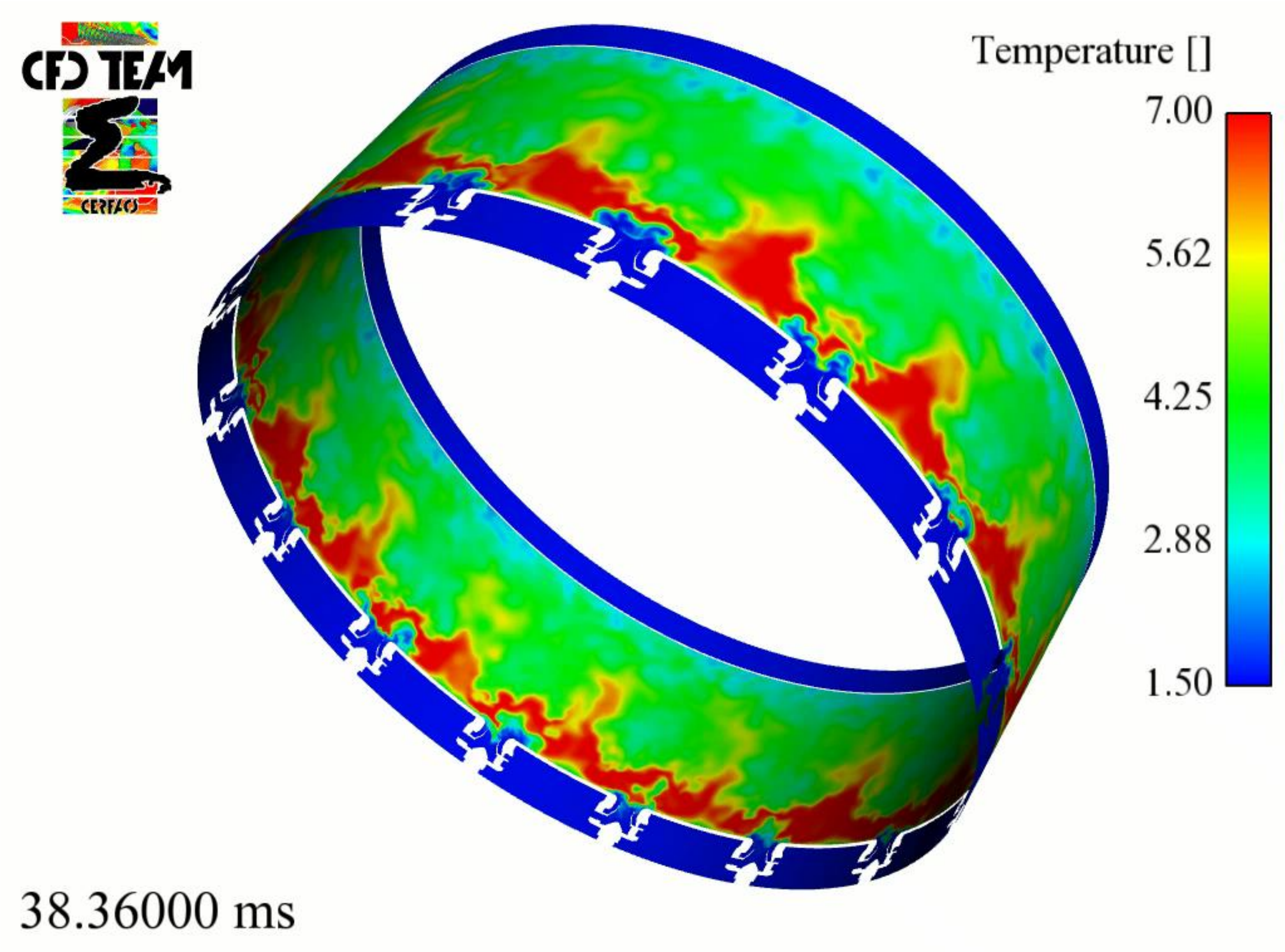
[4] Colin et al., 2000

Example of brute-force LES: azimuthal thermo-acoustic instability



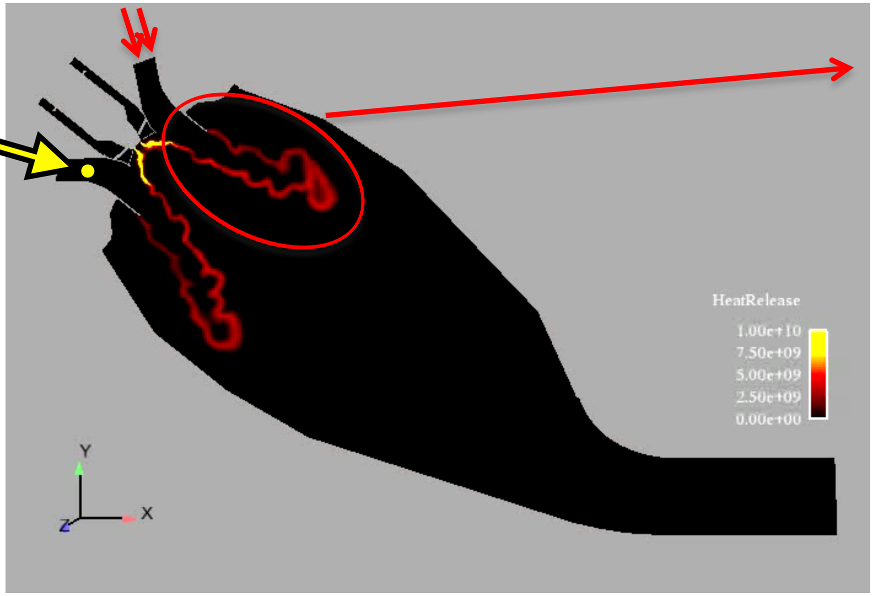
• Temporal evolution of pressure typical of the expression of two counter-rotating pressure waves: self-sustained azimuthal thermo-acoustic instability.

Example of brute-force LES: azimuthal thermo-acoustic instability



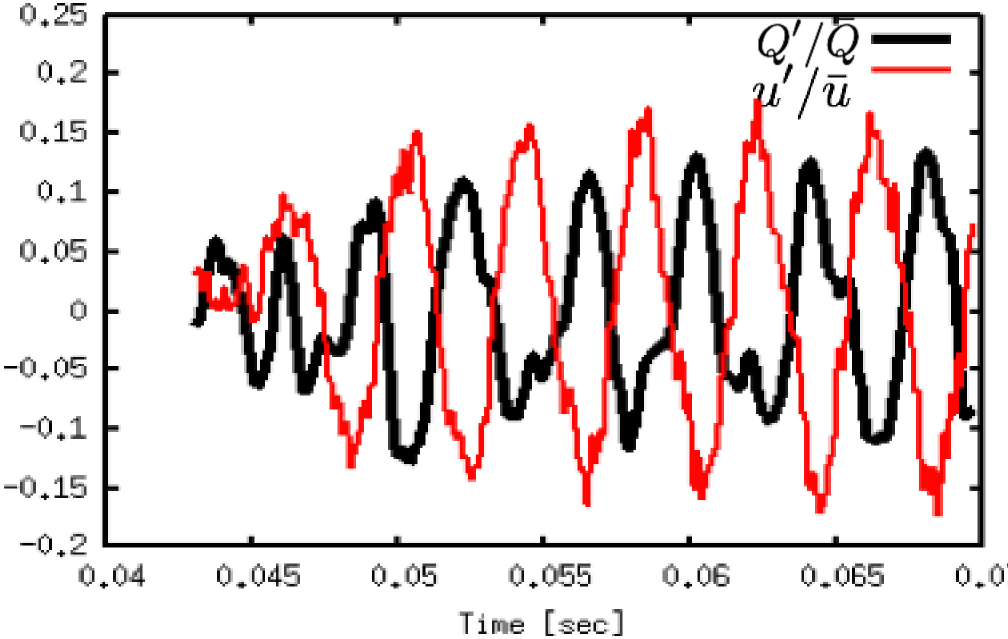
• Unexpected implication of the instability: azimuthal oscillation of combustion and the temperature field.

FTF evaluation by LES



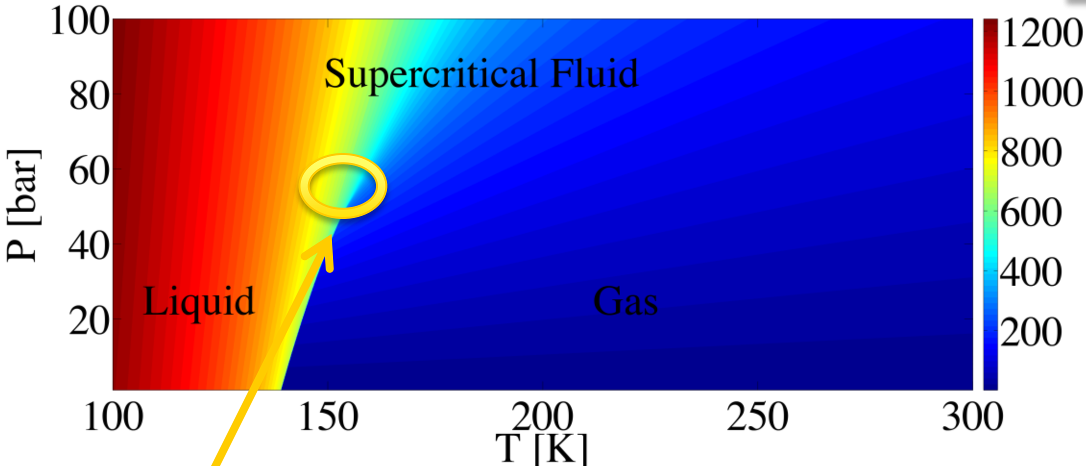
- Pure tone excitation at diagonal swirler inlet
  - Amplitude of pulsation: 6% of mean velocity
- Pulsation frequencies:
  - 90 Hz
  - 120 Hz
  - 250 Hz (shown here)
- Flame Transfer Function:

frequency	n	tau
90 Hz	1.11	1.6 msec
170 Hz	0.47	2.5 msec
250 Hz	0.63	1.9 msec



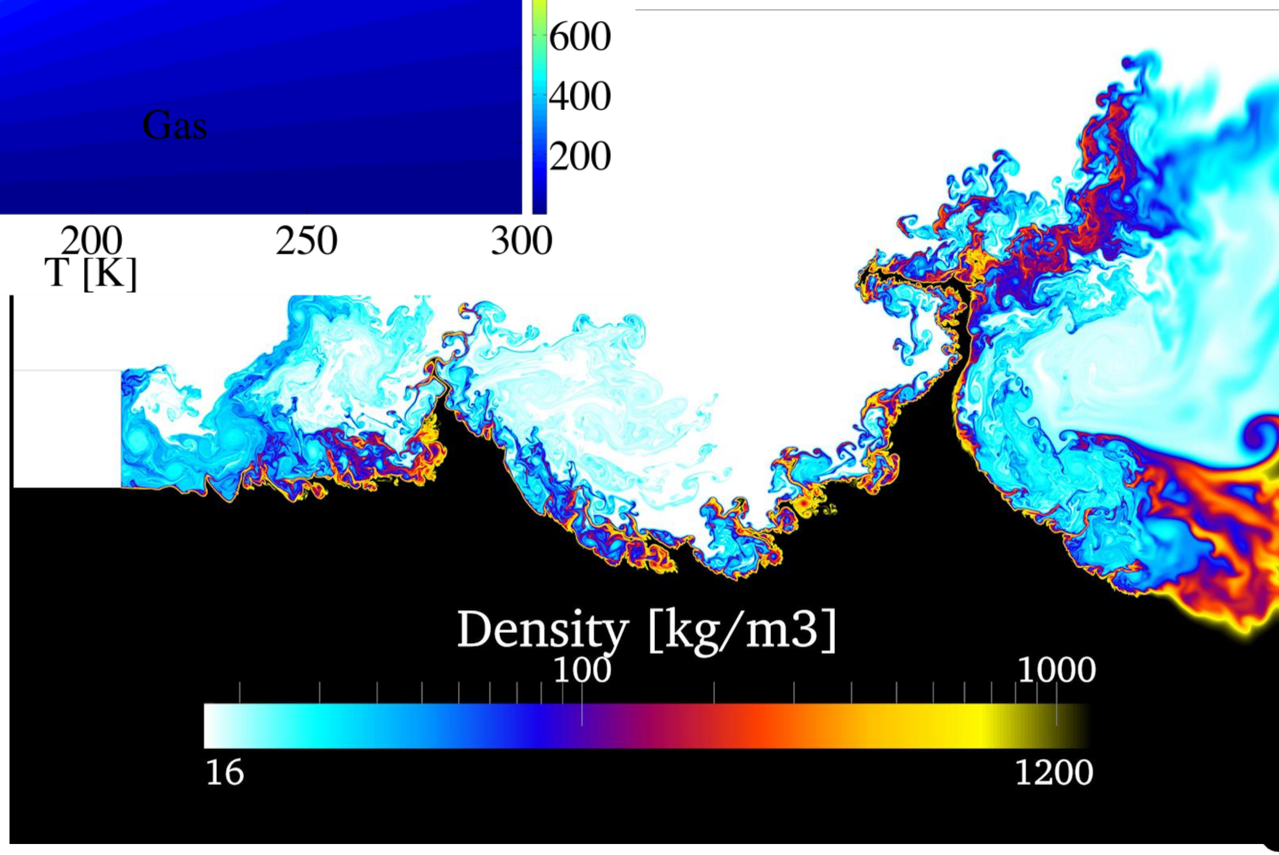
Transcritical Injection

Vulcain: 110 bars, LOx injected at 80K



Density [kg/m^3]

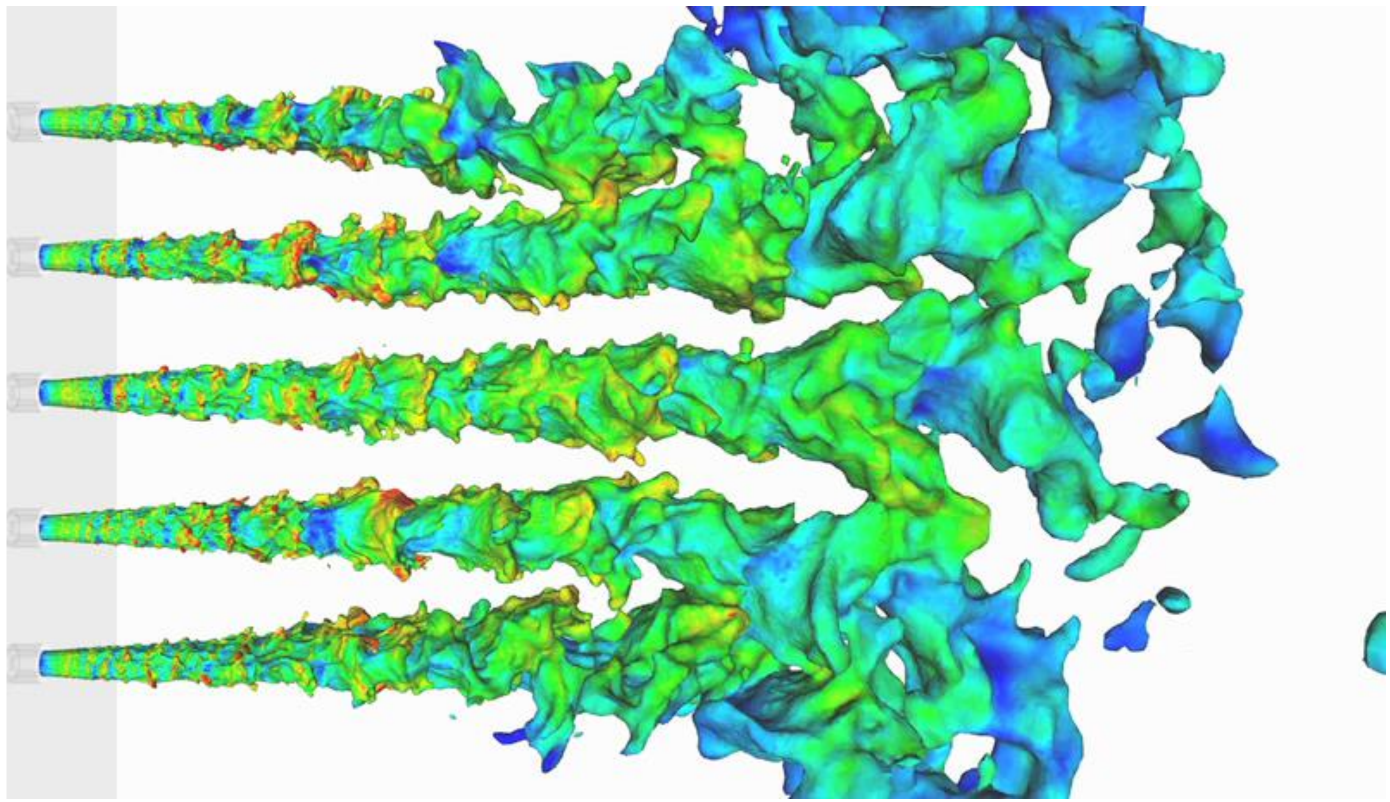
Critical point



Example 3 : Supercritical flows

CURIE
8.5M CPU.h

T. Schmitt, H. Layal, M. Boileau, S. Ducruix, S.Candel (EM2C),
A. Ruiz, G. Staffelbach, B. Cuenot and T. Poinsot (CERFACS)



L. Hakim et al, Proc. of the Combustion Institute, 2014

Example 3 : Supercritical flows

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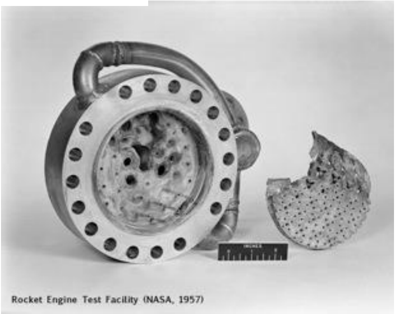
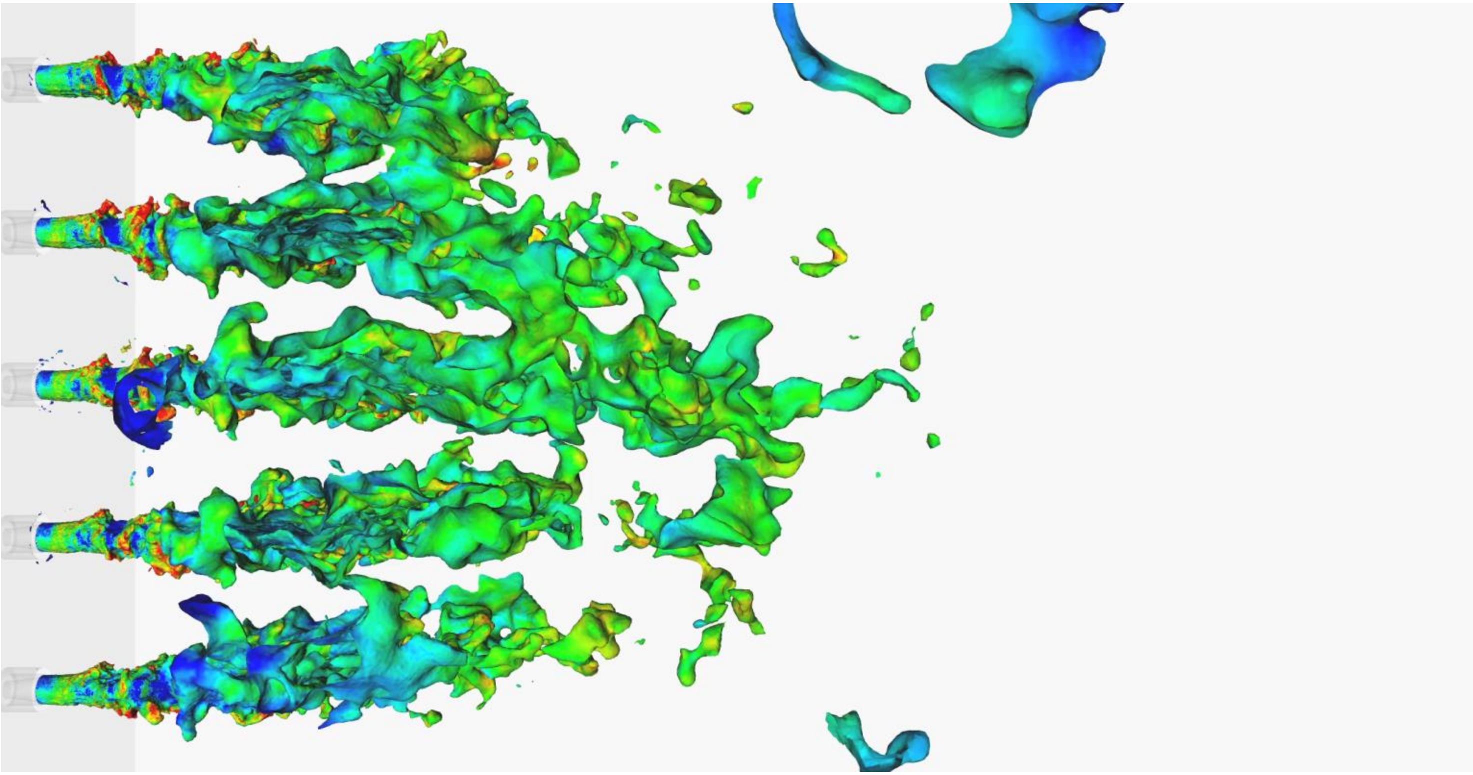
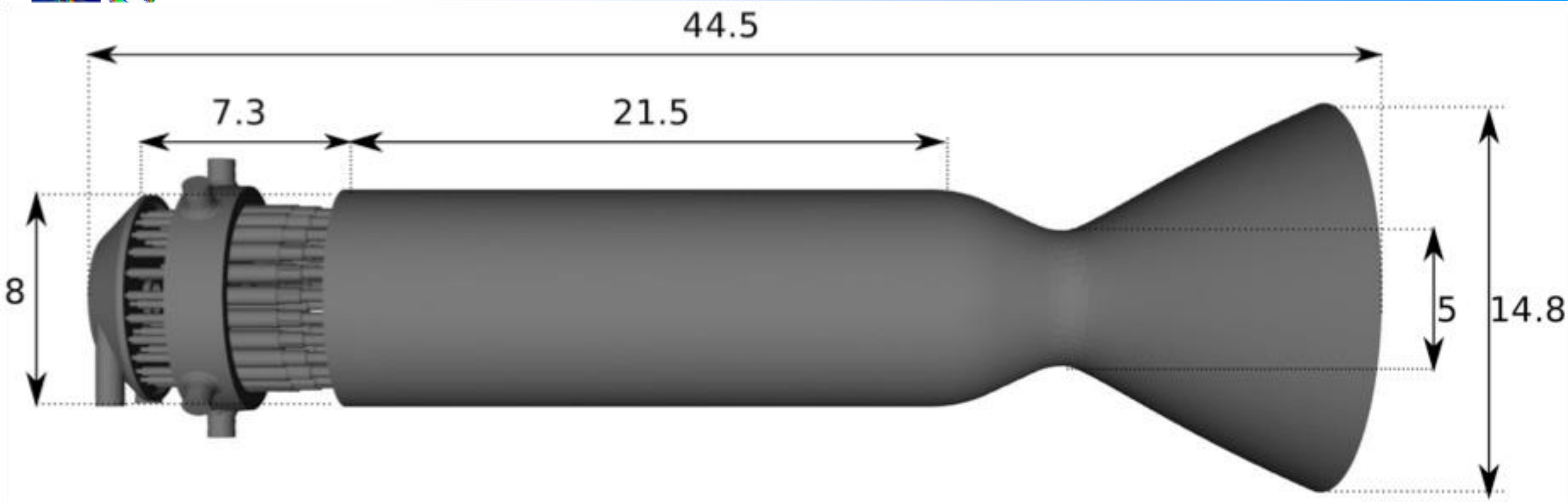
EM2C





L. Hakim et al, Proc. of the Combustion Institute, 2014



Preliminary simulation on a very coarse grid

HF-7 test case

Urbano et al., REST Modelling Workshop, 2014

Mesh and cost
38 M elements
min dx = 80 micron

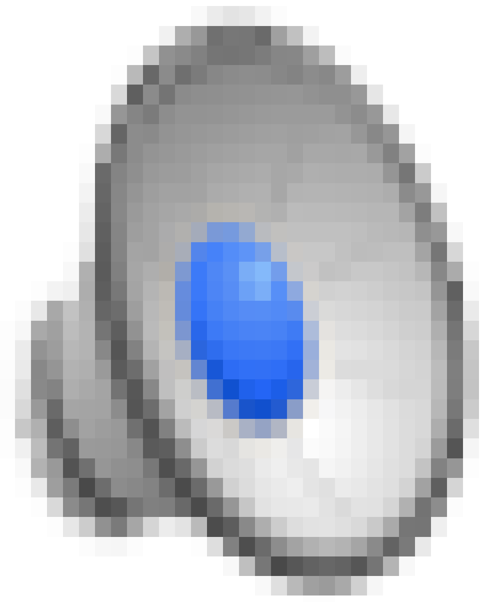
CPU cost
1 ms = 68400 cpu hr
5 ms = 345 000 cpu hr

BlueGene Q, 2048 procs
169 hrs = **7** days

LP4 (unstable?)
O/F = 6
m_{O2}=5.75 kg/s
m_{H2}=0.96 kg/s

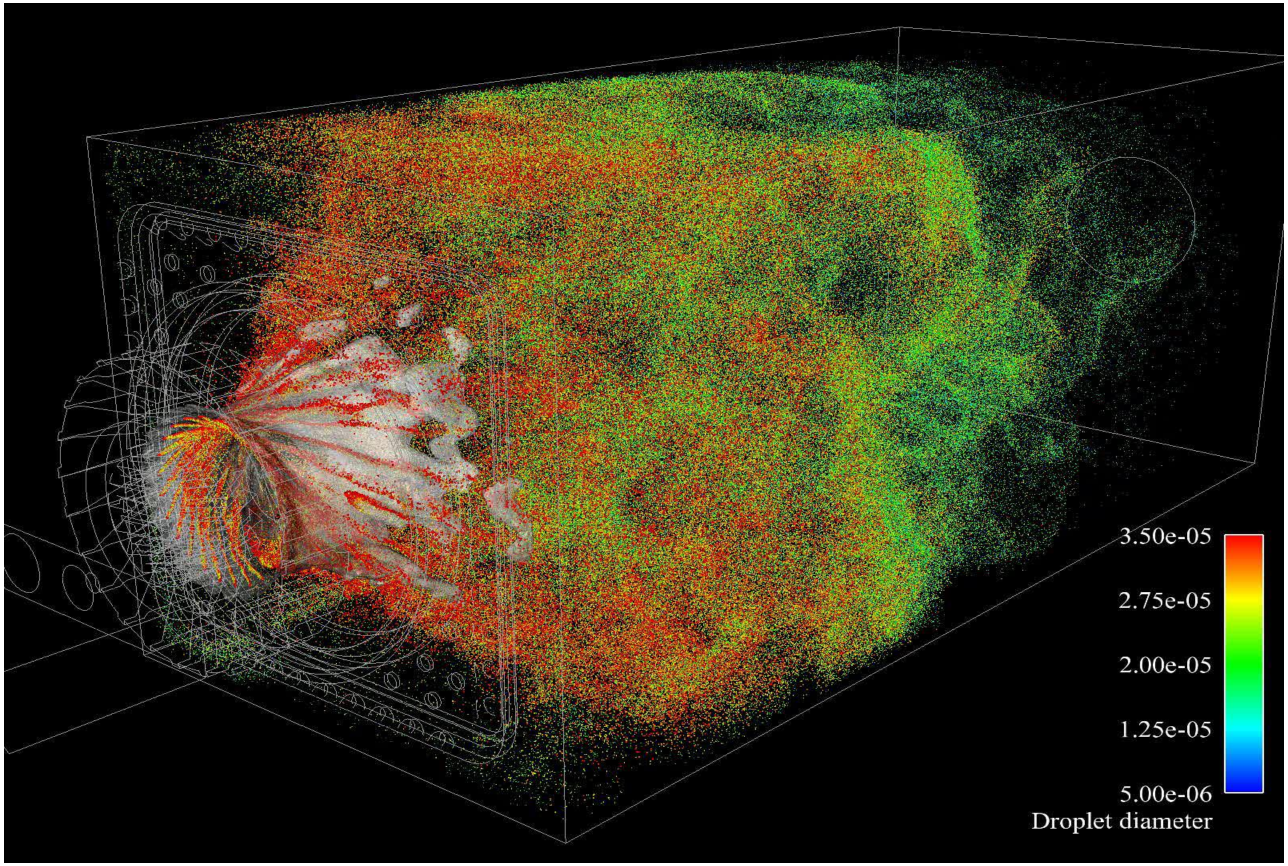
Theoretical estimations
p_{cc}=80 bar
T_{cc}=3660 K

Example 3 : Supercritical flows



Other applications :

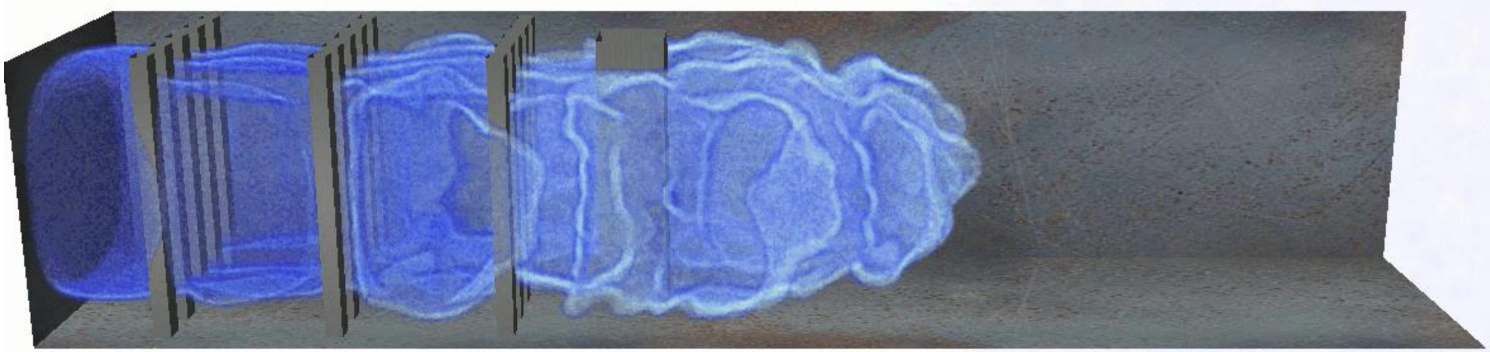
- Two-phase flows and combustion



Conclusions and Perspectives

Other applications :

- Two-phase flows and combustion
- Transition to detonation



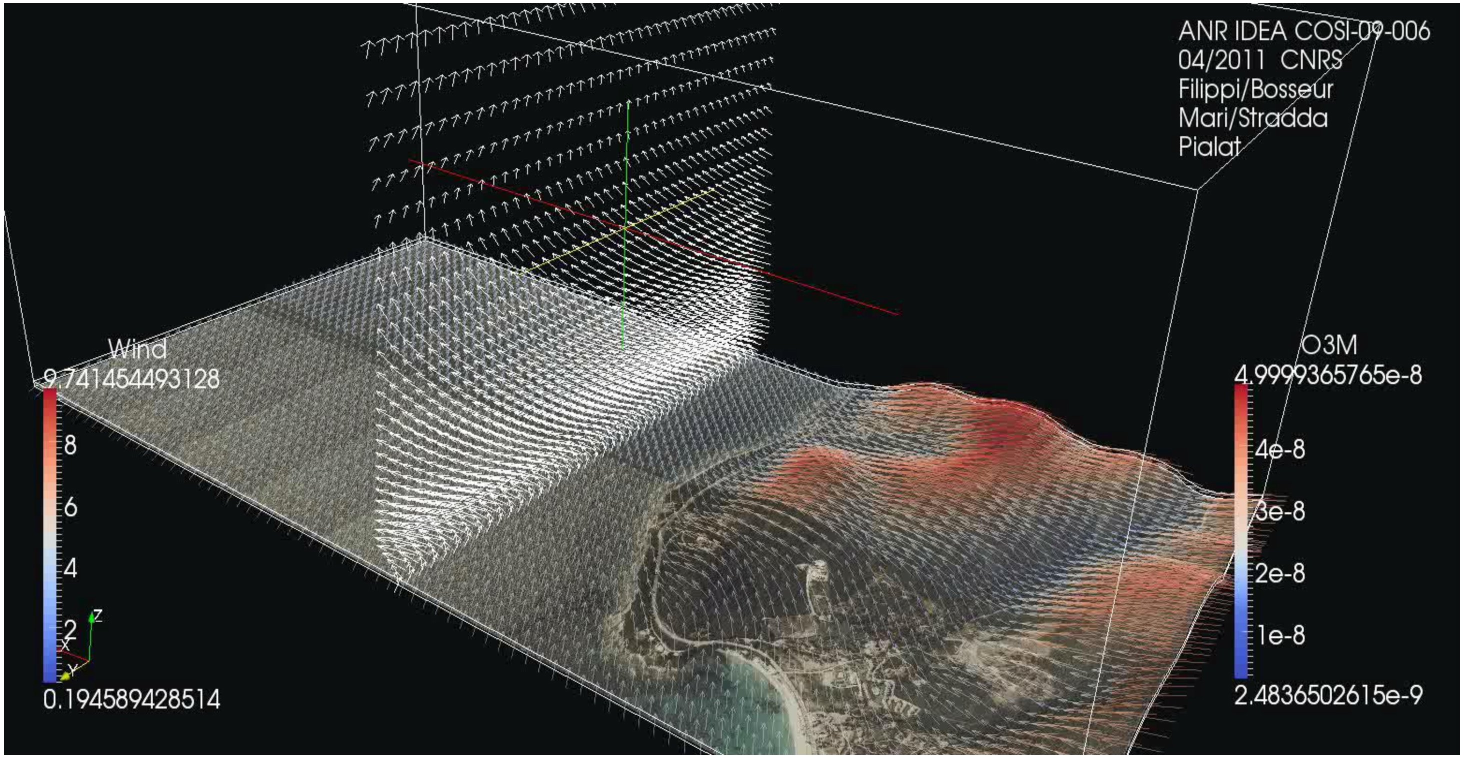
Time: 58.0

2013 - 20M BG P
2014 - 86M BG Q

P. Quillatre

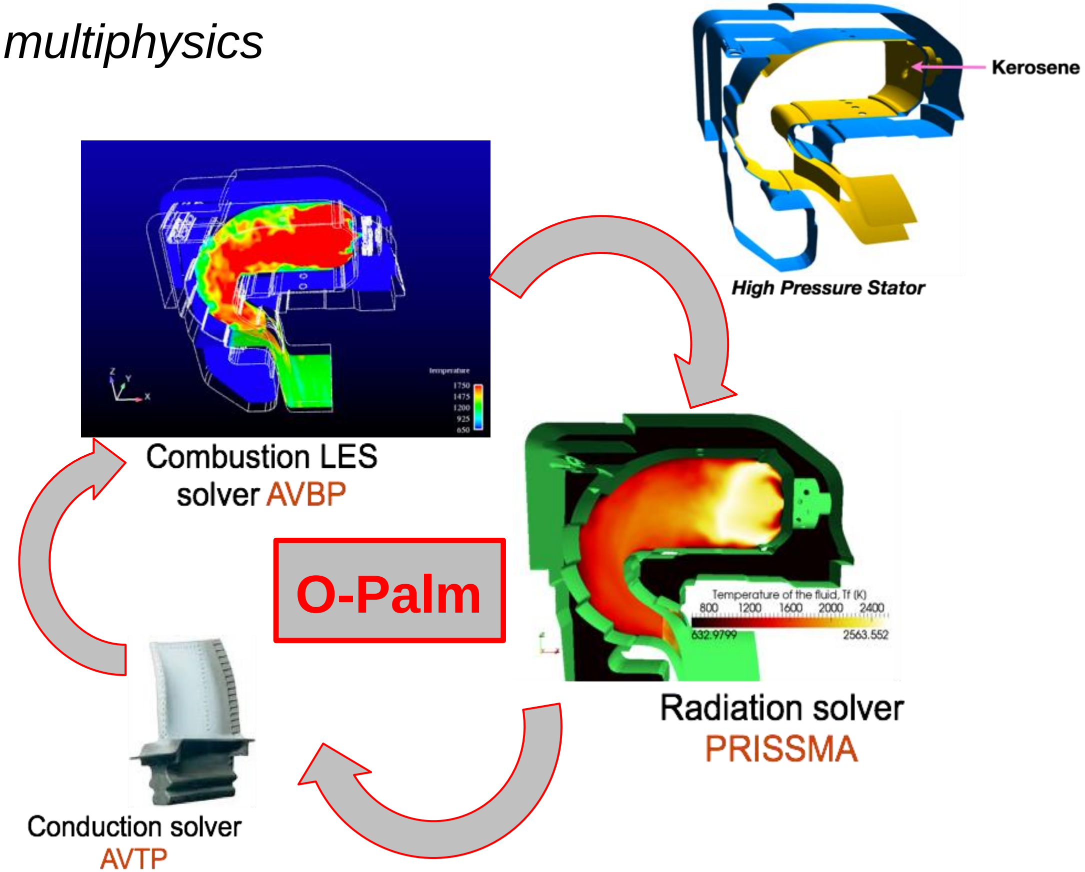
Other applications :

- Two-phase flows and combustion
- Transition to detonation
- Fires

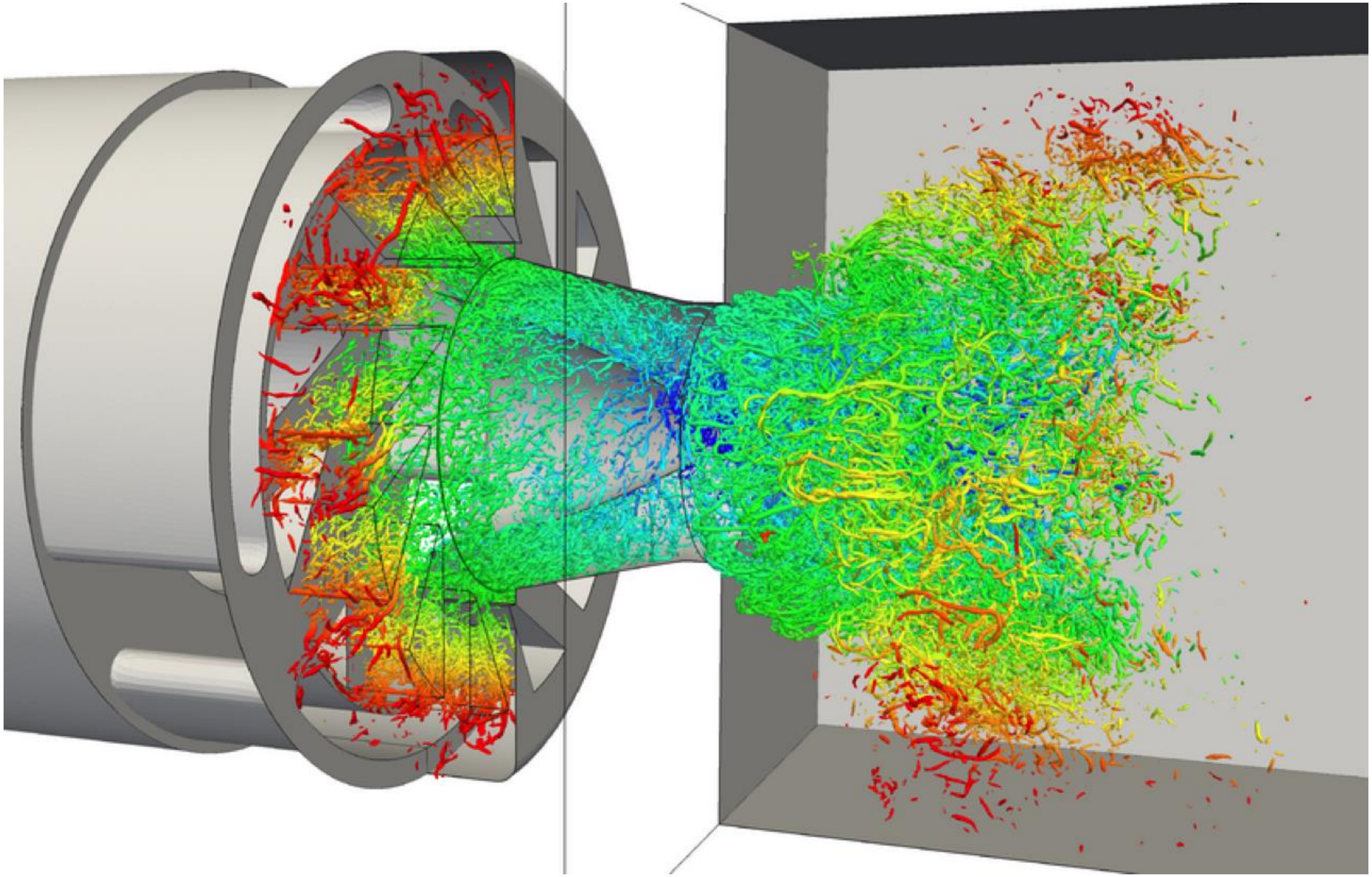


Other applications :

- Two-phase flows and combustion
- Transition to detonation
- Fires
- *Coupled multiphysics*



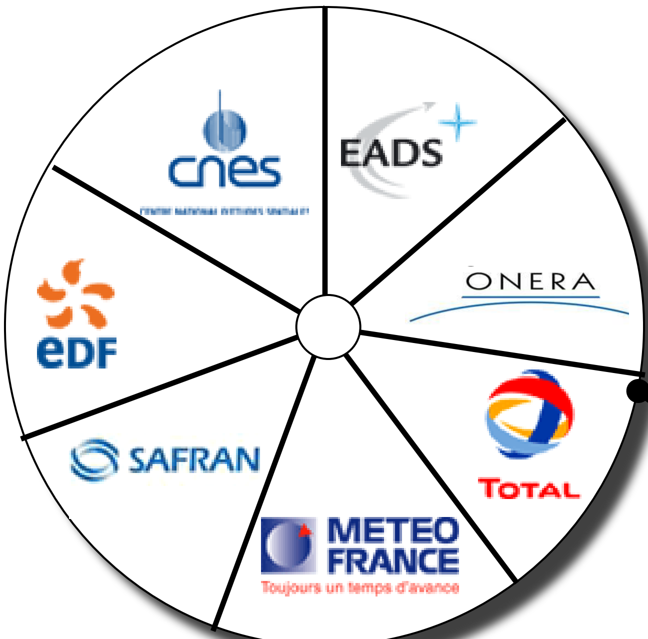
Modeling issues : towards DNS?

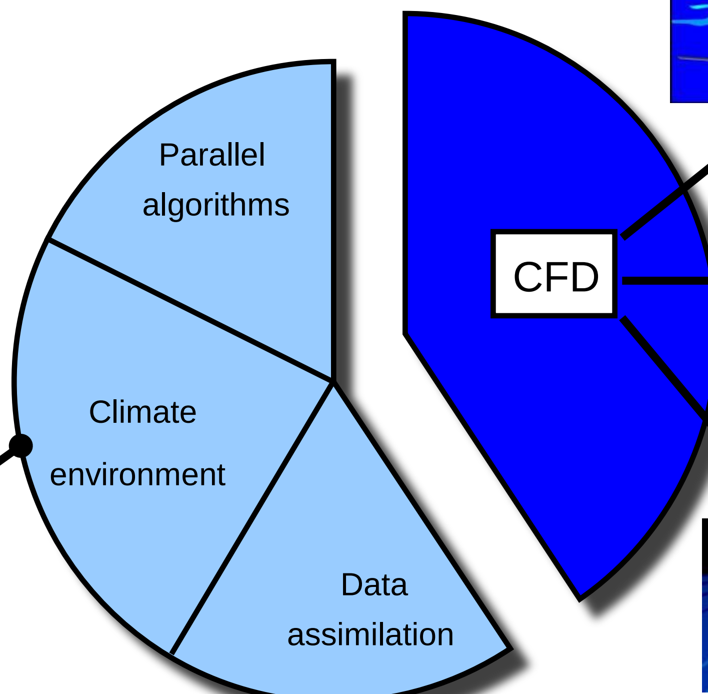


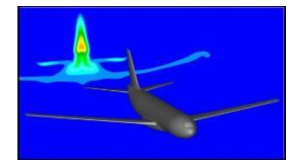
Large-Eddy Simulation of the semi-industrial PRECCINSTA burner with 2.6 billion cells.
Visualization of smallest vortices colored by their distance to the axis [Moureau et al., 2012]

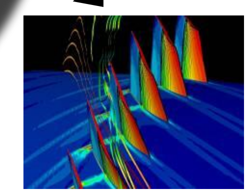
CERFACS is a private research center

7 shareholders, ~120 people in 5 teams









- Expertise in scientific computation
- Access to large computational resources

http://www.cerfacs.fr