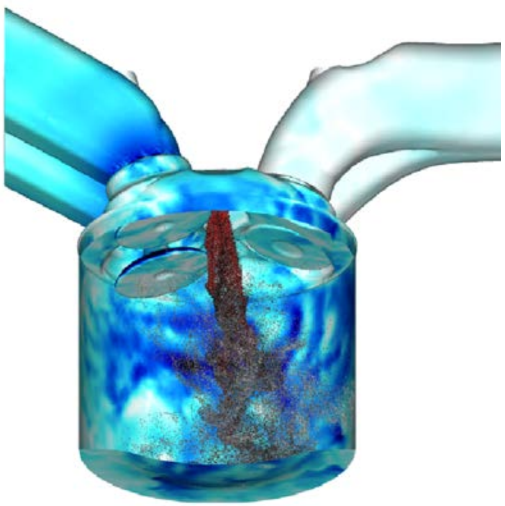
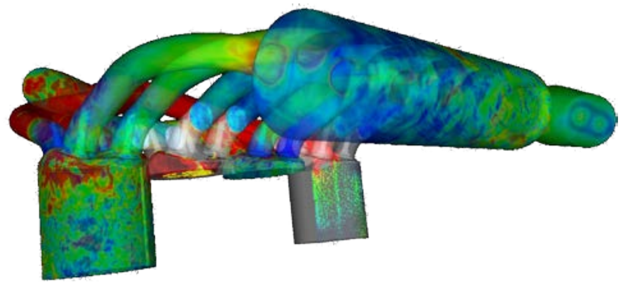
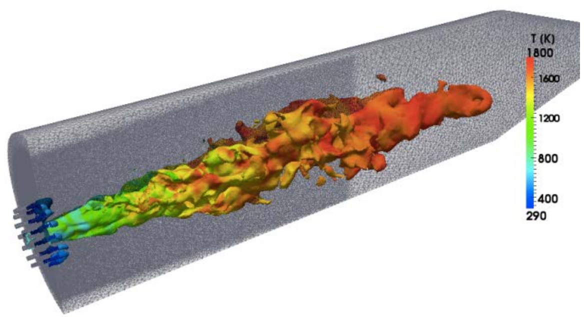
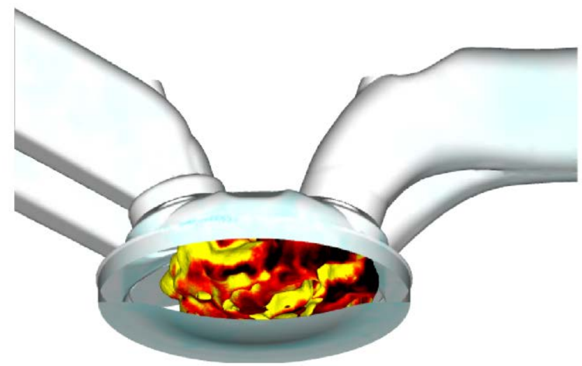
Modélisation LES d’écoulements turbulents réactifs industriels
–
Domaines automobile et procédés









C. Angelberger, O. Colin, A. Robert, K. Truffin, C. Locci

Direction Systèmes Moteurs & Véhicules

INSTITUT CARNOT
IFPEN Transports Energie

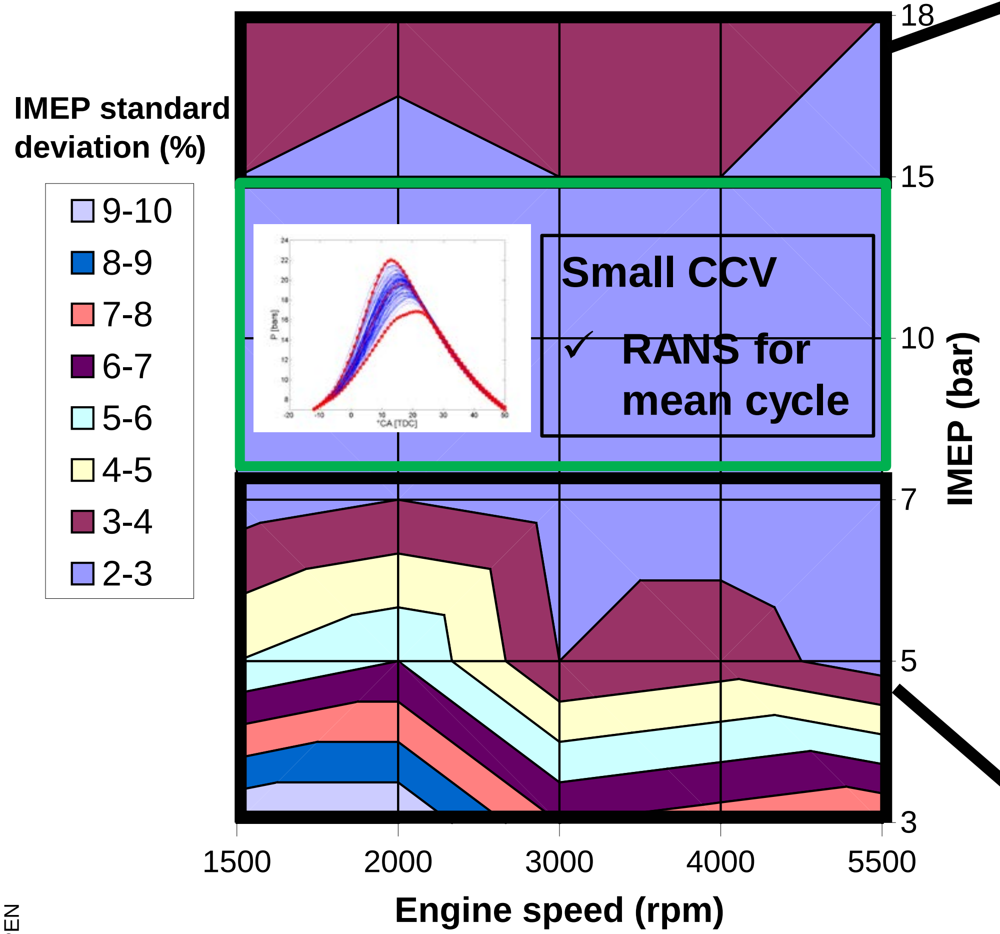
ifp Energies nouvelles

Contenu

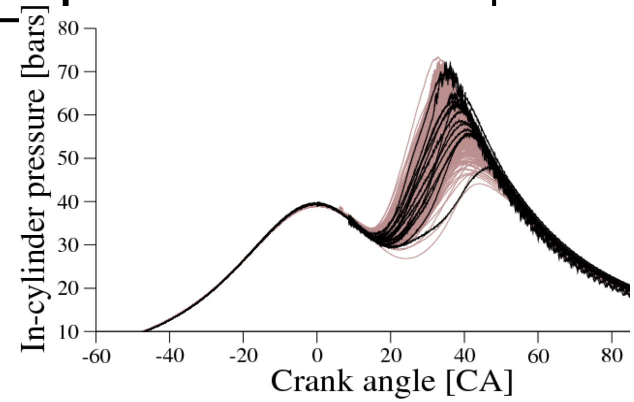
- **Intérêt de la LES pour prédire la combustion dans les moteurs à piston**
- **Etude LES du cliquetis dans un moteur à allumage commandé downsizé**
- **LES de combustion sans flamme**
- **Conclusions & perspectives**

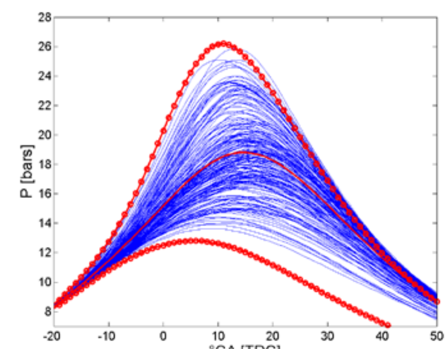
Intérêt de la LES pour prédire la combustion dans les moteurs à piston

Cyclic Combustion Variability (CCV) in spark-ignition engines



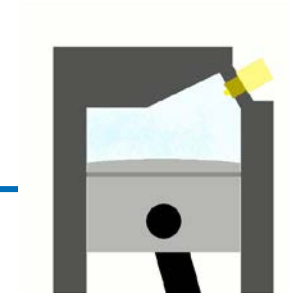
High CCV at high load
- ✓ due to enrichment
- ✓ impacts knock limit



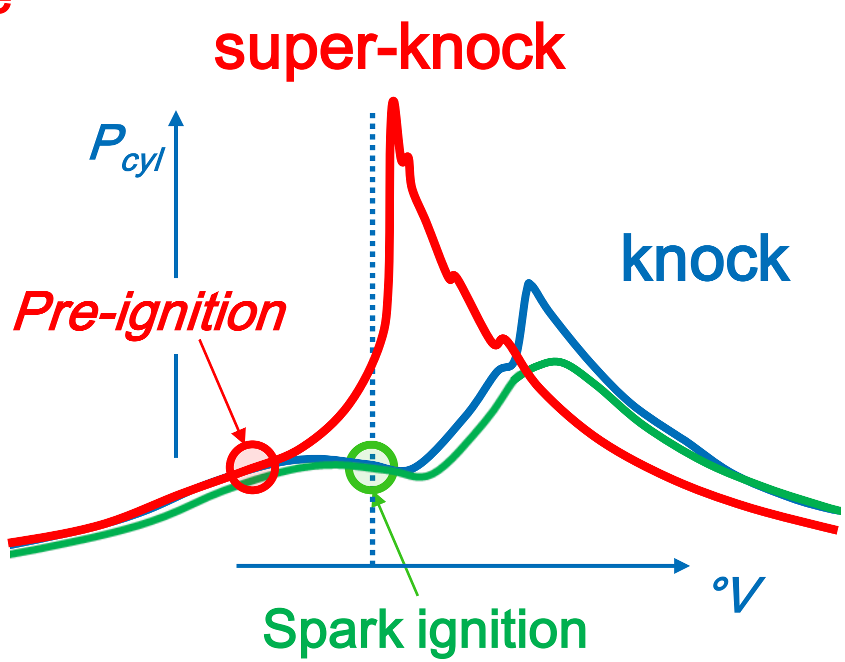


High CCV at low load & idle
- ✓ due to high EGR rates

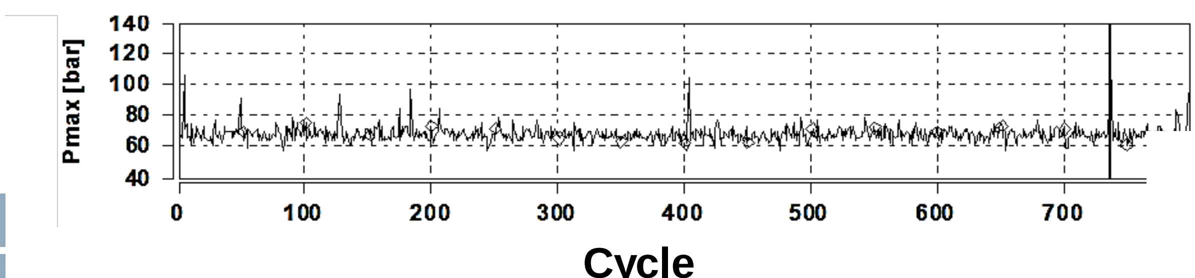
Abnormal combustion & CCV



Immediate damage



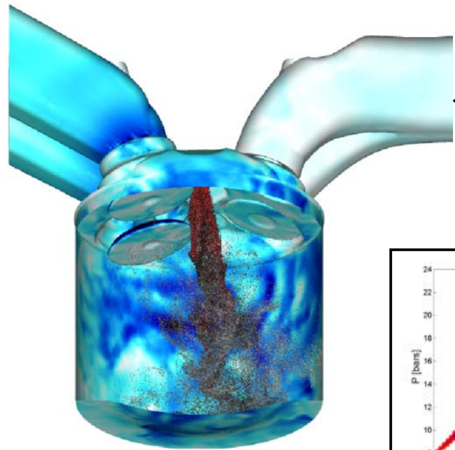
Fatigue damage



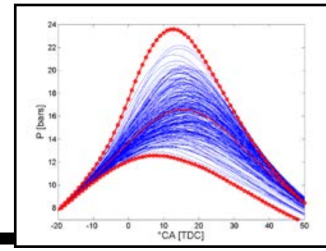
- Limits of abnormal combustion intrinsically linked to cyclic variability

The difficulty of predicting Cyclic Combustion Variablity in SI engines

Intake system
- ✓*turbulence*
- ✓*flow dynamics*
- ✓*acoustics*



Exhaust system
- ✓*turbulence*
- ✓*flow dynamics*
- ✓*acoustics*



Combustion chamber

- ✓ *trapped mass*
- ✓*global composition (EGR, IGR, F/A eq. ratio)*
- ✓ *large scale flow (swirl, tumble)*
- ✓*small scale turbulence*
- ✓ *Injection strategy*
- ✓ *wall conditions*
- ✓ *Ignition (spark & auto)*

- **CCV result from interactions between many non-linear phenomena**
- **Predicting CCV requires a 3D CFD approach** **LES**
  - that predicts individual engine cycles
  - and gives access to detailed, instantaneous & local flow phenomena

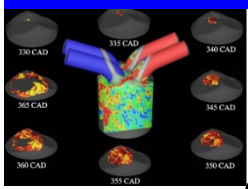
The French concerted research framework around LES for ICE around AVBP

PhDs: 18 since 2001
GIS SUCCESS + Renault, PSA Peugeot-Citorën,

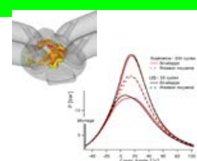
numerics, validated physical models

AVBP development & maitenance
CERFACS & IFPEN

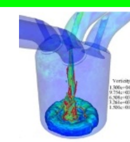
EC FP5 LESSCO2
Feasibility of CCV by LES



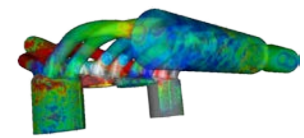
ANR SGEmac
LES method for CCV



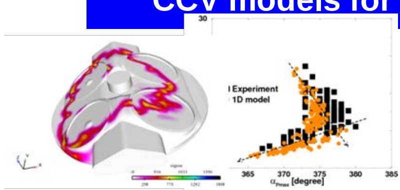
ANR SIGLE
LES of engine sprays



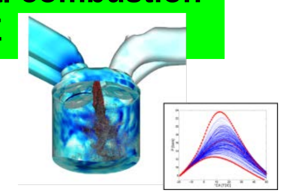
ANR CamPaS
multicyl._LES



EC FP7 LESSCCV
Exploiting LES for proposing CCV models for 1D CFD



ANR ICAMDAC
LES & 1D-CFD of CCV & abnormal combustion in downsized DI-SIE



ANR ASTRIDE
LES & 1D-CFD of transients in DI-SIE

Groupepent Scientifique Moteur (GSM)

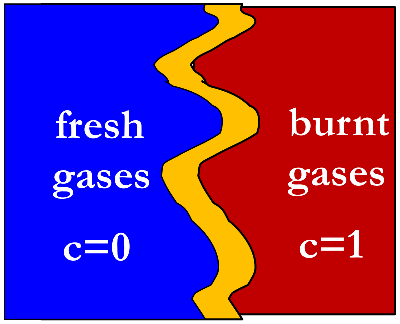
Industrial LES methodologies & Applications

Etude LES du cliquetis dans un moteur à allumage commandé downsizé

Predicting "normal" combustion: The ECFM-LES model

- **Transport equation for a progress variable**

$$\frac{\partial \overline{\rho}\widetilde{c}}{\partial t} + \nabla.(\overline{\rho}\widetilde{\mathbf{u}}\widetilde{c}) = \nabla.\left(\overline{\rho}\frac{\nu_t}{Sc_t}\nabla\widetilde{c}\right) + \rho^u S_l \overline{\Sigma}_{\widetilde{c}}$$

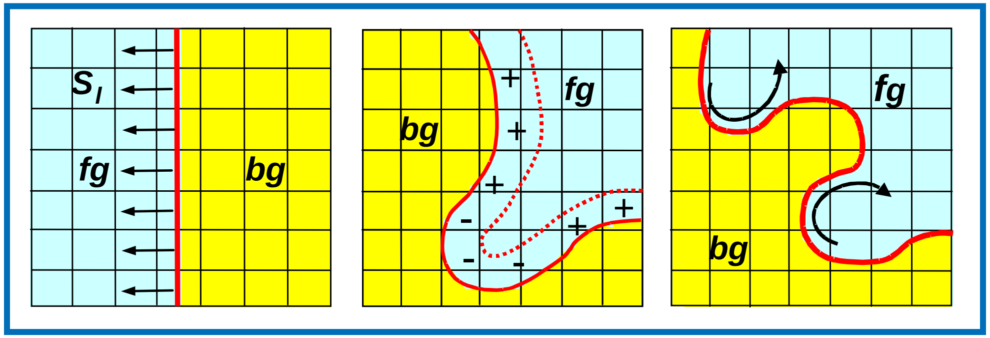


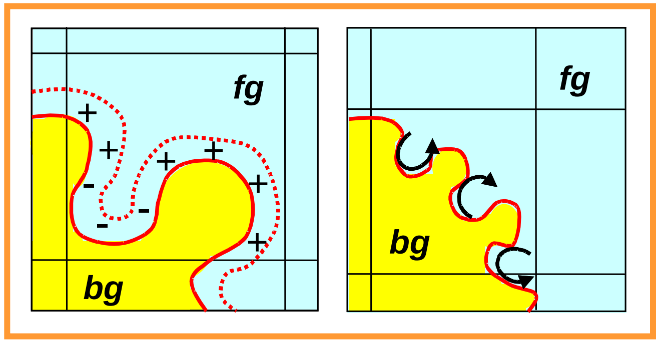
- **Transport equation for the flame surface density**

Richard & al., 31st Symp. Comb. 2007

$$\frac{\partial \overline{\Sigma}_{\widetilde{c}}}{\partial t} = \boxed{T_{res} + P + C_{res} + S_{res}} + \boxed{T_{sgs} + C_{sgs} + S_{sgs}}$$

resolved contributions **unresolved contributions**





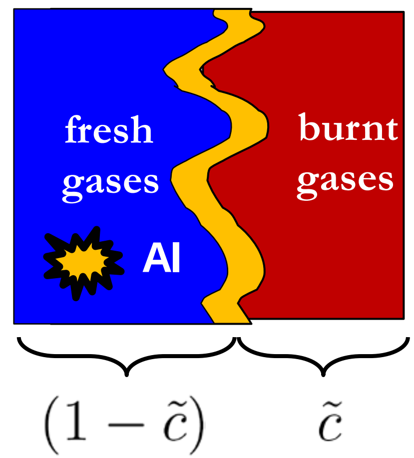
+ spark ignition + flame-wall + burnt gases chemistry

C

Predicting fresh gases' auto-ignition: The *Tabulated Kinetics of Ignition* (TKI-LES[2]) model

- **Definition of a auto-ignition progress**

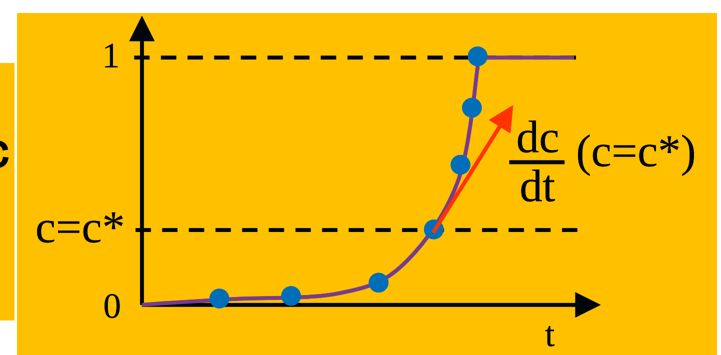
$$\boxed{c^{TKI} = \underbrace{\widetilde{Y}^{TKI}_{fuel}}_{\text{consumed by AI}} / \left(\widetilde{Y}^{TKI}_{fuel} + \underbrace{\widetilde{Y}_{fuel}}_{\text{available for AI}}\right)}$$



- **Total progress reaction rate**

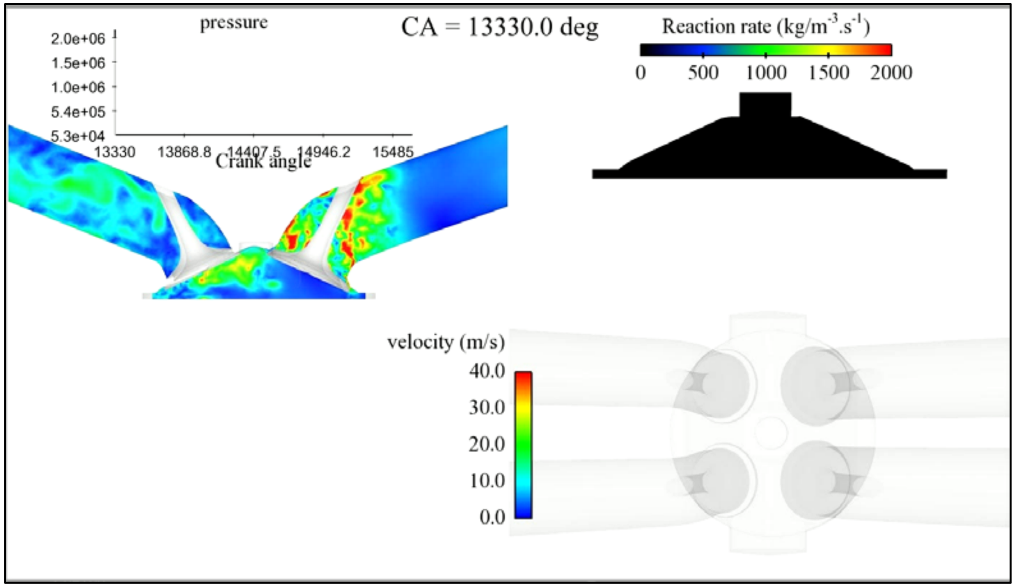
$$\bar{\rho}\tilde{\dot{\omega}}_c = \underbrace{\rho_u S_l \bar{\Sigma}_{\tilde{c}}}_{\text{Propagation with ECFM-LES}} + \underbrace{(1-\tilde{c})\bar{\rho}\tilde{\dot{\omega}}_c^{AI}}_{\text{AI}}$$

- A priori tabulated for isobaric homogeneous reactors as a function of T^u, p, ϕ, dilution and c
- Read during the computation from this table based on filtered local conditions

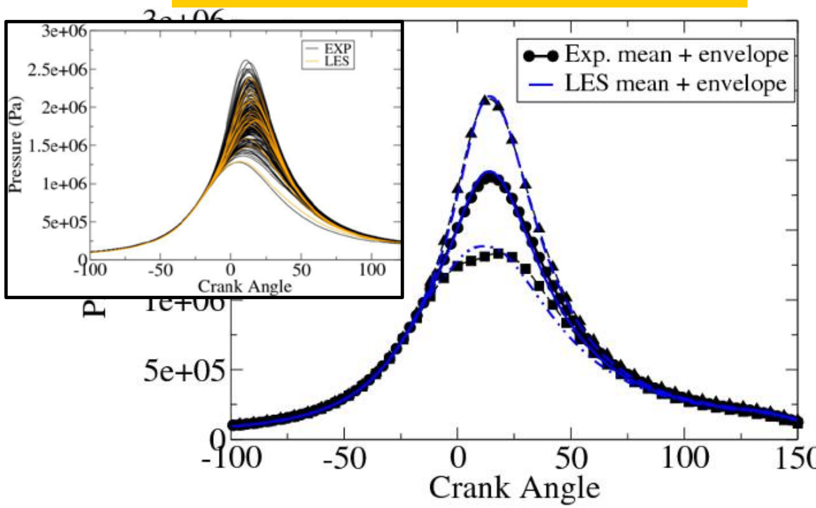


[2] G. Lecocq, S. Richard, J.-B. Michel, and L. Vervisch. Proceedings of the Combustion Institute, 33(2) :3105 – 3114, 2011.

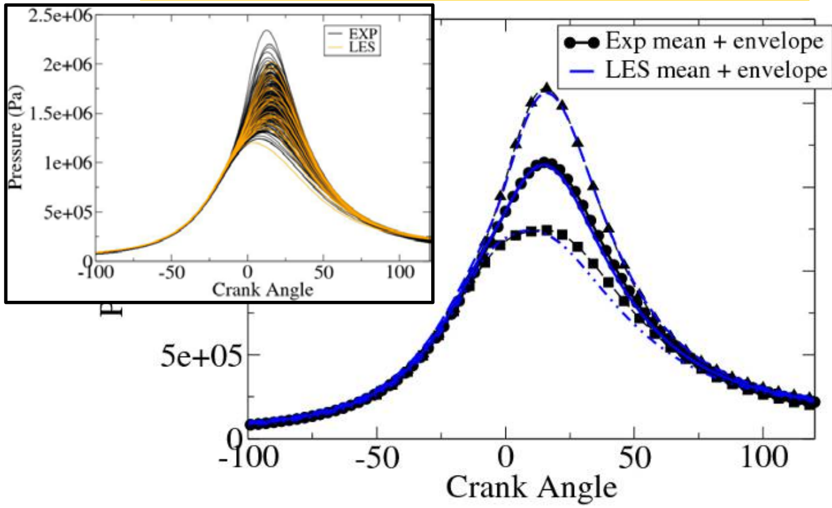
Quantitative prediction of CCV by LES for the two unstable points



Instability by dilution



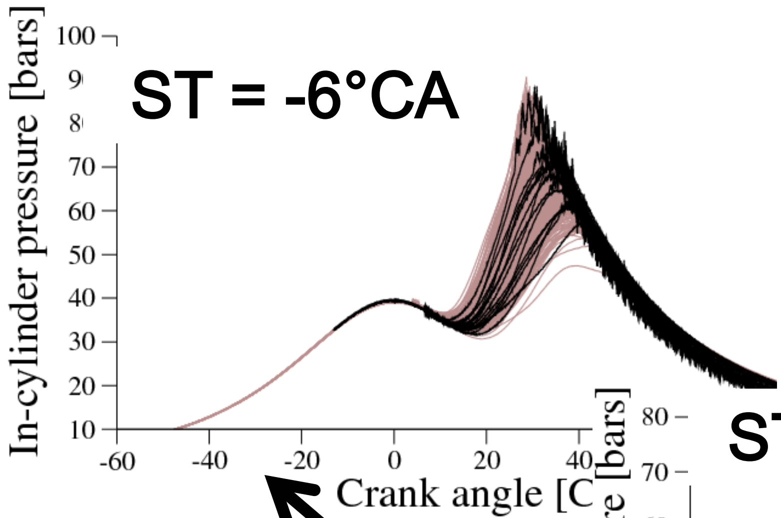
Instability by leaning out



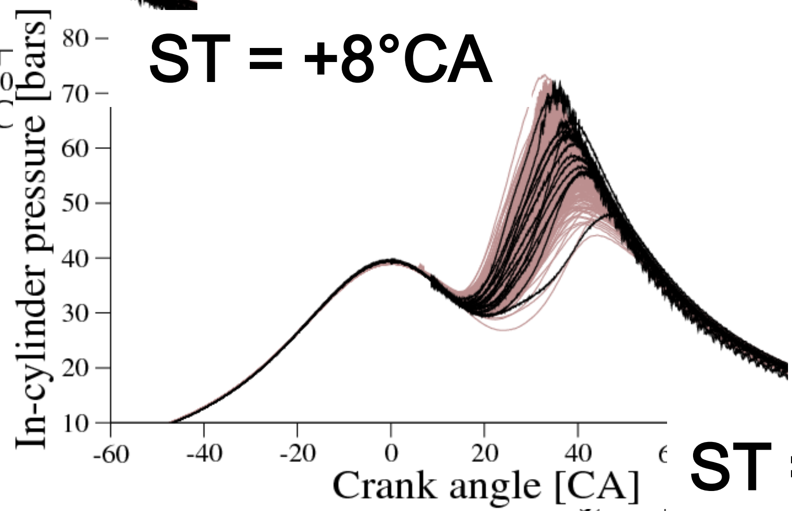
- **Multiple consecutive cycles simulated by LES**
- **Approx. 20h/cycle on 350 cores**
- **Meshes 2-12Mcells (tetrahedra)**

Comparing LES predictions with experimental findings

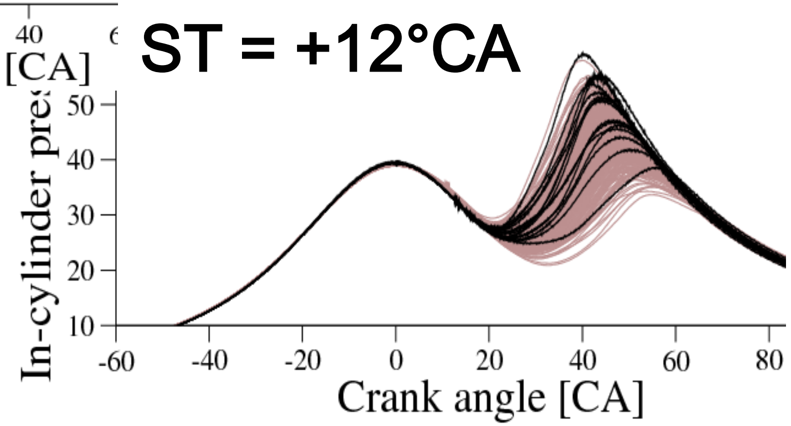
- 15 LES cycles are few compared to 500 experimental cycles
- Yet a qualitative reproduction of exp. tendencies was achieved



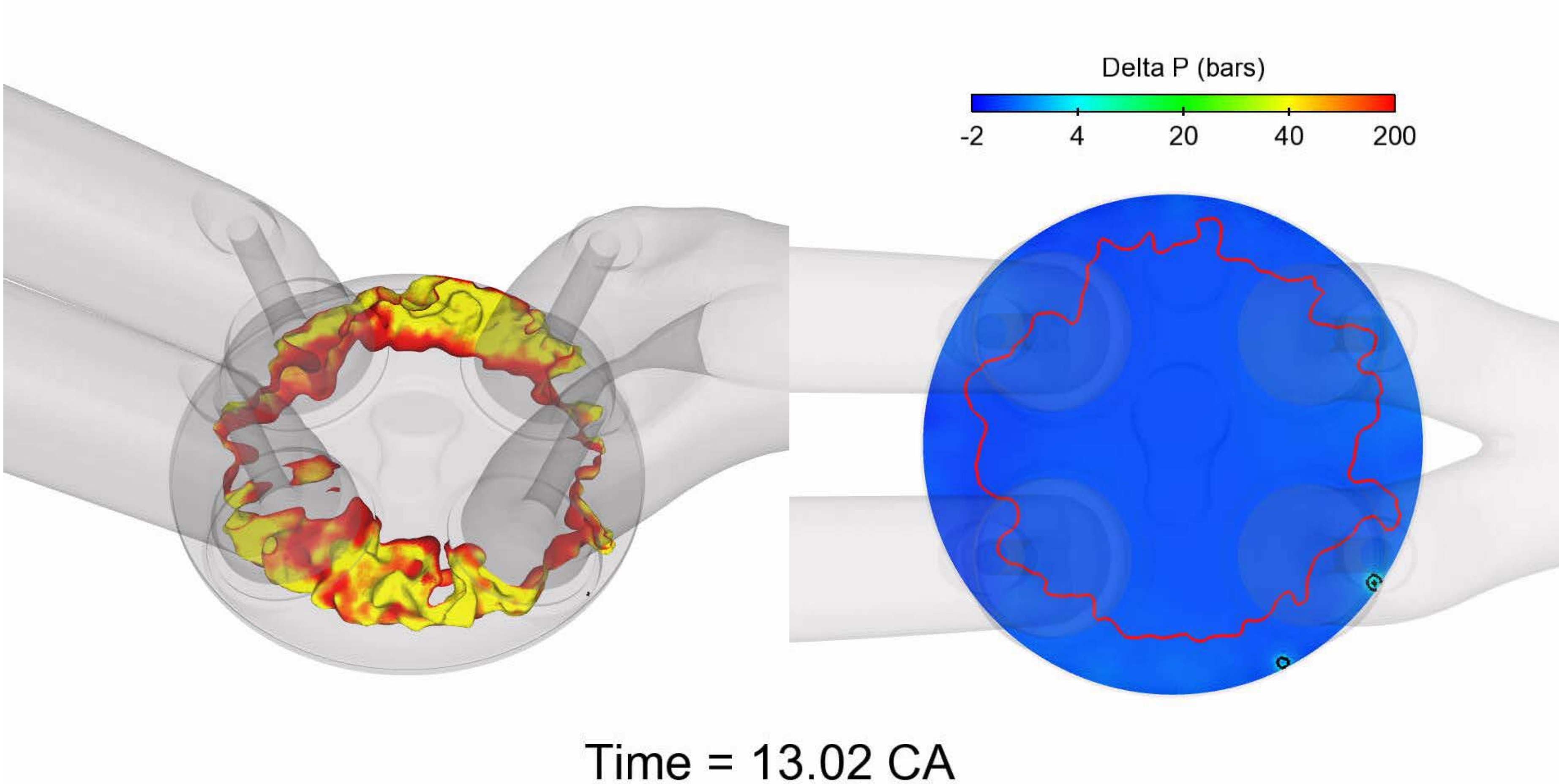
"more" knock



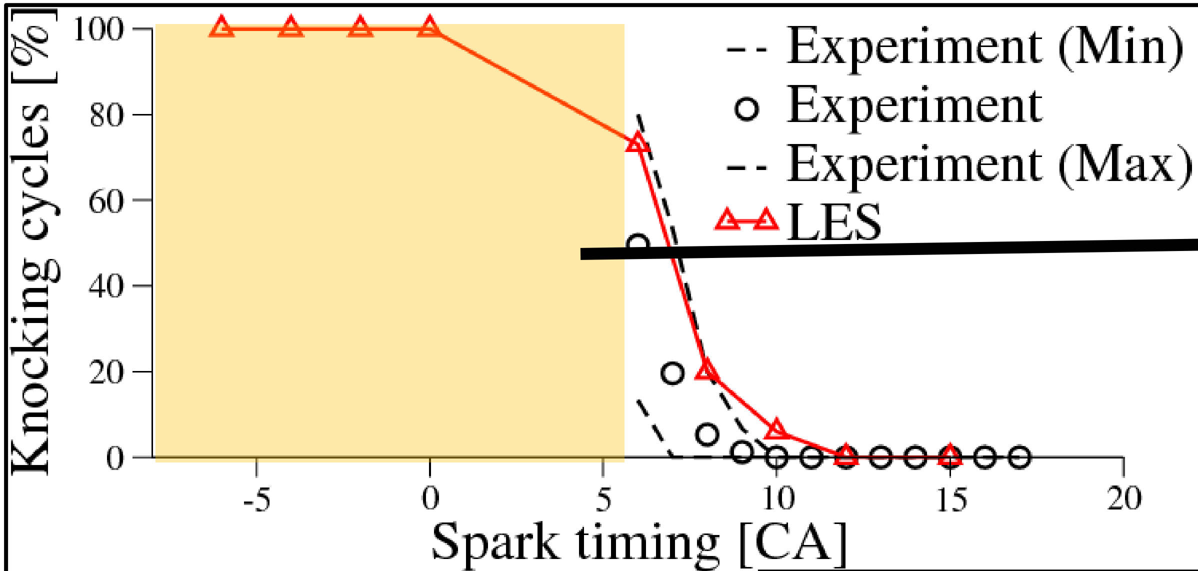
"less" knock



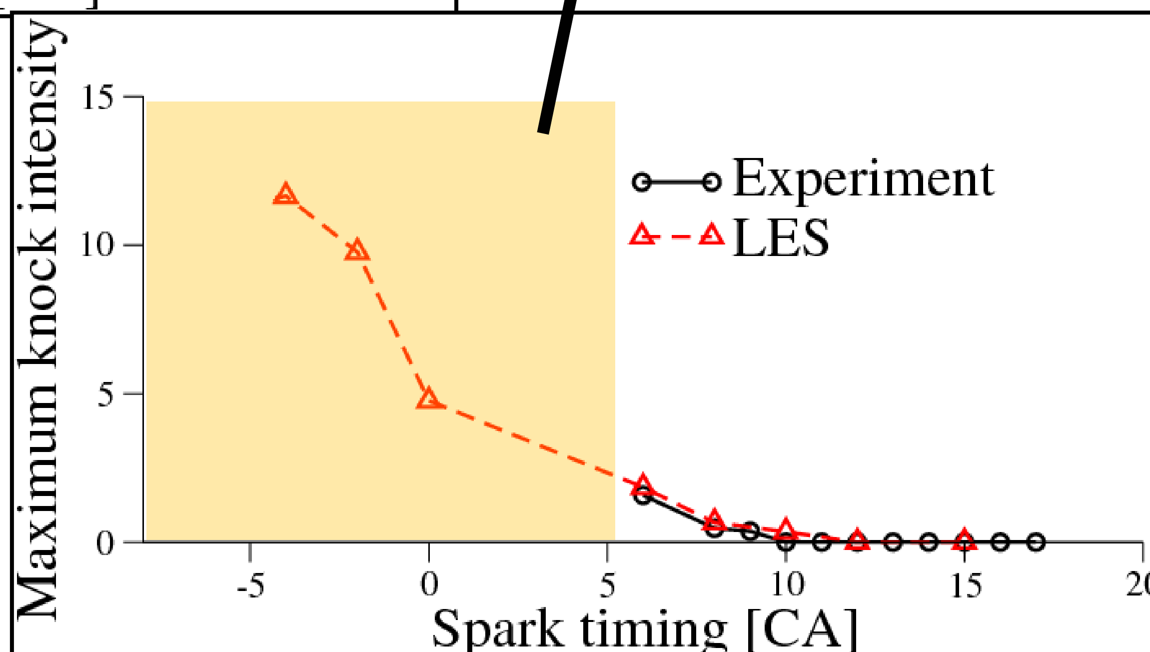
Temporal zoom on an exterme knocking cycle predicted by LES



Quantitative study of knock :
% knocking cycles & max. intensity

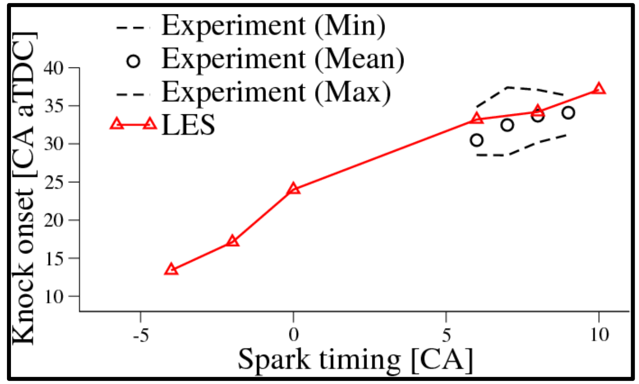


Cannot be studied in experiments!

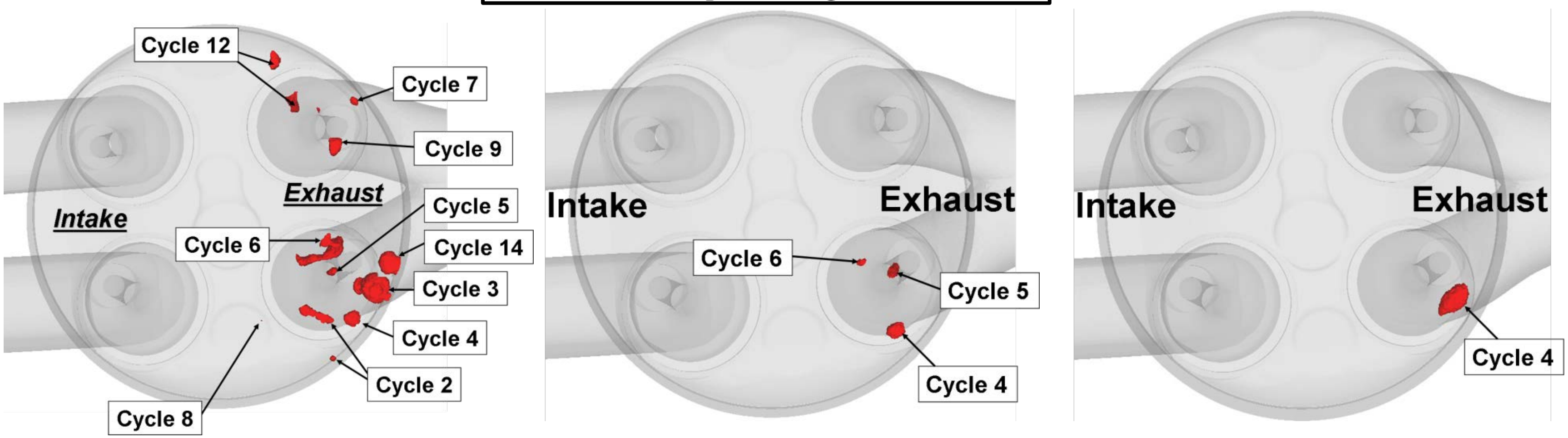


- **All post-processing of knock characteristics were performed using the same tool for LES and experiments**

Spatial & temporal occurrence of knock onset

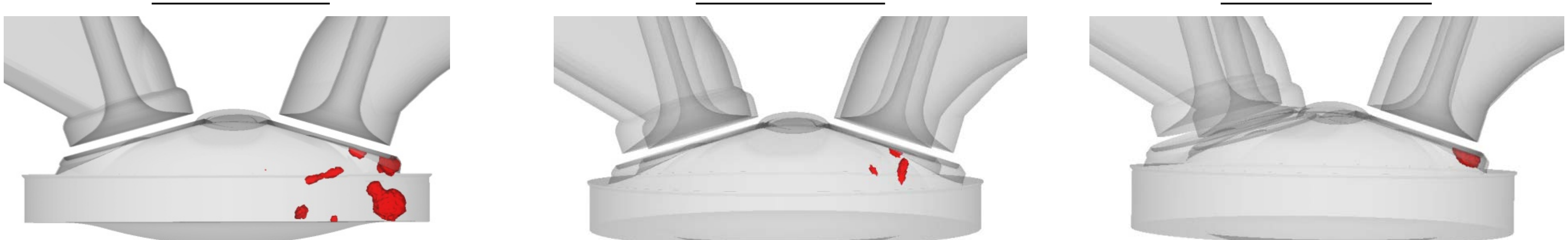


Top view



ST= 6°CA | ST = 8°CA | ST = 10°CA

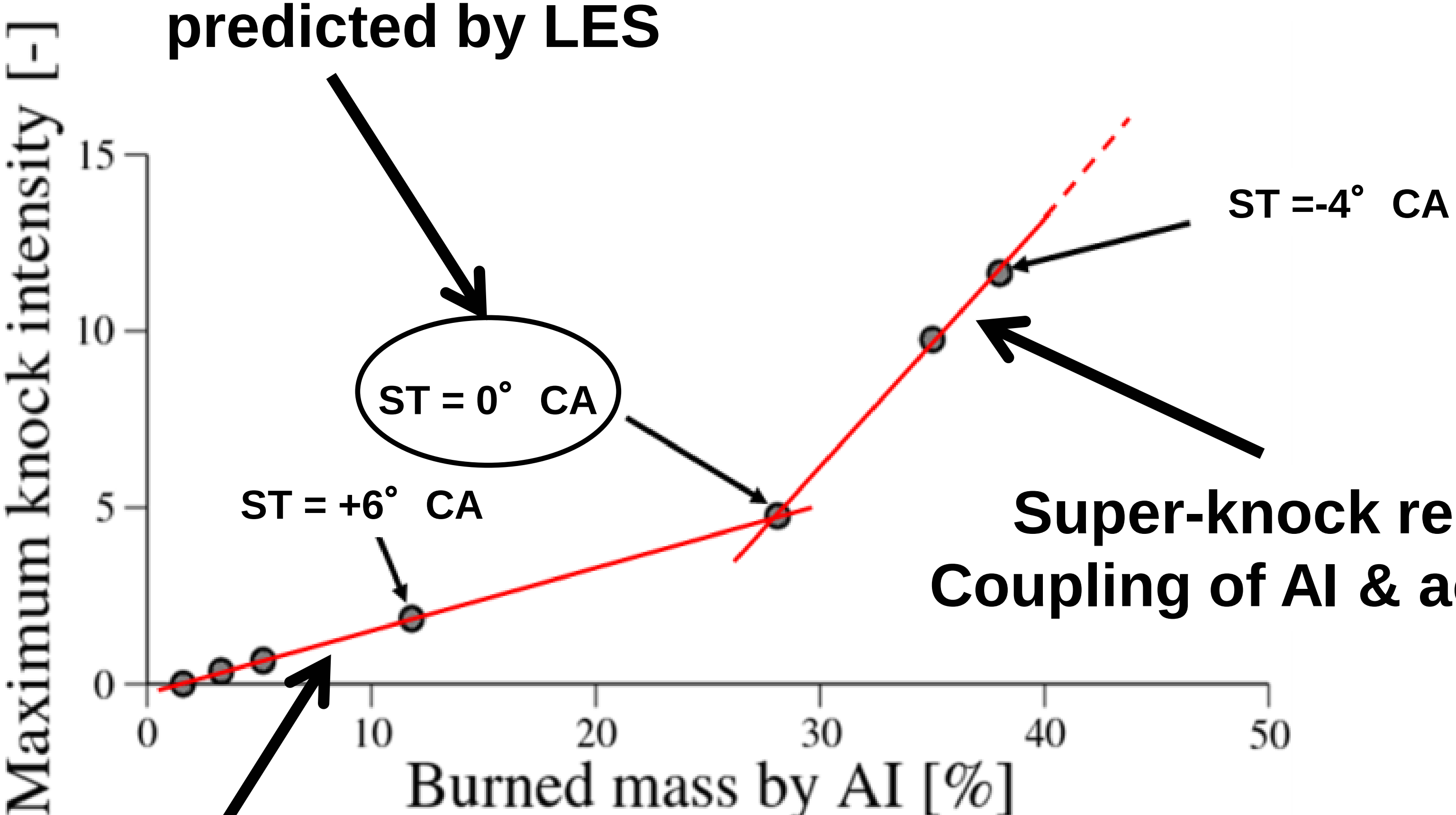
Side view



15

Different scenarios depending on the spark advance

Transition can be predicted by LES

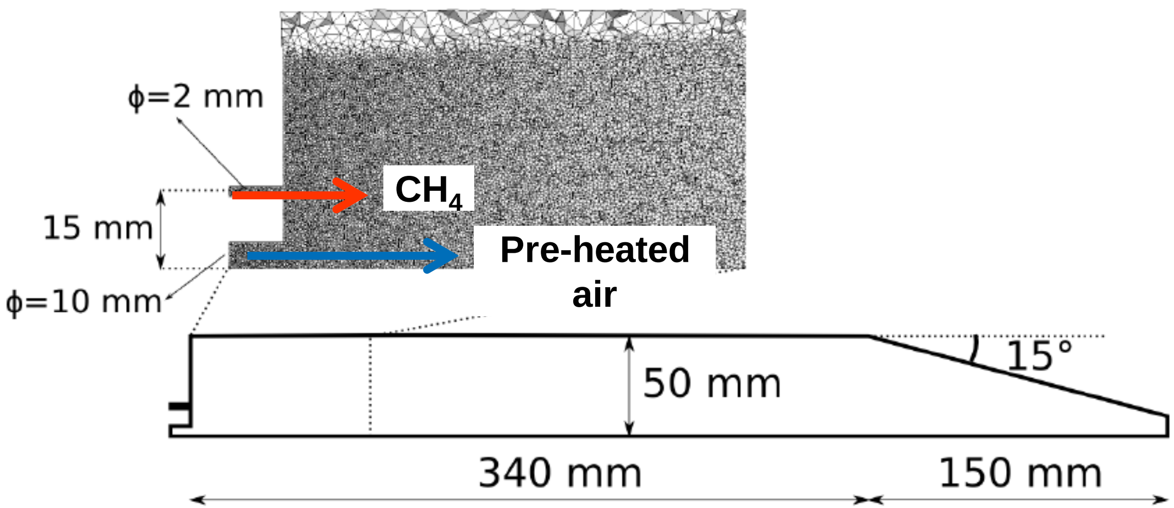


Super-knock regime: Coupling of AI & acoustics

"Standard" knock regime: Isolated spots

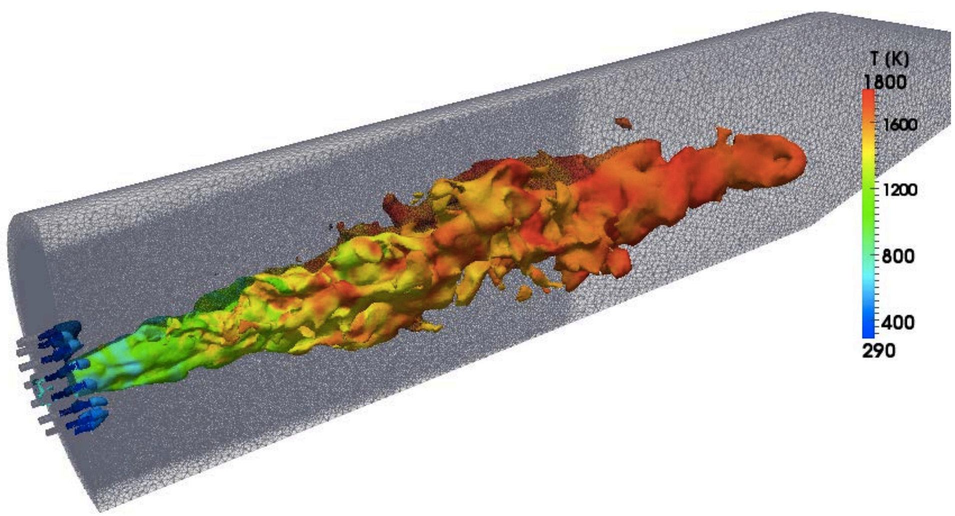
LES de combustion sans flamme

The flameless model burner of Verissimo

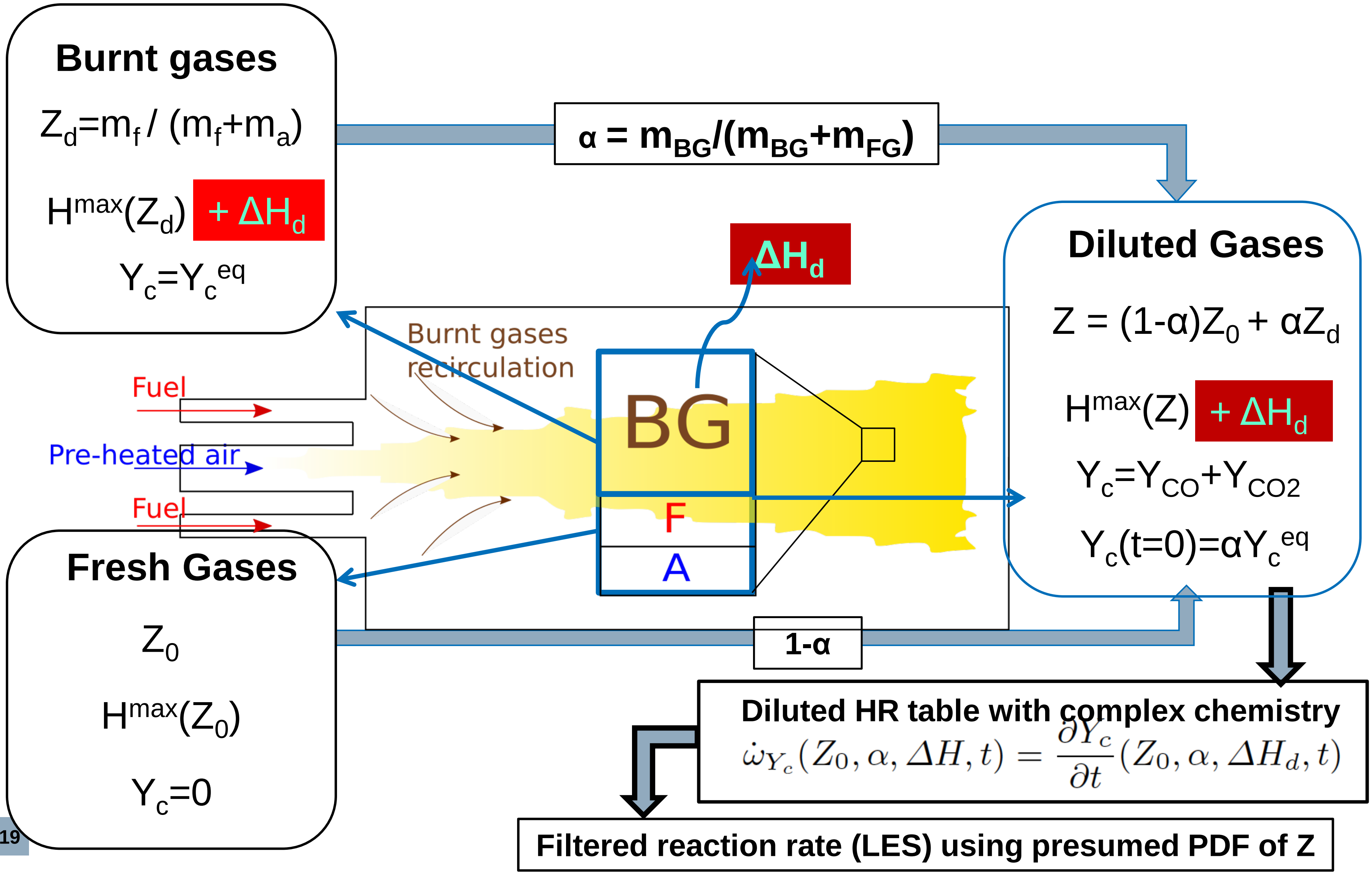


- **Main inlet**
  - Heated air at 673 K
  - Velocity 113.2 m/s
- 16 CH_4 **injectors**
  - Velocity 6.2 m/s
- **Burnt gases recirculation favored by high air momentum**
- **10 KW of total power**

- **Numerical setup:**
  - 20 million tetrahedral cells
  - Minimum cell size: 0.3 mm

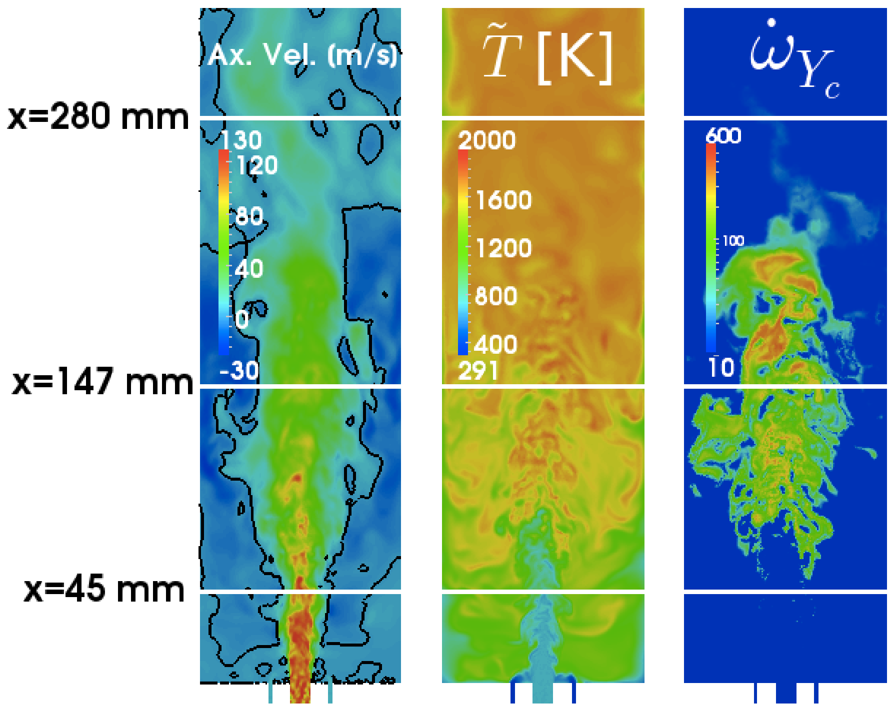


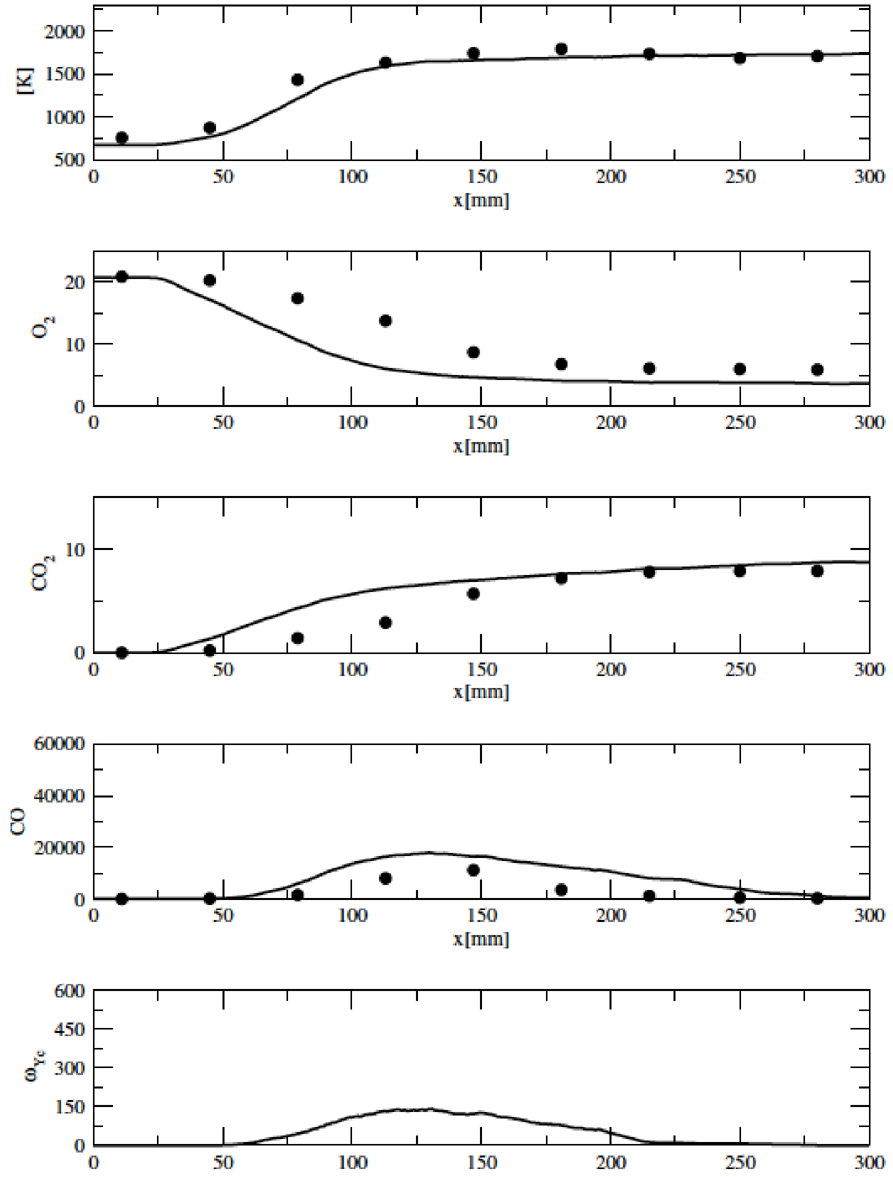
Modelling flameless combustion: The Diluted Homogeneous Reactor (DHR) model



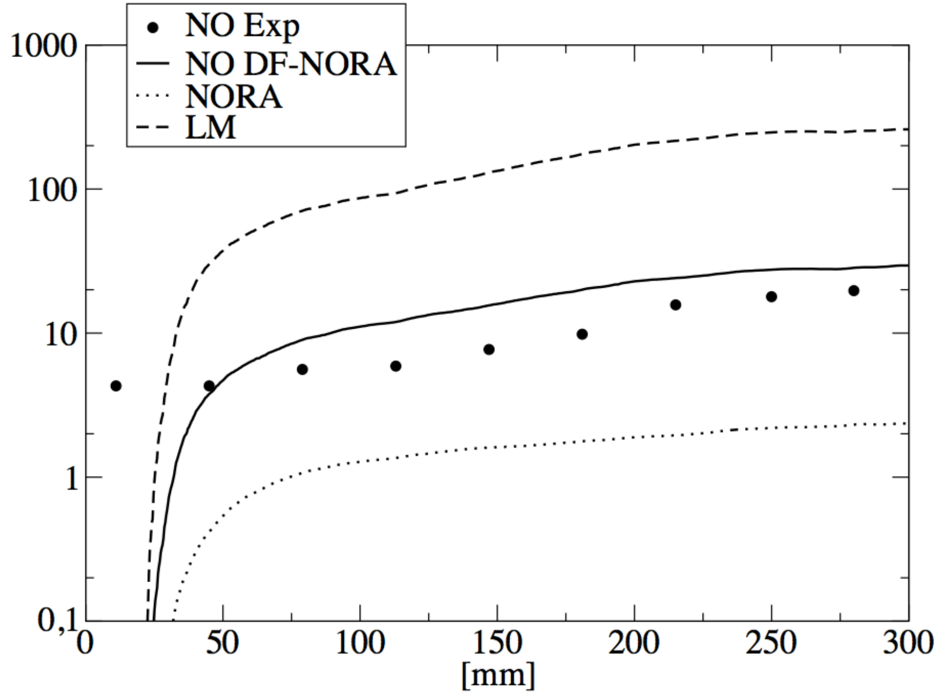
LES predictions of time-averaged mean profiles

Instantaneous LES fields





Prédiction des NOx en sortie brûleur



	Strain	Strain=0	Enthalpy loss	NO non linear
NORA [Vervisch,2011]	● (red)	● (green)	● (green)	● (orange) (No Prompt)
LM [Ihme,2008] (FPV)	● (green)	● (red)	● (green)	● (red)
Zoller [2011] (PDF)	● (green)	● (red)	● (green)	● (green)
DF-NORA (PCM)	● (green)	● (green)	● (green)	● (green)

Conclusions & Perspectives

- **Standard CFD tools based on RANS reach their limits when it comes to certain physical questions**
  - RANS allows fast evaluations of design variations under the hypothesis of small cyclic variations
- **LES on practical meshes require accurate sub-grid models**
  - Combustion, sprays, mixing, pollutants
- **LES allows predicting & understanding cyclic combustion variability in piston engines**
  - Illustrated for studying and understanding knock in dowmsized engines)
- **LES generally allows improving predictions of flows where mixing phenomena are crucial**
  - Illustrated using flameless combustion

- **LES will also allow gaining a deeper insight into other non-cyclic engine phenomena**
  - Super-knock, fast operating point transients, cold starts, combustion mode switching, …

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Acknowledgements:

- ✓ **Financial support from Groupement Scientifique Moteur, Renault, PSA Peugeot-Citroën**
- ✓ **Financial support from ANR (SGEmac, CamPas, ICAMDAC & ASTRIDE projects)**
- ✓ **Financial support by the European Commission (LESSCO2 & LESSCCV projects)**
- ✓ **Computing resources provided by GENCI & PRACE**