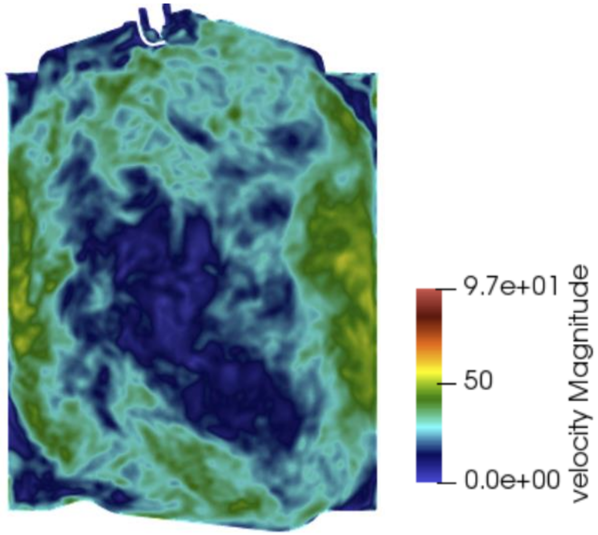
# ECFM-LES modelling with AMR for the CCV prediction and analysis in lean-burn conditions

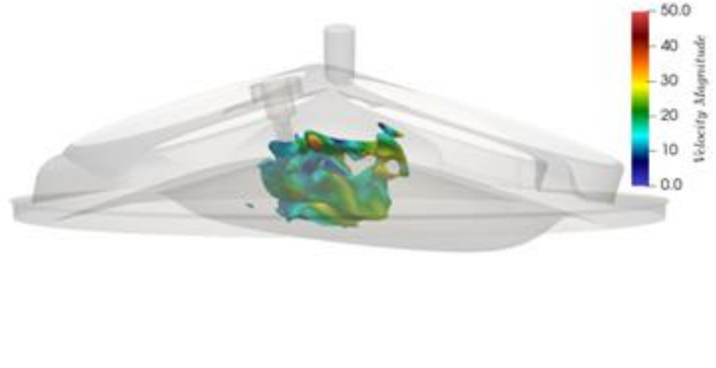
*LES4ECE 16-18/06/2021*

G. Maio[1], K. Truffin[1], O. Colin[1], O.Benoit[2] and S. Jay[1]

1) IFP Energies nouvelles, 1 et 4 avenue de Bois-Préau, 92852 Rueil-Malmaison, France ; Institut Carnot IFPEN Transports

2) TOYOTA GAZOO Racing Europe GmbH, Chassis & Powertrain Development, Toyota Allee 7, 50858 Köln, Germany

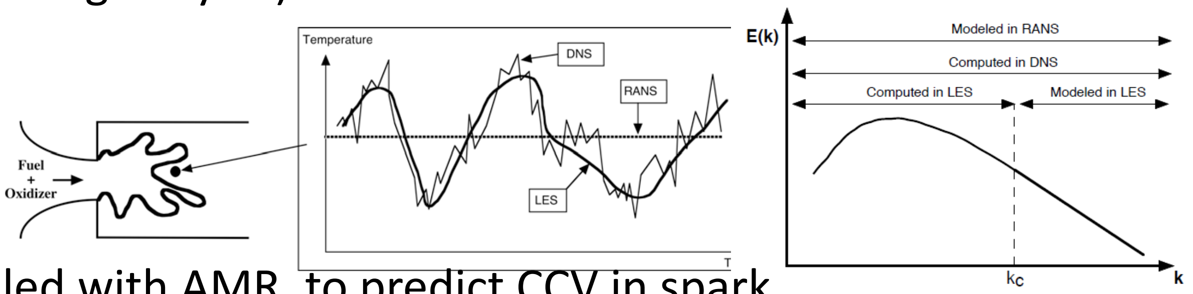


# CONTEXT: PERSPECTIVES FOR LES OF SPARK IGNITION ENGINES



- Extra-lean-burn technologies in modern spark-ignition engines
  - Increase combustion efficiency and tackle pollutant formation [1]
  - Attractive for the usage of alternative zero-emission fuels such as hydrogen [2]
  - High level of the CCV (cycle-to-cycle variability) can be encountered (IMEP covariance higher than 3%)
  - Need for predictive tools to reproduce CCV such as LES [3]
- LES in spark ignition engine for lean burn conditions
  - Cycle to cycle variations (deviation from the mean phase averaged cycle)
  - knock prediction
  - Air/Fuel mixing prediction
  - Improve ignition description -> flame kernel development




- Objectives of the study
  - Validate an LES modelling framework based on ECFM coupled with AMR, to predict CCV in spark ignition engines in extra-lean conditions
  - Account for the effect of stretch/differential diffusion on the laminar flame speed, which is important in diluted flame conditions

*[1] Nagasawa T, Okura Y, Yamada R, Sato S, Kosaka H, Yokomori T et al. Thermal efficiency improvement of super-lean burn spark ignition engine by stratified water insulation on piston top surface. International Journal of Engine Research 2020:146808742090816.*

*[2] Wang J, Duan X, Liu Y, Wang W, Liu J, Lai M-C et al. Numerical investigation of water injec-tion quantity and water injection timing on the thermodynamics, combustion and emissions in a hydrogen enriched lean-burn natural gas SI engine. International Journal of Hydrogen Energy 2020;45(35):17935–52.*

*[3] Using large-eddy simulation and multivariate analysis to understand the sources of combustion cyclic variability in a spark-ignition engine. Combustion and Flame 2015;162(12):4371–90.*

# OUTLINE



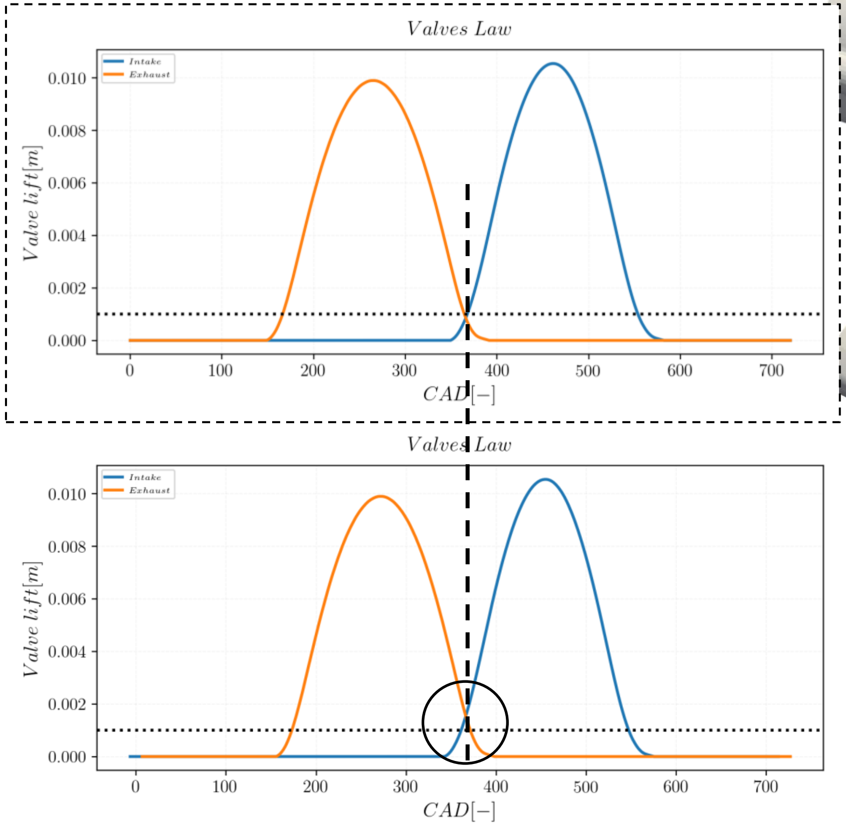
- TGR-E benchmark configuration
- Mesh and numerical set-up
- Overview of the Cold AERO results + Spray calibration results
- Reactive LES results
- CCV analysis
- Summary and perspectives

# CONFIGURATION

MOBILITÉ DURABLE

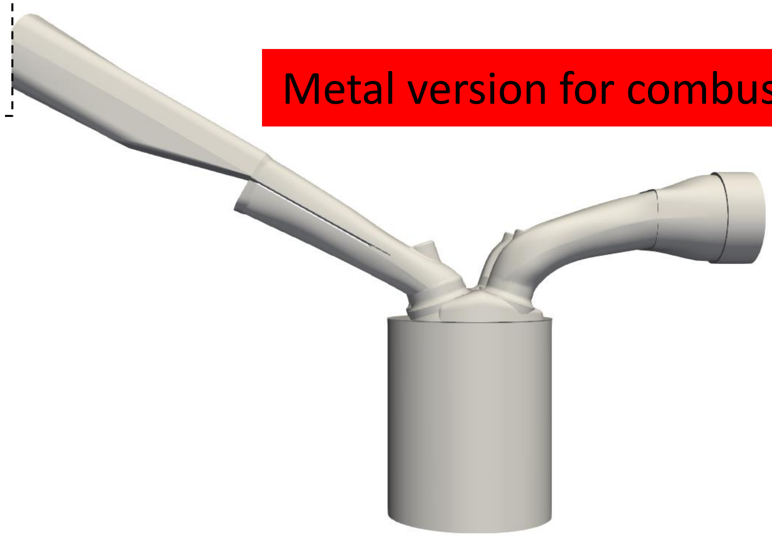
- Single cylinder optical and metal engine, operating in lean conditions ($\lambda = 1.83$), jointly developed by TGR-E and FEV [1, 2]
- Differences just in the manifold and valves law
- Engine specifications:

| | |
|---|---|
| Bore / Stroke | 85.5 / 101.5 mm |
| Displacement volume | 583 cm^3 |
| Geometrical compression ratio | 13.4 |
| Ignition system energy | Max 500mj |
| Fuel direct injection | 7 holes |
| Engine speed | 1900RPM |
| IMEP | 1.2MP |




Transparent version for AERO-PIV

Metal version for combustion



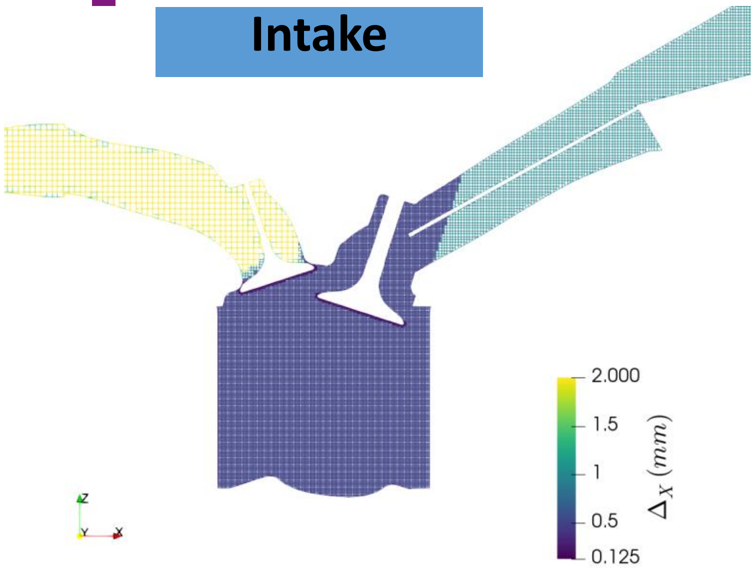

[1] *Luszcz P., Takeuchi K., Pfeilmaier P., Gerhardt M. et al., "Homogeneous Lean Burn Engine Combustion System Development – Concept Study" 2018, 19th Stuttgart International Symposium.*

*[2] Study of Ignition Processes of a Lean Burn Engine using Large-Eddy Simulation,* O. Benoit, P. Luszcz, Y. Drouvin, T. Kayashima, P. Adomeit, A. Brunn, S. Jay, K. Truffin, C. Angelberger, SAE International, 2019

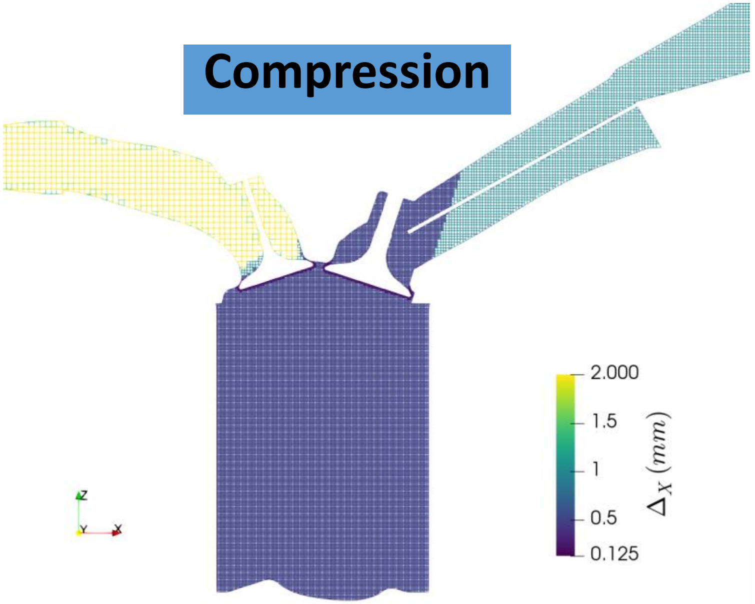
# MESH SNAPSHOTS DURING THE DIFFERENT PHASES

MOBILITÉ DURABLE

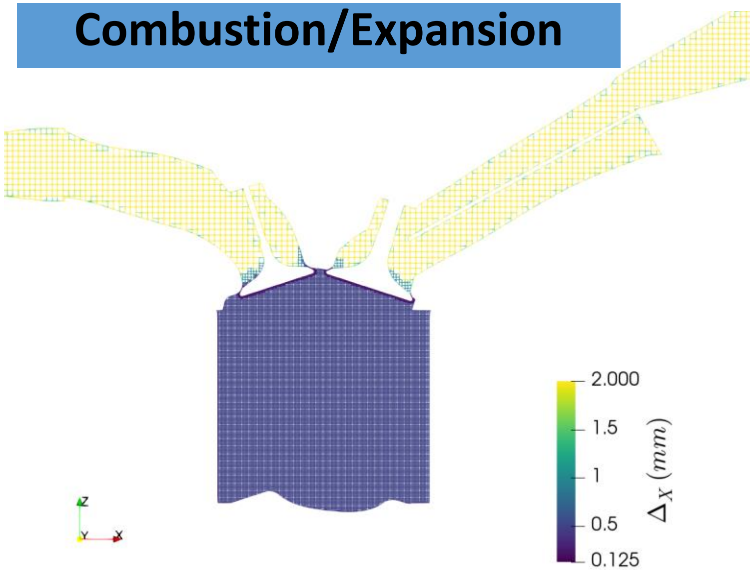
Intake

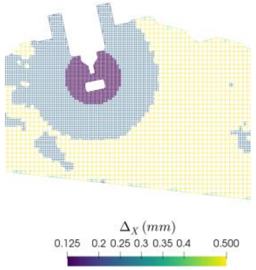



Compression

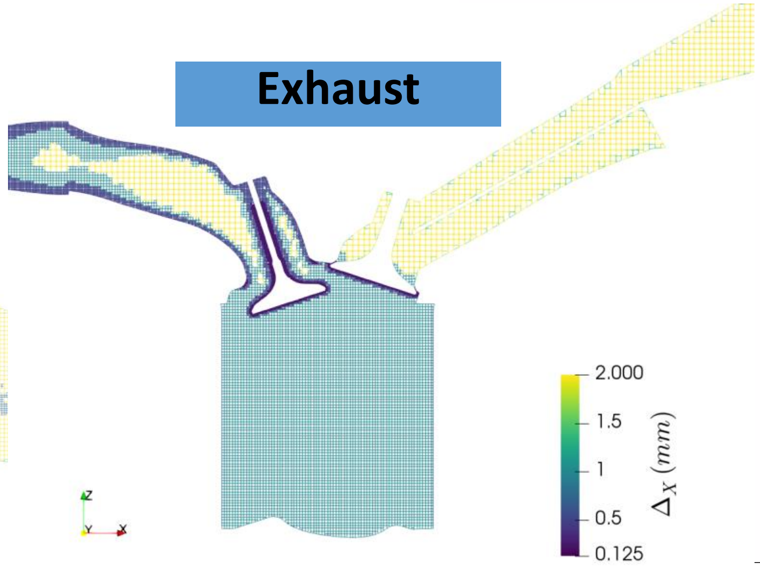



Combustion/Expansion

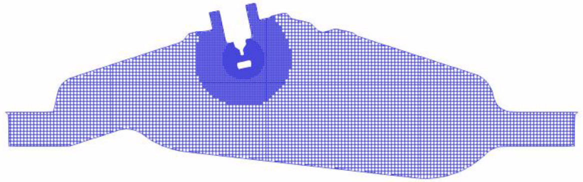



Exhaust




| Engine Zone | Mesh size [mm] |
|---|---|
| Cylinder | 0.125 - 1.0 |
| Intake | 0.5 - 2.0 |
| Exhaust | 0.5 – 2.0 |



- AMR progress variable (min cell size = 0.25mm)

# NUMERICAL SET-UP

MOBILITÉ DURABLE

- **LES solver:** CONVERGE V3.0.15 [1]
- **Temporal scheme**: semi-implicit Crank-Nicolson (*implicit_fraction:0.5*)
- **Spatial scheme**: second order central (*fv_upwind_factor:0.5*)
- **Turbulence modeling:** Dynamic Smagorinsky model [2]

→ validated versus PIV in Cold/Aero simulation

- **Spray modeling set-up:**
  - Primary break-up modelled with Rosin-Rammler distribution imposing MSD
  - KH (Kelvin-Helmholtz)-RT(Rayleigh-Taylor) secondary breakup model
  - Drop vaporization model: Frossling correlation

→ validated versus closed vessel experimental data

- **AMR:** based on the sub-grid progress variable criterion during the combustion stroke.
- **ISSIM [3] model for ignition: (**Spark advance=20.3)
- **ECFM-LES model [4]:**
  - Turbulent efficiency function: Bougrine
  - $S_l$ model = Yahyaoui
  - Stretch model [5]

→ validated versus reactive experimental data


*[1] Richards, K.J., Senecal, P.K. Pomraning, E.: CONVERGE (v2.4),. Convergent Science, Inc., Madison, WI 2017*

*[2] Germano, M., Piomelli, U., Moin, P., and Cabot, W.H., "A Dynamic Subgrid-Scale Eddy Viscosity Model," Physics of Fluids A, 3(7), 1760-1765, 1991. DOI: 10.1063/1.857955*

*[3] Colin O, Truffin K. A spark ignition model for large eddy simulation based on an FSD transport equation (ISSIM-LES). Proceedings of the Combustion Institute 2011;33(2):3097–104.*

*[4] Vermorel O, Richard S, Colin O, Angelberger C, Benkenida A, Veynante D. Towards the un-derstanding of cyclic variability in a spark ignited engine using multi-cycle LES. Combustion and Flame 2009;156(8):1525–41.*

*[5] Benoit, O., Truffin, K., Jay, S. et al. Development of a Large-Eddy Simulation Methodology for the Analysis of Cycle-to-Cycle Combustion Variability of a Lean Burn Engine. Flow Turbulence Combust (2021).*

# OUTLINE

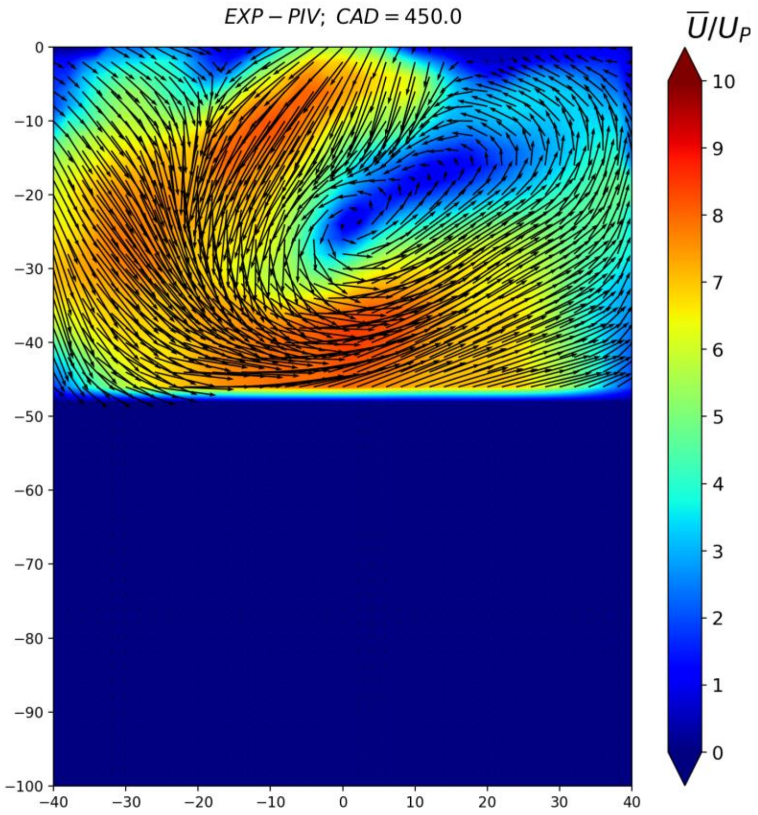
MOBILITÉ DURABLE

- TGR-E benchmark configuration
- Mesh and numerical set-up
- Overview of the Cold AERO results + Spray calibration results
- Reactive LES results
- CCV analysis
- Summary and perspectives

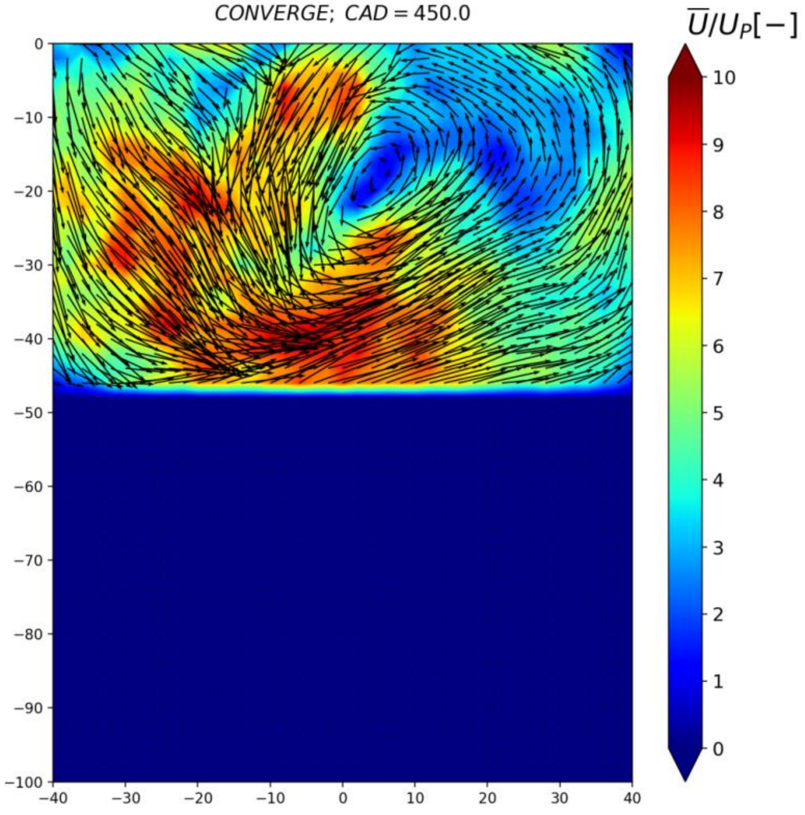
# COLD AERO: LES STATISTICS COMPARISON (MEAN)

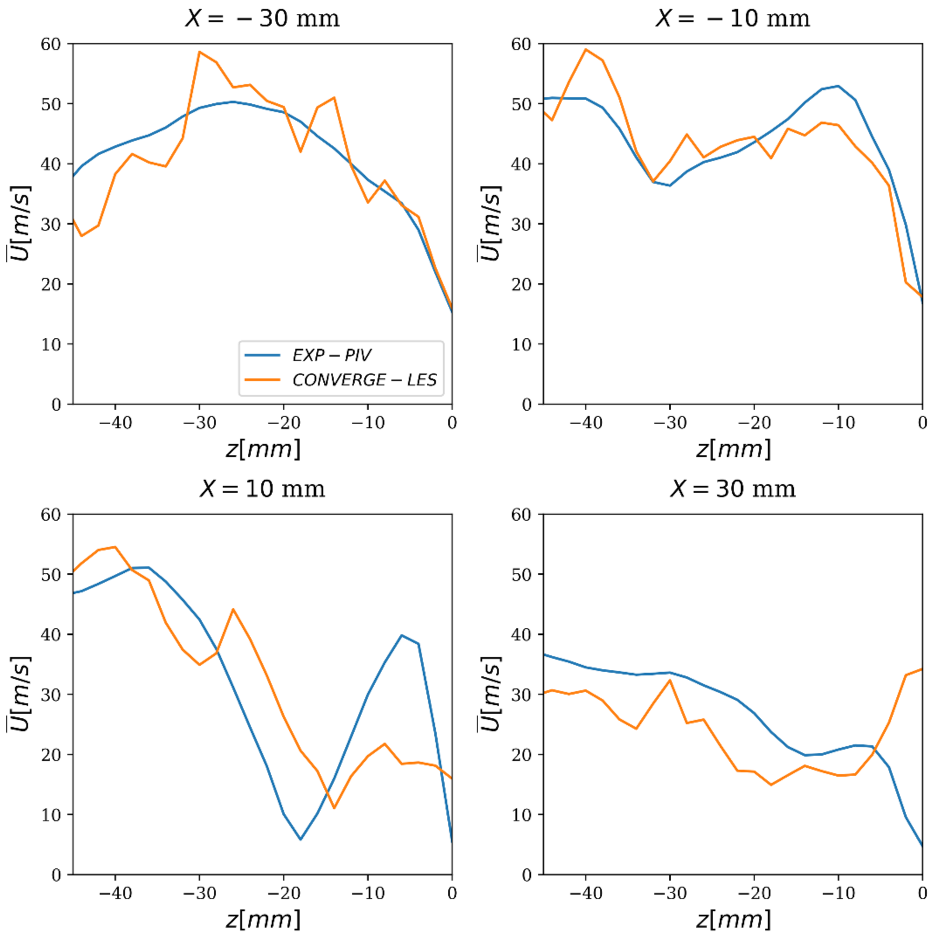
- Numerical phase-averaged velocity fields obtained from ten consecutive cycles are compared to PIV experimental data (averaged over 30 cycles) on the tumble mid-plane during the **intake** and the compression stroke.
- Velocity is non-dimensionalized by the mean piston velocity

**EXP PIV CAD = 450 (intake stroke)**




**LES-MEAN CAD = 450 (intake stroke)**



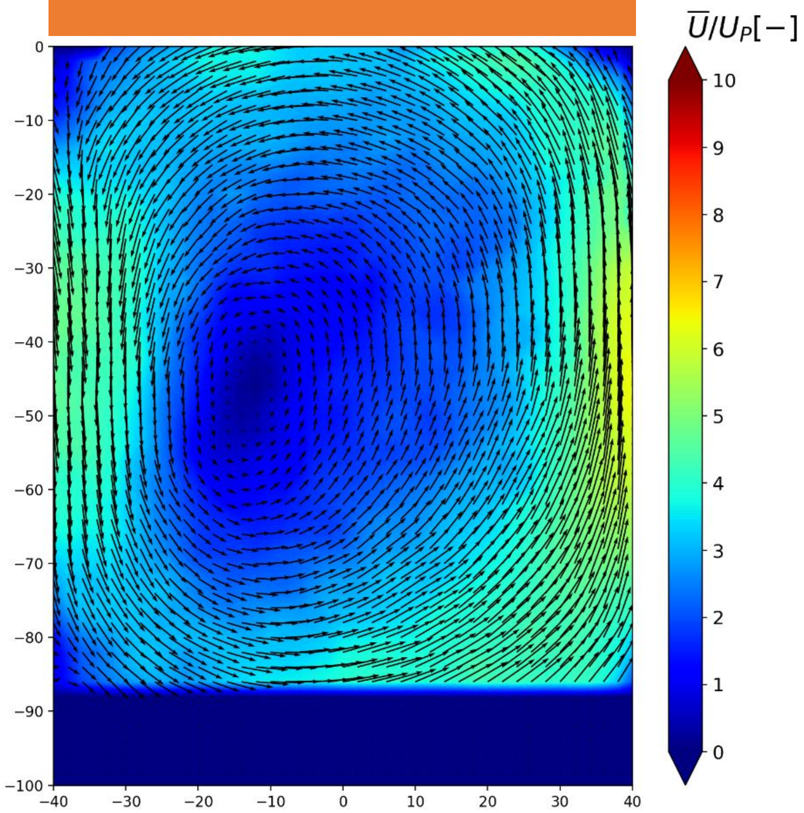



# COLD AERO: LES STATISTICS COMPARISON (MEAN)

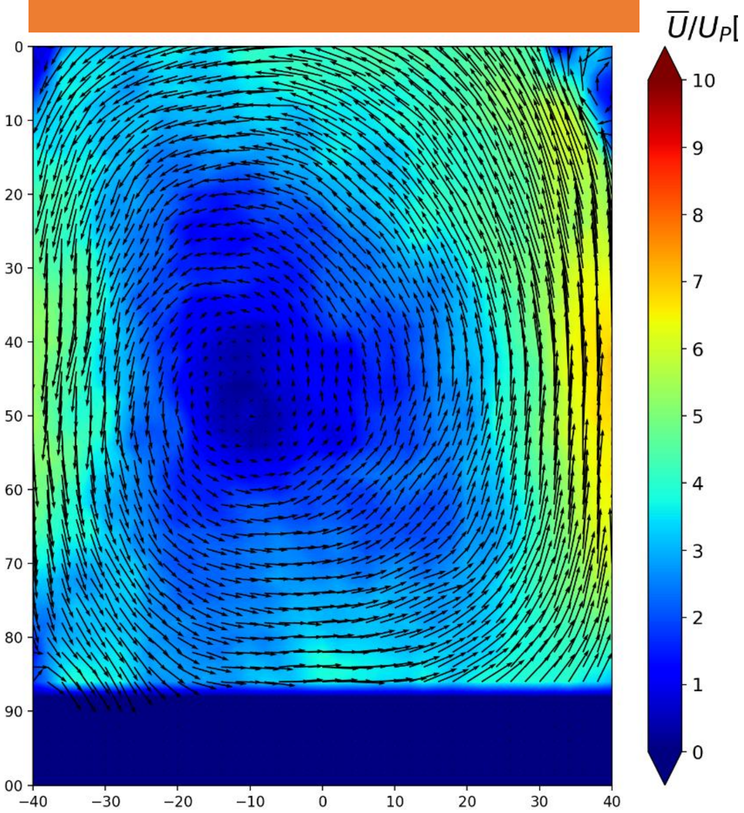
MOBILITÉ DURABLE

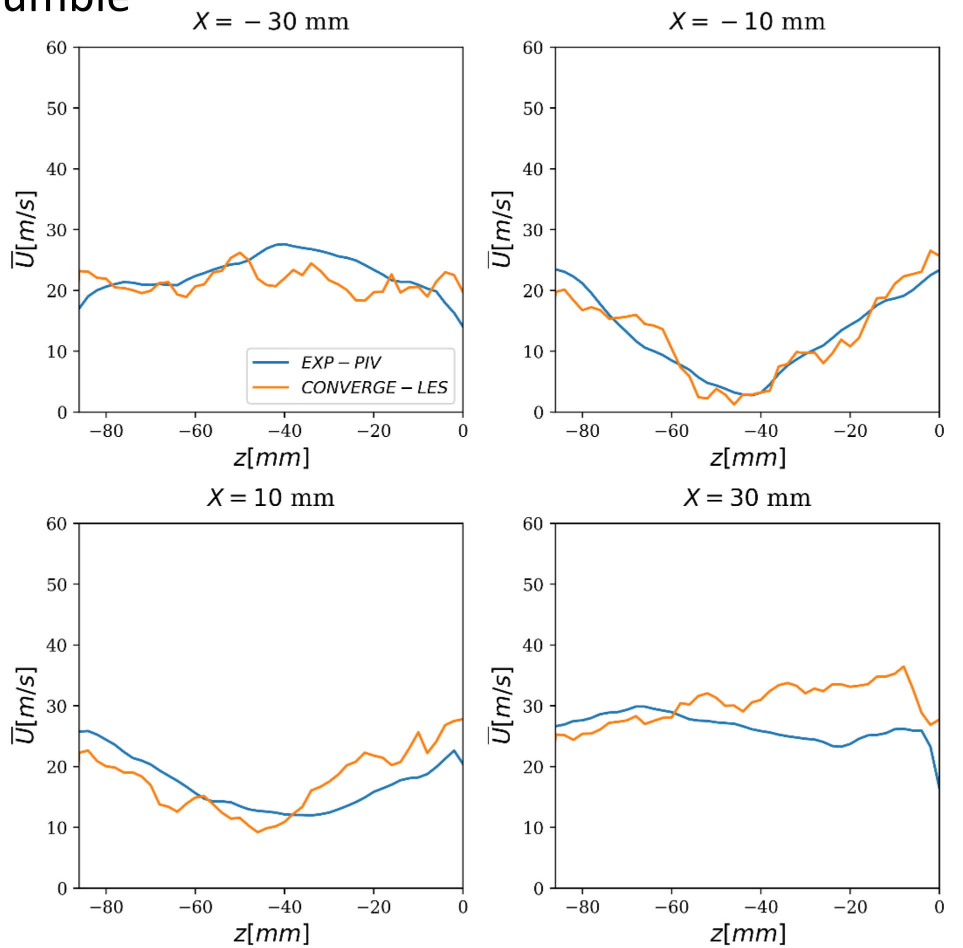
- Numerical phase-averaged velocity fields obtained from ten consecutive cycles are compared to PIV experimental data (averaged over 30 cycles) on the tumble mid-plane during the intake and the **compression** stroke.

**EXP PIV CAD = 570 (compression stroke)**




**LES-MEAN CAD = 570 (compression stroke)**



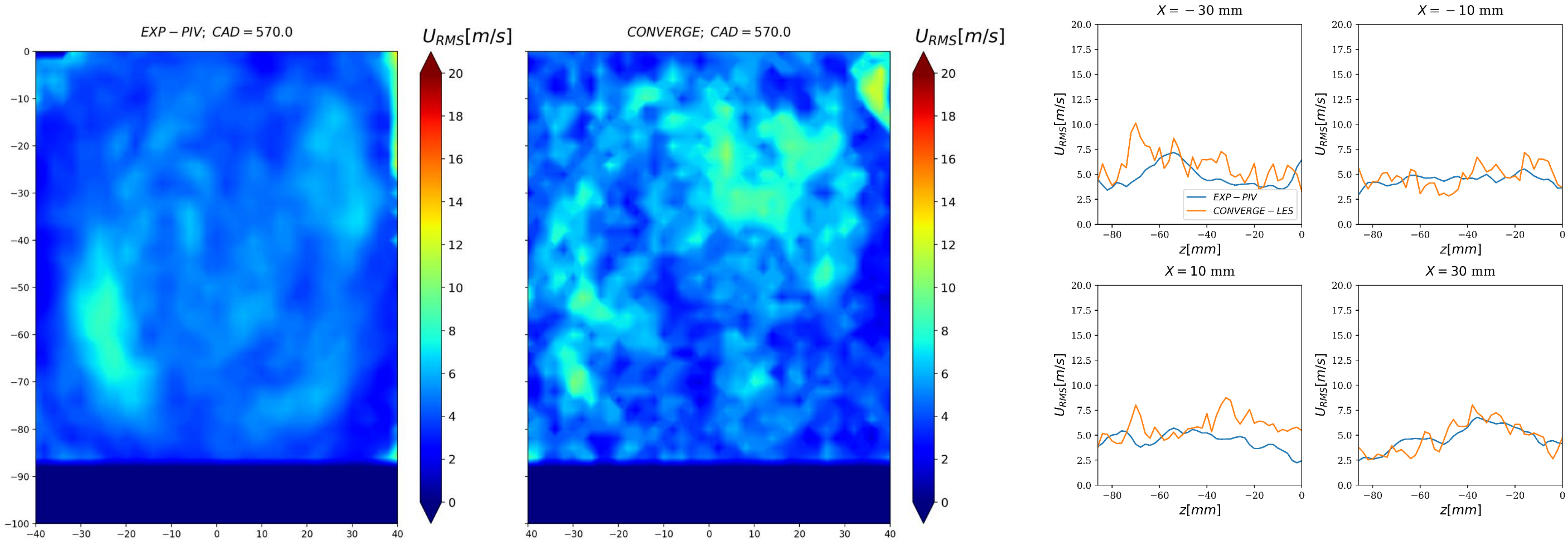




- Good reproduction of the in-cylinder velocity distribution (tumble center location).
- Slight over-estimation in the  recirculation zone
- Results confirmed from the 1D longitudinal profiles

# COLD AERO: LES STATISTICS COMPARISON (RMS)

MOBILITÉ DURABLE

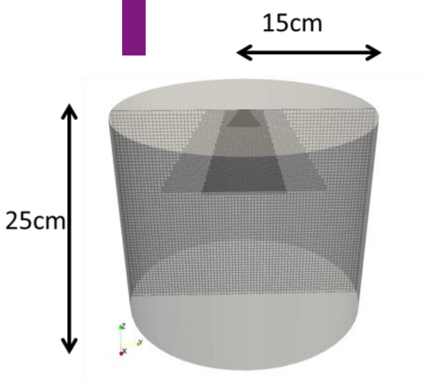
- RMS of the numerical velocity fields obtained from ten consecutive cycles are compared to PIV experimental data (averaged over 30 cycles) on the tumble mid-plane during the intake and the **compression** stroke.

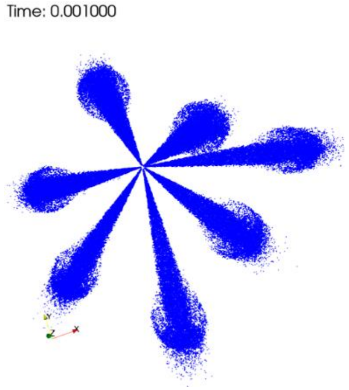



- The RMS magnitudes are well captured
- The numerical field is less smooth than the experimental one → poor statistical convergence for RMS

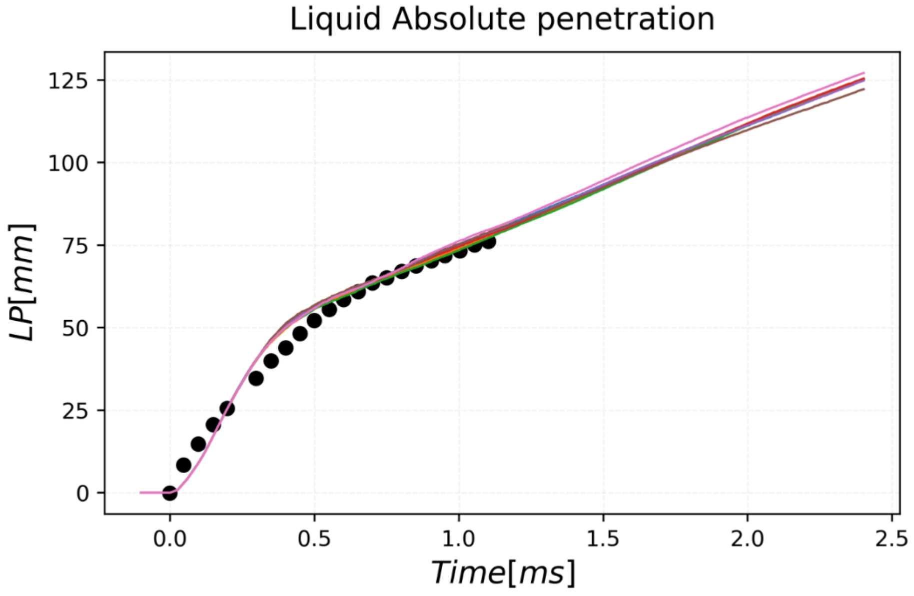
# SPRAY CALIBRATION: CLOSED VESSEL SIMULATION

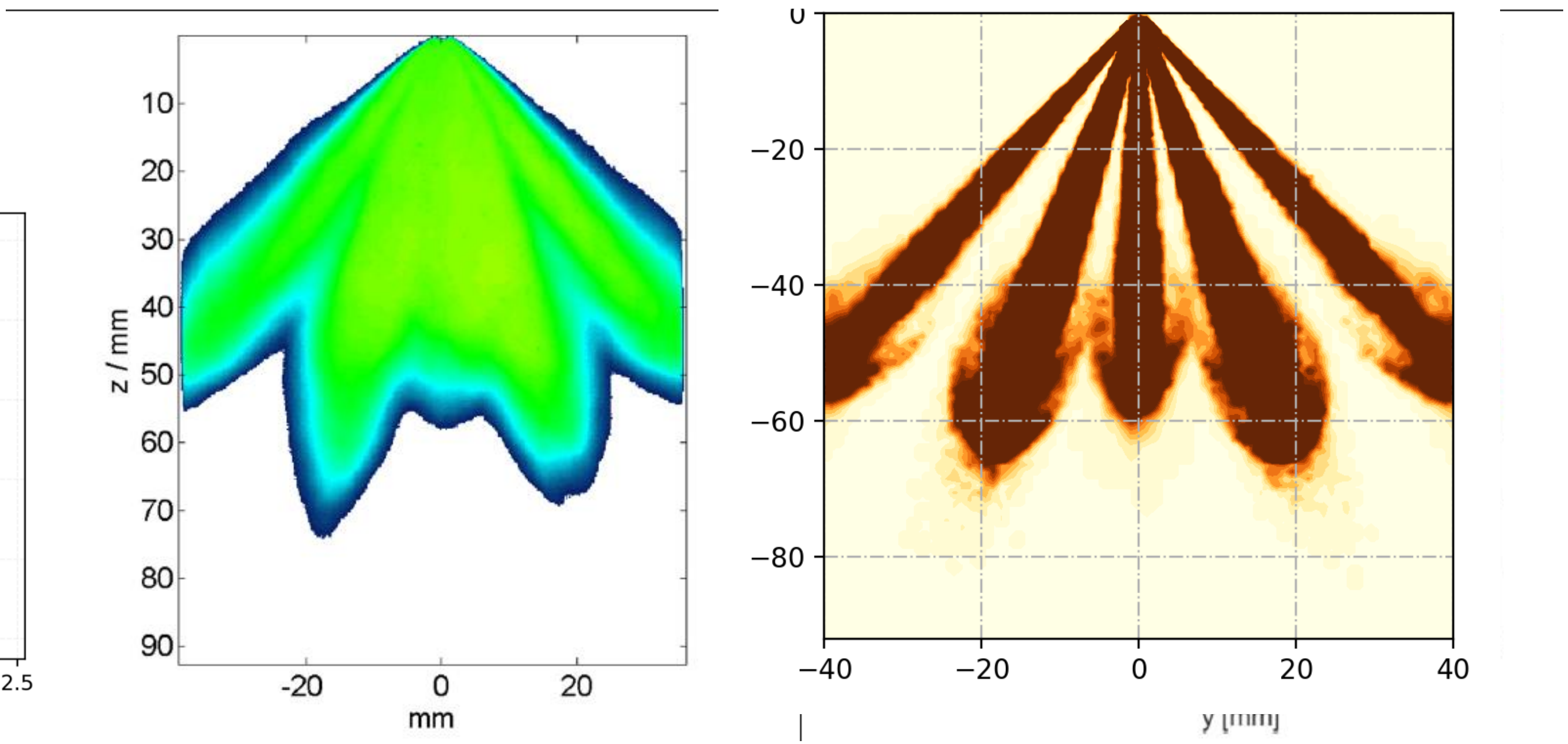





- CFD spray 1 ms after the 1st droplet gets out of the nozzle.




- Liquid penetration shows discrepancy in the first region, but further downstream is correctly retrieved
- Numerical results shows good quantitative and qualitative agreement with experiments

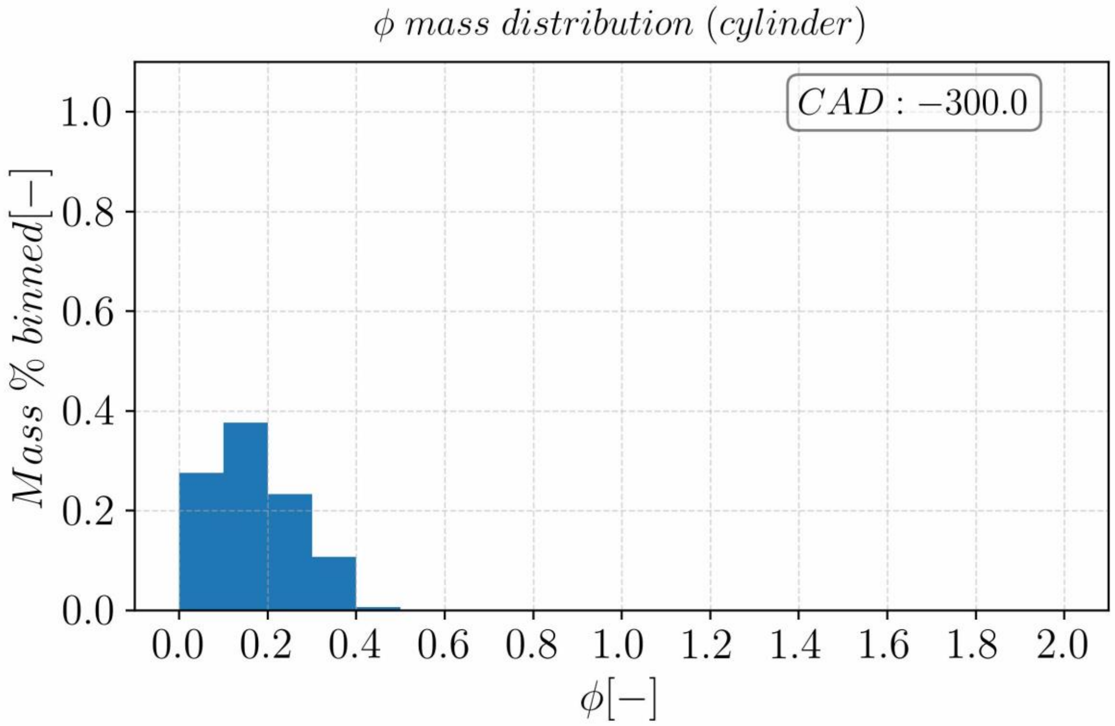
# OUTLINE



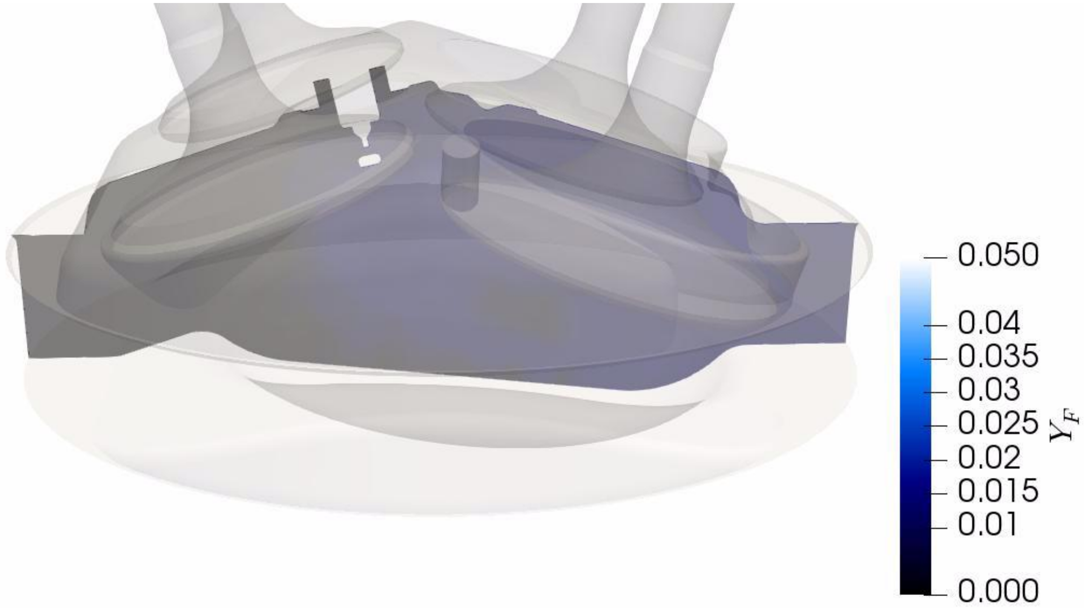
- TGR-E benchmark configuration
- Mesh and numerical set-up
- Overview of the Cold AERO results + Spray calibration results
- Reactive LES results
- CCV analysis
- Summary and perspectives

- Equivalence ratio pdf distribution in cylinder as function of the CAD




- Spray evolution and mixture formation in the cylinder mid-plane




- Spray set-up model validated in a closed vessel simulation
- With the prescribed spray set-up a good mixing quality is achieved → almost homogeneous mixture before ignition

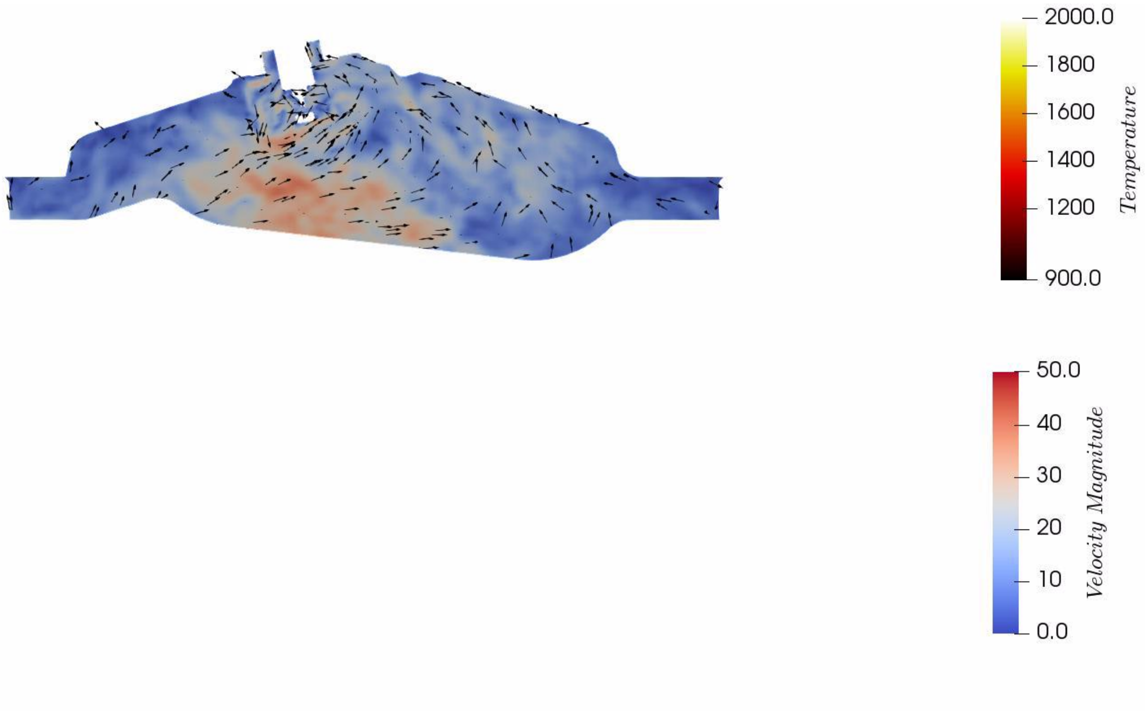
 

# LES REACTIVE SIMULATION (3D/2D FLAME VISUALISATION)

MOBILITÉ DURABLE

Iso-C at 0.05 colored by Velocity Magnitude


Velocity field on the tumble mid-plane with 10 iso-C colored by temperature



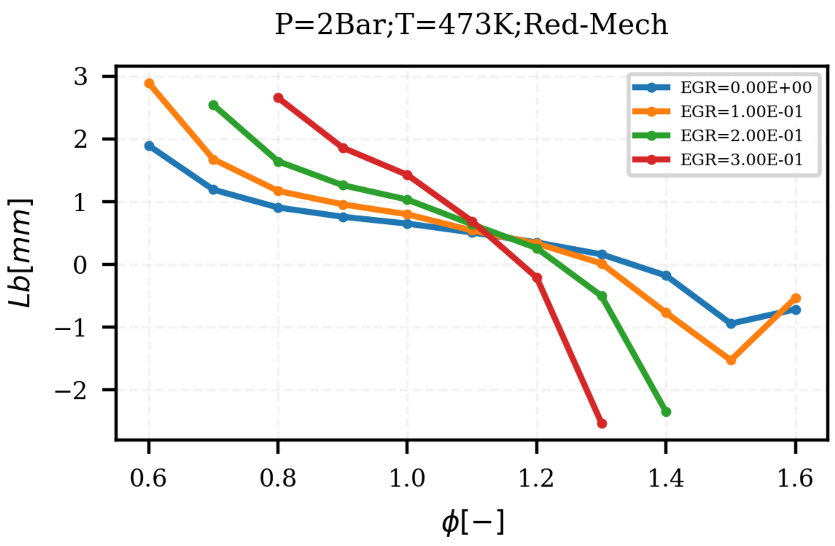

- Flame kernel evolution confirms the resolution of the flame/turbulence interaction

# ADD A STRETCH MODEL : ECFM STRETCH

$$S_b = S_b^0 - L_b * K$$

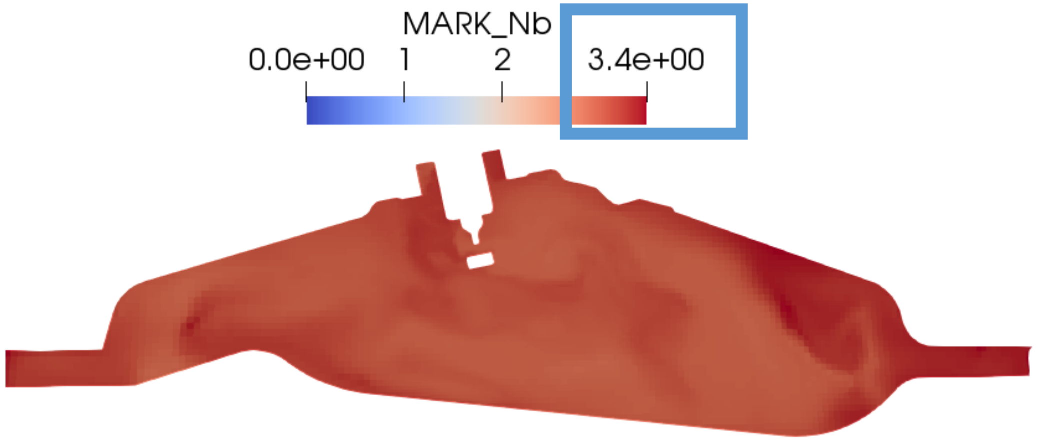
MOBILITÉ DURABLE

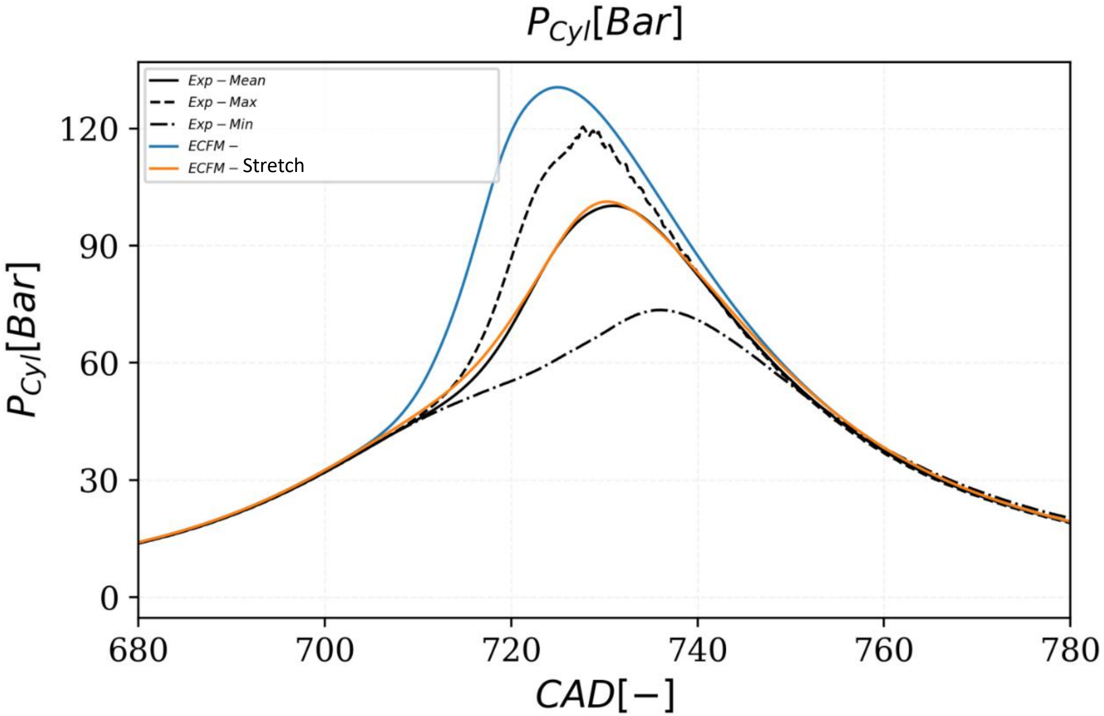
- Correlation developed to account stretch effect on flame speed [1]:




$$L_b = M_b(\Phi, T_0, P) * \delta_l^0(\Phi, T_0, P, X_{EGR})$$

- Accounting for the stretch effect on the laminar flame speed allows to retrieve the experimental pressure signal without modifying the experimental spark advance, as pointed out in [1].



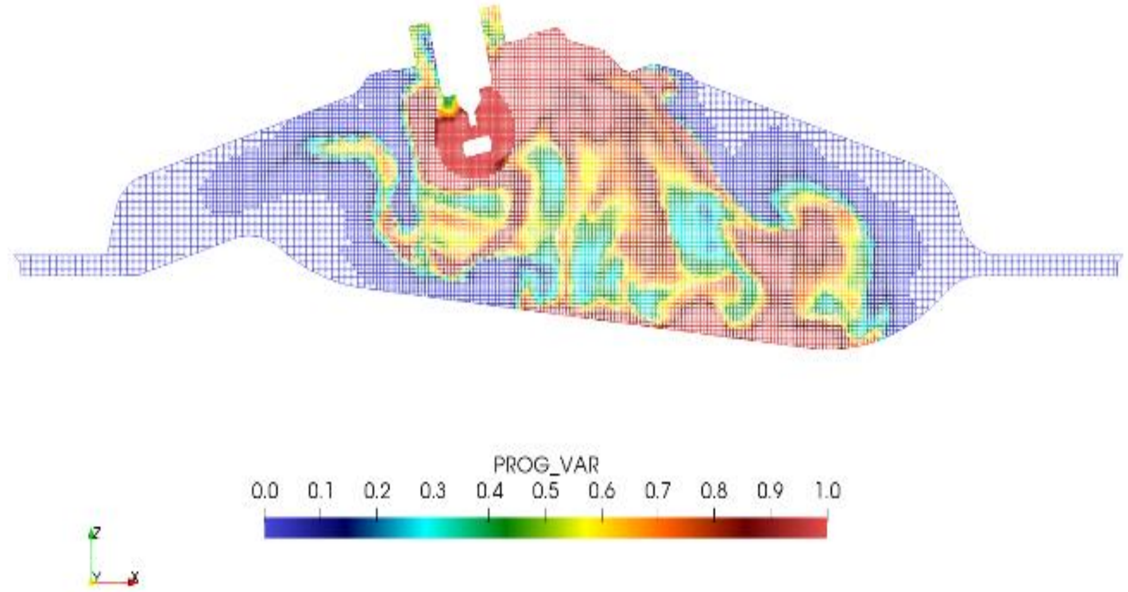


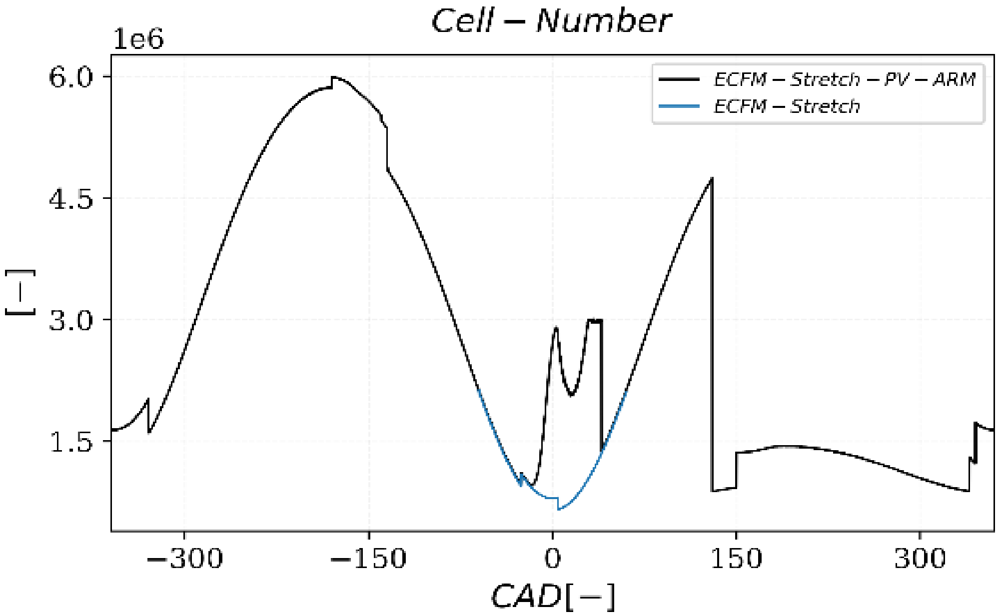
*[1] Benoit, O., Truffin, K., Jay, S. et al. Development of a Large-Eddy Simulation Methodology for the Analysis of Cycle-to-Cycle Combustion Variability of a Lean Burn Engine. Flow Turbulence Combust (2021).*

# ECFM COUPLED WITH AMR BASED ON PROGRESS VARIABLE CRITERION



**CAD=-4**




- The computational cost is strongly mitigated by using AMR in CONVERGE.
- In addition to a local mesh refinement around the spark-plug, AMR allows to locally refine the computational grid to improve flame resolution without non-necessary refinement outside the reaction zone (the criterion is based on the ECFM progress variable with a minimum cell size of 0.25 mm in the flame front)
- Moderate impact of AMR on the total number of cells only in the combustion phase.

# OUTLINE

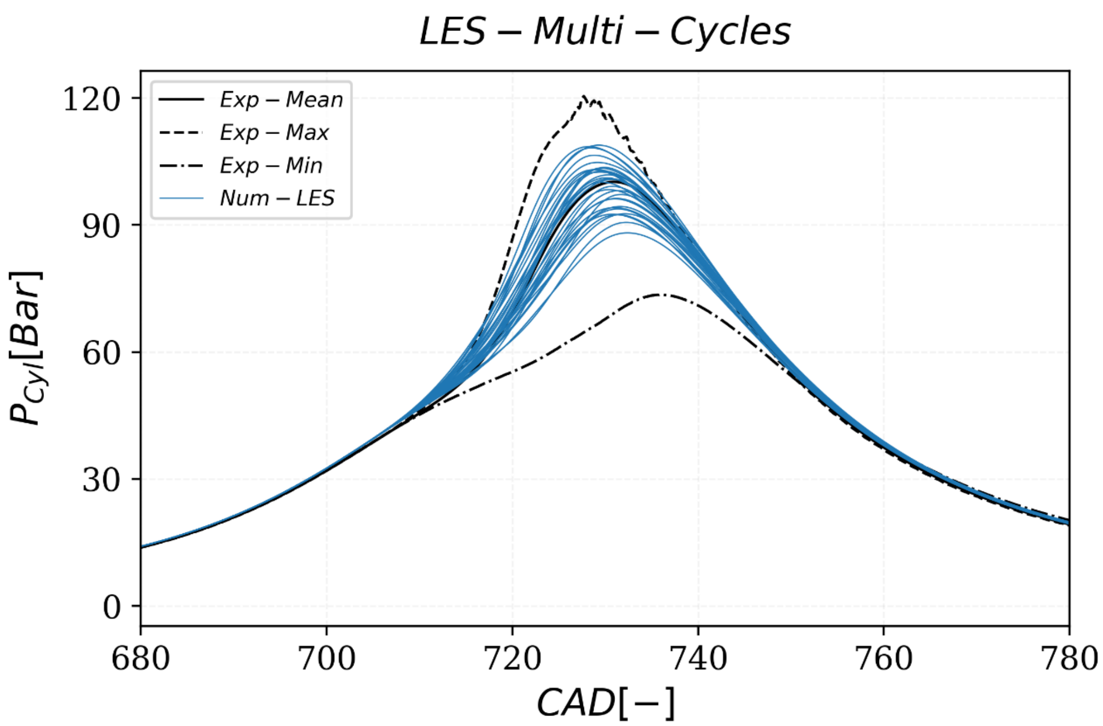
MOBILITÉ DURABLE

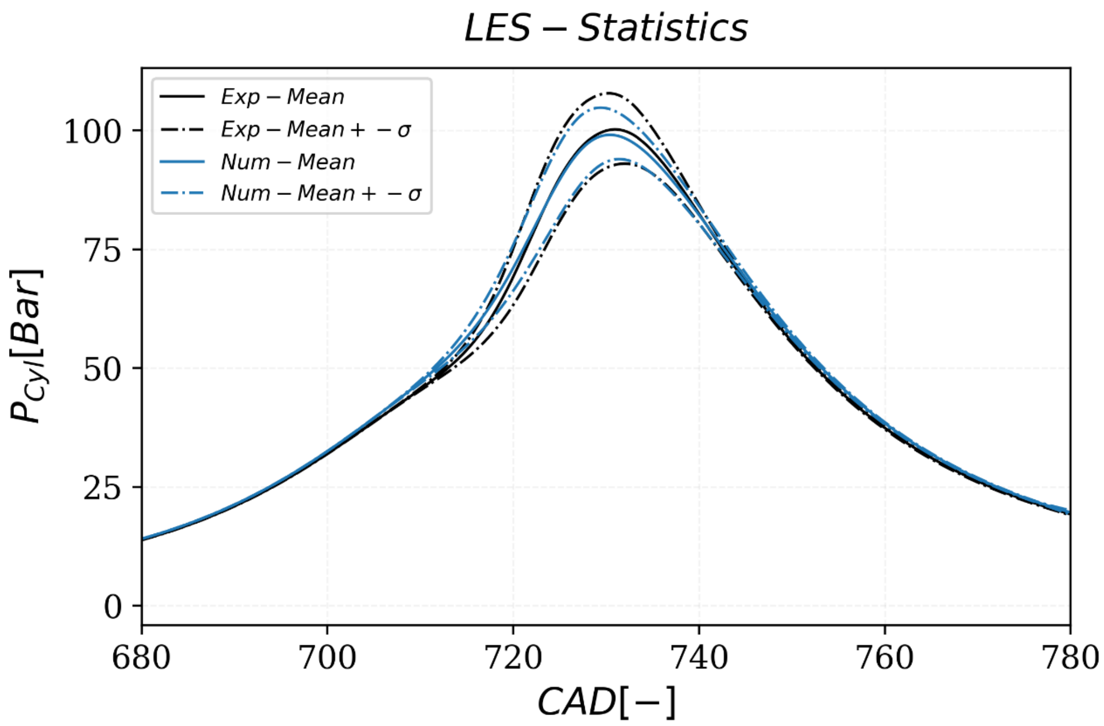
- TGR-E benchmark configuration
- Mesh and numerical set-up
- Overview of the Cold AERO results + Spray calibration results
- Reactive LES results
- CCV analysis
- Summary and perspectives

# LES REACTIVE: PRESSURE ENVELOPE AND ITS STATISTICS



- Pressure envelope over 30 cycles for numerical data and 1000 for experiments
  - Comparison of the numerical pressure envelope with the experimental one
  - Computation of the pressure statistics



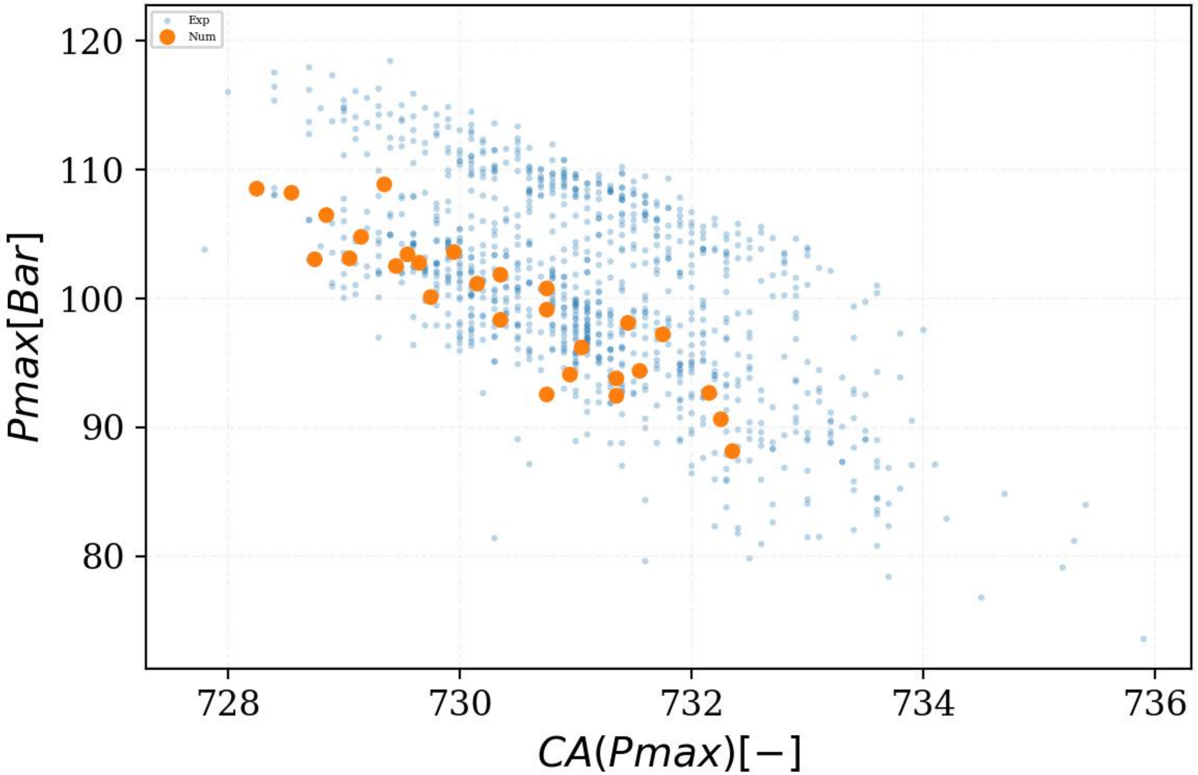



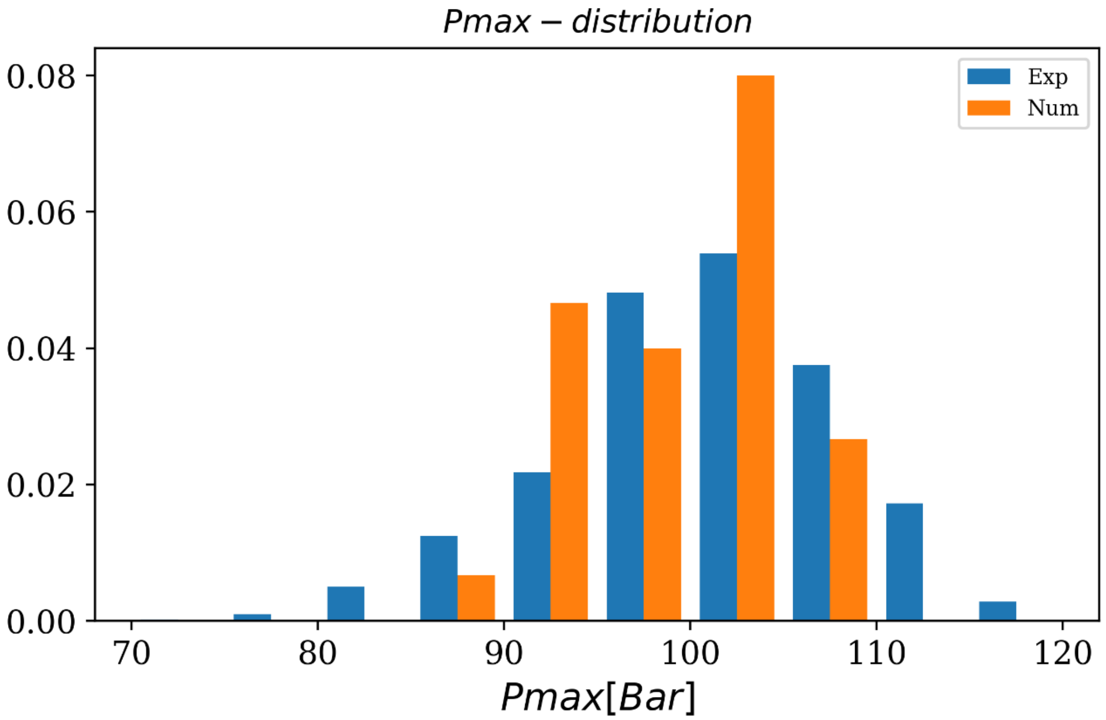

- Numerical pressure envelope shows an important cycle-to-cycle variability that is confirmed by the pressure statistics (mean and standard deviation)
- However, numerical pressure signals shows an earlier ignition compared to experiments
- Difficulty to reproduce the extreme cycles

# LES REACTIVE: PMAX DISTRIBUTION (MATEKUNAS DIAGRAM [1])





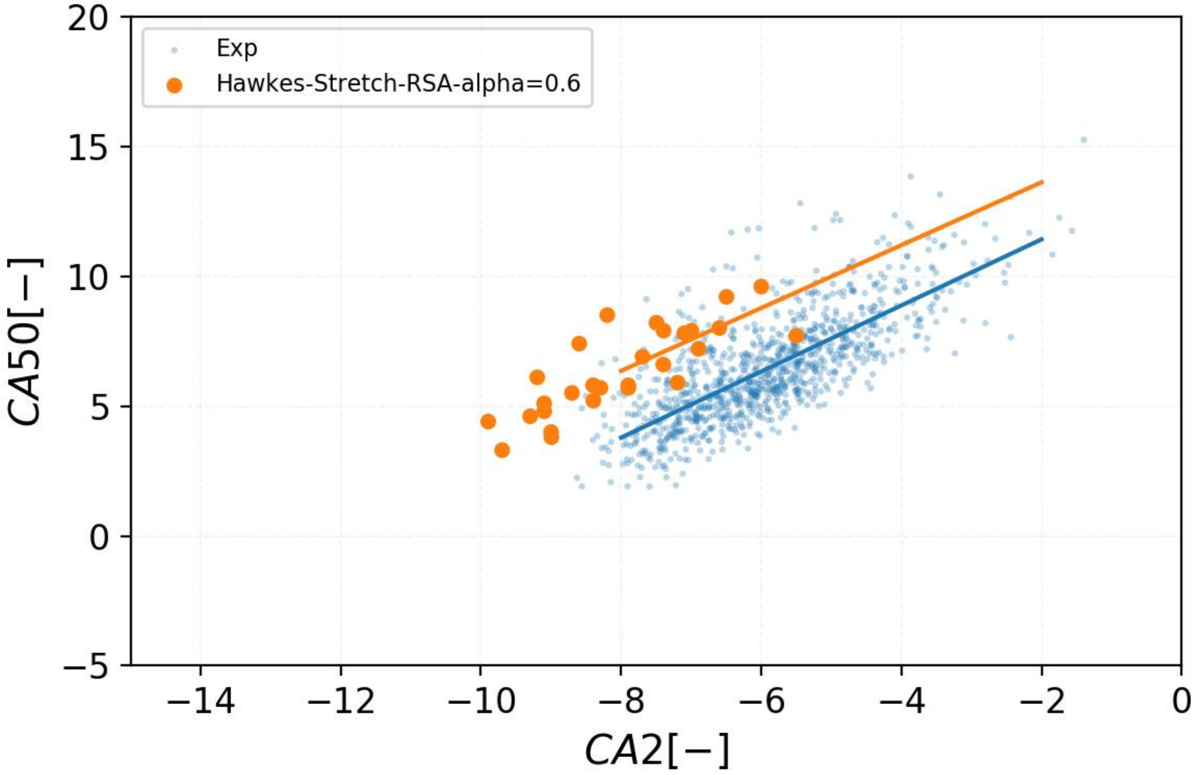



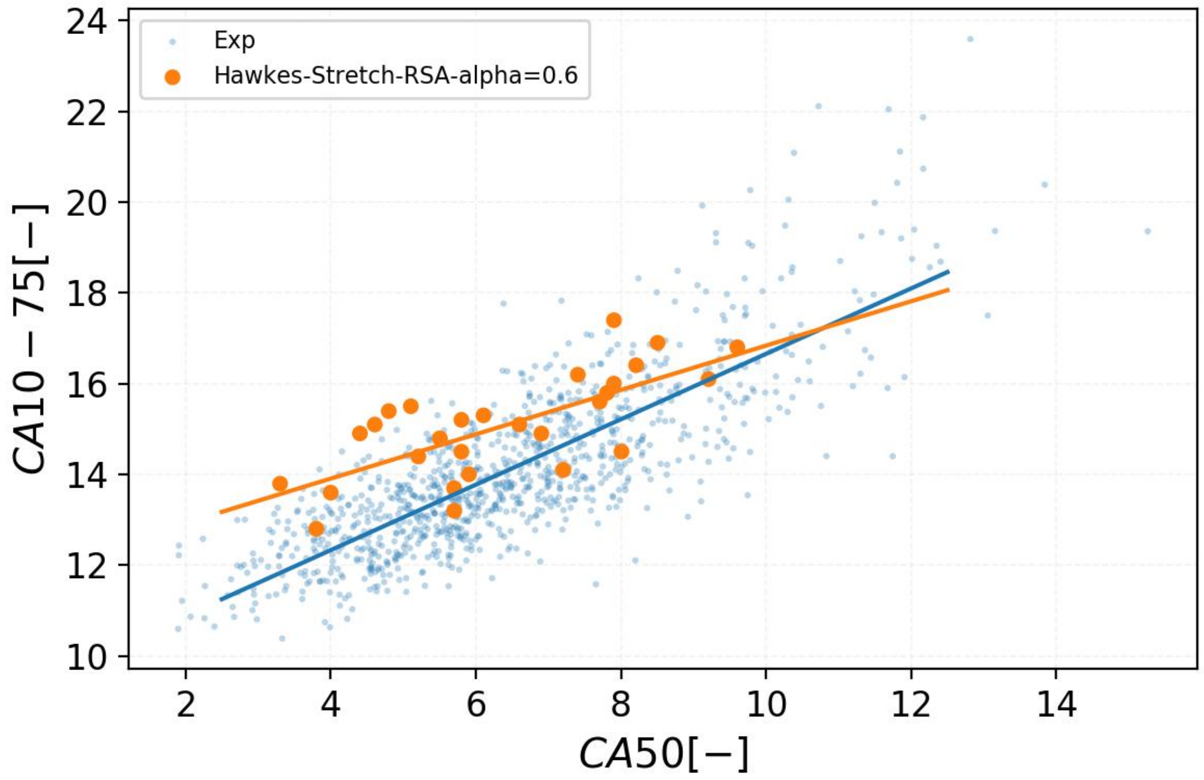

- The experimental linear behavior is correctly reproduced by numerical simulations. It confirms the capability of the LES approach to reproduce CCV
- Difficulties to reproduce boundary experimental cycles (Pmax and Pmin) → extreme cycles
- The discrepancy in the Pmax distribution shape could be due to the lower number of cycles

*[1] Matekunas FA. Modes and Measures of Cyclic Combustion Variability. In: SAE Technical Pa-per Series. 400 Commonwealth Drive, Warrendale, PA, United States: SAE International; 1983.*

# LES REACTIVE: CA50VSCA2 & CA10-75VSCA50





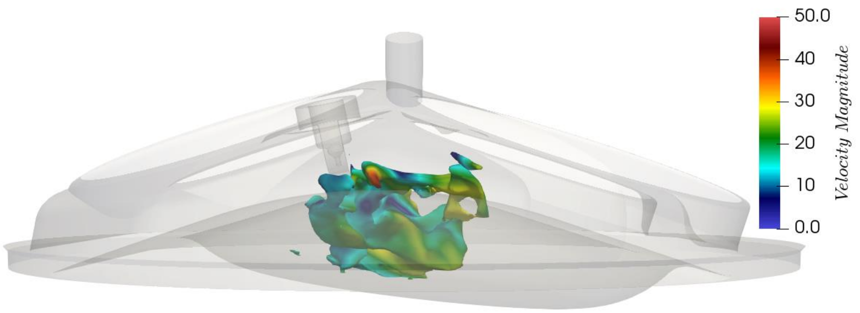

- An early ignition CA2 is confirmed by the CA50-CA2 scatter plot
- The linear experimental behavior and the scattering amplitude are correctly reproduced

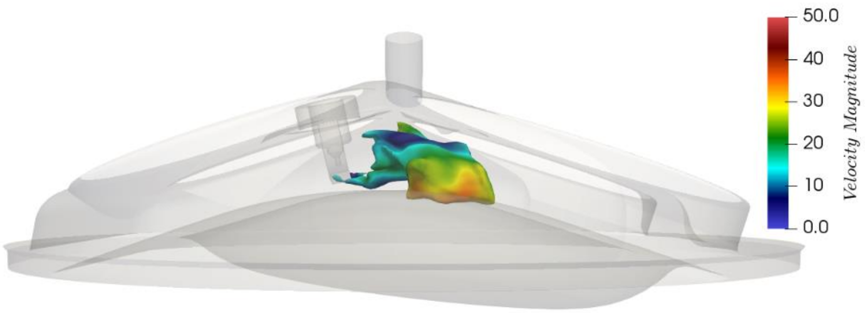
# LES REACTIVE: COMPARISON BETWEEN FAST AND SLOW CYCLES

- Iso-C at C=0.5 coloured by the local velocity

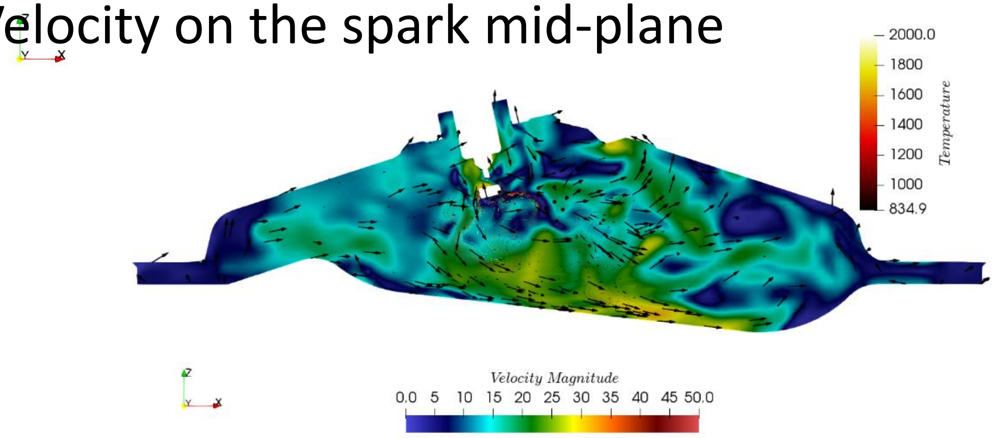
Cycle 17 / CAD: -10

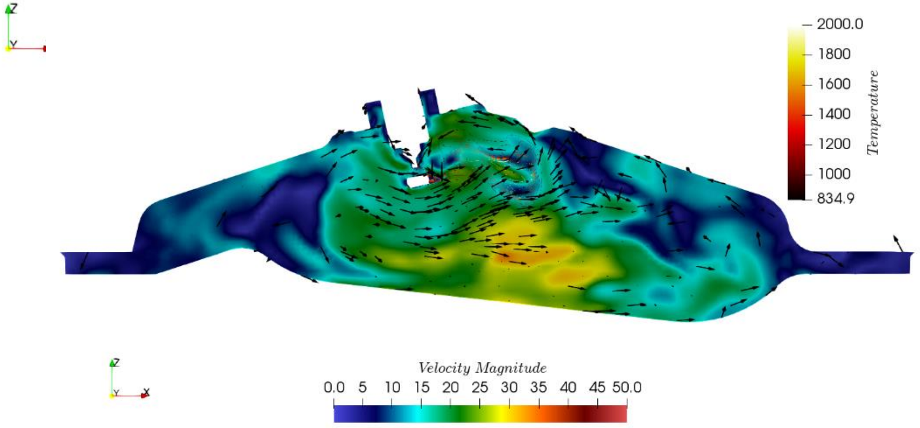



Cycle 20 / CAD: -10




- Velocity on the spark mid-plane




- The initial flame kernel development is affected by the aerodynamic field and turbulence intensity around the spark-plug and this constitutes one of the origin of the CCV.

# OUTLINE



- TGR-E benchmark configuration
- Mesh and numerical set-up
- Summary of the Cold AERO results
- Reactive LES results
- CONVERGE scalability test and CPU performances
- Summary and perspectives

# SUMMARY AND CONCLUSION

- An LES modelling framework, combining the ECFM-LES approach and AMR is proposed
- Flame stretch effect on laminar flame speed is accounted in ECFM-LES
- The LES set-up is validated, using CONVERGE V3.0 software, to predict the aerodynamic field and combustion in a super-lean spark ignition engine configuration
- A satisfactory cycle to cycle variation is observed in the numerical pressure signals. It is confirmed by comparing multi-cycle pressure statistics to the experimental ones
- Some discrepancies occur: extreme cycles prediction and Pmax distribution -> but they could be attributed to the low number of cycles

## PERSPECTIVES

- Turbulent combustion model → compute the same configuration with Thickened Flame Model (TFM)
- Investigate the origin of the cycle-to-cycle variations

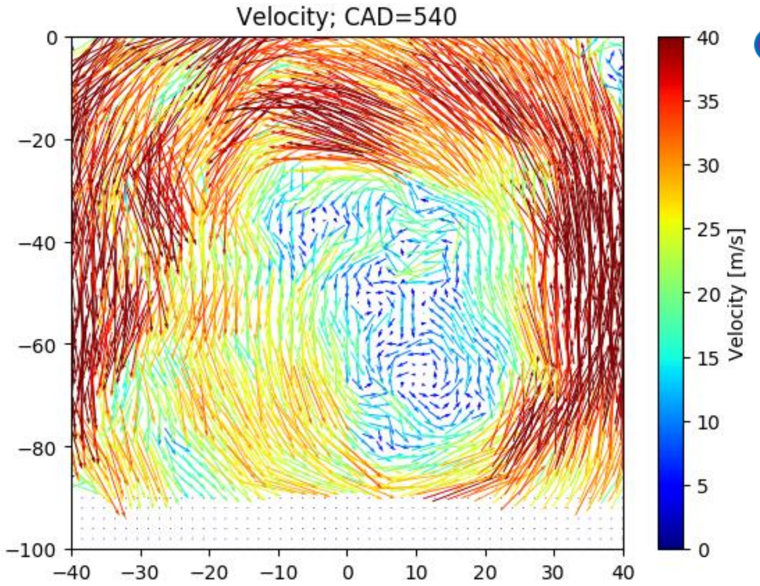
 | 

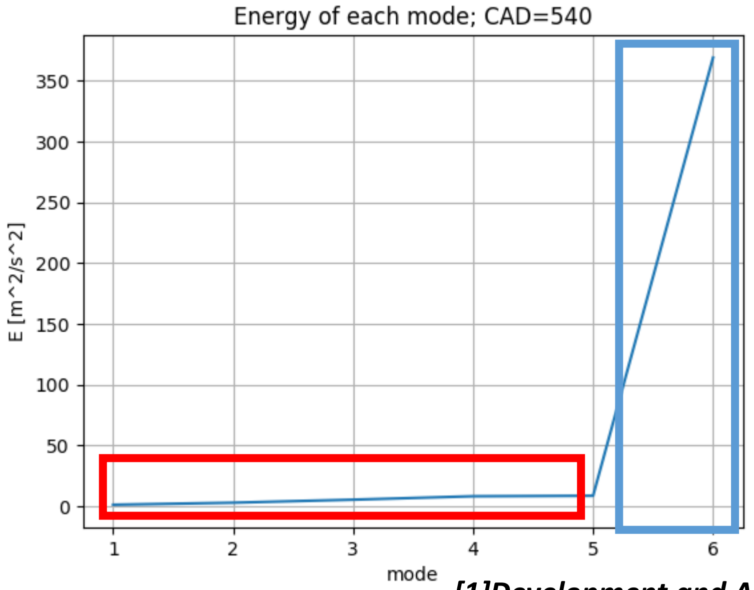
# PERSPECTIVES : EMD POST-PROCESSING TOOL (APPLICATION TO LES) [1]

MOBILITÉ DURABLE

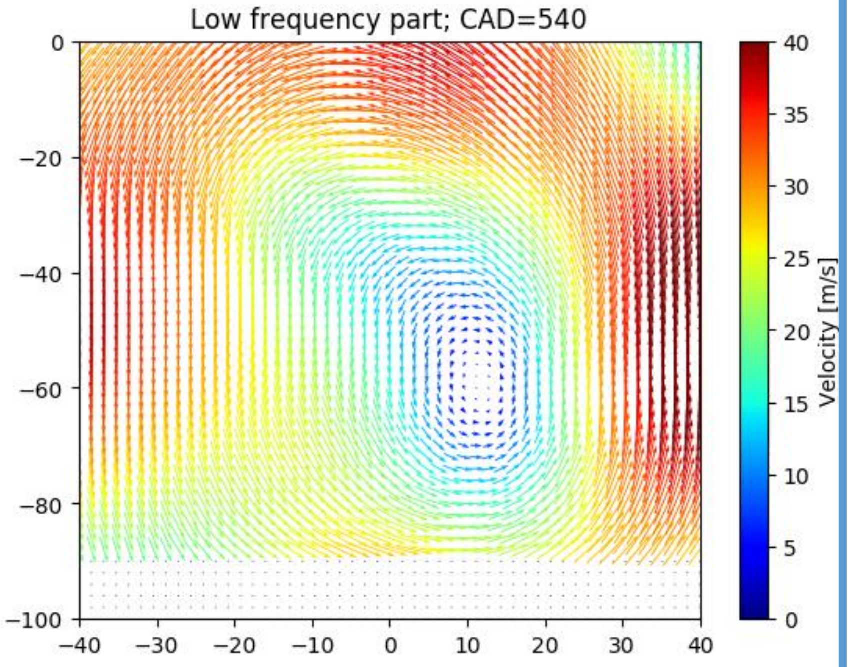
- Data-analysis tools to find the origins of cycle-to-cycle combustion variabilities and their links to aerodynamics (***On-going PhD Thesis of Zhihao Ding, 2021***)

$$U(x,y) = \sum_{k=1}^{N} BIMF_k(x,y) + r_N(x,y)$$

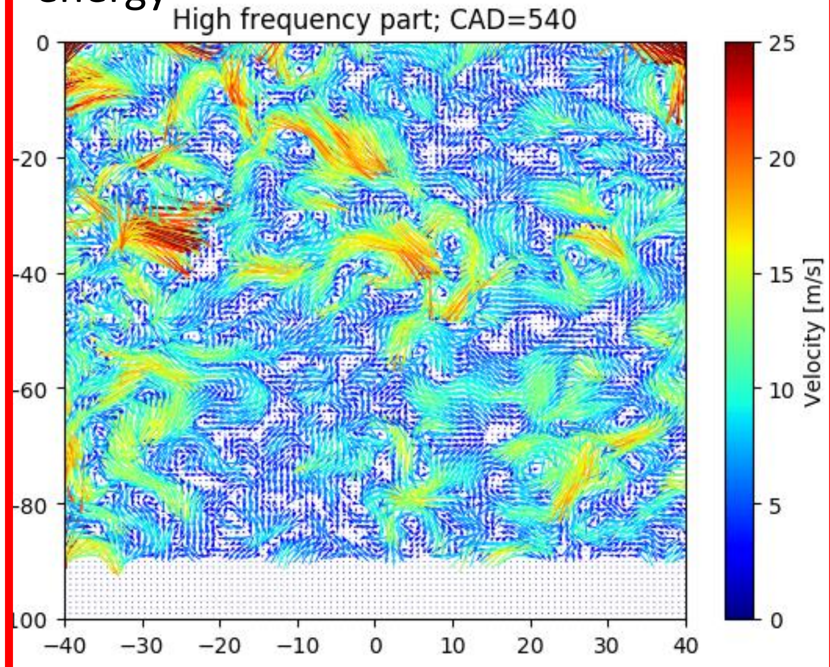



**Global movement**: large turbulent scales having higher energy




**Random turbulent fluctuation**: small turbulent structures having lower energy




*[1]Development and Application of Bivariate 2D-EMD for the Analysis of Instantaneous Flow Structures and Cycle-to-Cycle Variations of In-cylinder Flow, Mehdi Sadeghi, Karine Truffin1, Brian Peterson, Benjamin Böhm and Stéphane Jay*


*Innover les énergies*

Retrouvez-nous sur :

www.ifpenergiesnouvelles.fr

@IFPENinnovation