

Diagnosics optiques dans les moteurs à combustion interne

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14^{EME} JOURNEES D'ECHANGES
DU RESEAU DES PLASMAS FROIDS

15-18 octobre 2018 - La Rochelle



- ❑ Objectifs en terme d'émission en CO₂ au regard des normes EU / US / reste du monde
- ❑ Pour atteindre l'objectif de réduction de CO₂ de l'UE de 80% d'ici 2050, le transport doit baisser ses émissions de 60%

Réduction de 80 % des émissions de gaz à effet de serre à l'horizon 2050 (100%= 1990)

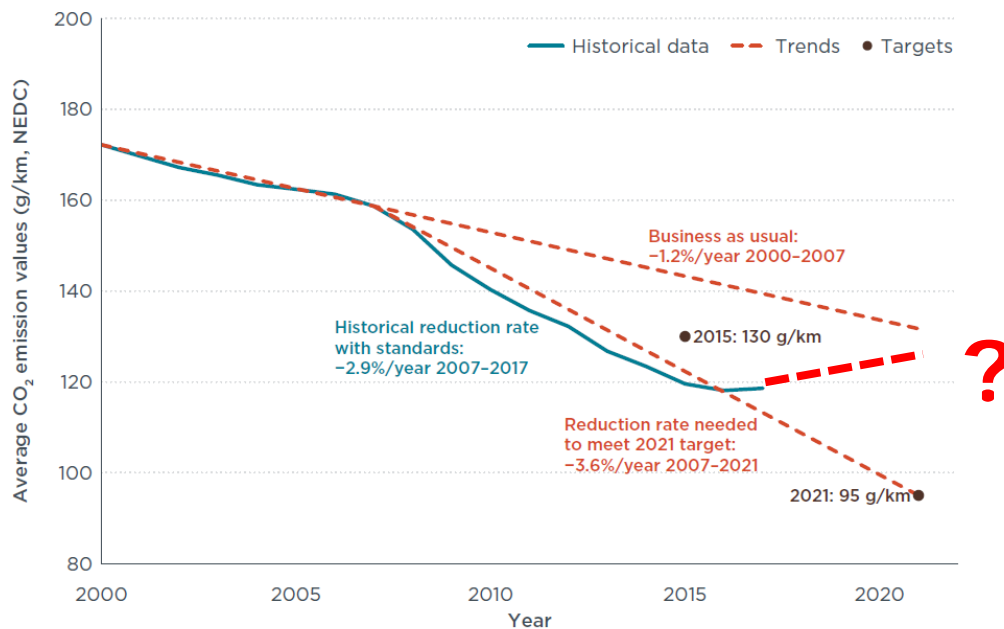
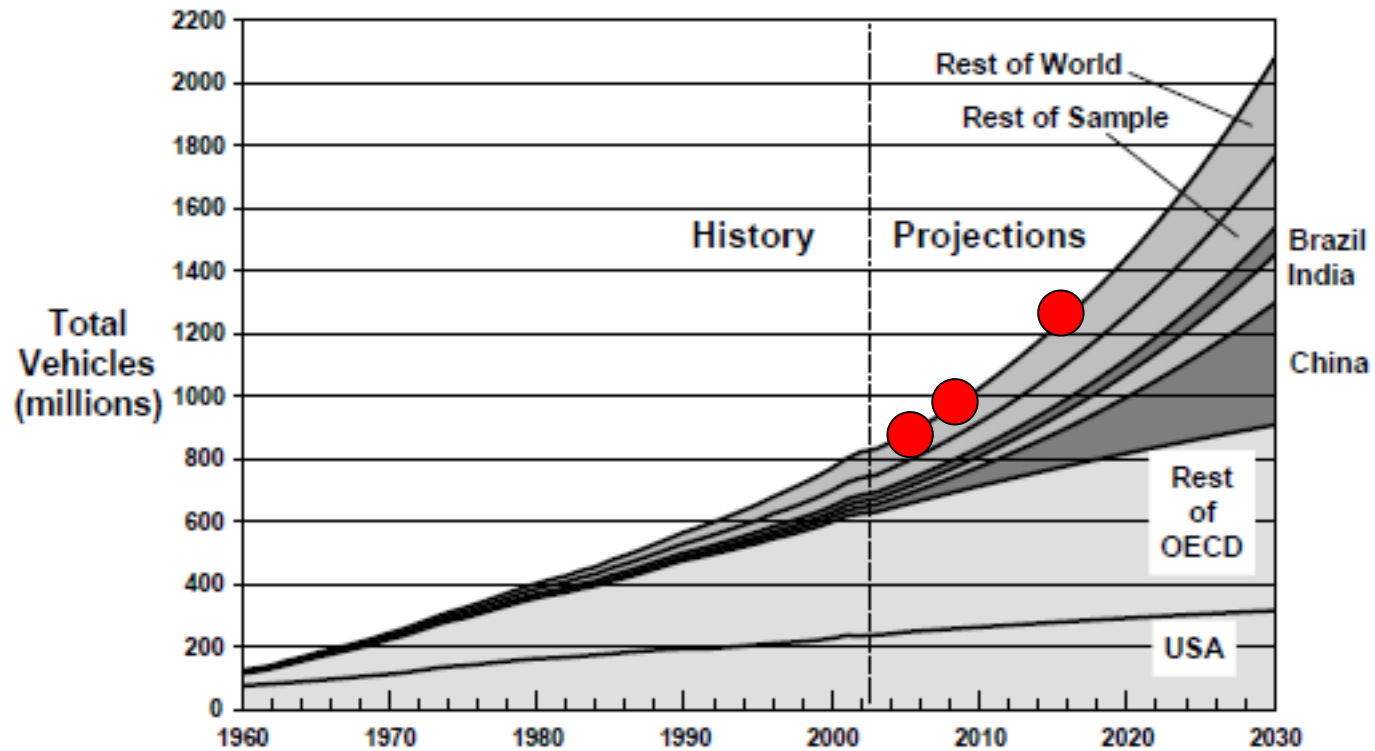


Figure 1. Historical average CO₂ emission values, targets, and annual reduction rates of new passenger cars in the EU.



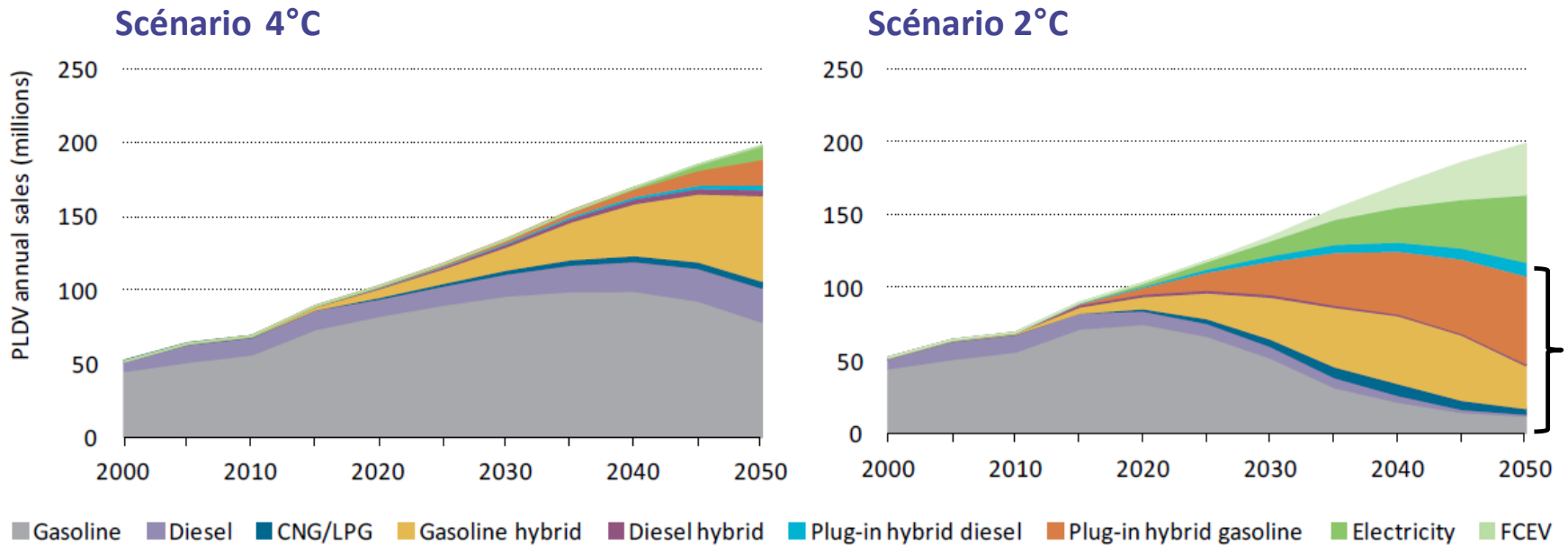
□ Horizon 2030



Dargay et al. 2007

● Mesures à postériori

☐ Scénarii proposés par l'IEA (International Energy Agency)



Moteur à combustion interne

In order to reach 2DS objectives, sales of non-conventional vehicles and fuels need to increase rapidly beyond 2015.

- **Augmentation massive du rendement des moteurs à combustion interne**
- **Optimisation de la plage de fonctionnement du moteur**
 - **Hybride série / parallèle / mixte**
- **Utilisation des biocarburants**
 - **Baisse des émissions de CO₂ (cycle de vie du CO₂)**
- **Diminution des émissions polluantes (ultra low emission)**



OBJECTIVES : EFFICACITÉ ÉNERGÉTIQUE SOUS CONTRAINTES

$$\eta_{\text{Brake}} = \eta_{\text{Combustion}} * \eta_{\text{Thermodynamic}} * \eta_{\text{GasExchange}} * \eta_{\text{Mechanical}}$$

Zéro émissions
polluantes

$$\eta = 1 - \frac{1}{\varepsilon^{\gamma-1}}$$

Fort γ & rapport volumétrique ε
Durée de combustion courte

Perte par pompage
(pas de papillon des gaz)

Moyenne et Forte
charges

Emissions polluantes :

- Le moteur à allumage commandé est meilleur que le moteur Diesel

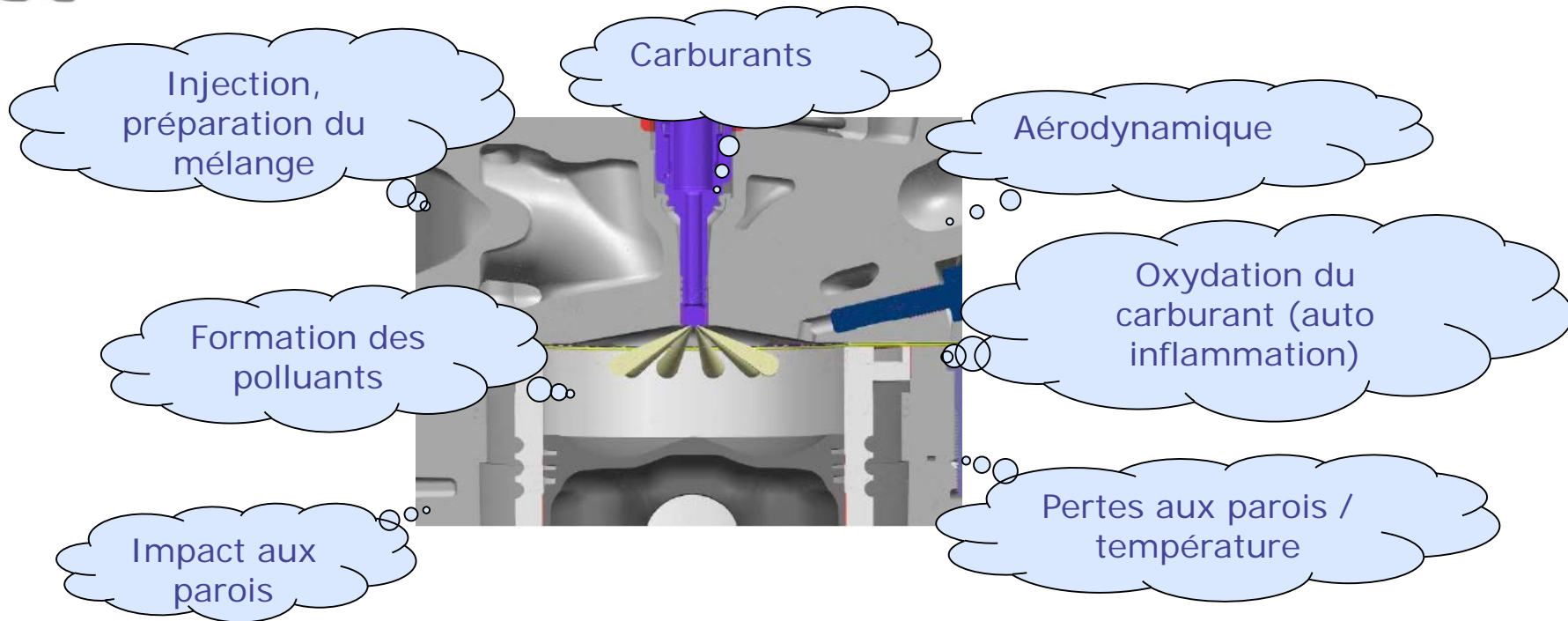
Rendement :

- Le Moteur Diesel est meilleur que le moteur à allumage commandé

Emissions polluantes & rendement :

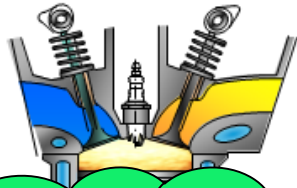
⇒ Quel moteur ? Quels modes de combustion avec quels (bio)carburants ?

- ❑ Pour améliorer le rendement et réduire à la source les émissions polluantes



NOUVEAUX MODES DE COMBUSTION

**Spark Ignition
(Essence)**



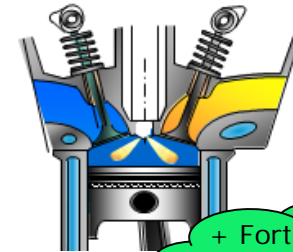
- + Faible émissions avec un catalyseur 3 voies
- Faible rendement en charge partielle et pleine charge

**HCCI
(Homogeneous Charge
Compression Ignition)**



- + Fort rendement
- + Ultra faible Émissions Nox et PM
- Contrôle de la combustion
- Puissance spécifique

**Compression Ignition
(Diesel)**



- + Fort rendement
- Émissions Nox et PM

LTC : Low Temperature Combustion

Fuel

- ~ 2030 : Essence
- ~ 2050 : Biocarburants

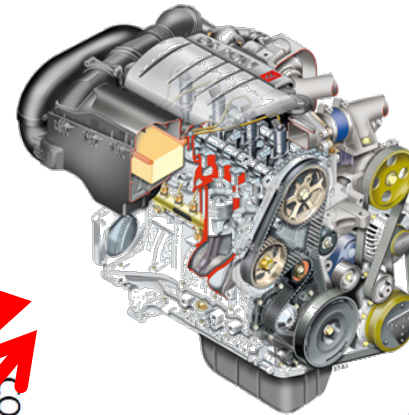
**Diesel PPC
(Partial premixed
combustion)**

- + control de la combustion par l'injection
- Rendement à forte charge
- Fuel « Diesel »

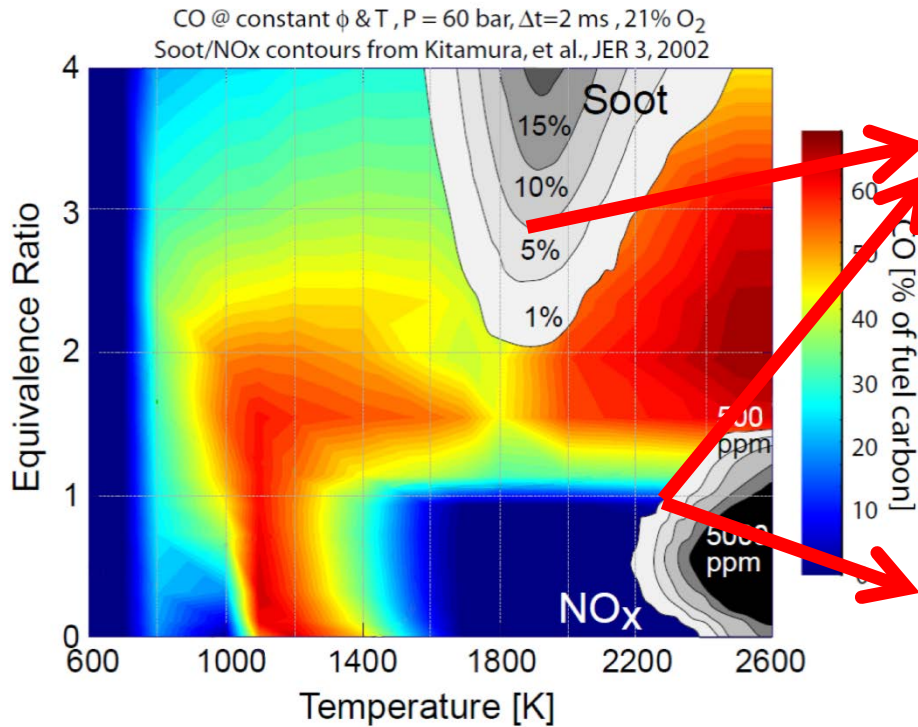
**Gasoline PPC
(Partial premixed
combustion)**

- + Fort rendement
- + Faible émissions de NOx et PM
- Contrôle de la combustion à faible charge

LOW TEMPERATURE COMBUSTION



Moteur à allumage par compression Diesel

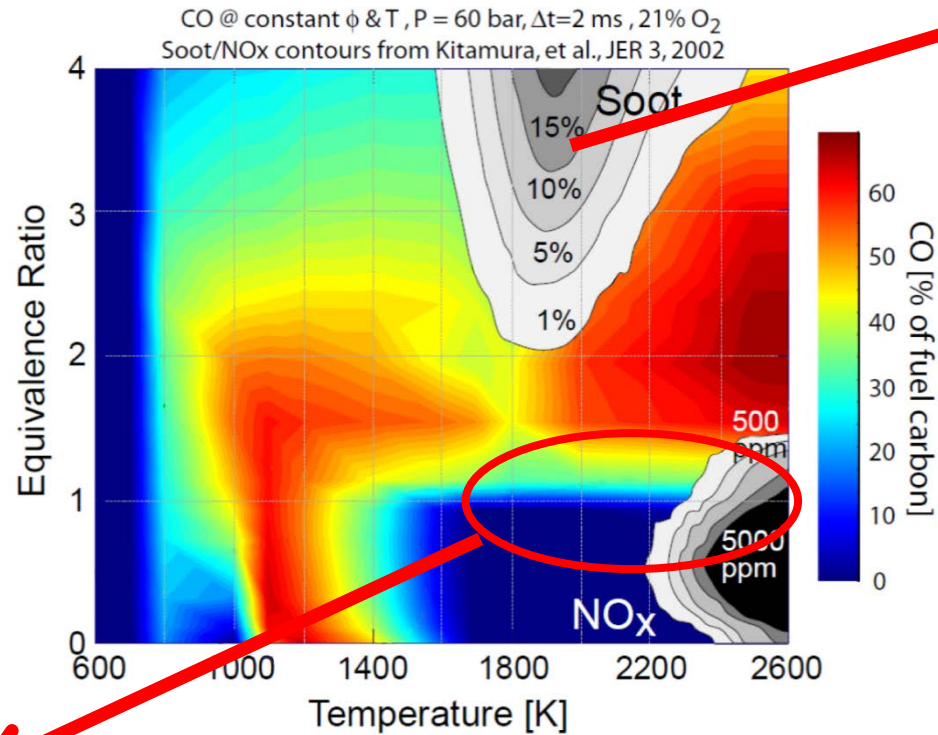


Quels sont les phénomènes physico chimiques ?

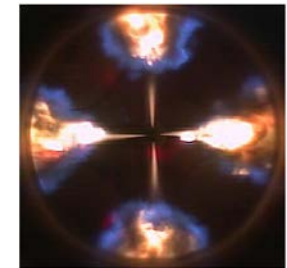


Moteur à allumage commandé (essence)

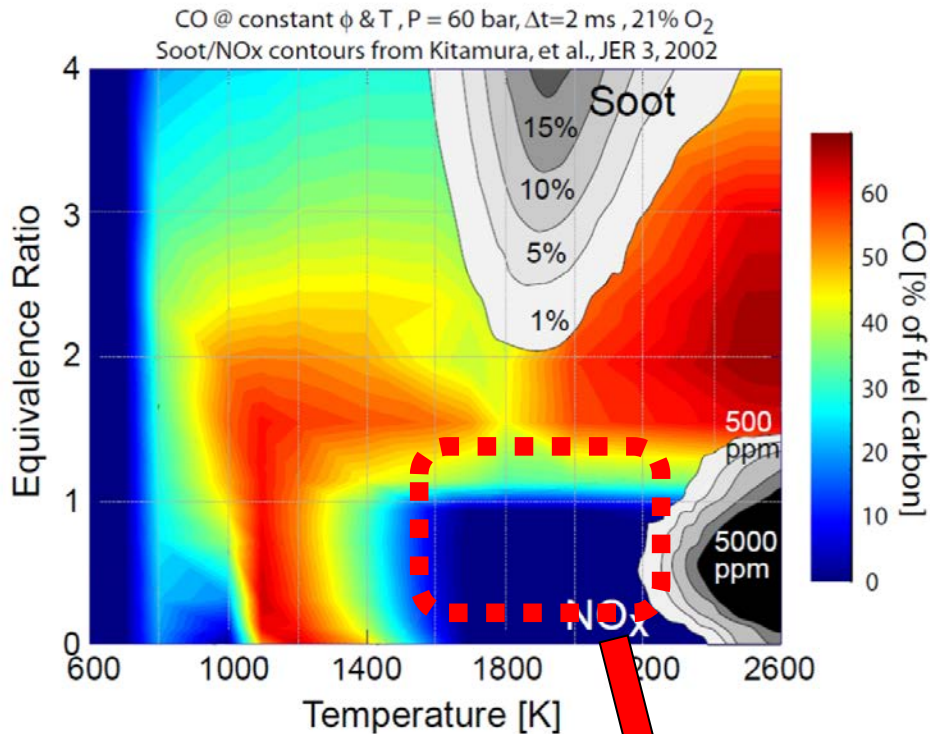
Moteur à allumage commandé



Moteur à allumage par compression



(A)



**Zone de
combustion idéal**

- **Maitrise de la préparation du mélange**
- **Inflammation du mélange**
- **Maitrise du dégagement de chaleur (phasage, bruit..)**
- **Réduction à la source des émissions polluantes**

Fuels :

- **2030 : Essence standard (faible réactivité)**
- **2050 : Biocarburants « légers » (maitrise potentielle de la réactivité)**

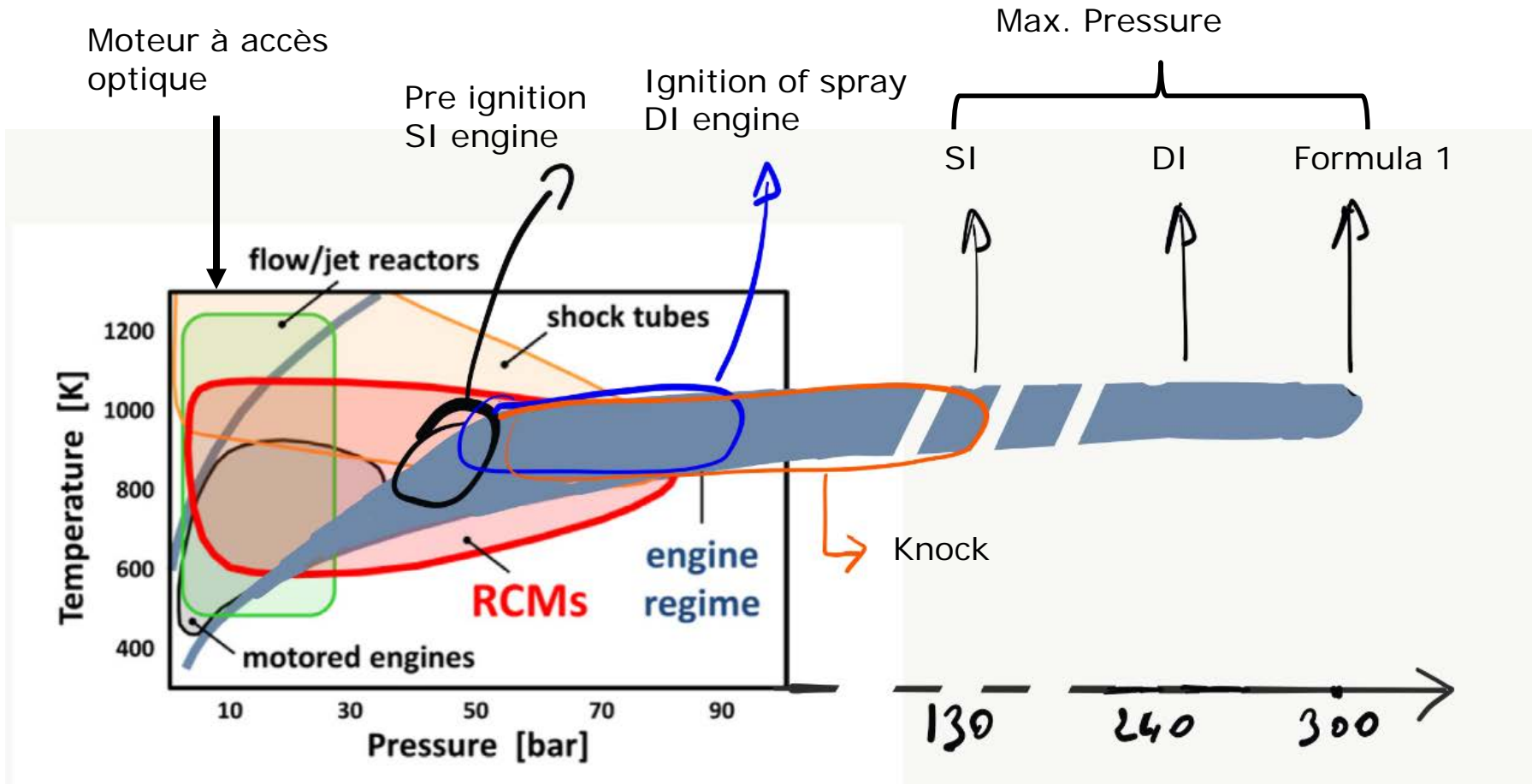
- Modélisation des mécanismes physico-chimiques (CFD) ☹
 - Petites échelles
 - Transitoires
 - Cinétique chimique
- Modélisation de la cinétique chimique de l'oxydation des carburants ☹
 - Diversification des carburants

Il faut des mesures pour valider les modèles !

⇒ **Diagnostics optiques**

⇒ **Moteurs à Accès Optiques**





From S. Goldsbrough & al. , PECS 2017

MOTEUR À ACCÈS OPTIQUES ... IDÉE NOUVELLE ?

□ Nicolaus Otto en 1872 !

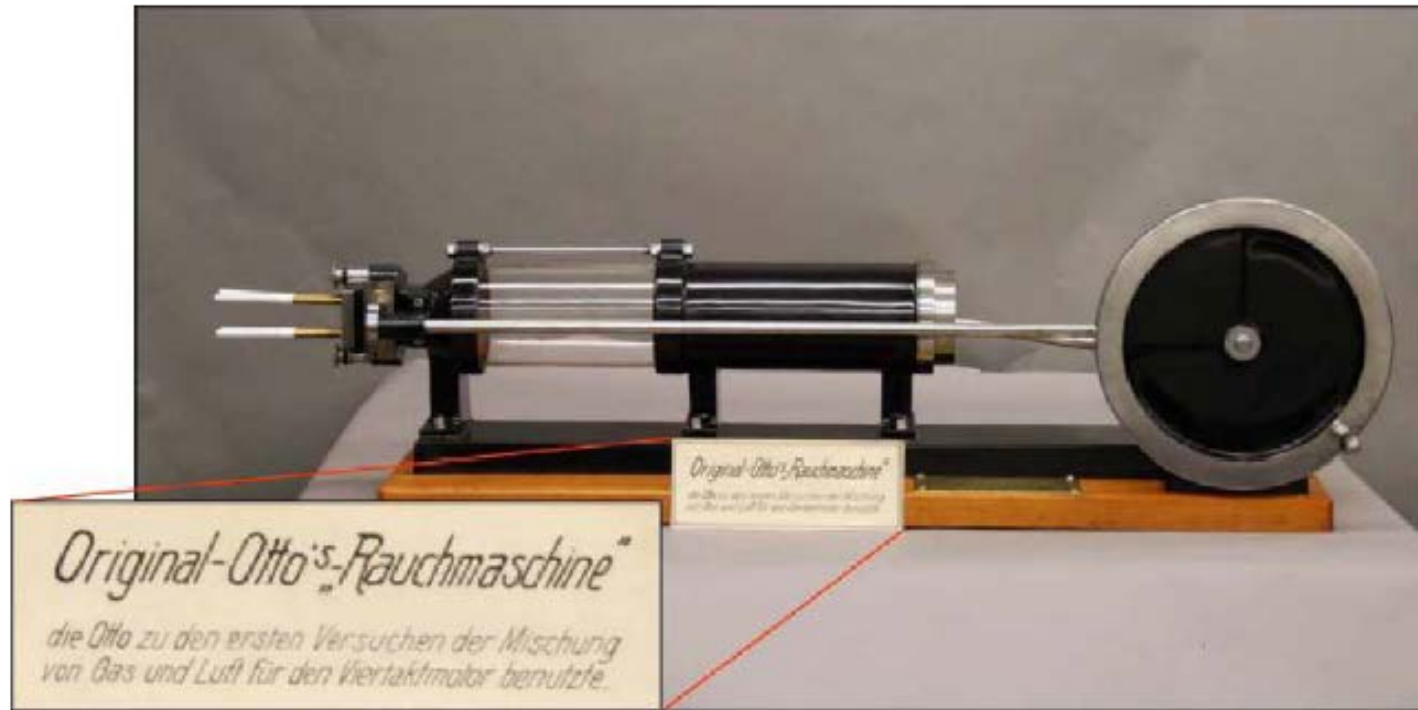


Figure 1. Nicolaus Otto's original "smoke machine". Photo courtesy of Bengt Johansson and Mattias Richter, Lund University.

MOTEUR À ACCÈS OPTIQUES ... IDÉE NOUVELLE ?

□ 1939...

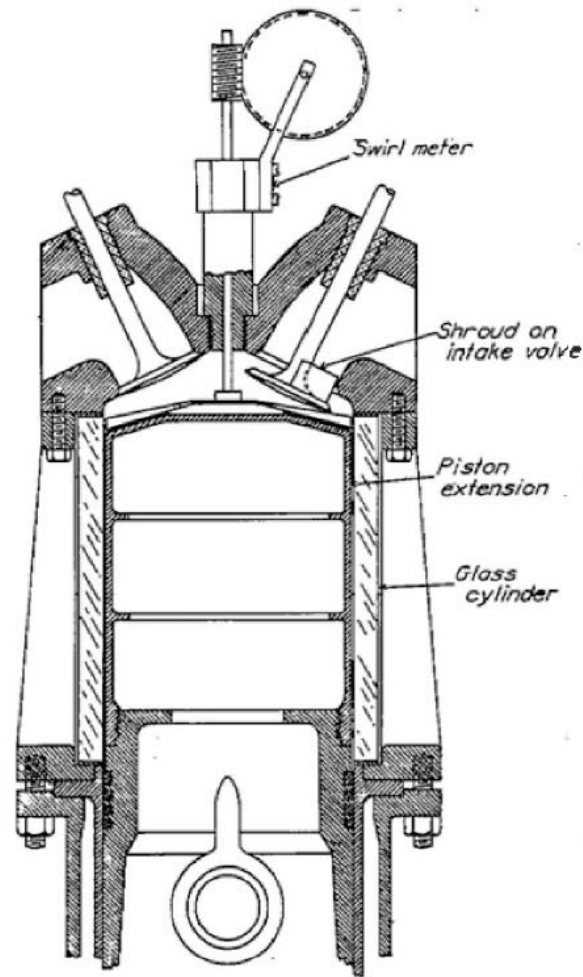


Figure 6. NACA's 1939 optically-accessible engine equipped with a full quartz liner [14]

MOTEUR À ACCÈS OPTIQUES ... IDÉE NOUVELLE ?

□ 1979...

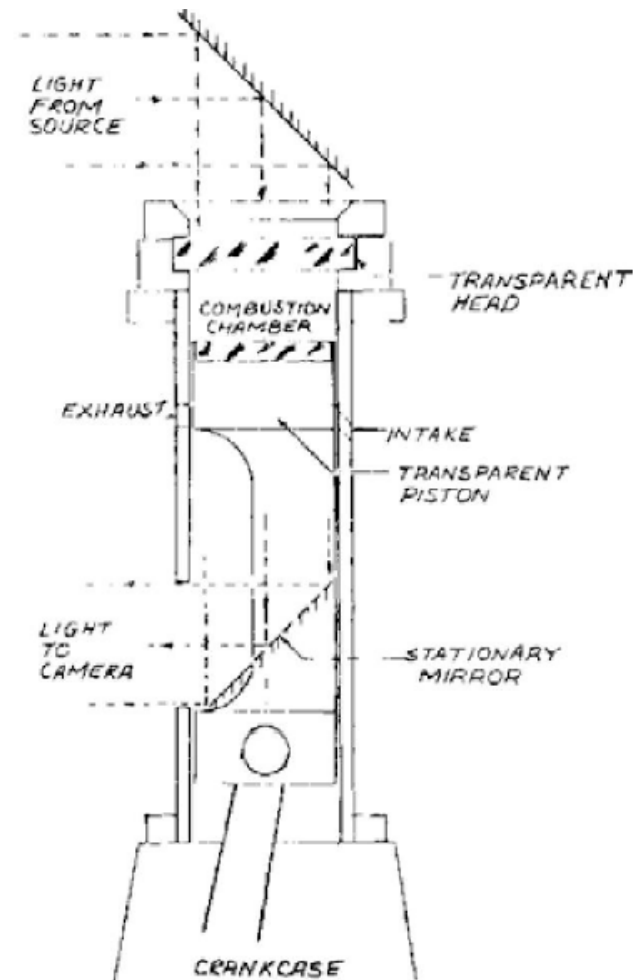
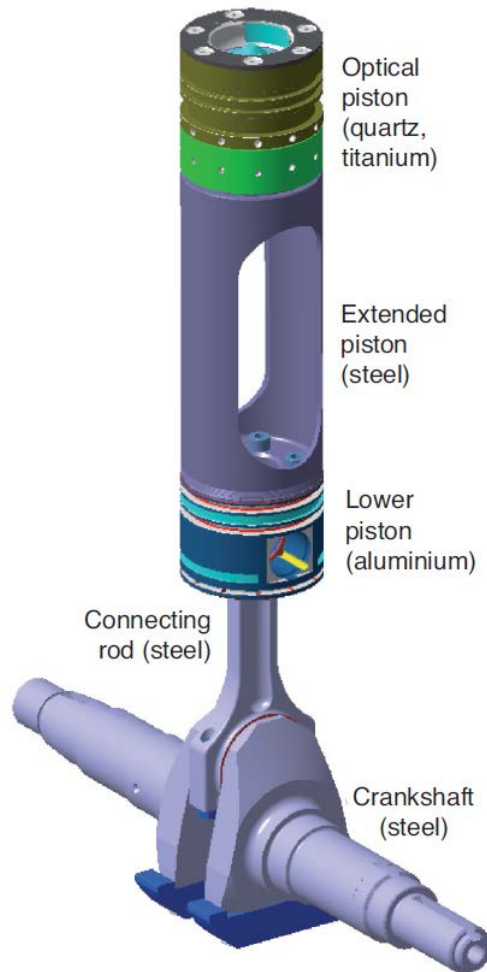
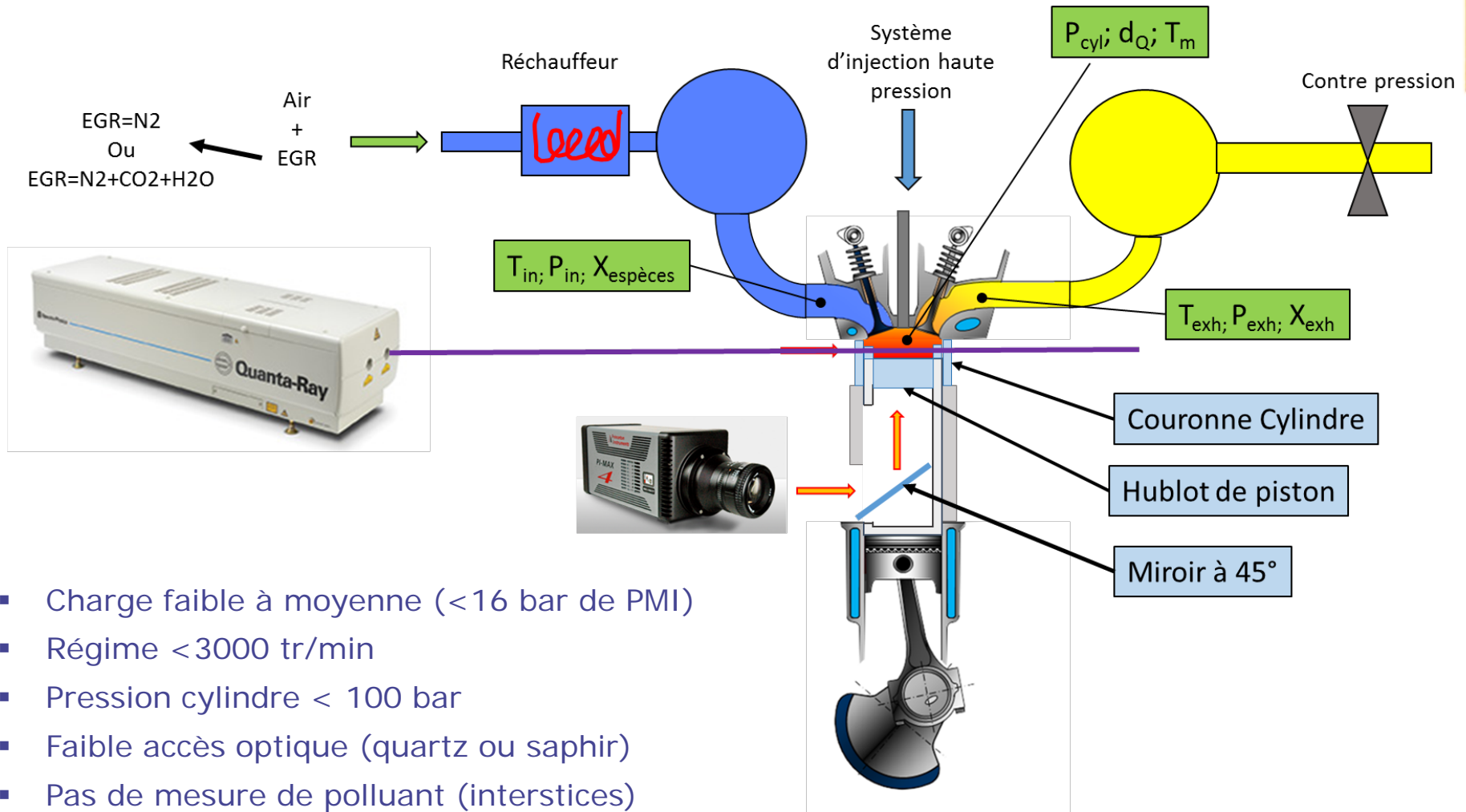


Figure 17. The ported, two-stroke engine employed by Princeton researchers for approximately two decades [44]

MOTEURS À ACCÈS OPTIQUES ACTUELS

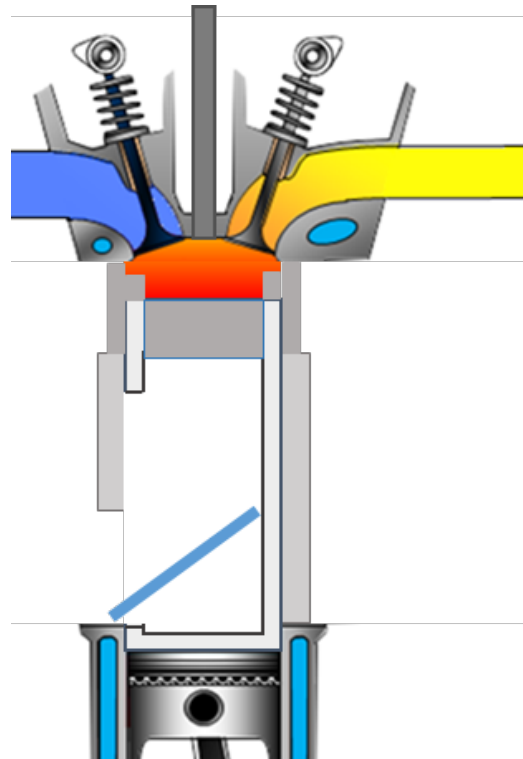




- Charge faible à moyenne (<16 bar de PMI)
- Régime < 3000 tr/min
- Pression cylindre < 100 bar
- Faible accès optique (quartz ou saphir)
- Pas de mesure de polluant (interstices)
- Faible temps de fonctionnement (thermique)
- Pas de lubrification

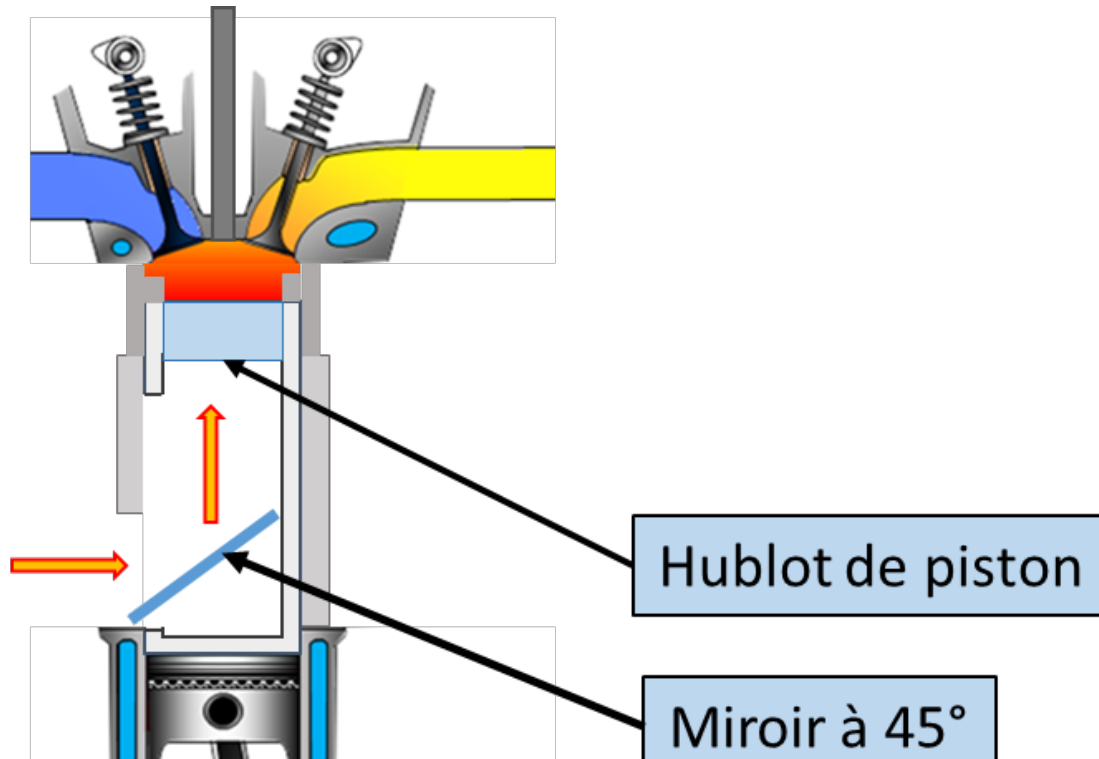
Configuration

- « Métallique »



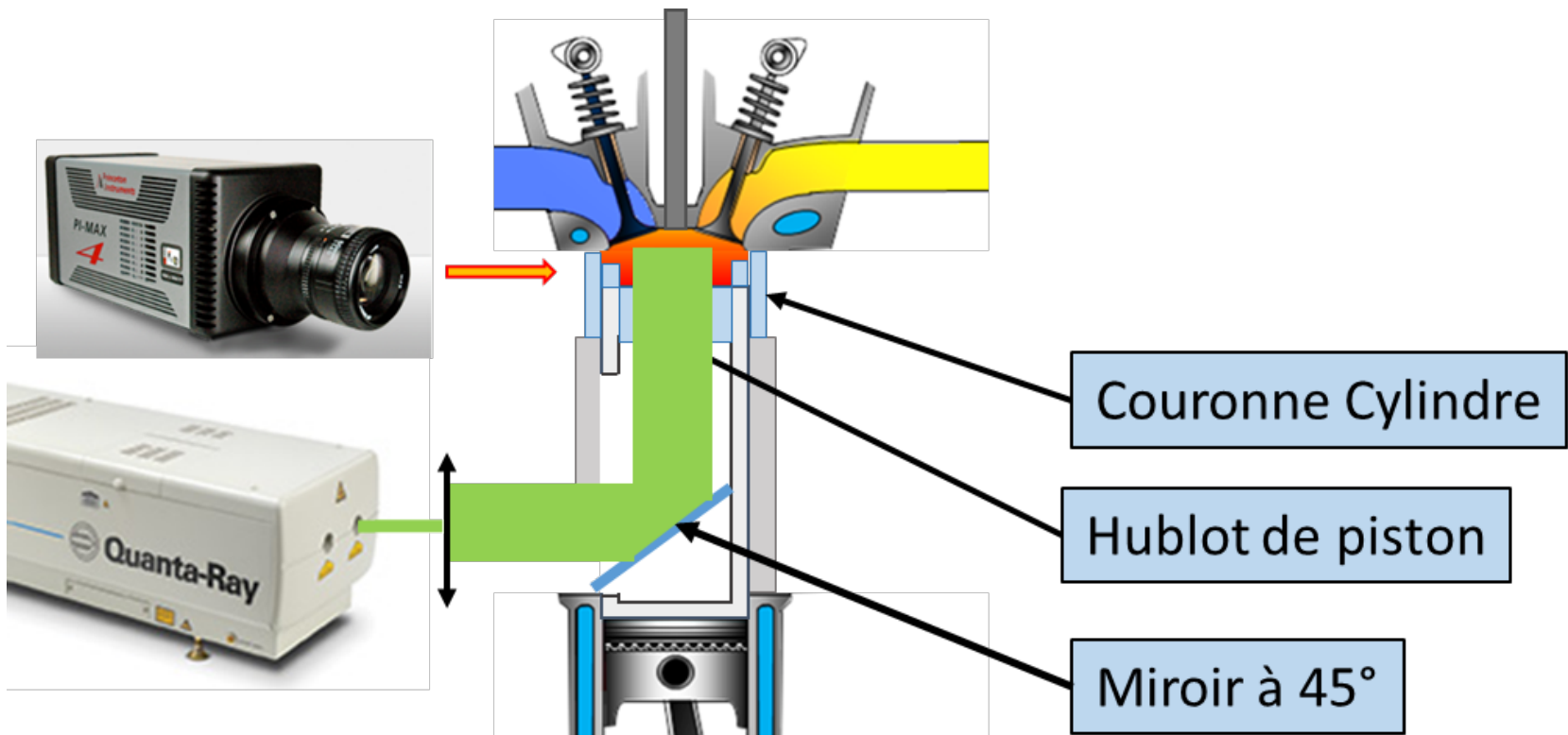
Configuration

- « Piston transparent »



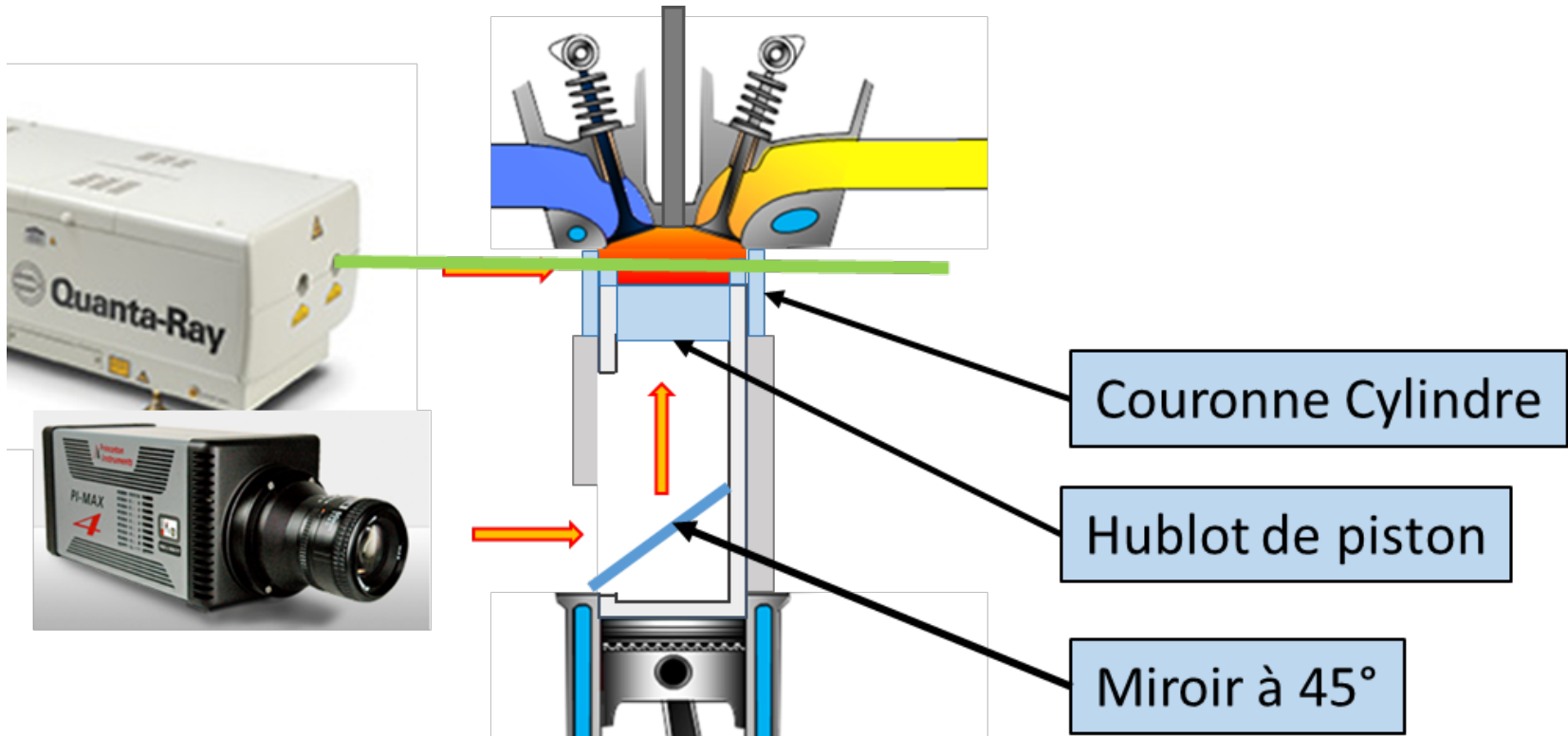
Configuration

- Piston transparent
- Cylindre/couronne transparente

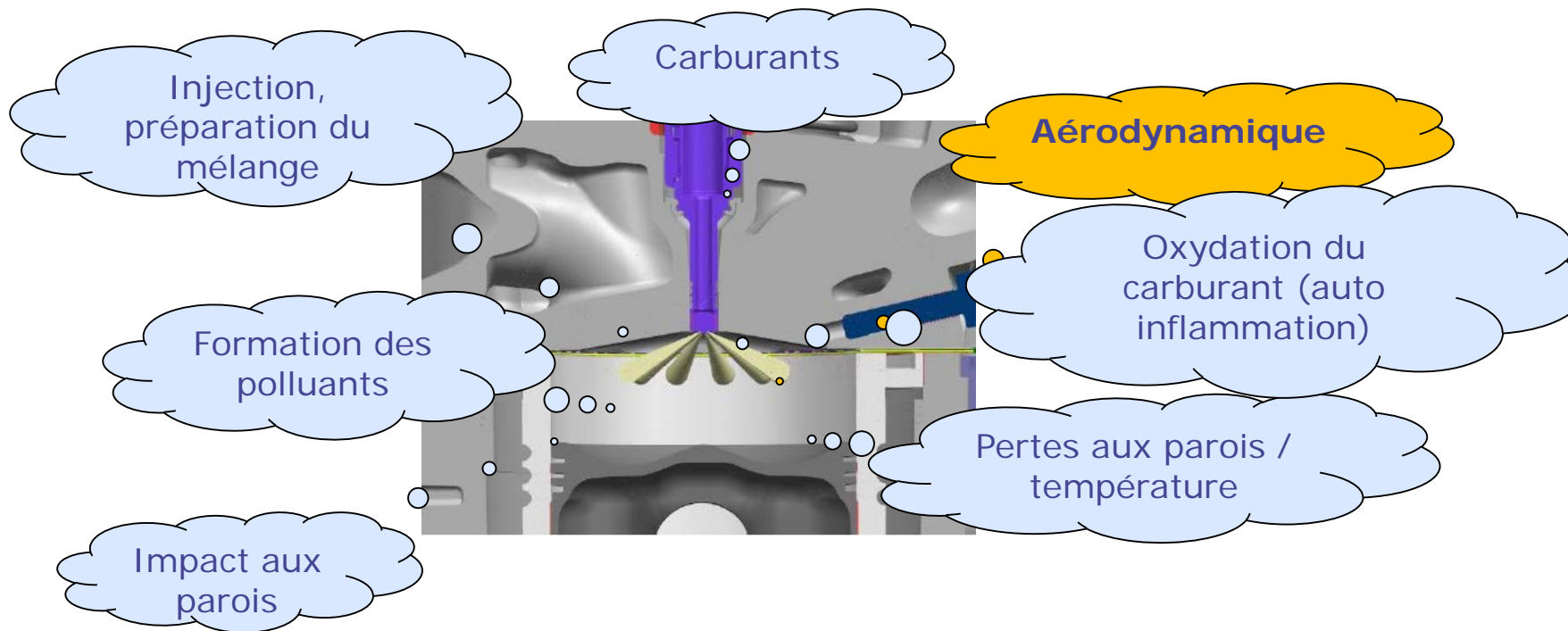


Configuration

- Piston transparent
- Cylindre/couronne transparente



□ Aérodynamique



CARACTÉRISATION DE L'AÉRODYNAMIQUE PAR PIV

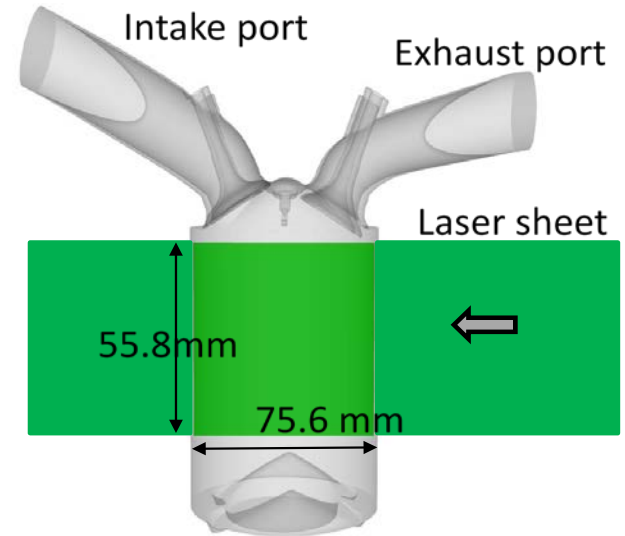
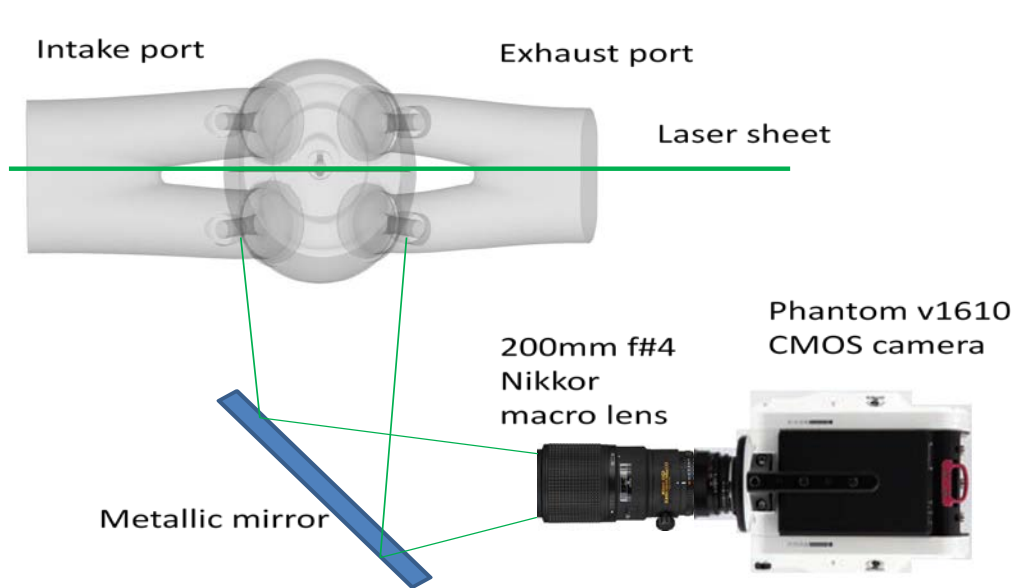
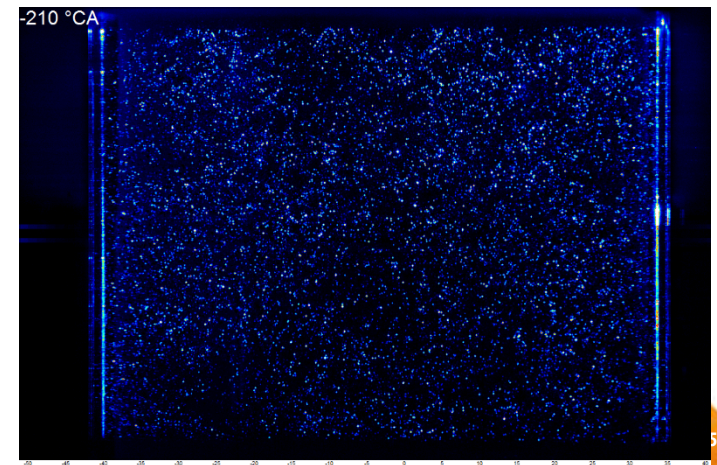
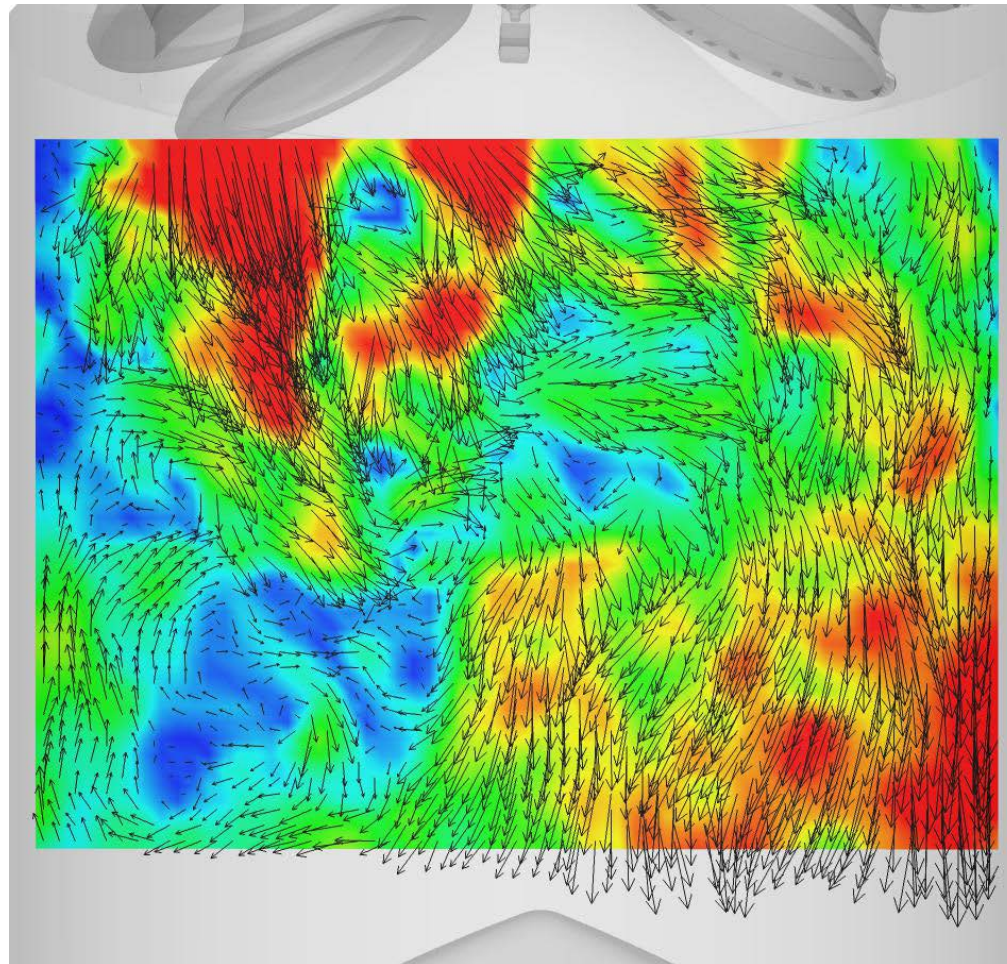


Image brute



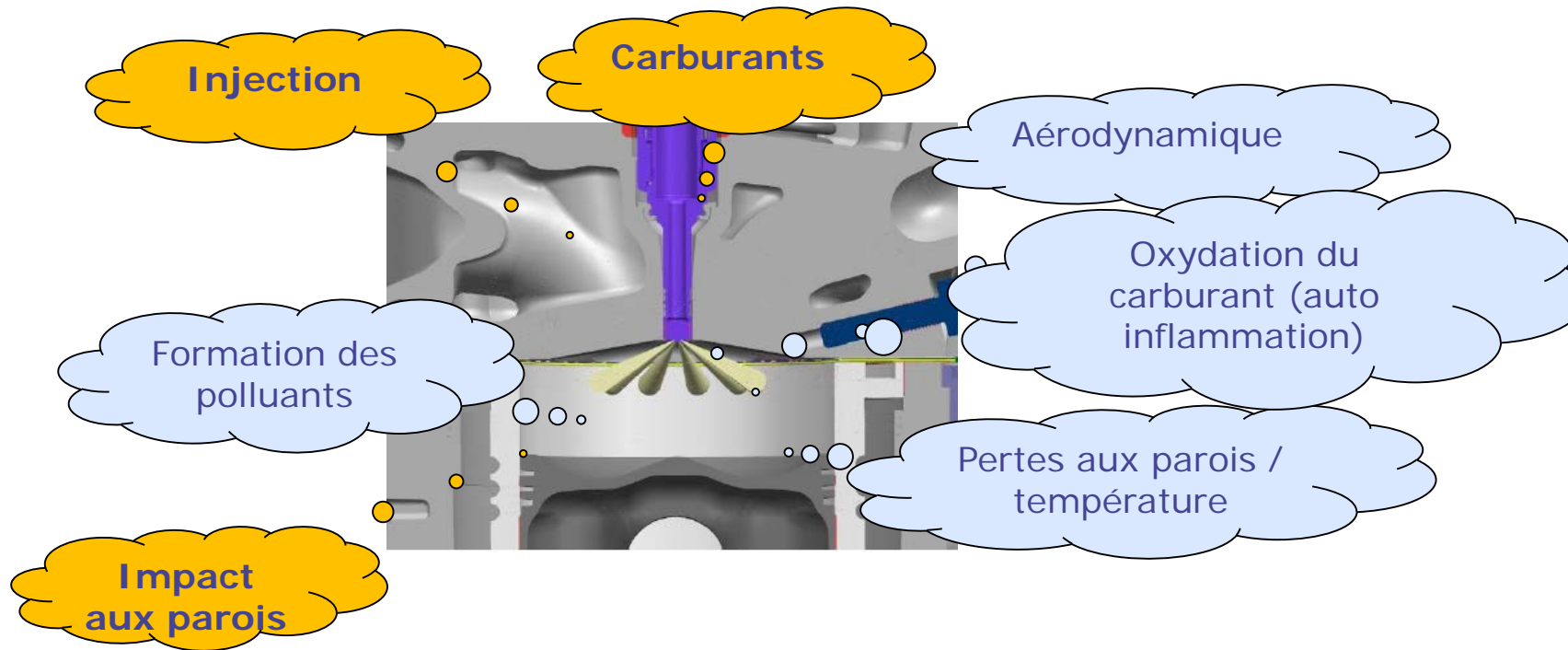
- Caméra rapide (1280x800 pixels²), 48 Gbytes de mémoire
- ~ 70 cycles enregistrés consécutivement
- Laser haute cadence PIV Laser Dual Hawk from Quantronix, 10 mJ/pulse @10 kHz
- Un champ de vitesse déterminé tous les 1.5 DV
- Résolution spatiale: 1.26x1.26 mm²
- Encemensement : huile de silicone

- ❑ Champ 2D et 2 composantes U et V de la vitesse
- ❑ $N=1400$ tr/min @ -154 DV avant le PMH





□ Préparation du mélange



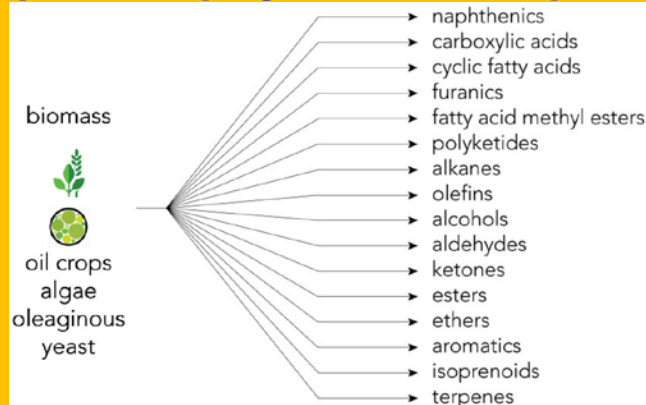
Système d'injection

- Pression
- Géométrie injecteur
nombre de trous
diamètre
- Couplage injection - bol

Développement du spray et préparation du mélange

- Pénétration liquide et vapeur du spray
- Richesse locale
- Impact aux parois

Propriétés physico-chimique du fuel

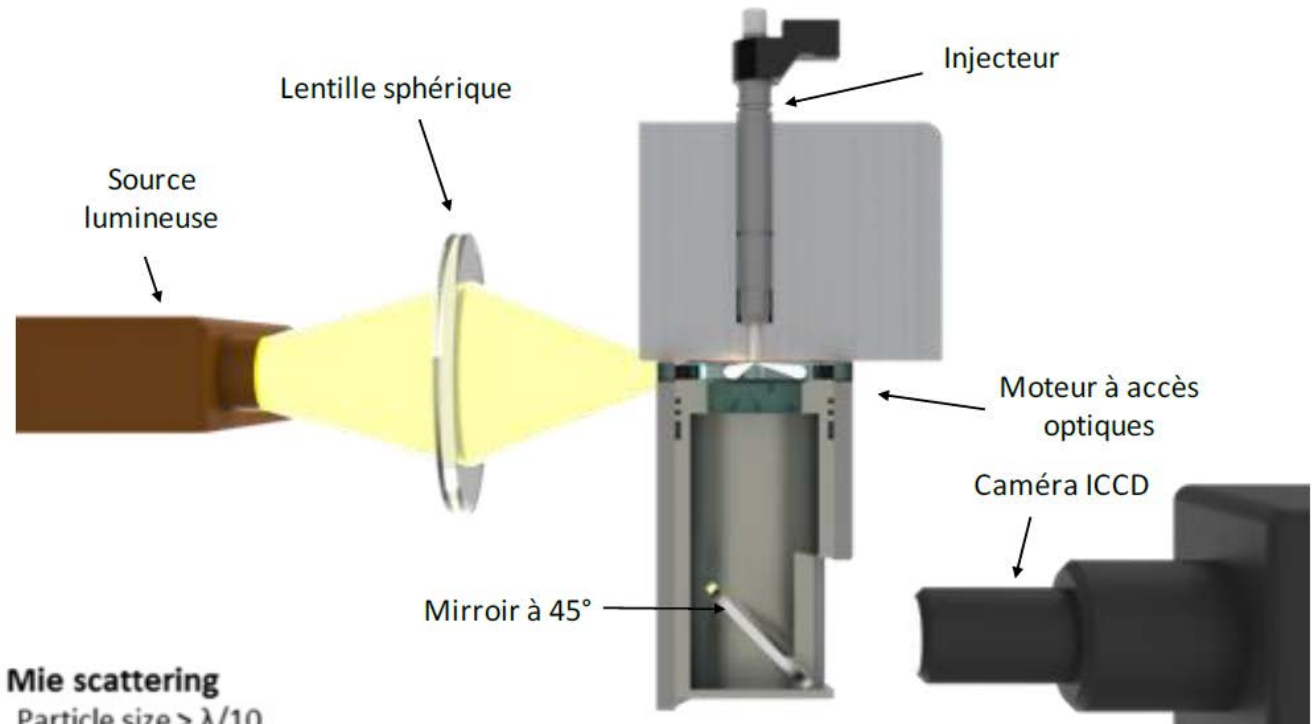


+ Essence

Performances et émissions

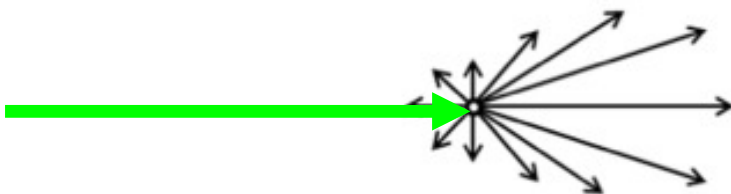
- Travail indiqué
- Formation des polluants

□ Diffusion de Mie



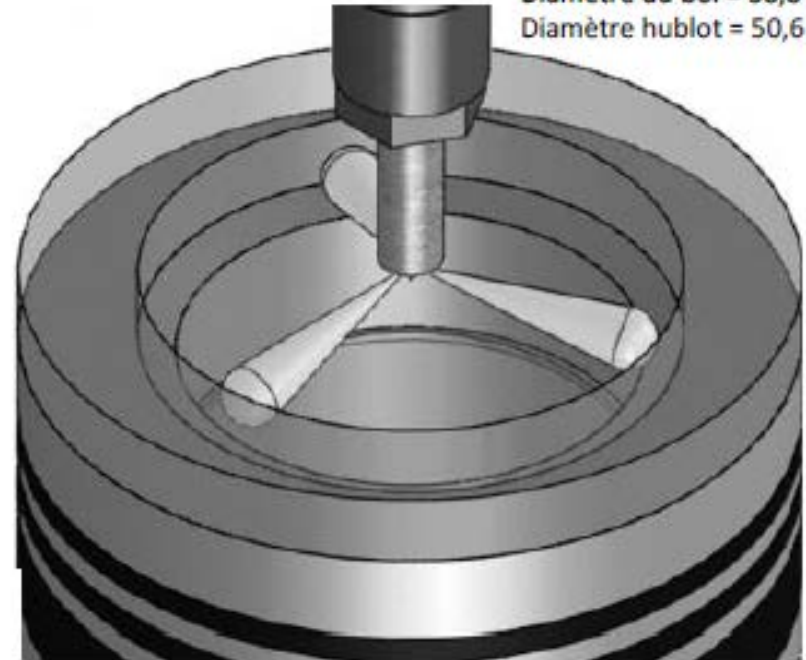
Mie scattering

- Particle size $> \lambda/10$
- Angle-dependent
- Inelastic scattering

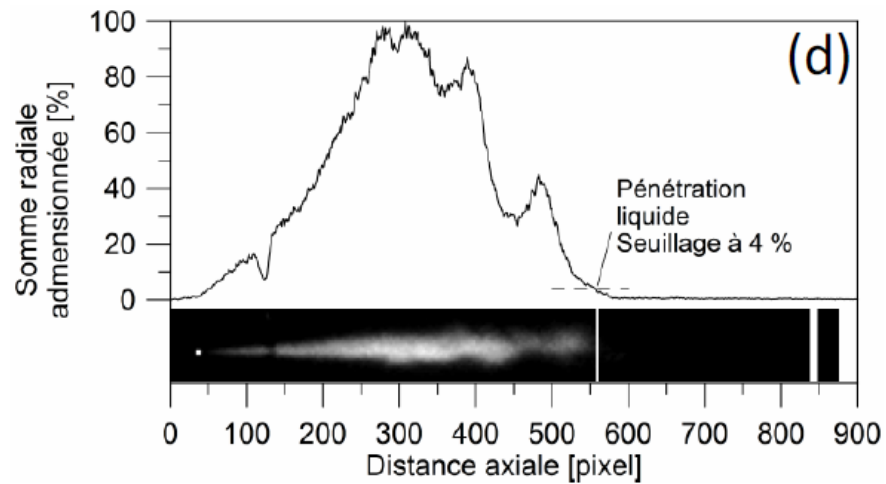
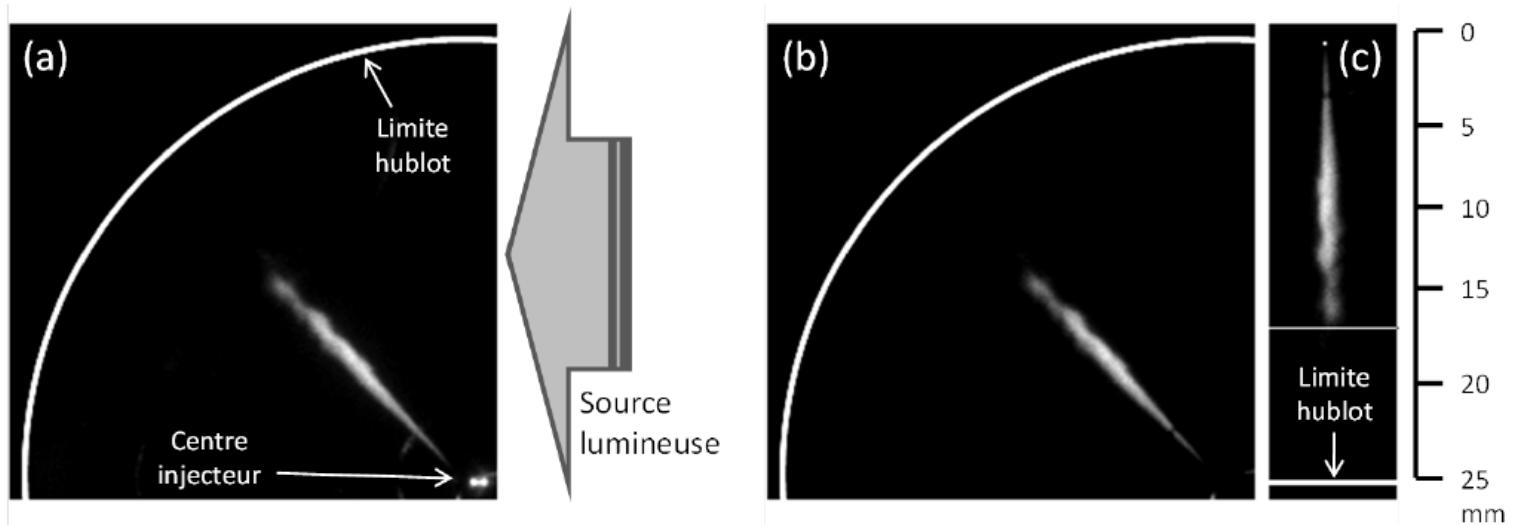


CARACTÉRISATION DE LA PHASE LIQUIDE

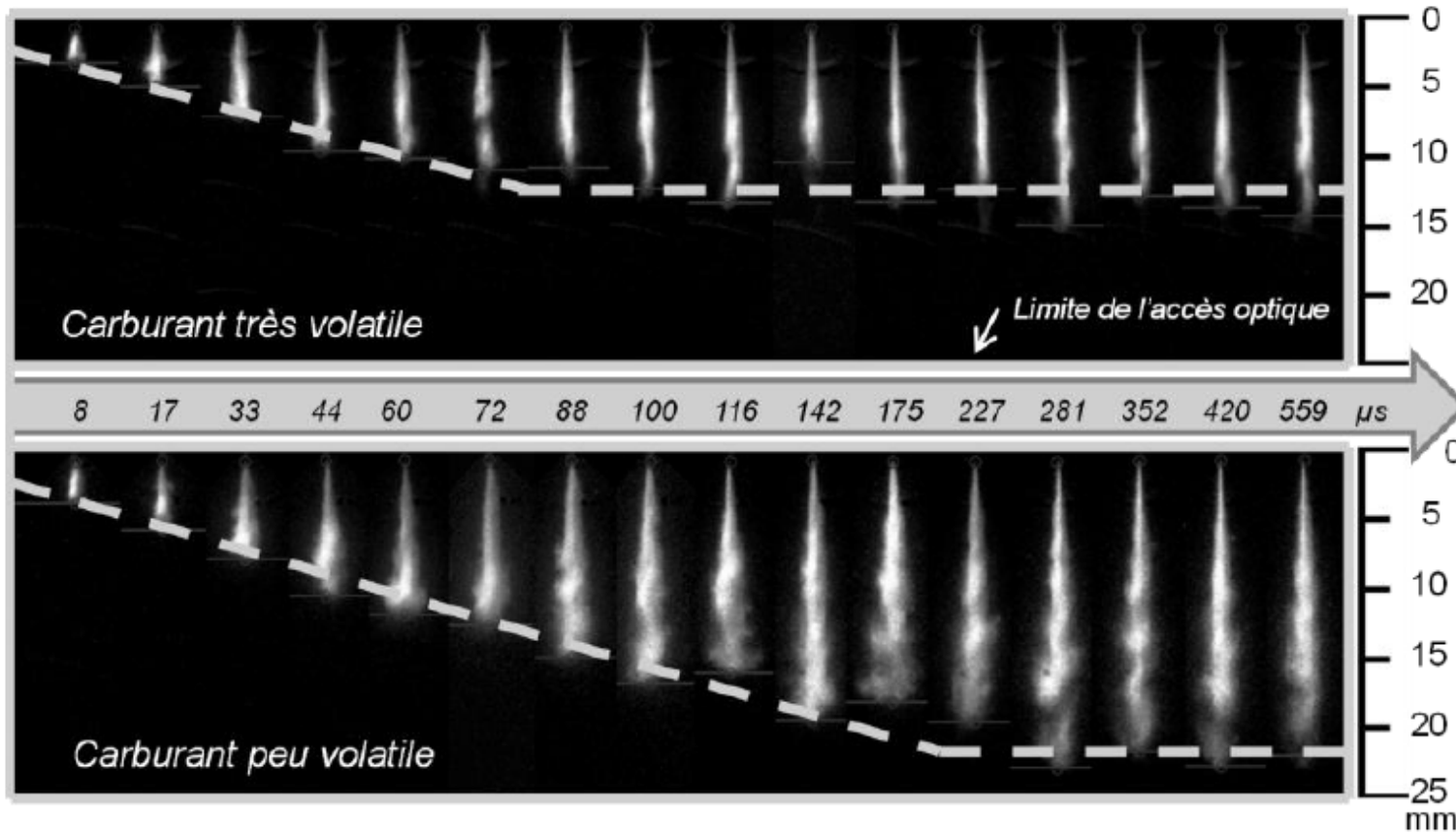
Profondeur du bol = 10 mm
Diamètre du bol = 58,8 mm
Diamètre hublot = 50,6 mm



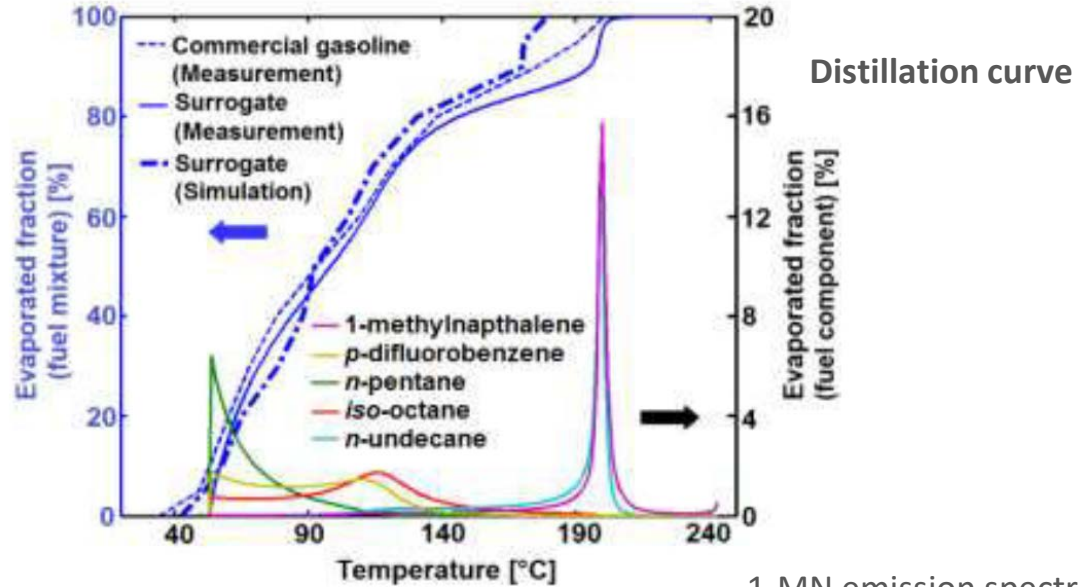
CARACTÉRISATION DE LA PHASE LIQUIDE



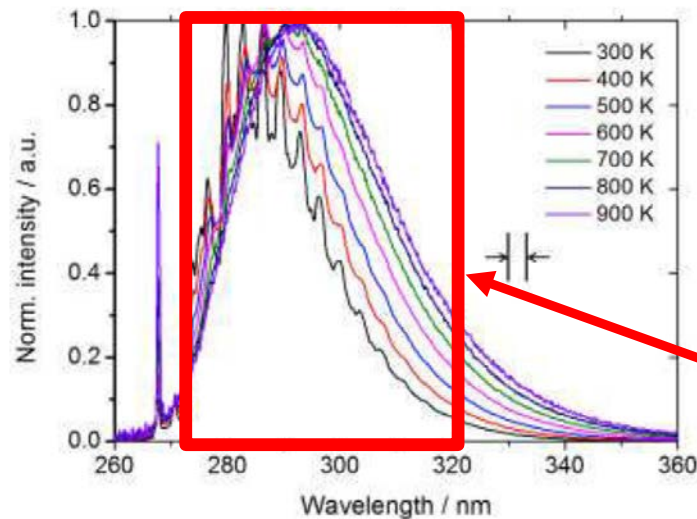
CARACTÉRISATION DE LA PHASE LIQUIDE



Fluorescence induite par Laser

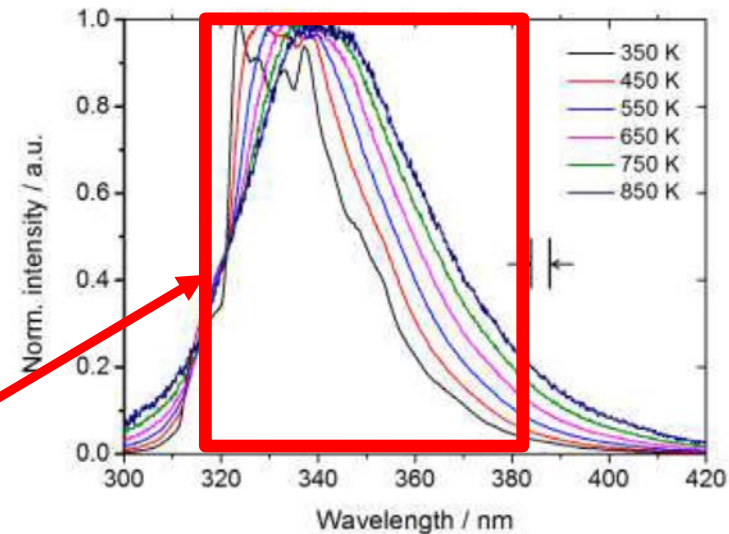


P-DFB emission spectra, P=1 bar, N2

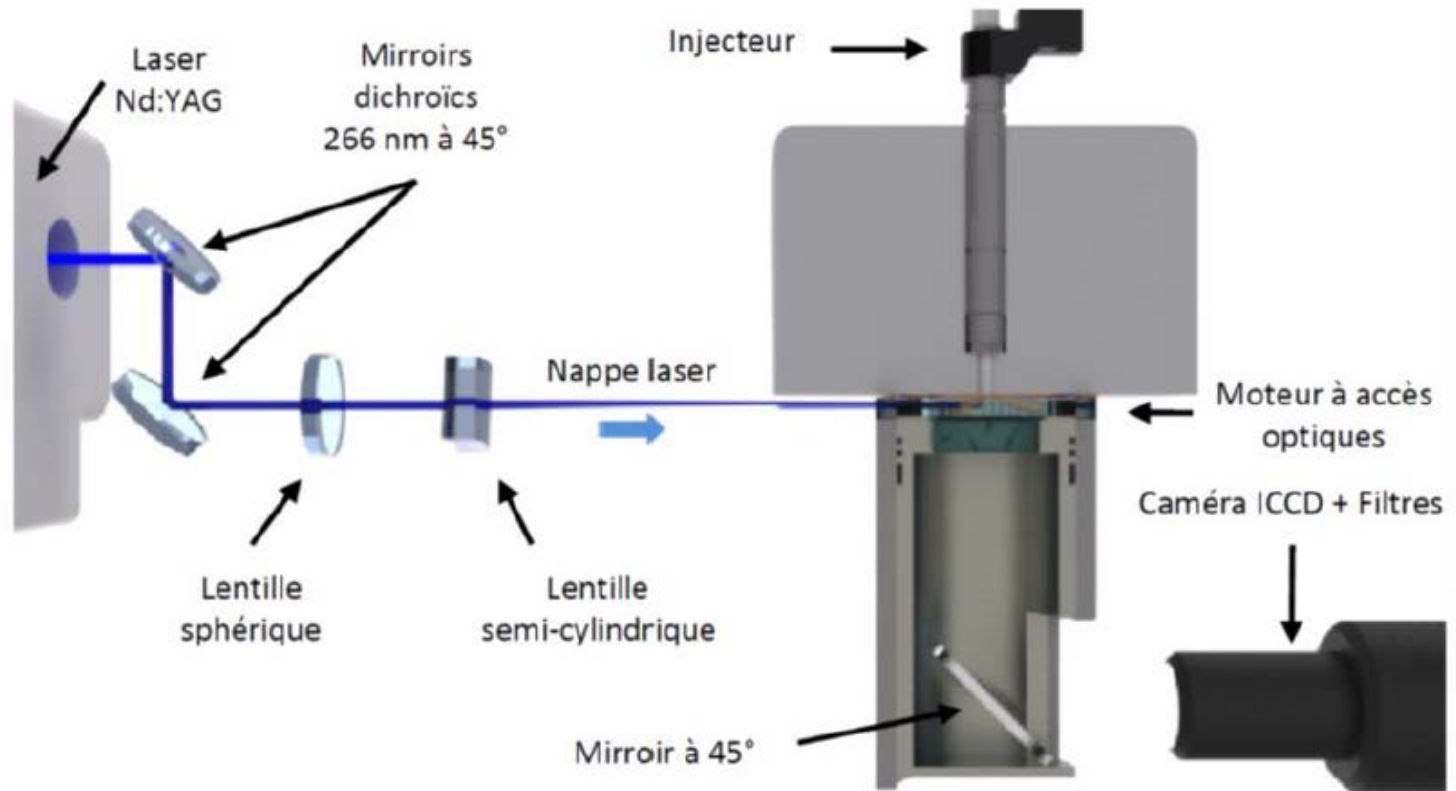


Band pass filter

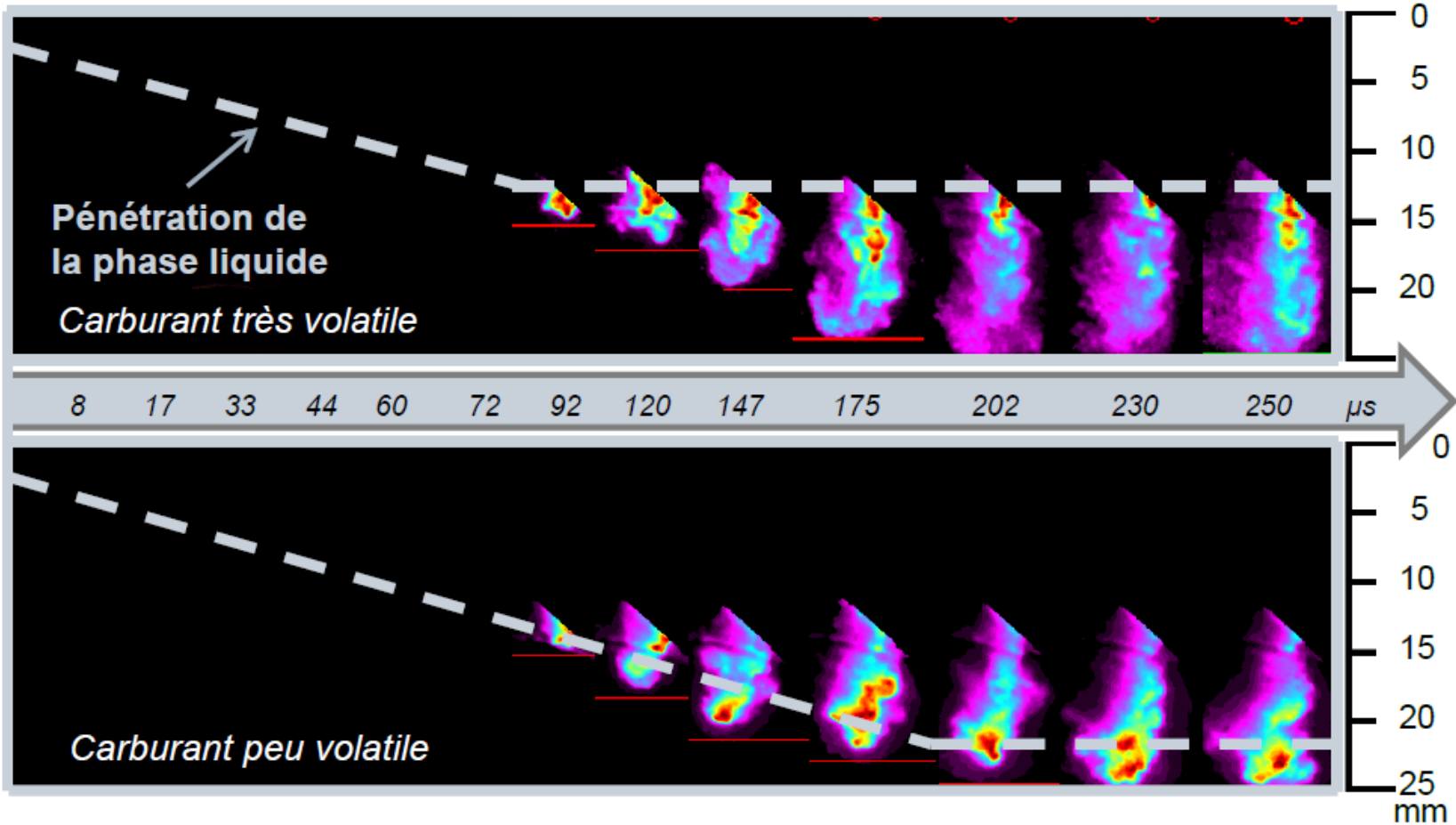
1-MN emission spectra, P=1 bar, N2



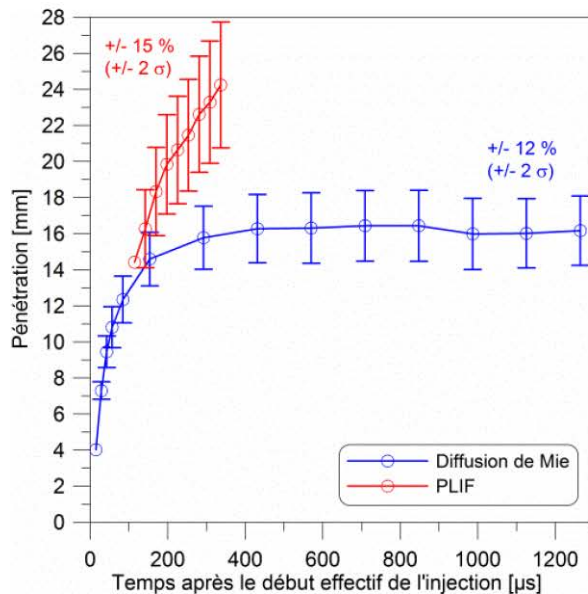
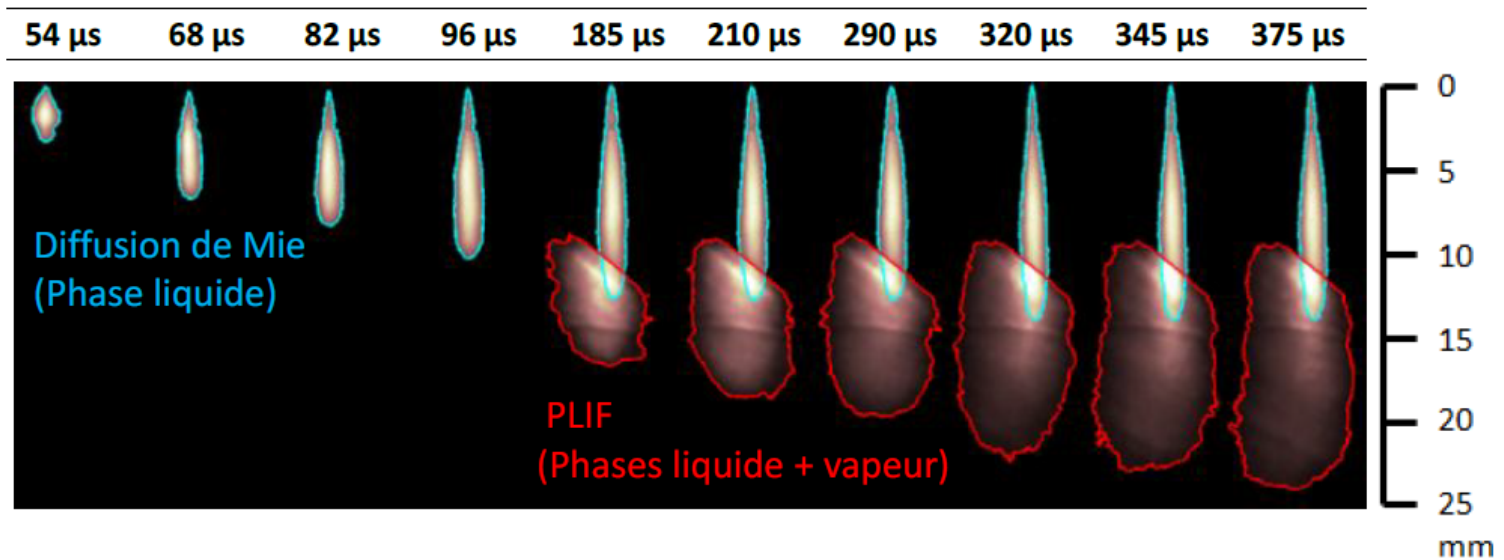
Fluorescence induite par Laser



CARACTÉRISATION DE LA PHASE VAPEUR



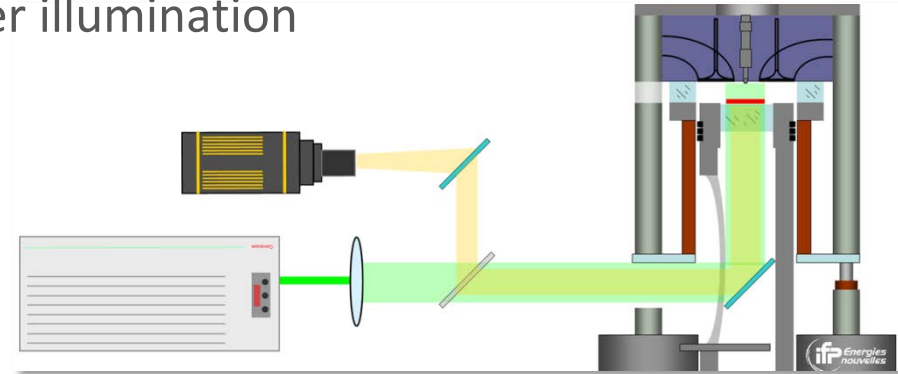
CARACTÉRISATION DE LA PHASE VAPEUR & LIQUIDE



Ex. Evolution temporelle du spray - Superposition de images moyennes de diffusion de Mie et de PLIF toluène – d-Dodécane, $P_{inj}=1300$ bar

□ Etude l'impact d'une stratégie de multi injection sur la formation de film liquide

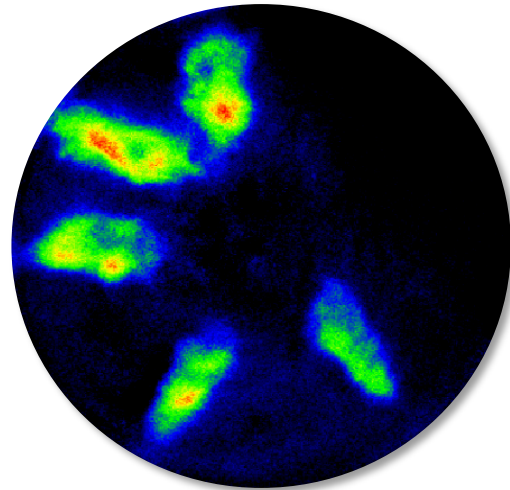
- Piston measurements : Direct laser illumination



Single injection

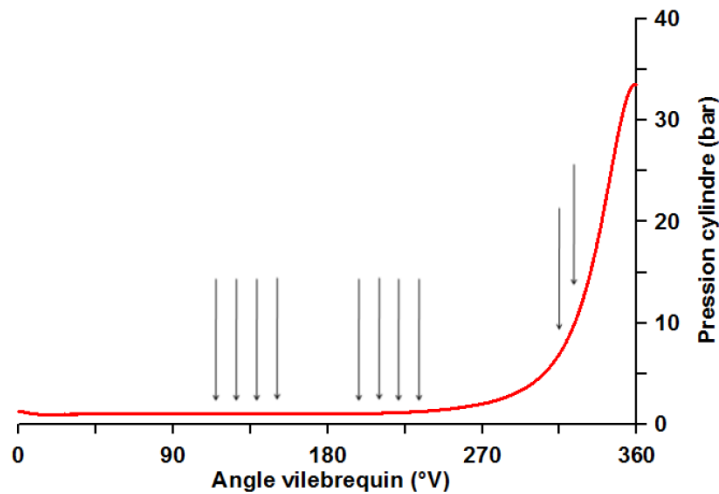


Quadruple injection

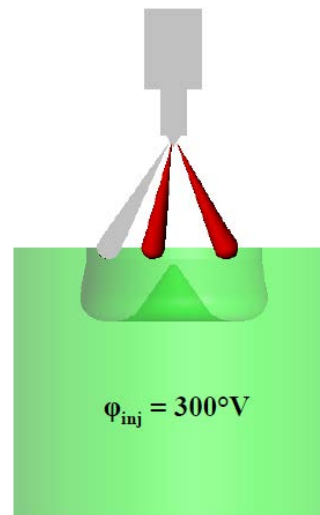


Diminution de la tailles des impact
➔ Diminution des films liquides en procédant à une multi-injection

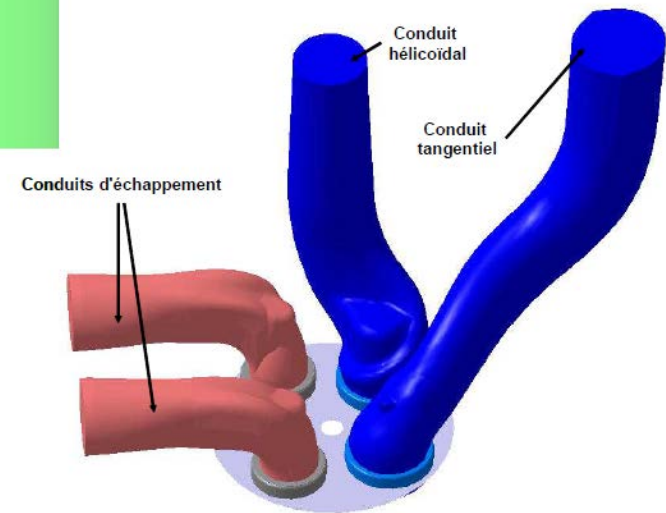
- Stratification du mélange air-carburant
- Stratification de l'EGR

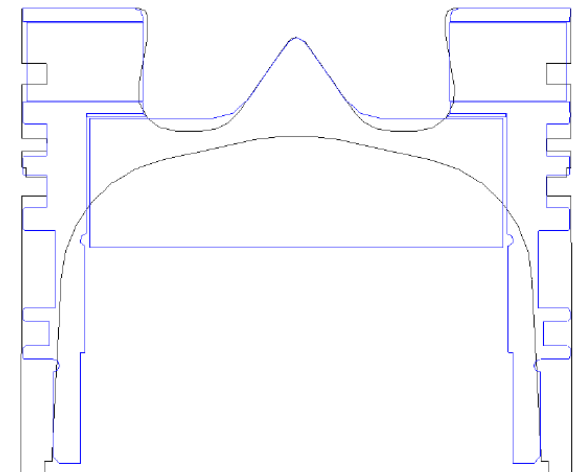
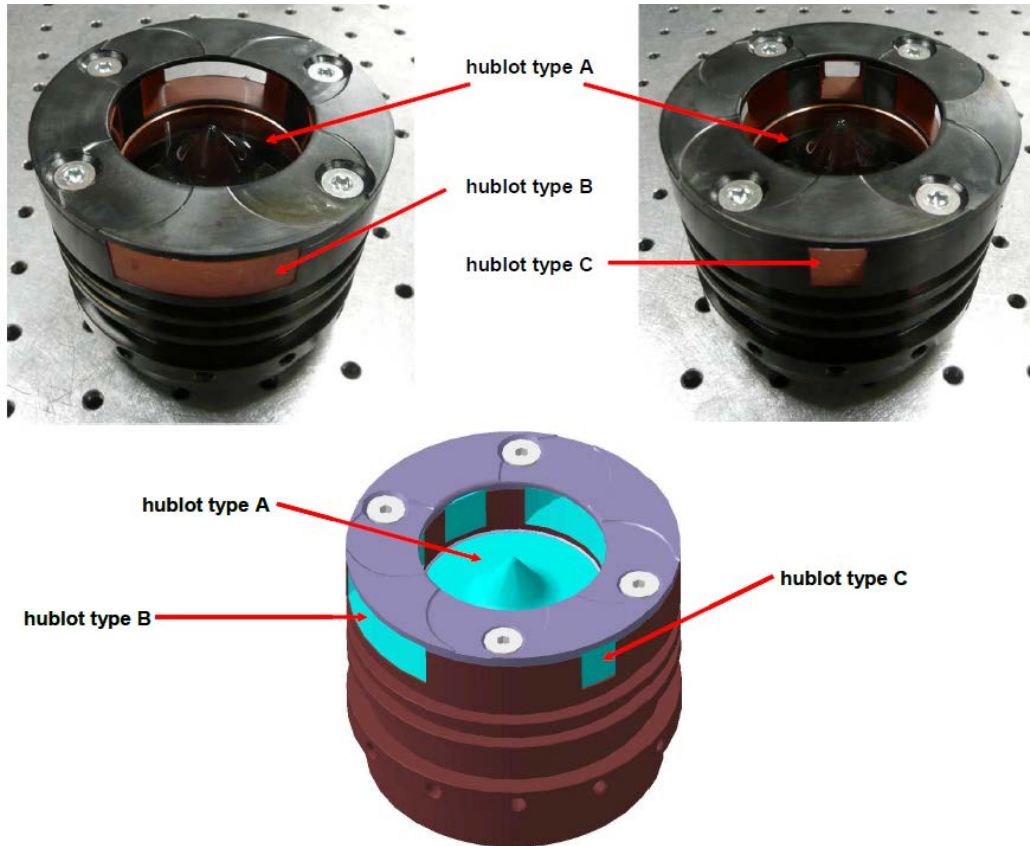


Multi injections précoces, $P_{inj}=600$ bar

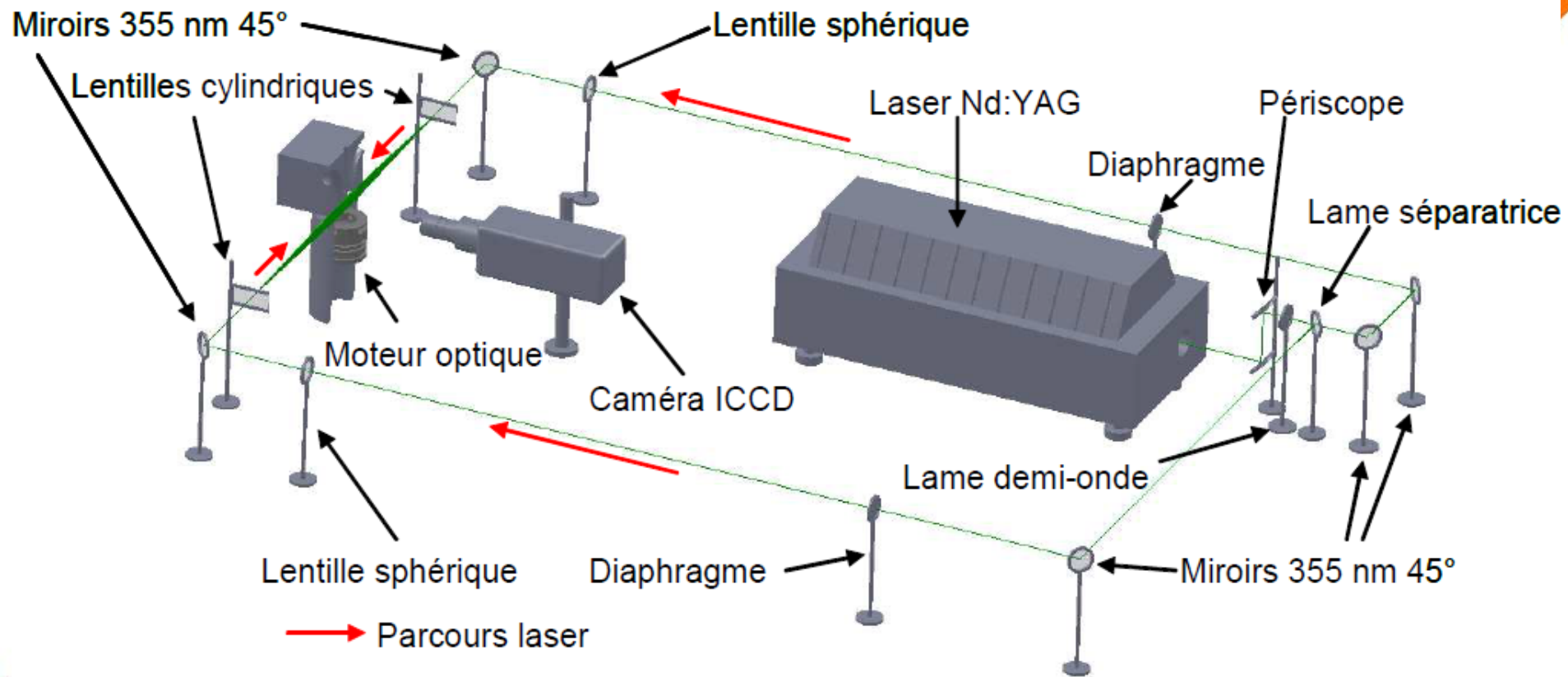


Bol « NADI », IFPEN
Injections précoces

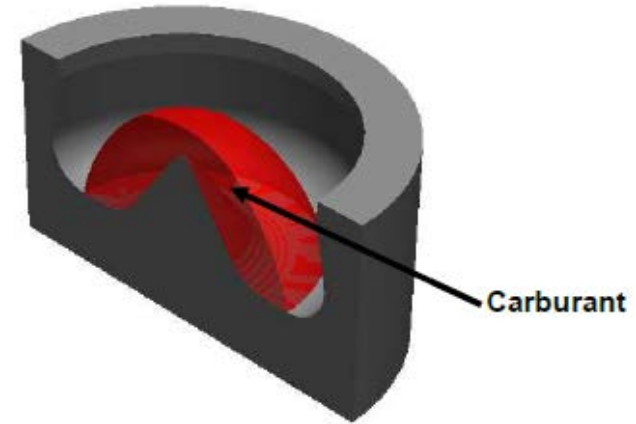
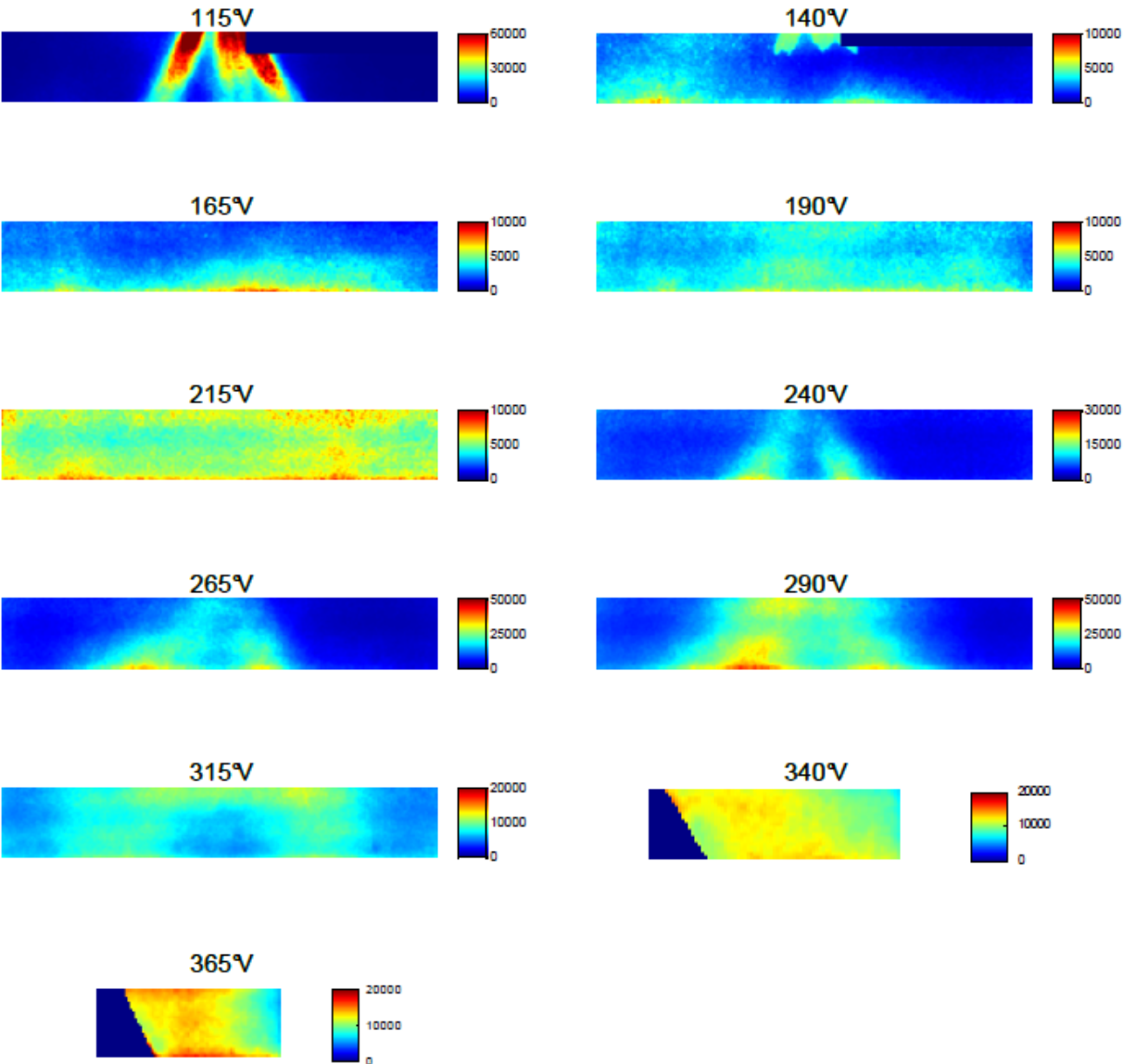




Comparaison de la géométrie
« opaque » et « optique »



☐ Fluorescence induite par Laser « Carburant »



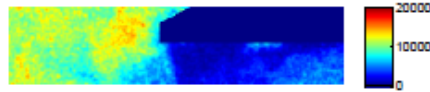
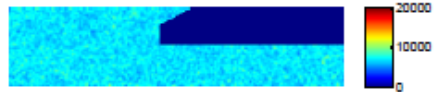
Fluorescence induite par Laser « EGR (traceur=biacetyl) »

Stratégie homogène

Stratégie stratifiée

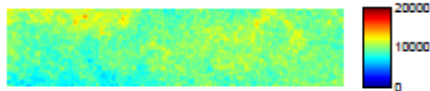
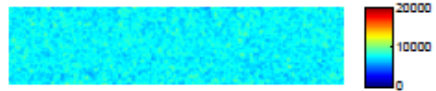
110V

110V



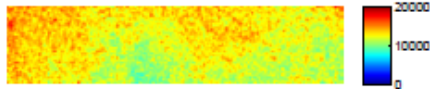
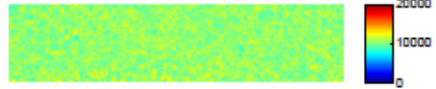
180V

180V



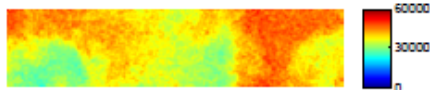
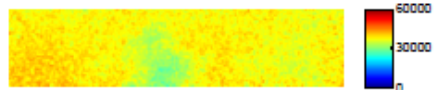
250V

250V



315V

315V



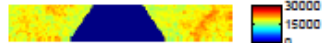
340V

340V



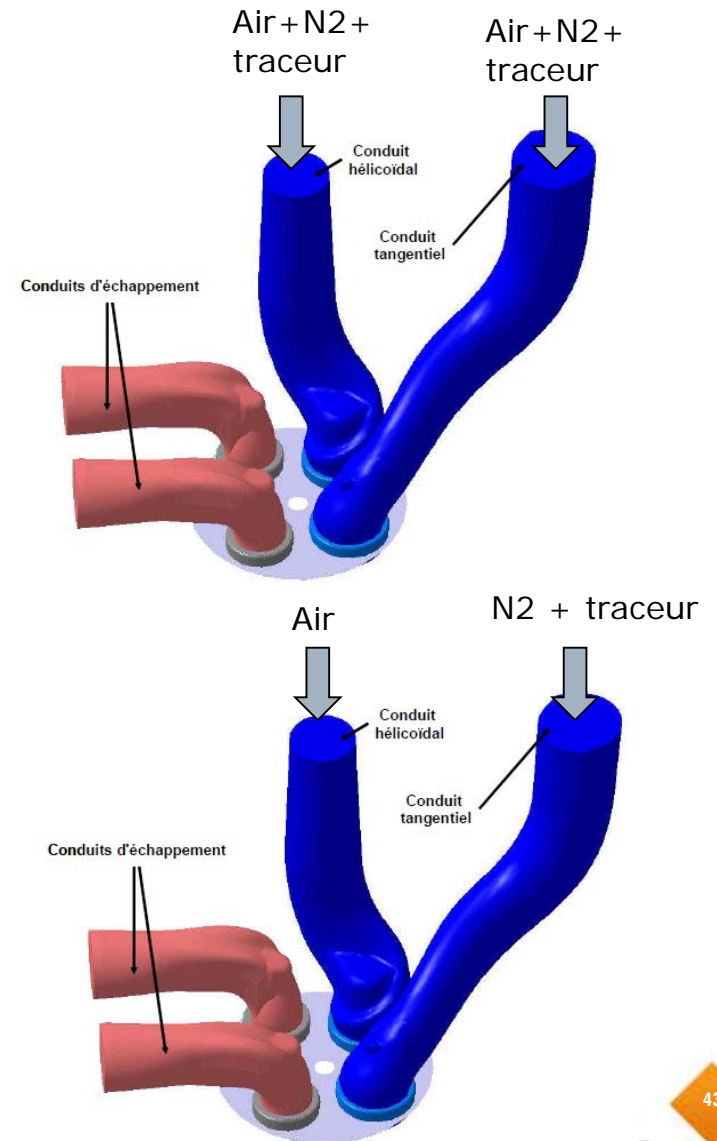
360V

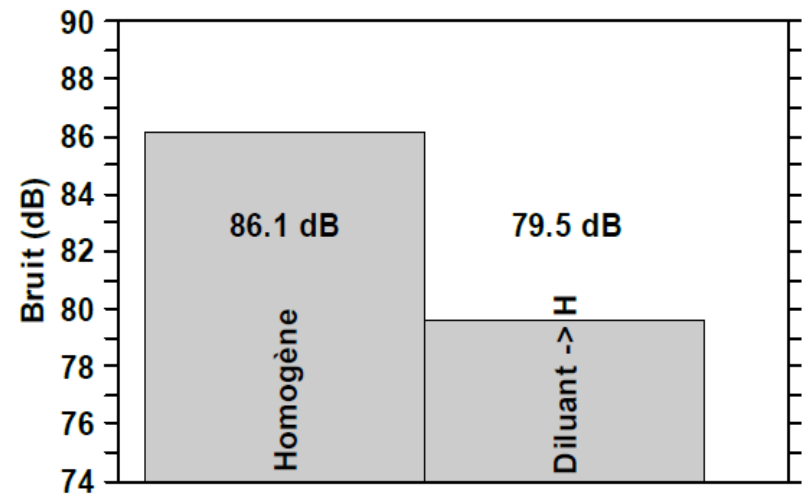
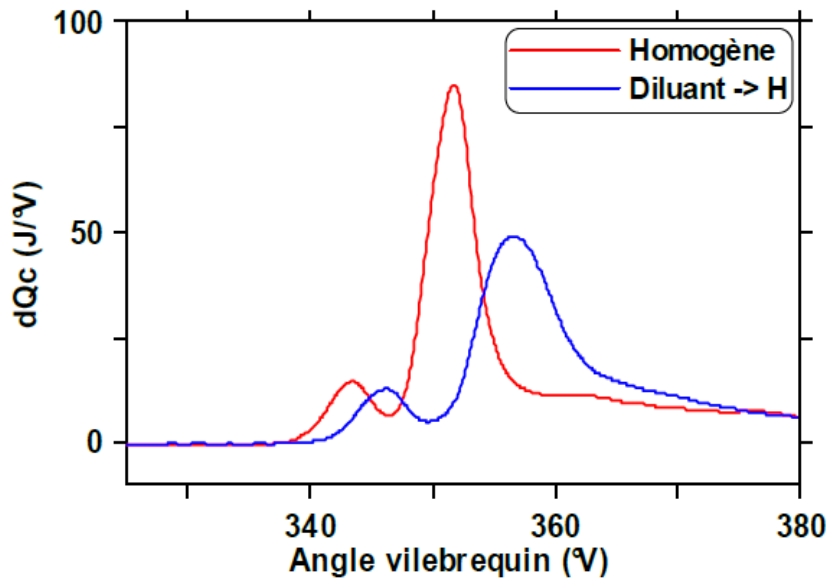
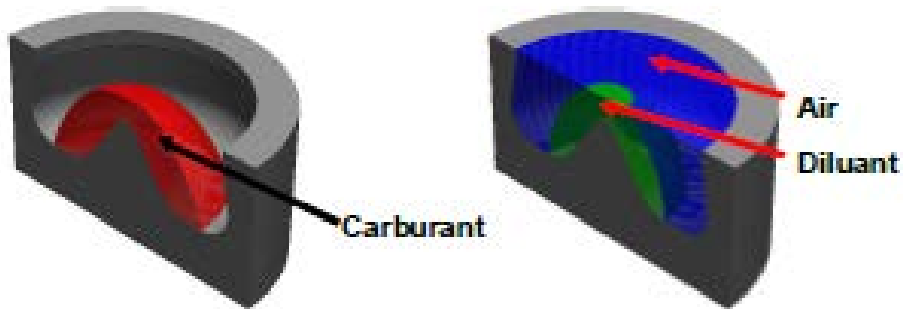
360V



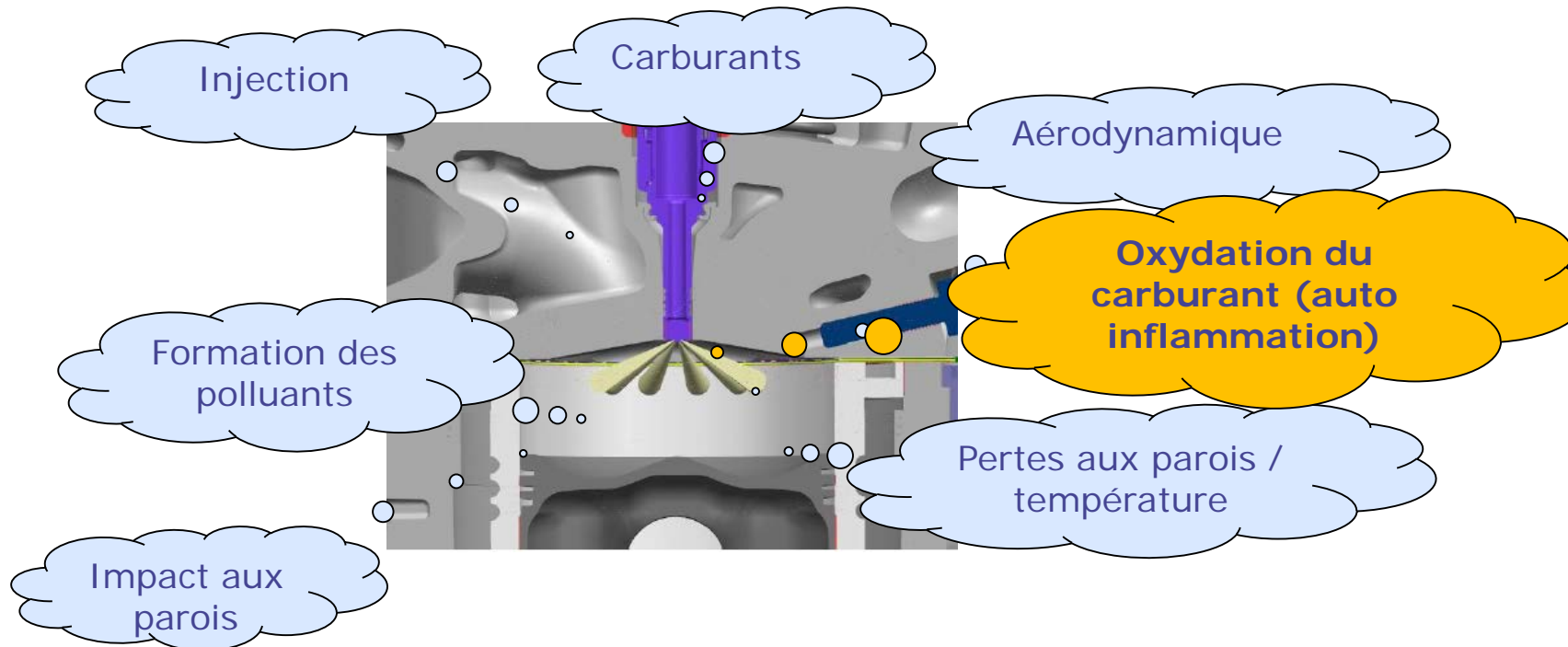
(a)

(b)

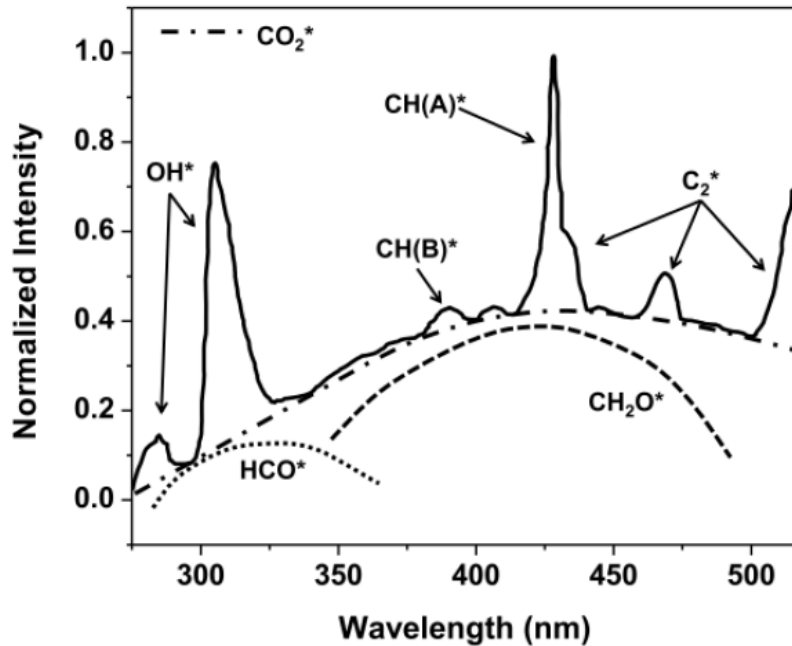




□ Préparation du mélange

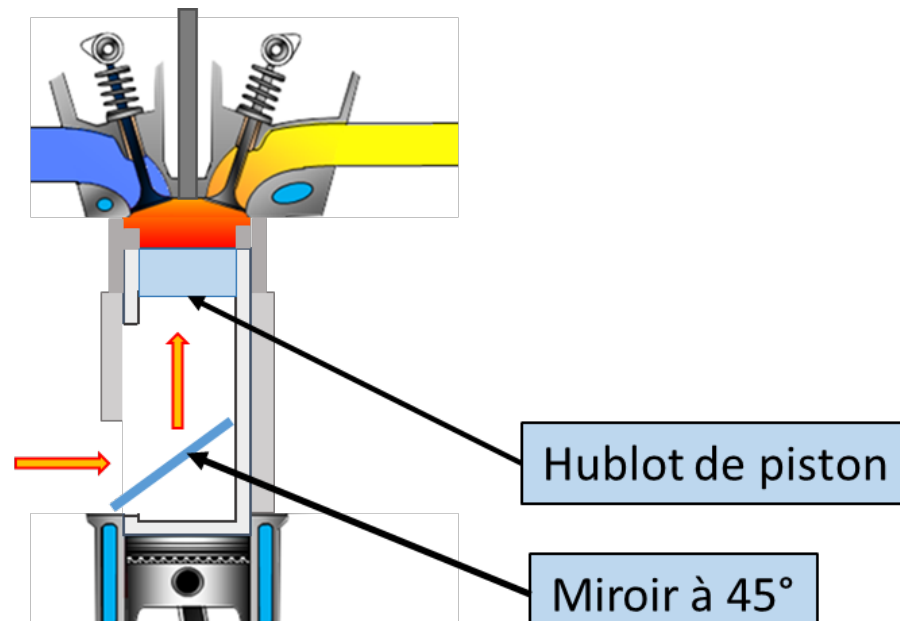


□ Chimio luminescence

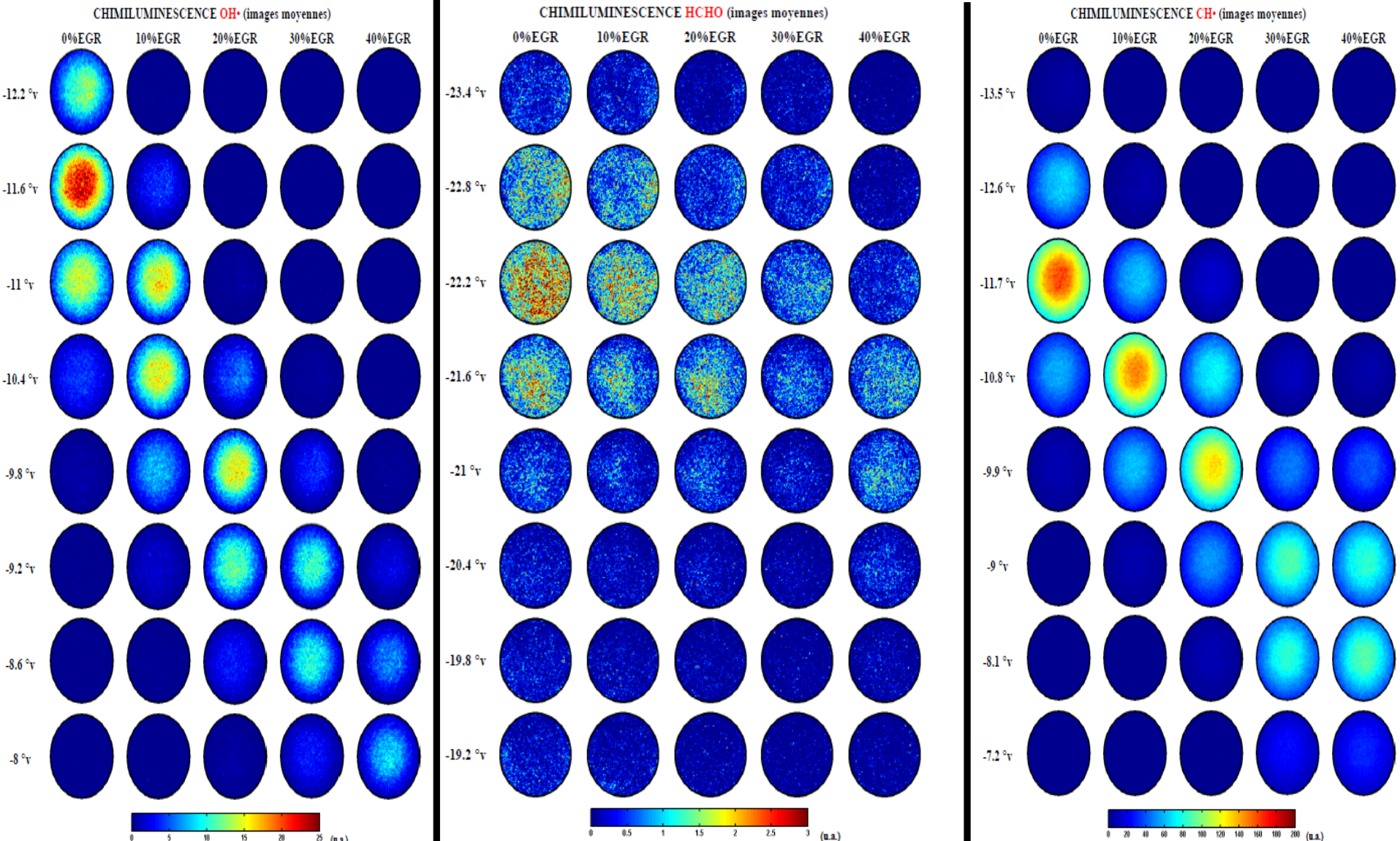


Emission spontanée de lumière par les radicaux:

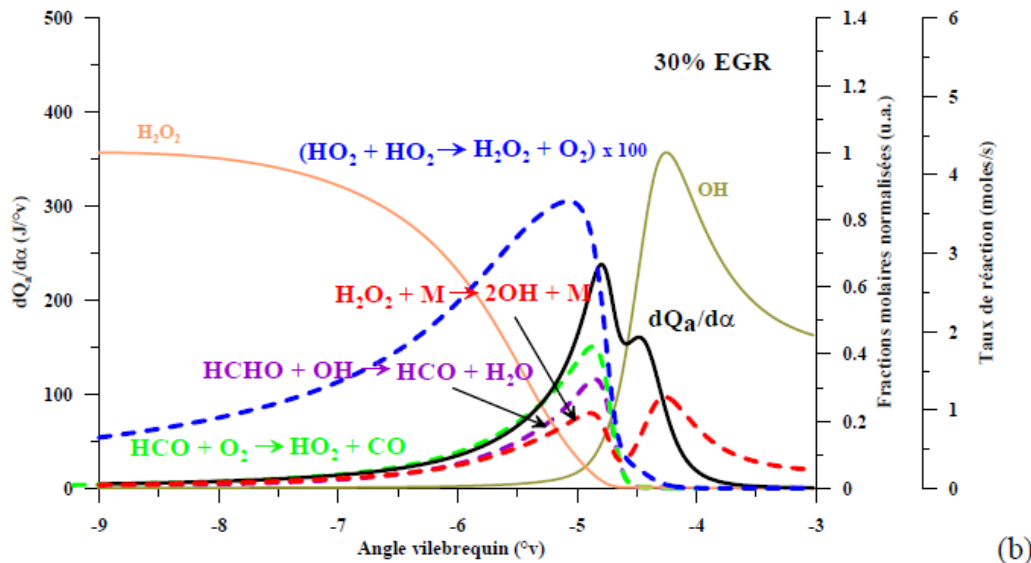
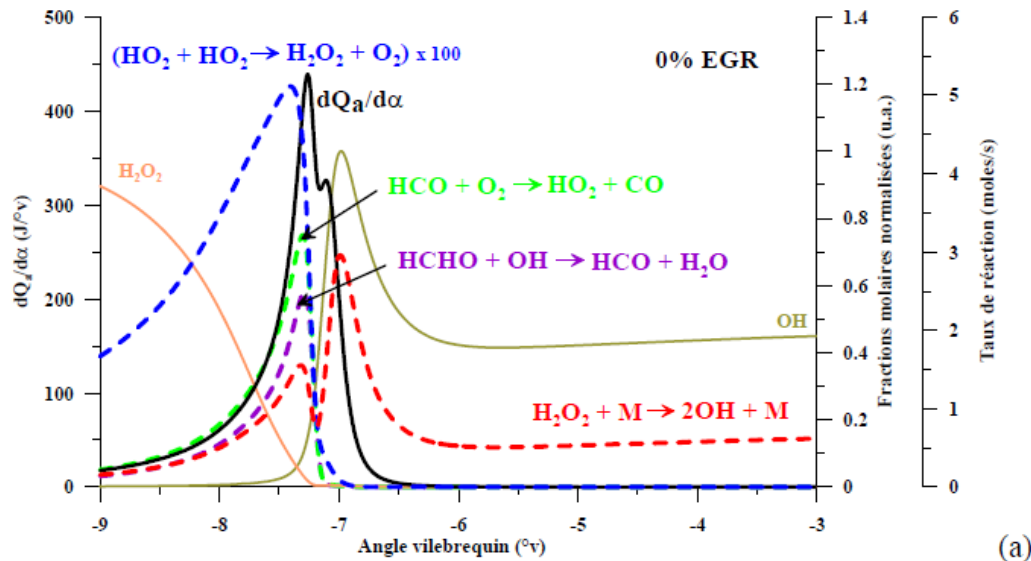
- λ en fonction du radical
- Intensification de la lumière (caméra ICCD)
- Filtre optique devant la caméra



□ Fuel: N-heptane, $\phi=0.3$



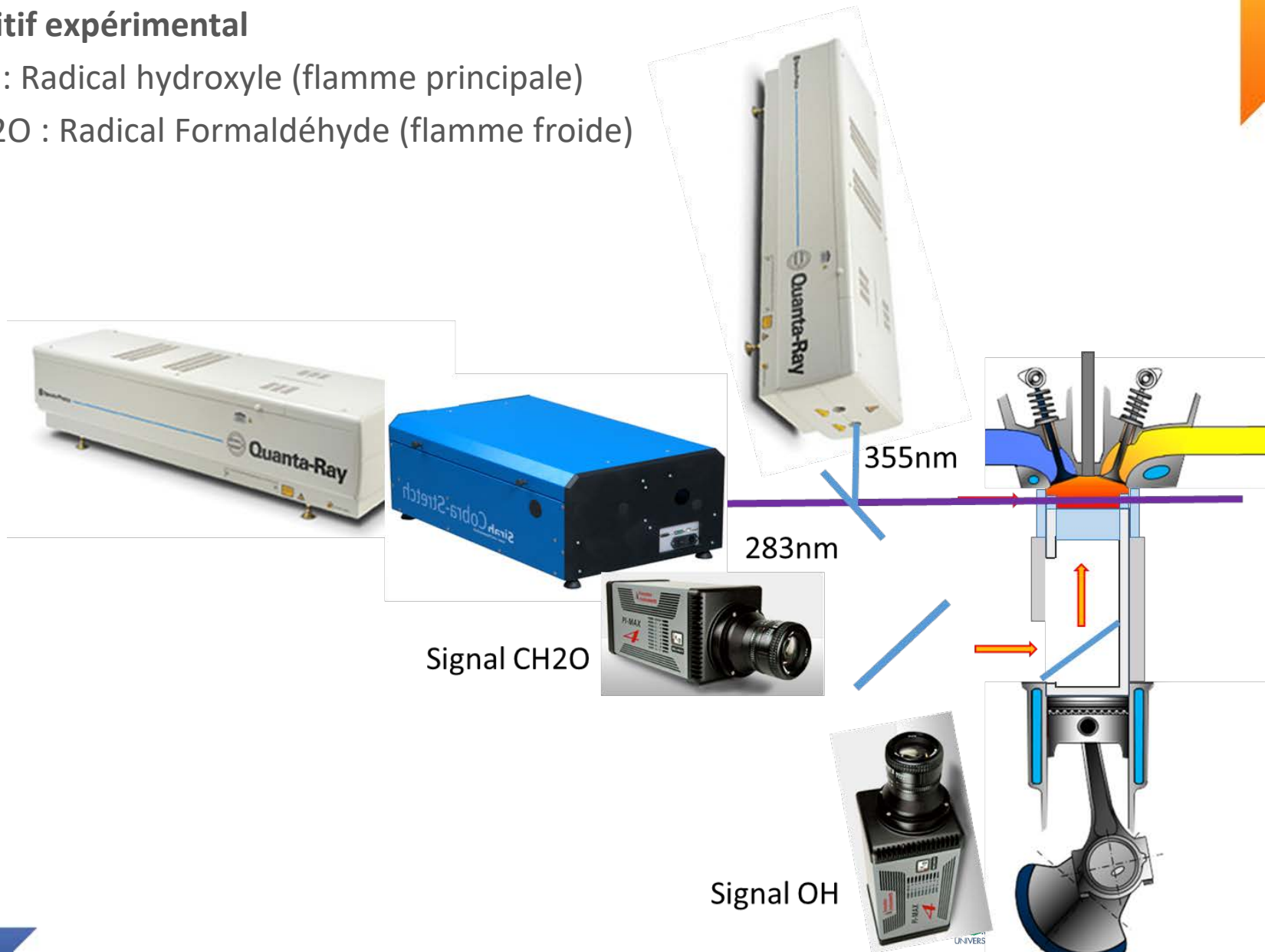
Comparaison et Validation des schémas cinétiques



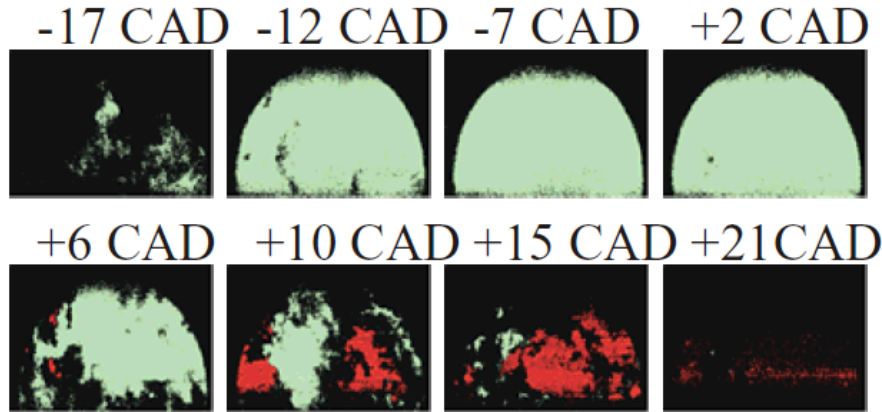
- Amélioration des schémas cinétiques
- Compréhension des voies réactionnelles de l'oxydation du carburant

□ Dispositif expérimental

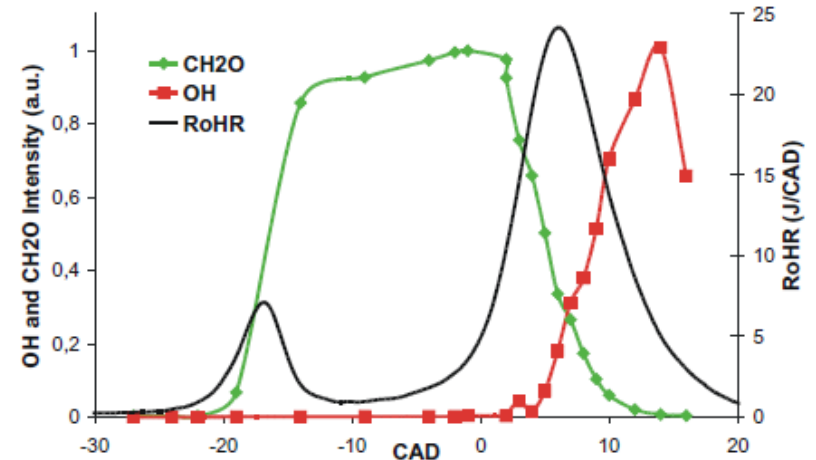
- OH : Radical hydroxyle (flamme principale)
- CH₂O : Radical Formaldéhyde (flamme froide)



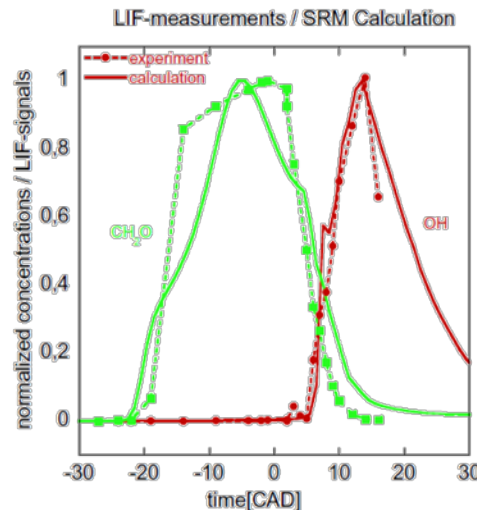
☐ Analyse des signaux durant le cycle



a. Visualisations LIF dans le cylindre (CH₂O : vert et OH : rouge)



b. Signaux moyens adimensionnés

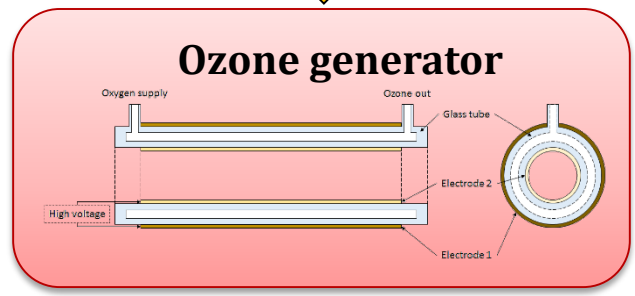


Comparaison mesures / calcul CFD

COMBUSTION ASSISTÉE PAR OZONE (COMBUSTION ASSISTÉE PAR PLASMA)

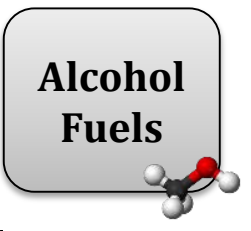
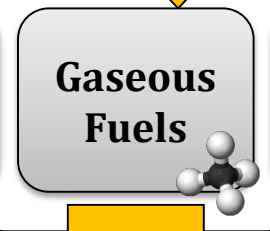


↓ How ozone is produced?



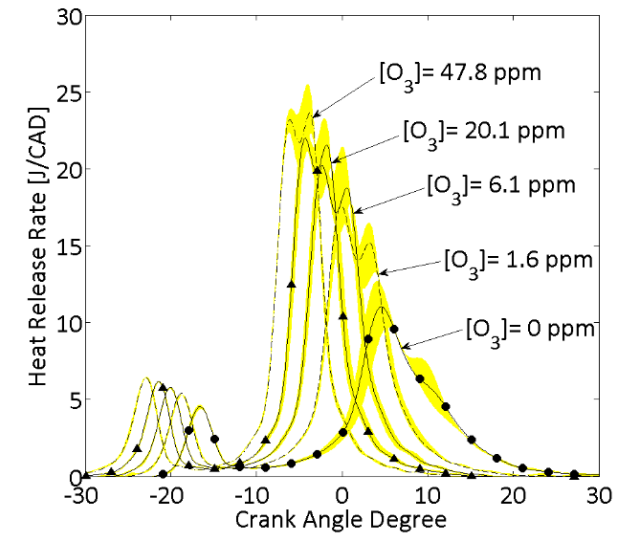
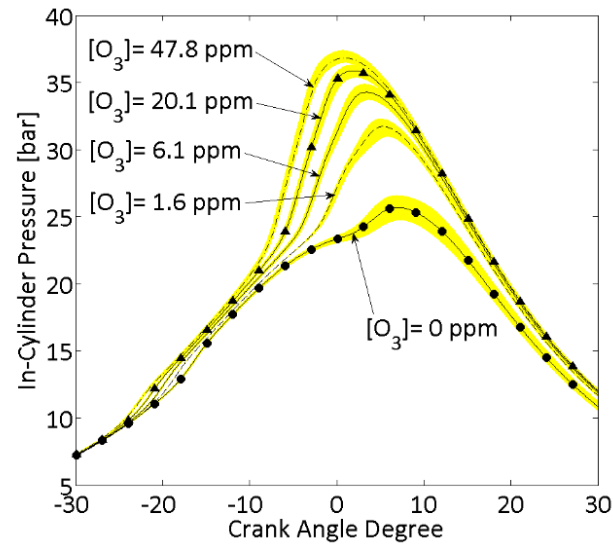
Integration in passenger cars?

Fuel interactions?

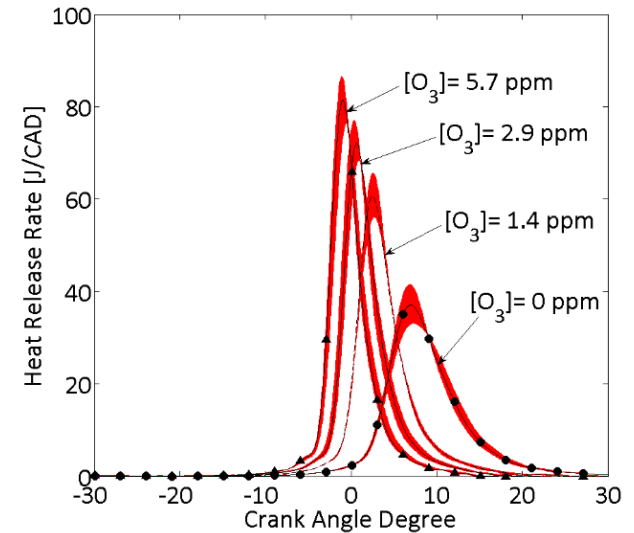
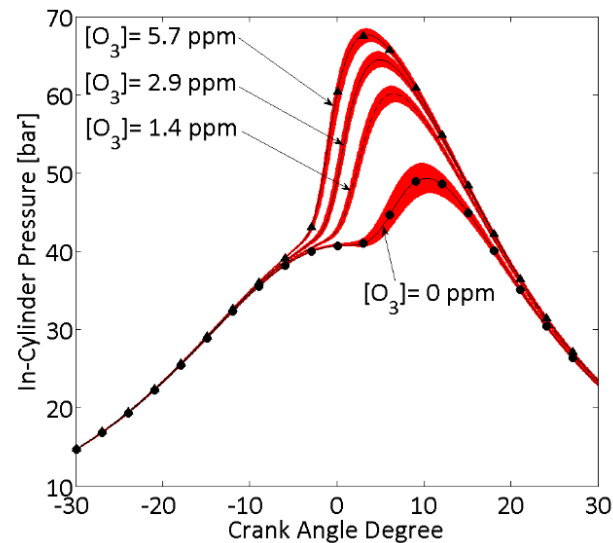


Study the potential of O3 to control HCCI & LTC combustion
With wide range of fuels

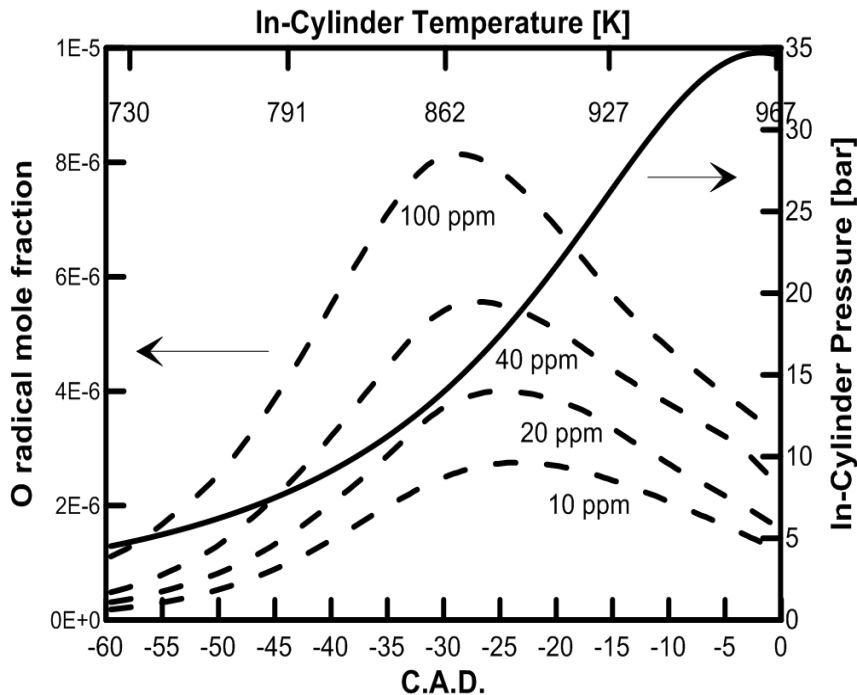
N-heptane
(Like Diesel)
 $\phi = 0.3$



Isooctane
(Like Gasoline)
 $\phi = 0.3$



From Chemkin



As the pressure and the temperature increase in the combustion chamber, O₃ decomposition yields to O atoms through the reactions :

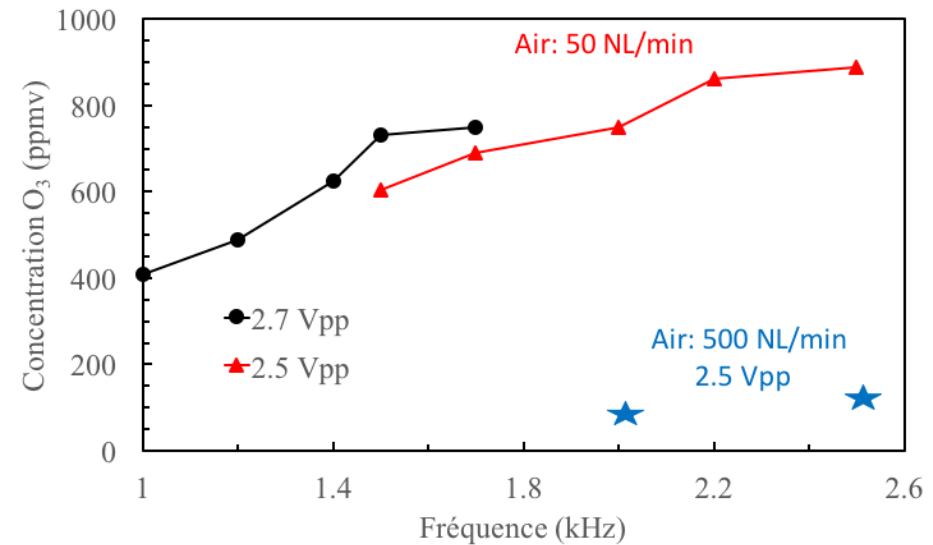


- O radical will react with the fuel during the end of the compression stroke
 - Here, **O₃** is not a pollutant gas !
 - And chemical mechanism need to be improve...

DEDICATED OZONE REACTOR FOR HCCI/GCI



Home made Ozone (GREMI) reactor
Using Air into the intake port



Characterization of the discharge :

In a constant flow bench & into the intake of engines

- Air, N₂, CO₂, H₂O
- Pressure (0.5 – 2 bar), Temperature (273K – 373K)
- High Voltage characteristics (Sinusoid, Nanosecond)
- Energy cost
- ...

MAZDA PATENT (SKYACTIV X ENGINE)

(12) **United States Patent**
Nagatsu et al.

(10) **Patent No.:** **US 9,719,441 B2**
 (45) **Date of Patent:** **Aug. 1, 2017**

(54) **CONTROL DEVICE FOR COMPRESSION
 IGNITION-TYPE ENGINE**

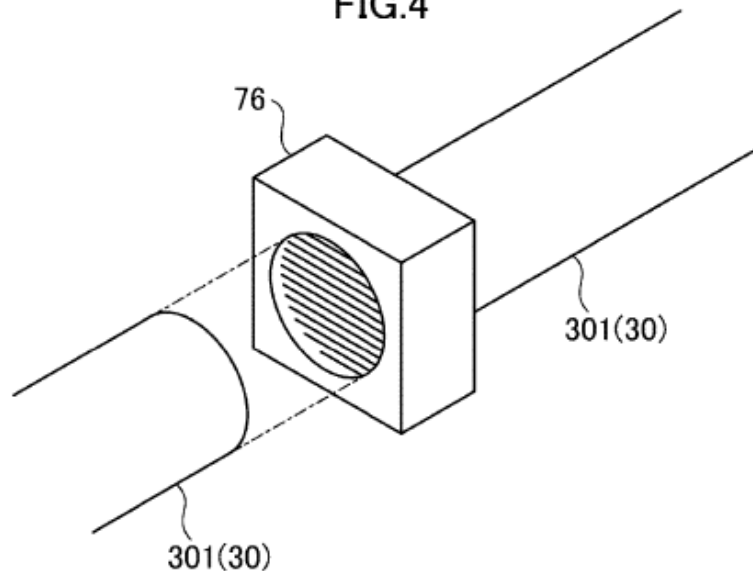
(52) **U.S. CL.**
 CPC **F02D 41/04** (2013.01); **F01N 3/0842**
 (2013.01); **F02B 3/08** (2013.01); **F02D 21/06**
 (2013.01);

(71) Applicant: **MAZDA MOTOR CORPORATION,**
 Hiroshima (JP)

(Continued)

U.S. Patent **Aug. 1, 2017** **Sheet 4 of 7** **US 9,719,441 B2**

FIG.4

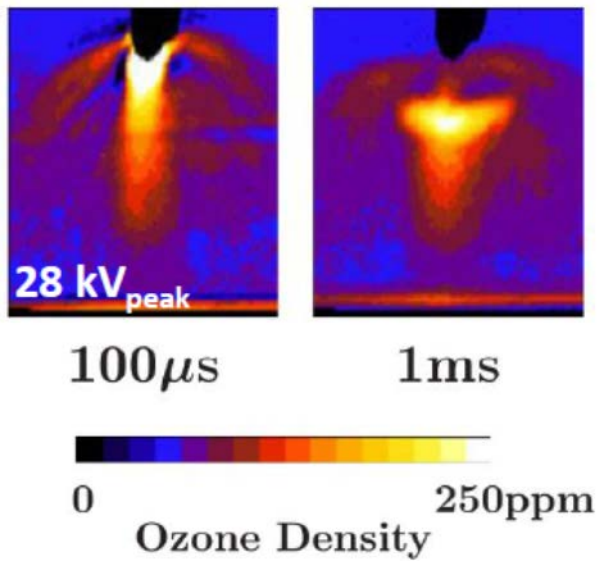


in the lower speed range.

**2. The control device of claim 1, further comprising:
 an ozonator configured to add ozone to the fresh air
 introduced into the cylinder, wherein
 the controller adds, in the lower speed range of the
 predetermined range, the ozone to the fresh air intro-
 duced into the cylinder using the ozonator.**

□ Corona, nanopulse Discharge ...

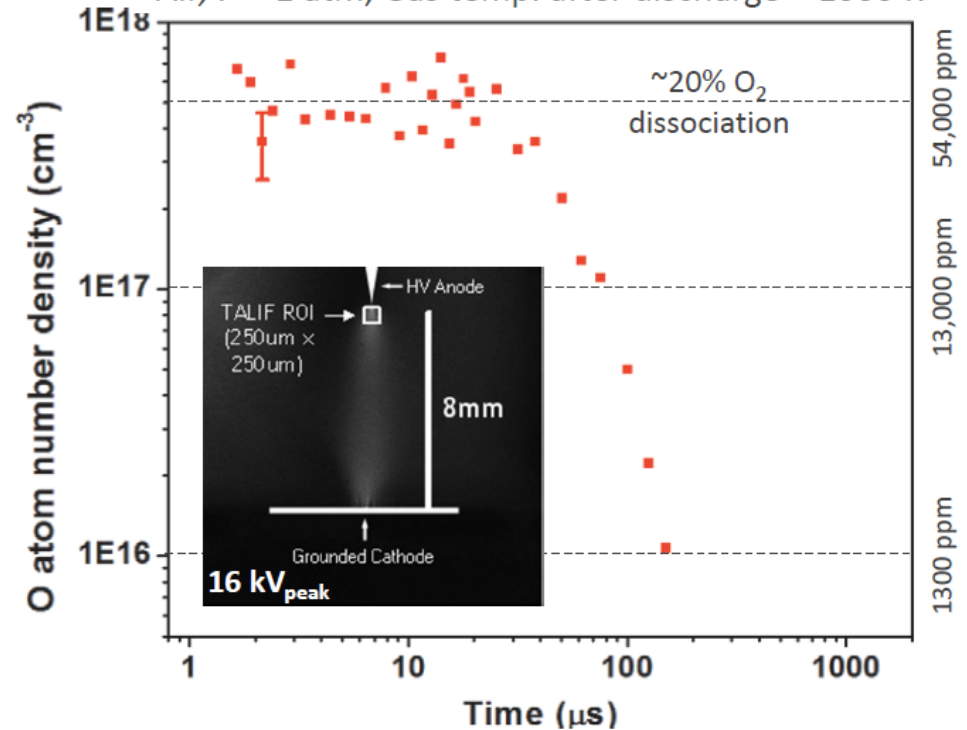
Absorption UV @ 266 nm



Ono & Oda, J. Phys. D: Appl. Phys., 2007

TALIF: Pendleton et al., J. Phys. D.: Appl. Phys. 46 (2013).

Air, $P = 1$ atm, Gas temp. after discharge ~ 1000 K



Decomposition

1. $O_3 + O_2 \leftrightarrow O_2 + O + O_2$
2. $O_3 + N_2 \leftrightarrow O_2 + O + N_2$
3. $O_3 + O_3 \leftrightarrow O_2 + O + O_3$

Fuel Interactions

4. $O_3 + CH_3 \leftrightarrow O_2 + CH_3O$
5. $O_3 + CH_4 \leftrightarrow HO_2 + CH_3O$

Fuel Oxidation

6. $RH + O \leftrightarrow R + OH$
7. $RH + OH \leftrightarrow R + H_2O$
8. $RH + O_2 \rightarrow R + HO_2$
6. $RH + HO_2 \rightarrow R + H_2O_2$

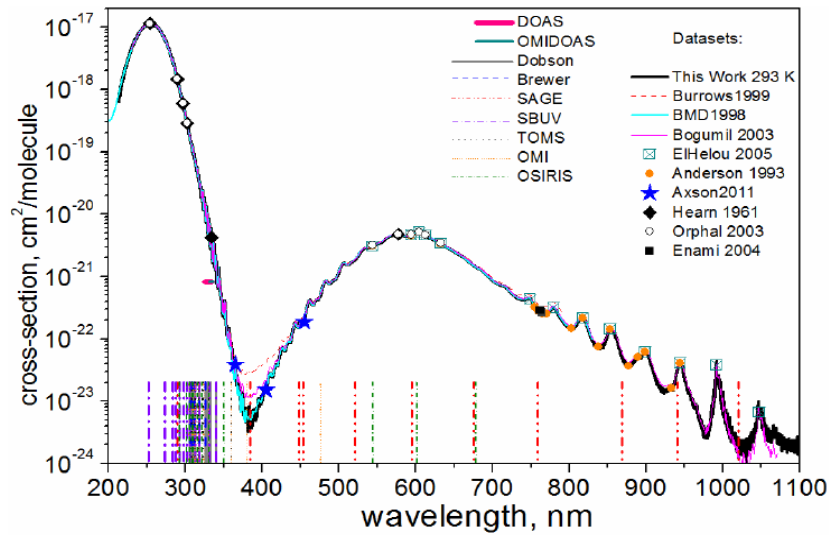


O_3 kinetics are not well known at high pressure/temperature conditions

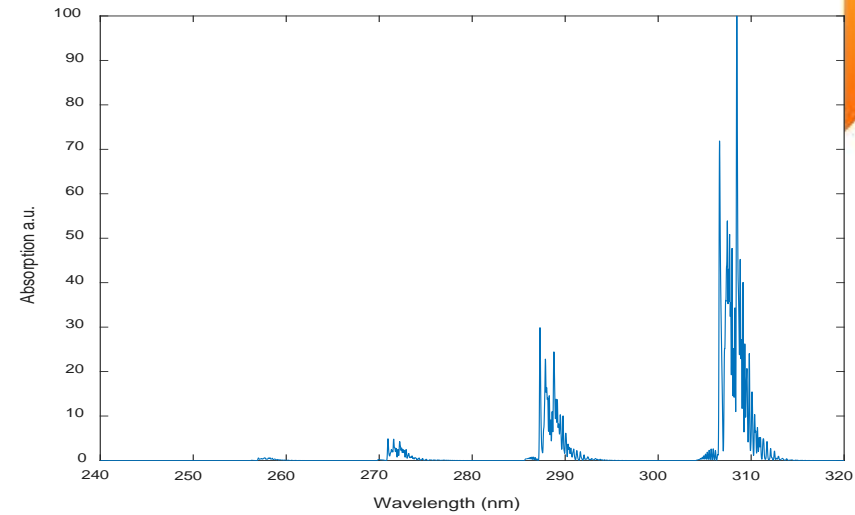
Current O_3 mechanisms lack accurate fuel/EGR interactions

Improve the O mechanism with the fuel

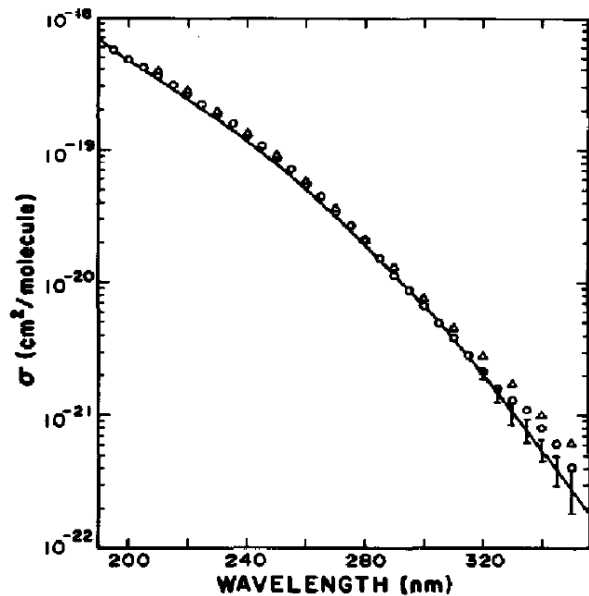
ABSORPTION SPECTRA NEAR 200-300 NM



Ozone absorption spectra (Atmos Meas. Tech, 7, 609-624, 2014)

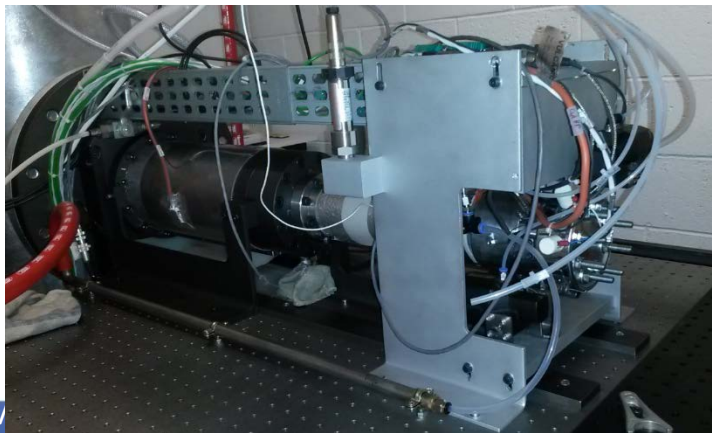
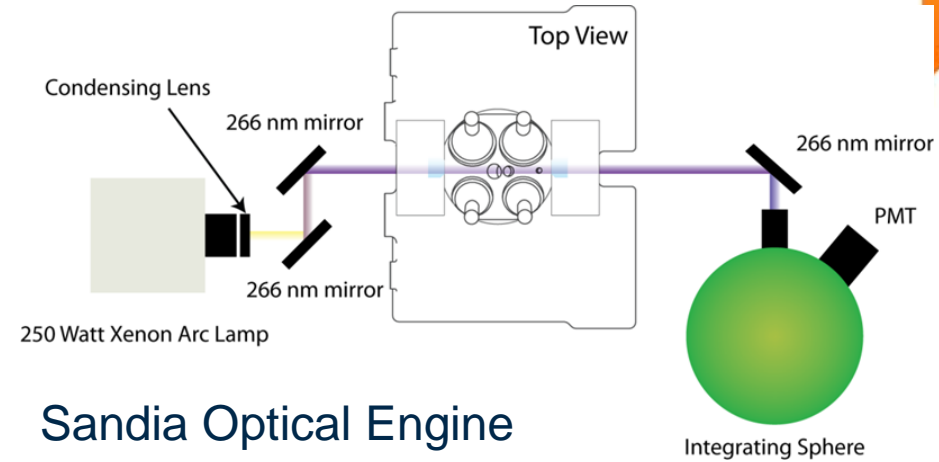
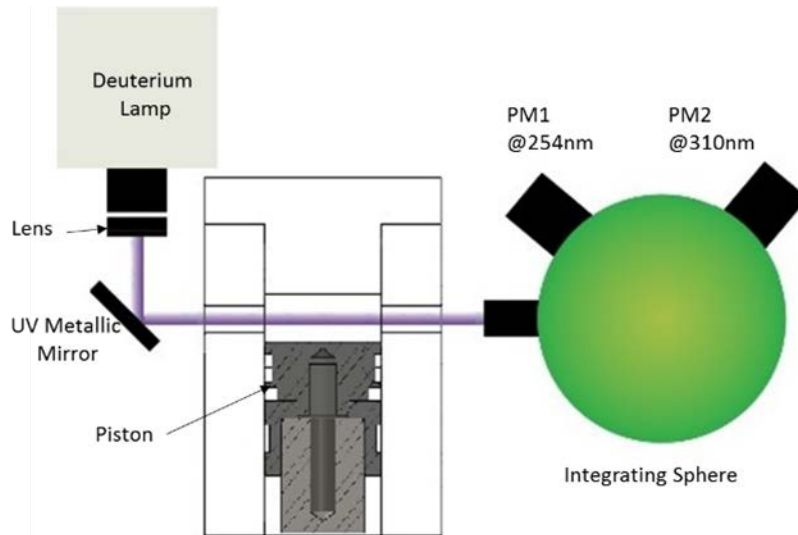


Absorption Spectra of OH. P=20bar, T=600K. from LIFBASE



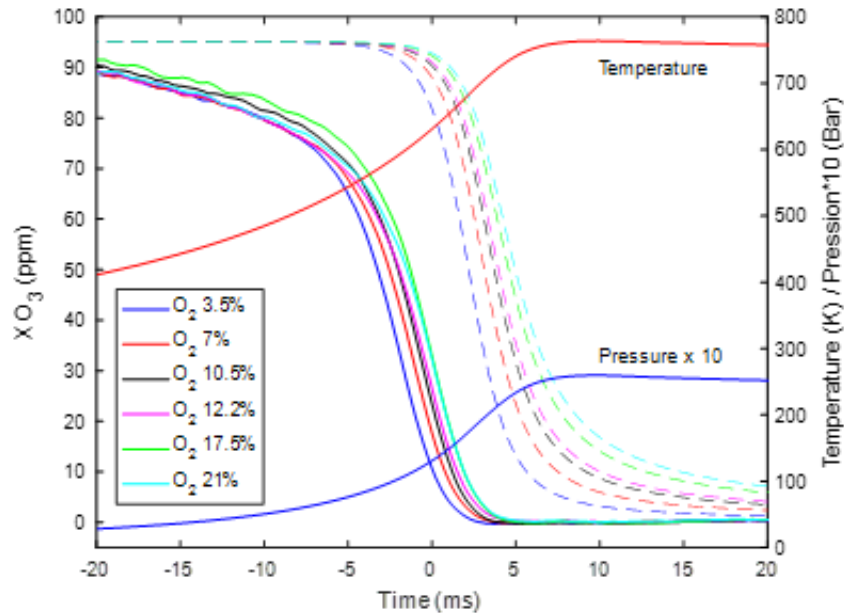
Absorption Spectra of H₂O₂, Molina et al. 1981

U. Orléans Optical Rapid Compression Machine (RCM)



Ekoto I. Foucher F., SAE 2018-01-1249

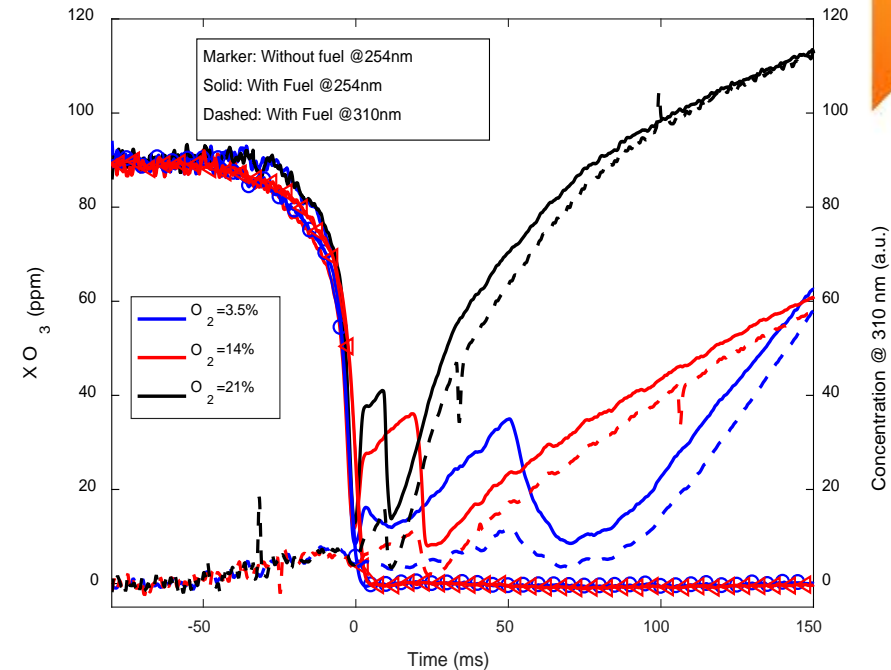
OZONE KINETIC MECHANISMS



Measured O₃ concentration in the RCM during the compression stroke (solid) compared to complementary Chemkin simulation results (dashed). The measured RCM pressure and temperature are also provided for reference.

Ekoto I. Foucher F., SAE 2018-01-1249

Work in progress ...

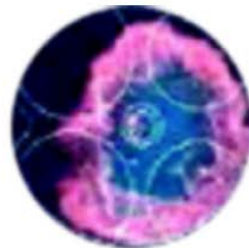


O₃ concentration measurement with or without fuel (marker) at 254nm (continuous line). Absorption measurement at 310nm (dashed).

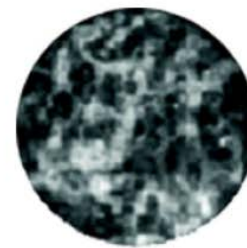
- ❑ Les diagnostics optiques sont des outils permettant d'améliorer la compréhension des phénomènes physico-chimiques de la combustion et d'améliorer les modèles numériques CFD.
- ❑ Les moteurs à accès optiques sont des dispositifs expérimentaux complémentaires aux moteurs « traditionnels » de recherche.
- ❑ L'hybridation des groupes motopropulseurs va permettre d'optimiser les points de fonctionnement des moteurs à combustion interne.
- ❑ Les combustions de basse température (Low Temperature Combustion) associées à de nouveaux carburants (biocarburants) sont une des solutions permettant d'augmenter le rendement des moteurs à combustion interne et de réduire drastiquement les émissions polluantes



Combustion diesel
(Flamme de diffusion)



Combustion essence
(Flamme de propagation)



Combustion homogène
(Pas de flamme)

Diagnosics optiques dans les moteurs à combustion interne

Fabrice FOUCHER

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Université d'Orléans

Laboratoire PRISME



14^{EME} JOURNEES D'ECHANGES
DU RESEAU DES PLASMAS FROIDS

15-18 octobre 2018 - La Rochelle

