PM Sensor Development and Simulation for Diesel Particulate Filter On Board Diagnostic

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CLEERS

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IFP Energies nouvelles

Outline

- Context and objectives
- PM sensor basic approaches
- PM sensor design optimization
- PM sensor response characterization and analysis
- Vehicle evaluation on chassis dyno
- PM sensor response modeling
- Conclusion and outlook

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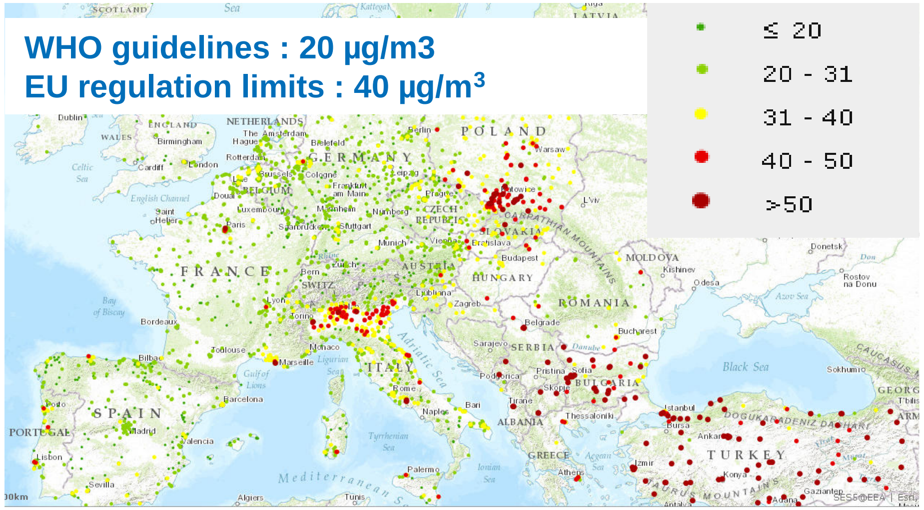
Context and objectives

- Air quality standards in many countries aim at reducing population exposure to air pollutants
  - PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, O_3…
- DPF now generalized to cope with more and more stringent emission standards, especially for on-road vehicle applications

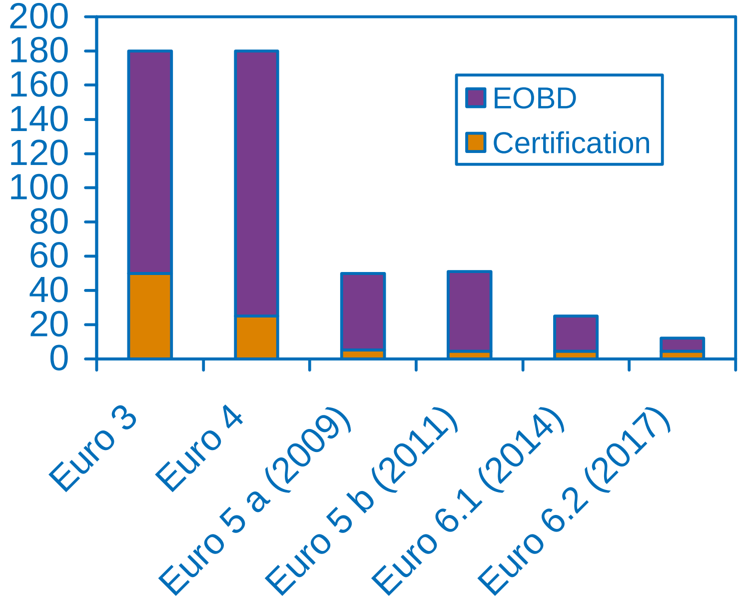
PM10 annual mean daily value (µg/m³) - 2012



Context and objectives

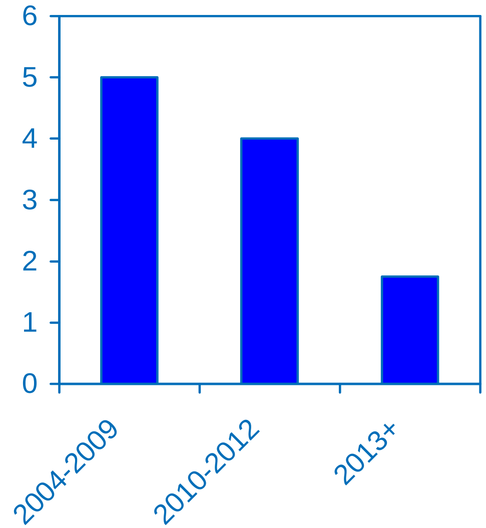
Europe LDV

PM mass certification and EOBD threshold limits (mg/km)



US LDV

PM OTL/Certification limit ratio



⇨Similar trend for HDV

⇨Need for accurate DPF filtration efficiency diagnostic

Context and objectives

- Today, detection of DPF failure is based on differential pressure sensor technology
  - Limited sensitivity: only severe DPF failures can be detected
  - Technology not able to meet future stringent EOBD threshold limits

⇨ Need for a more sensitive technology such as an on-board PM sensor downstream of the DPF

- Various PM sensor technologies under development
  - Continuous and cumulative measurement concepts

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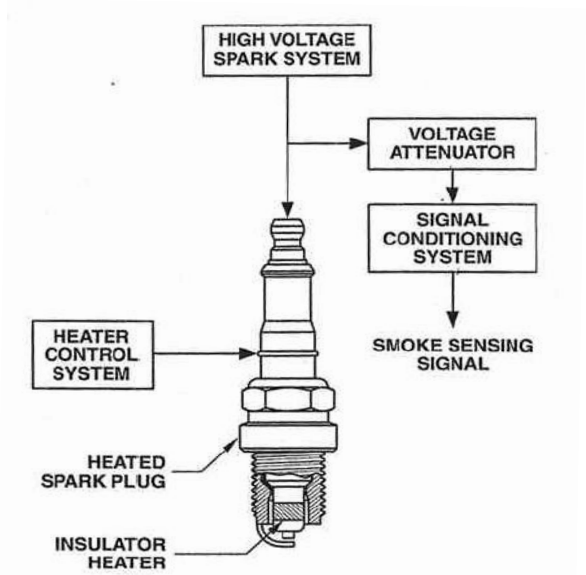
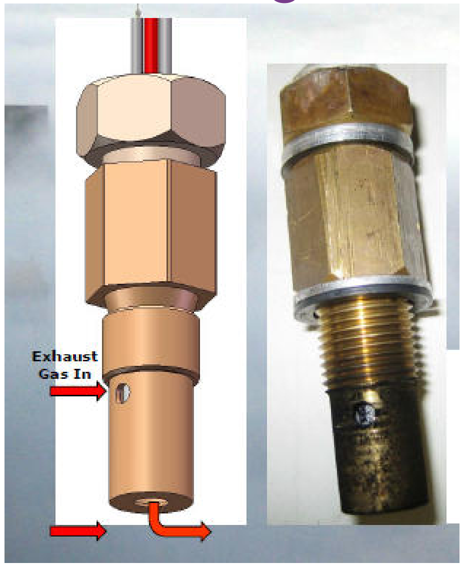
PM sensor basic approaches: Spark discharge

- PM concentration related to changes in the voltage waveform of a repetitive, low energy spark discharge



Source : Journal of Engineering for Gas Turbine and Power / March 2009, Vol. 131 / Allen et al.

Source : SAE 2006-05-0285 / Gheorghiu et al.



Source : SAE 2012 OBD Symposium / Stuttgart / Gheorghiu

⇨Cross-sensitivities to check

⇨ High voltage to manage

PM sensor basic approaches: Electrochemical polarization

- Produced by a difference in O_2 partial pressures between 2 electrodes, which is due to PM deposit and oxidation on the anode

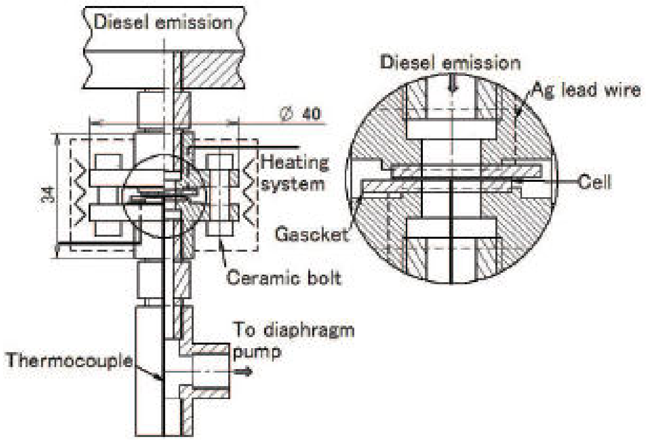


Figure 2: Setup of the electrochemical cell sensor.

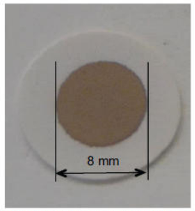


Figure 3: Photograph of the electrochemical cell.

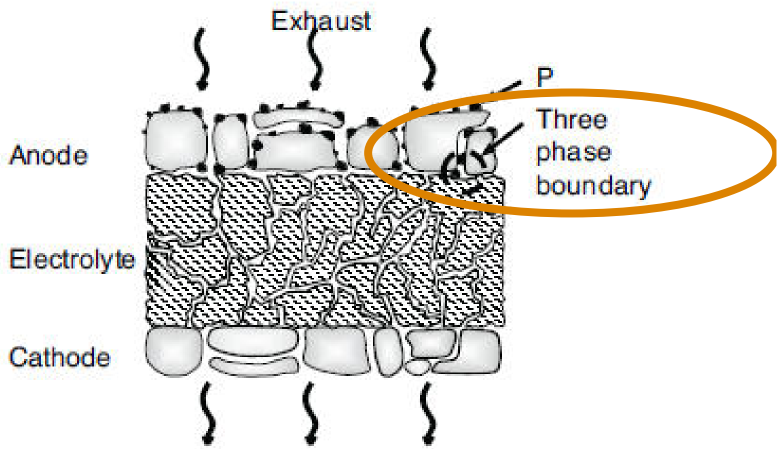


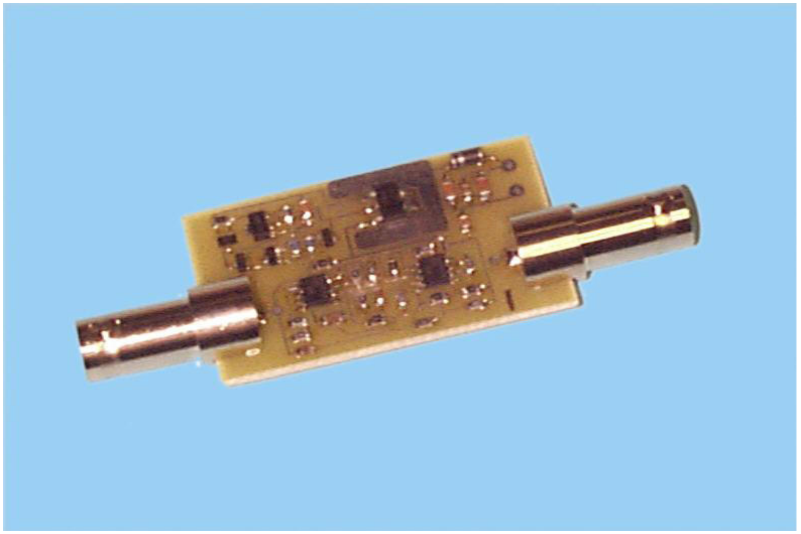
Figure 8: Schematic diagram of PM detection in the sensor system.

Source : SAE 2011-01-2059 / Yoshihara et al.

⇨Very localized phenomenon

PM sensor basic approaches: The electrostatic concept: image charge

- Measurement of the current emitted by the inherent PM electrical charge

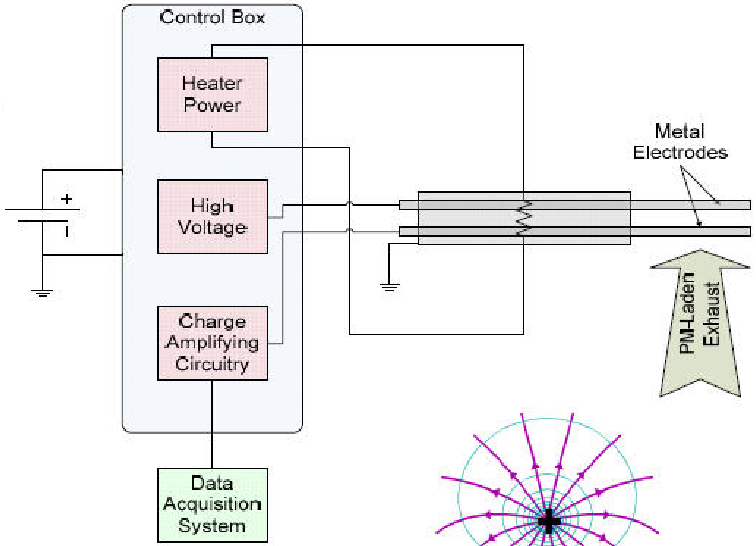


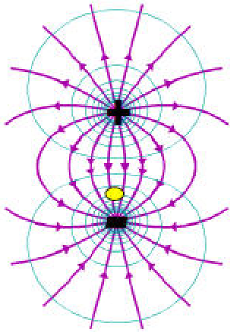
Source : ETH Conference 2004 / Kittelson et al. / University of Minnesota

⇨ Poor response signal due to the globally neutral particulate charge within the exhaust pipe

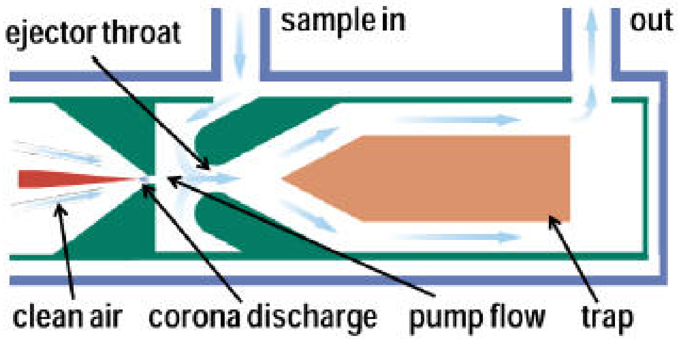
PM sensor basic approaches: The electrostatic concept: corona discharge

- The corona discharge increases PM electrical charge





Source : DEER 2009 / Hall et al.

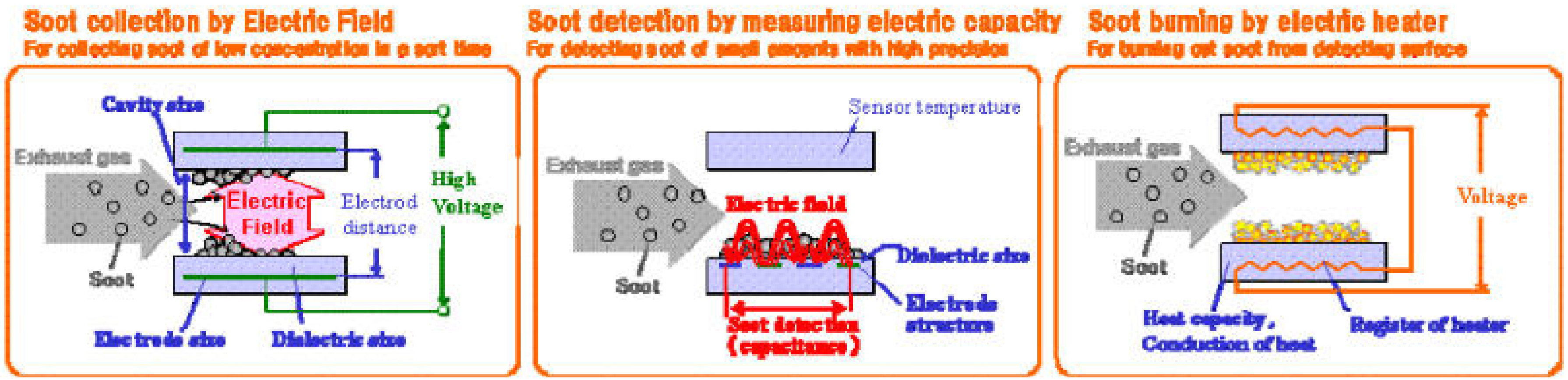


Source : SAE 2011-01-0626 / Zamaras et al.

⇨ High voltage management necessary

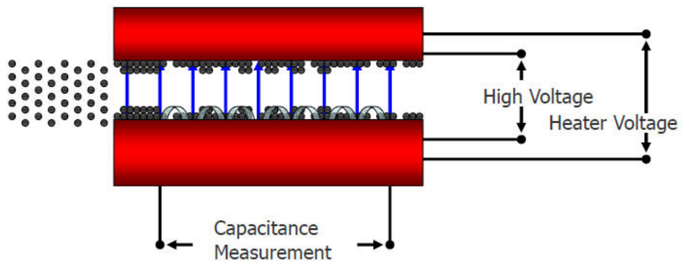
PM sensor basic approaches : Electrostatic capacity

- Detection of PM accumulation related to changes in electrostatic capacity



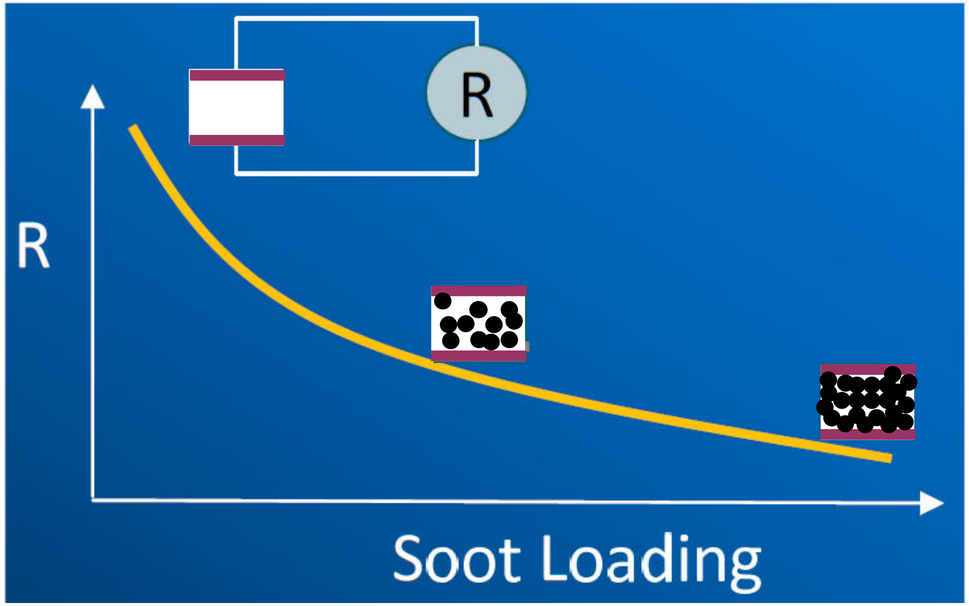
Source : SAE 2011-01-0302 / Kono et al.

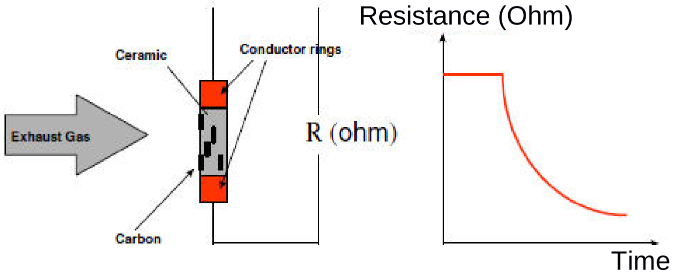
⇨ High voltage to manage



PM sensor basic approaches: The resistive concept

- Resistance decreases as conductive carbonaceous particulates accumulate between the electrodes





Source : IFPEN patent FR2760531

⇨ Concept widely studied due to simplicity and low cost

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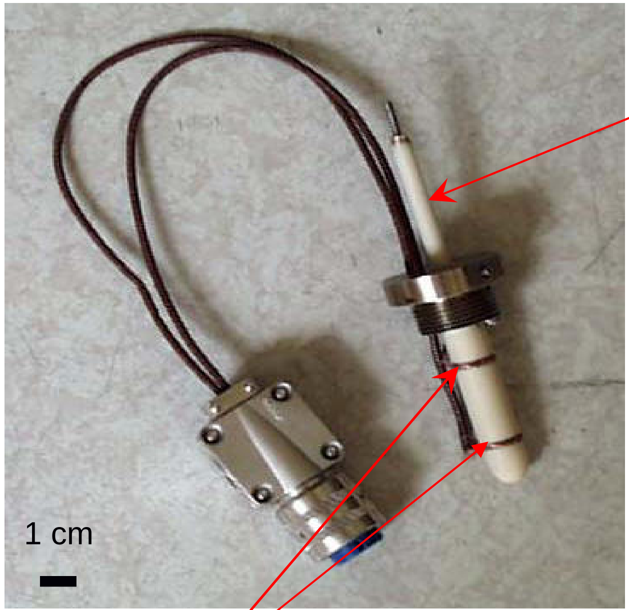
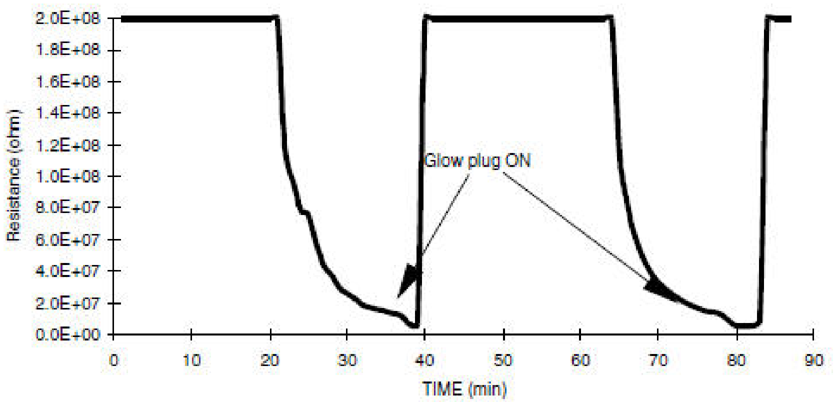
PM sensor design optimization
From the first prototype in 2000...

- Prototype developed for concept validation

Glow plug for soot burning



Two electrodes for resistance measurement

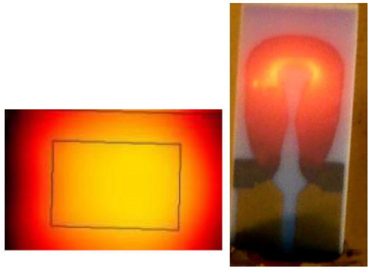


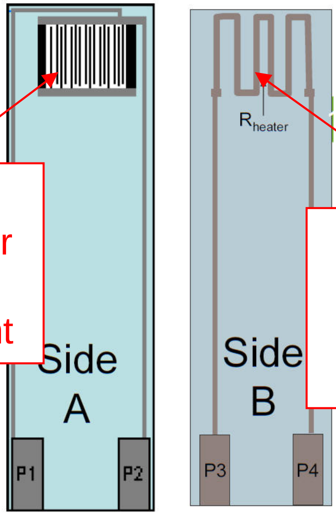
Source : SAE 2000-01-0472 / Bouchez et al.

PM sensor design optimization ...to a pre-industrial version today

Sensitive element

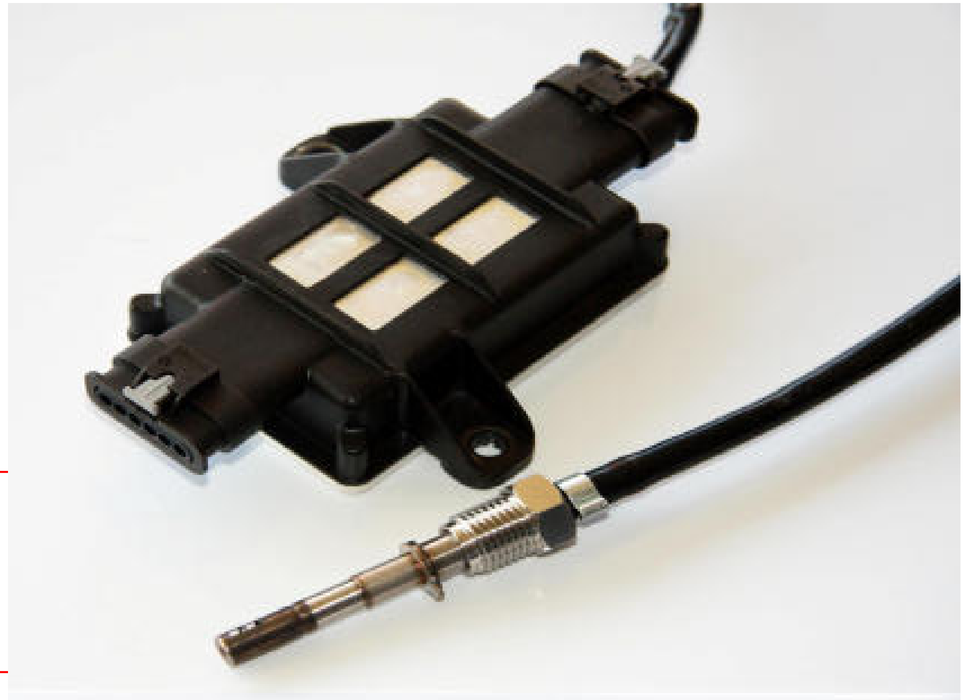
Packaging & control unit





Interdigital electrodes for resistance measurement

Heater for soot burning (regeneration)

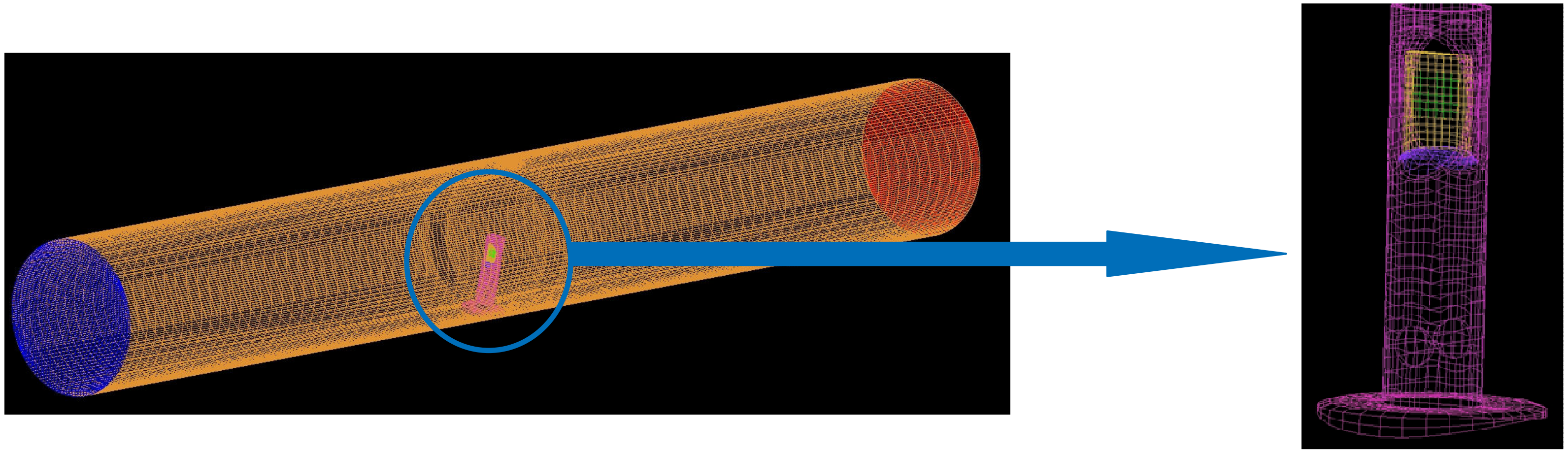


PM sensor design optimization
3D CFD of the flow around sensor shield

- Objectives:
  - homogeneous PM deposition
  - avoid deposition of large particles
  - limited heat exchanges for efficient and fast soot burning

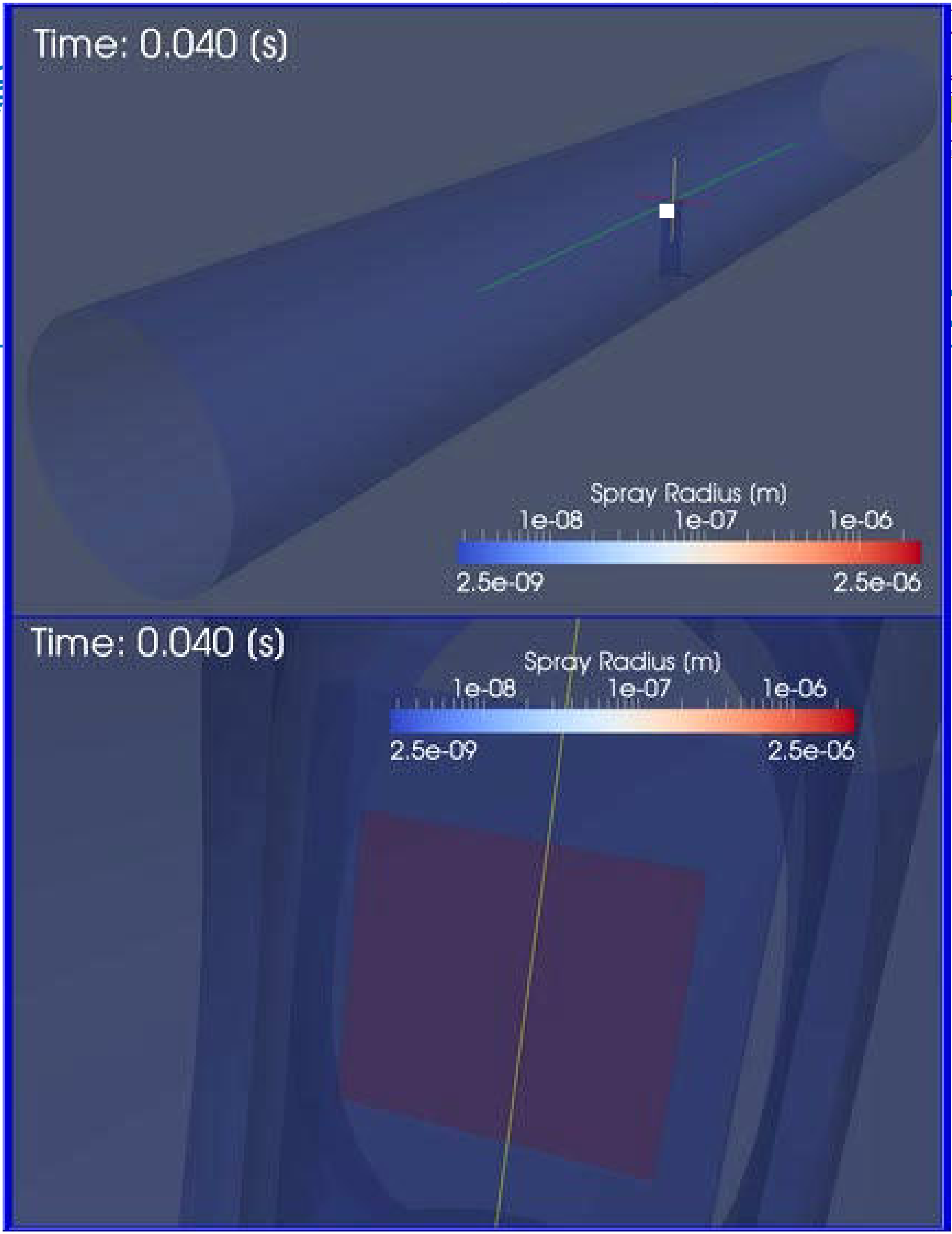
PM sensor design optimization
3D CFD of the flow around sensor shield

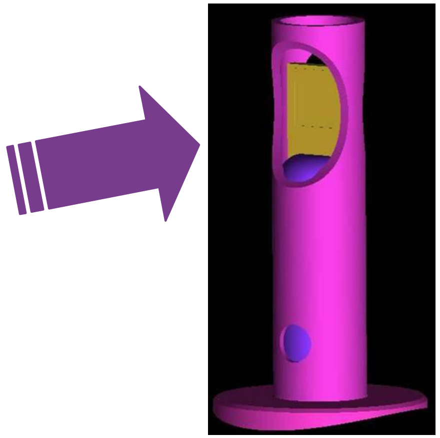
- K-Epsilon RNG turbulence model for fluid
- Lagrangian representation for particles
  - Based on spray liquid injection models (no evaporation)
  - Turbulent dispersion also taken into account for particles
  - Simultaneous injection of different particle sizes
- 255 000 cells and 268 000 nodes
  - 64 processors → 25 to100 h (depending on flow conditions)



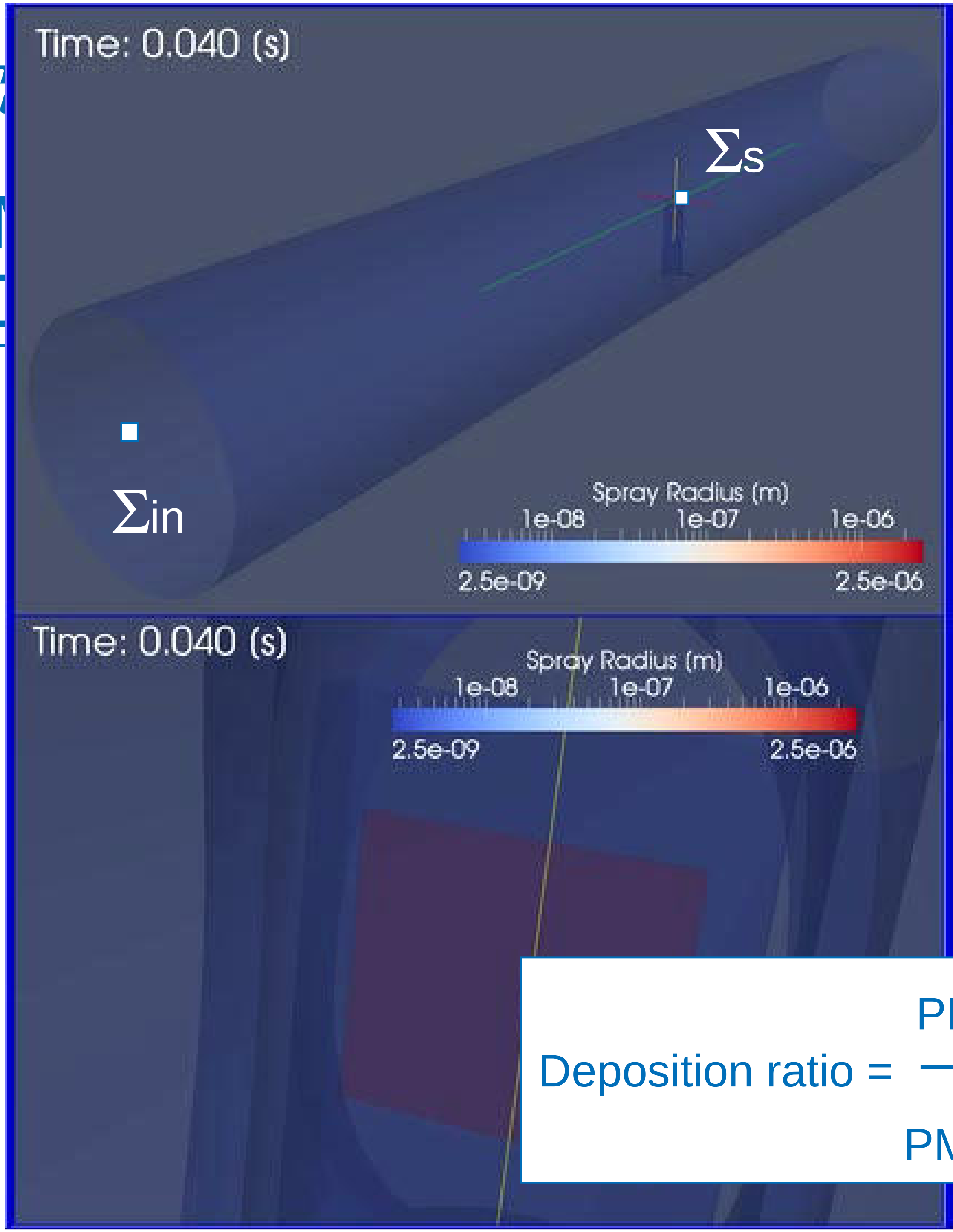
/ J. Lavy

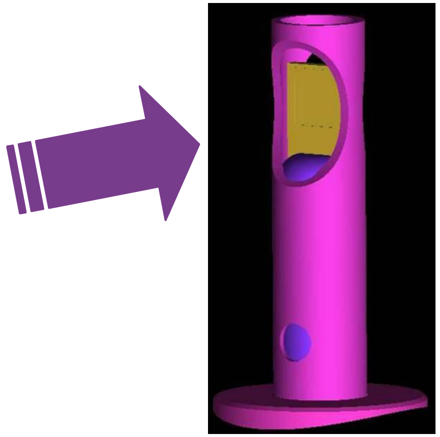
PM
3D … r shield





PM
3D … sor shield

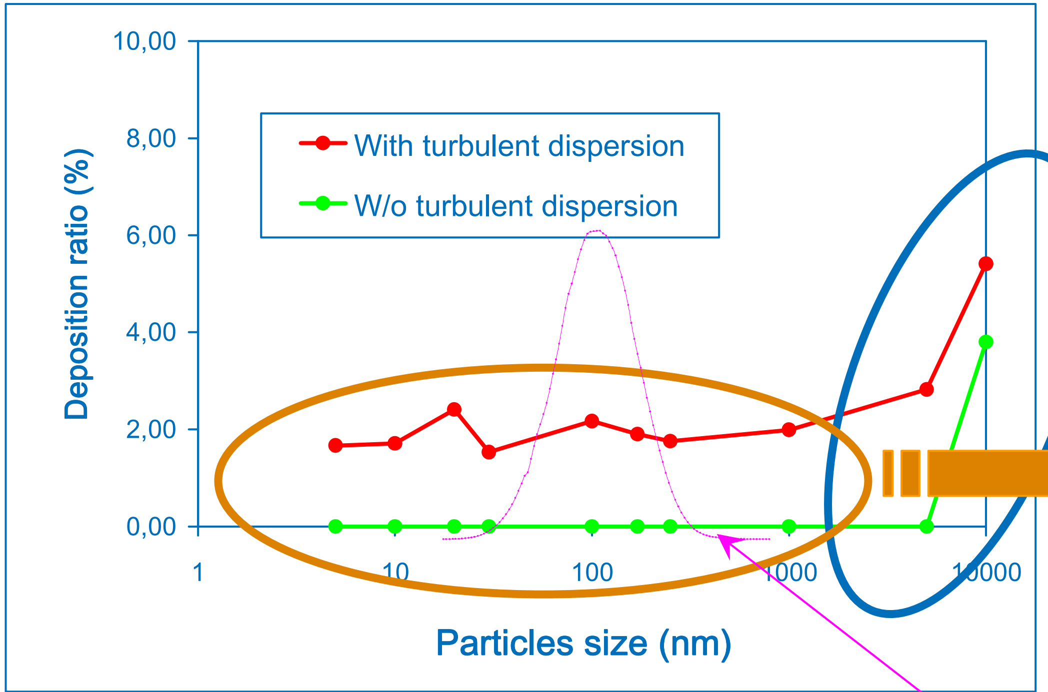




$$\text{Deposition ratio} = \frac{\text{PM deposited on } \Sigma s}{\text{PM flowing through } \Sigma in}$$

PM sensor design optimization
3D CFD of the flow around sensor shield

- Turbulent dispersion and particles inertia effects



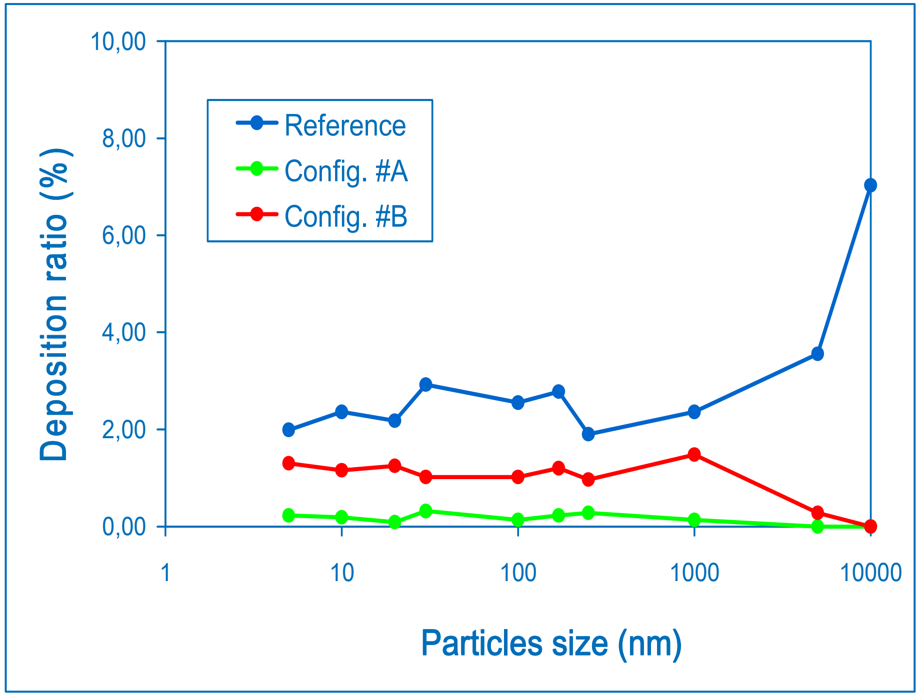
Particles above 5 µm deposited by inertial impaction

Particles below 5 µm deposited by turbulent dispersion

Typical Diesel Particulate size distribution

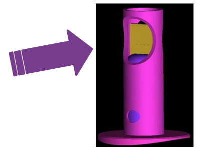
PM sensor design optimization
3D CFD of the flow around sensor shield

- Various configurations tested

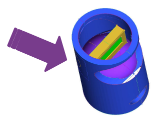


⇨Best experimental results with Config.#B

- Reference design :



  - large particles impact a lot
- Config. #A :
  - no impact of large particles
  - low impact of smaller particles
- Config. #B :



  - no impact of large particles
  - impact of smaller particles remains significant

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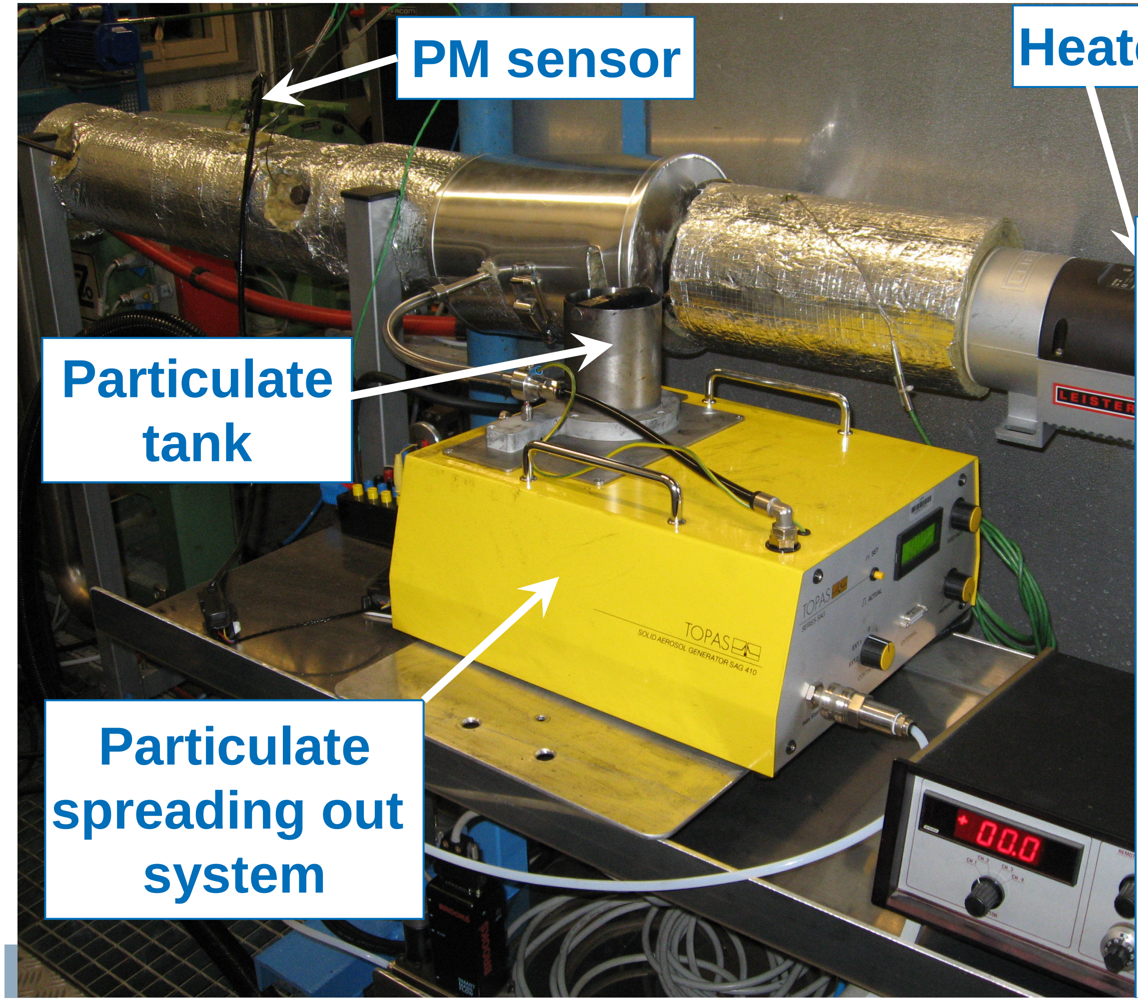
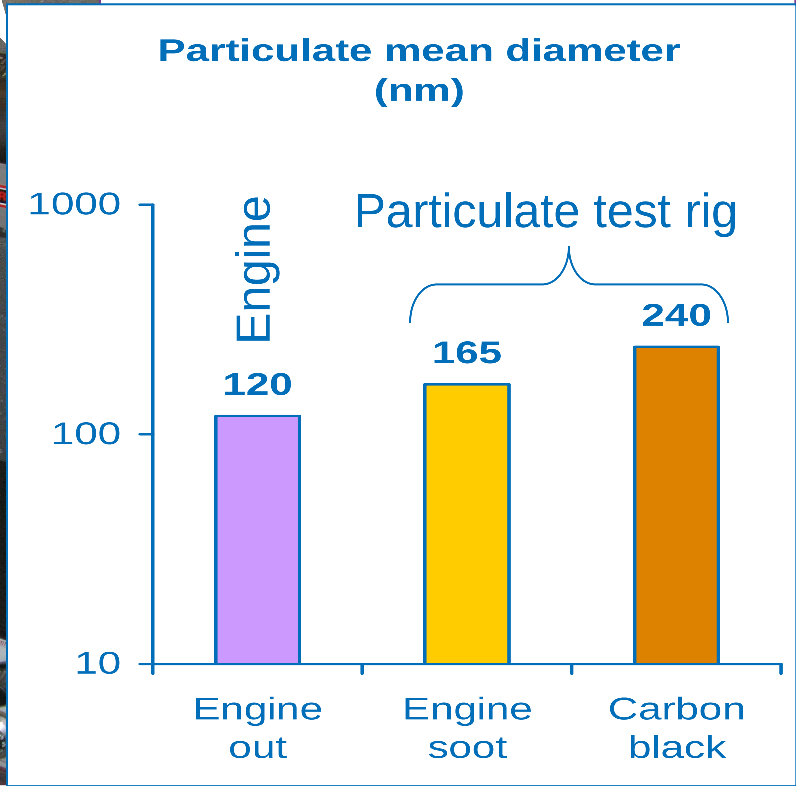
PM sensor response characterization and analysis

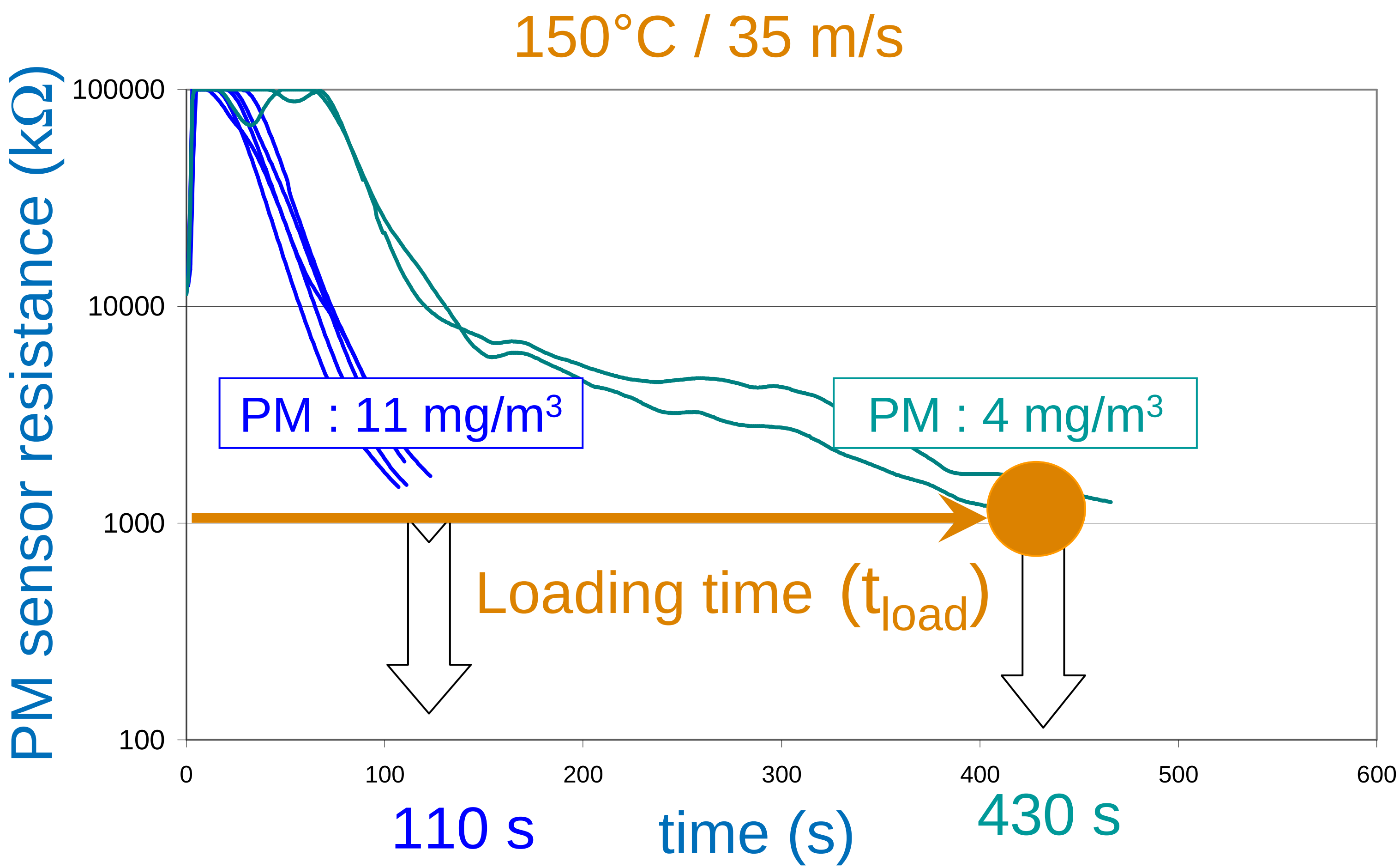
Development of a specific PM test bench rig

Φ: **39** mm
Flow rate: **0 → 350** m³/h
Flow velocity: **0 → 80** m/s
Temperature: **20°C → 450** °C
PM concentration: **0 → 250** mg/m³



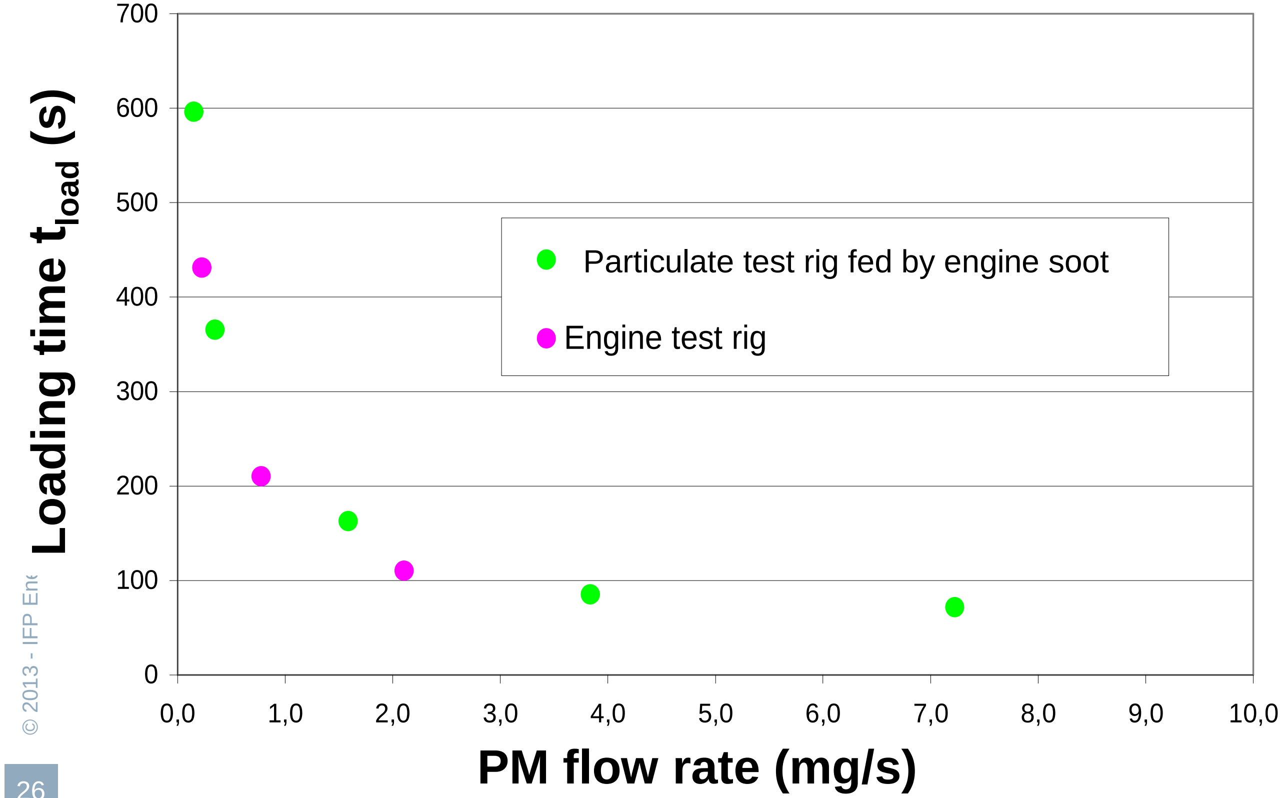


PM sensor response characterization and analysis



PM sensor response characterization and analysis

- Comparison between particulate and engine test rigs results



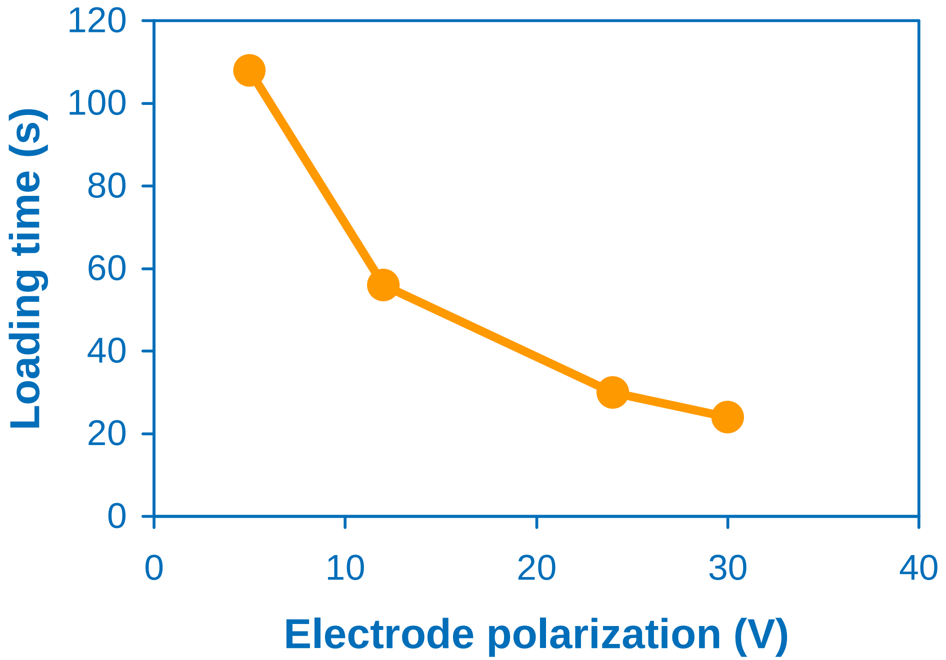
➪ Similar results

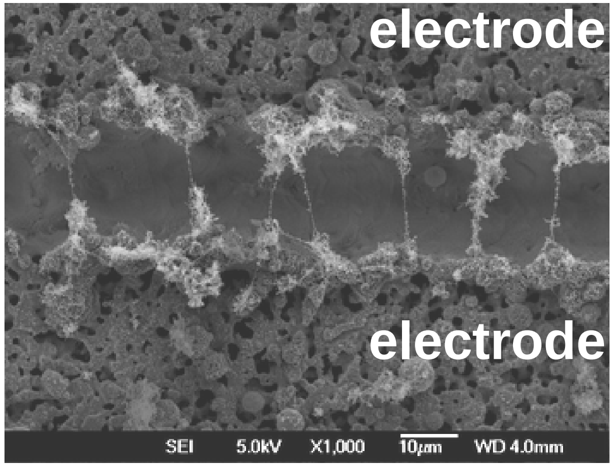
➪ Particulate test rig representative of engine conditions and phenomena

PM sensor response characterization and analysis

- PM sensor sensitivity enhanced by electrode polarization

Fixed flow rate and soot concentration

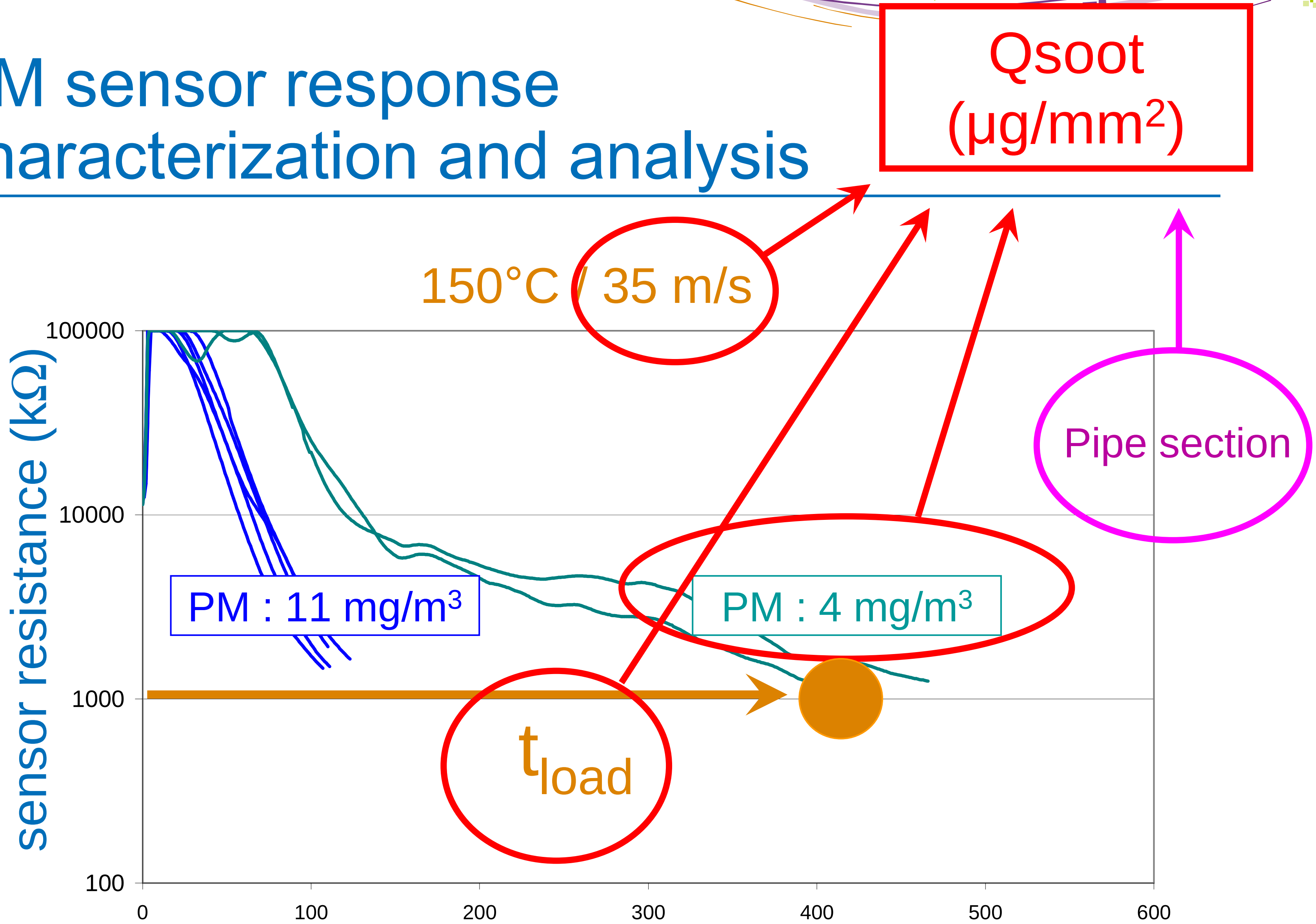




➪ Polarization favors formation of particle bridges

➪ Better deposition rate ? (to be confirmed)

PM sensor response characterization and analysis

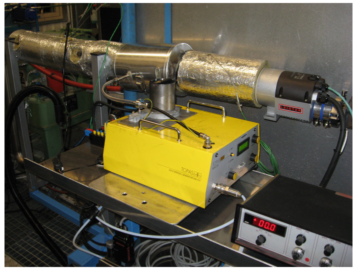


➪ Qsoot should be a constant value in perfect conditions

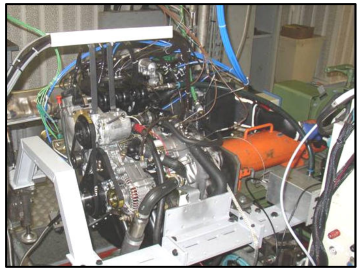
PM sensor response characterization and analysis

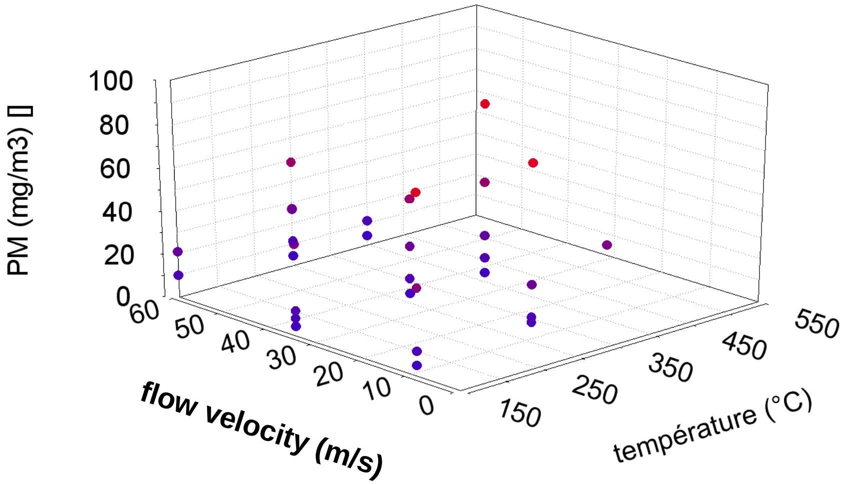
- Test repartition vs. PM, flow velocity and temperature

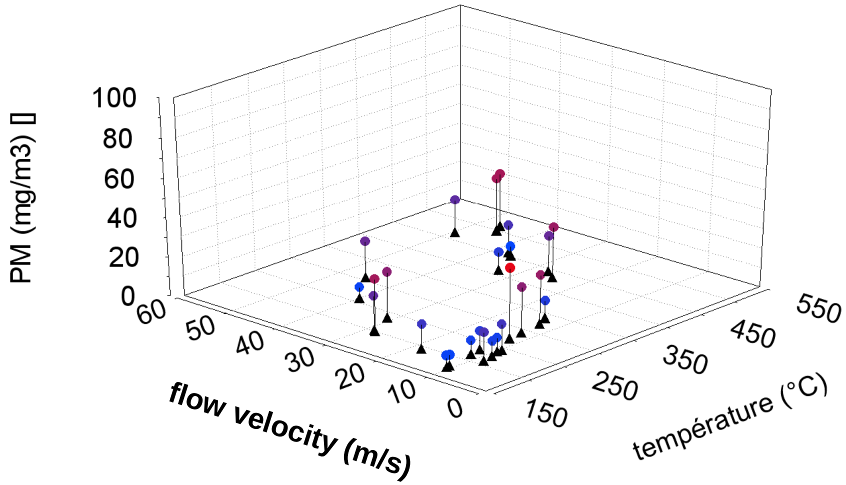
Particulate test rig



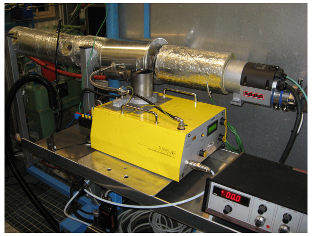
Engine Bench

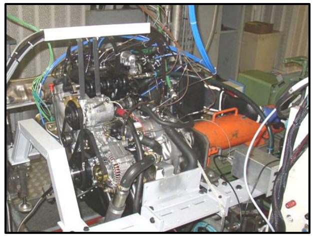


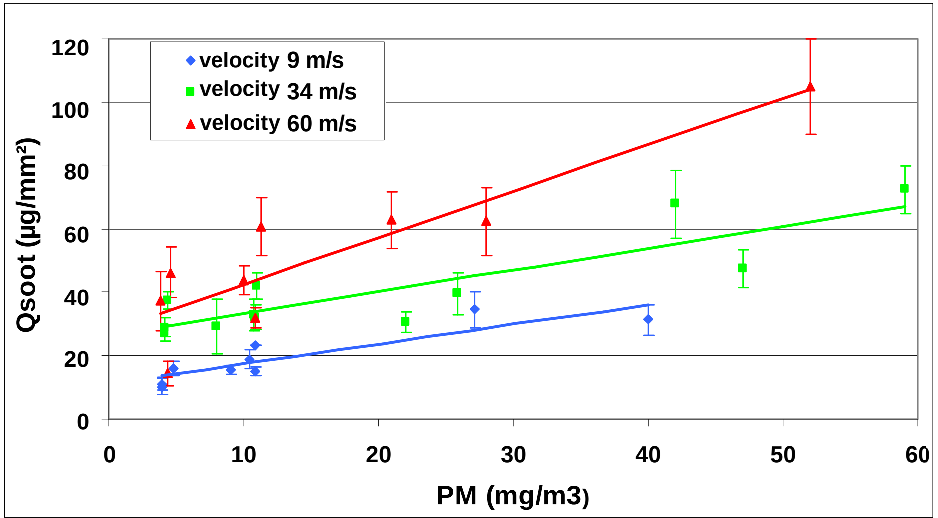


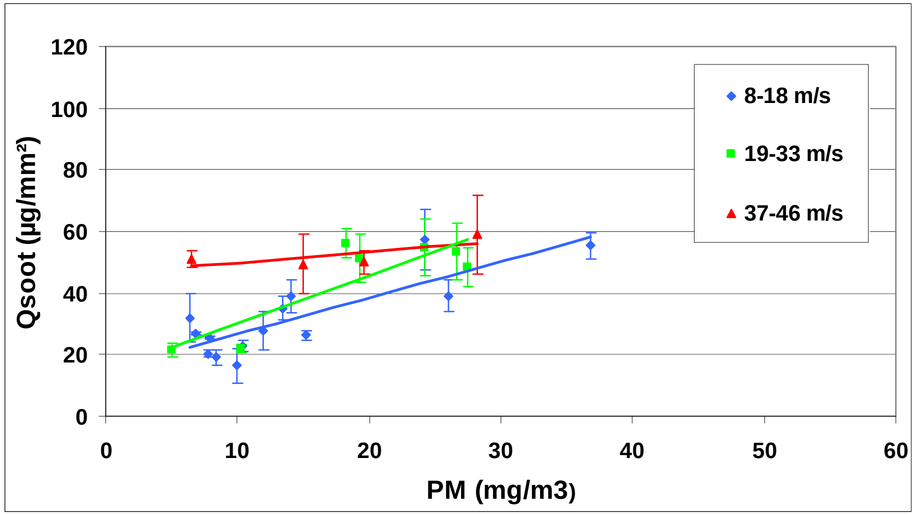


PM sensor response characterization and analysis









- Similar tendency whatever the test bench
- Dominant effect of flow velocity and soot concentration on sensor response

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Vehicle evaluation on chassis dyno

Citroën C4 - €4 DV6 engine

EXXOtest
CAN logger

IXXAT CANbridge

Drilled DPF to simulate
different failure levels

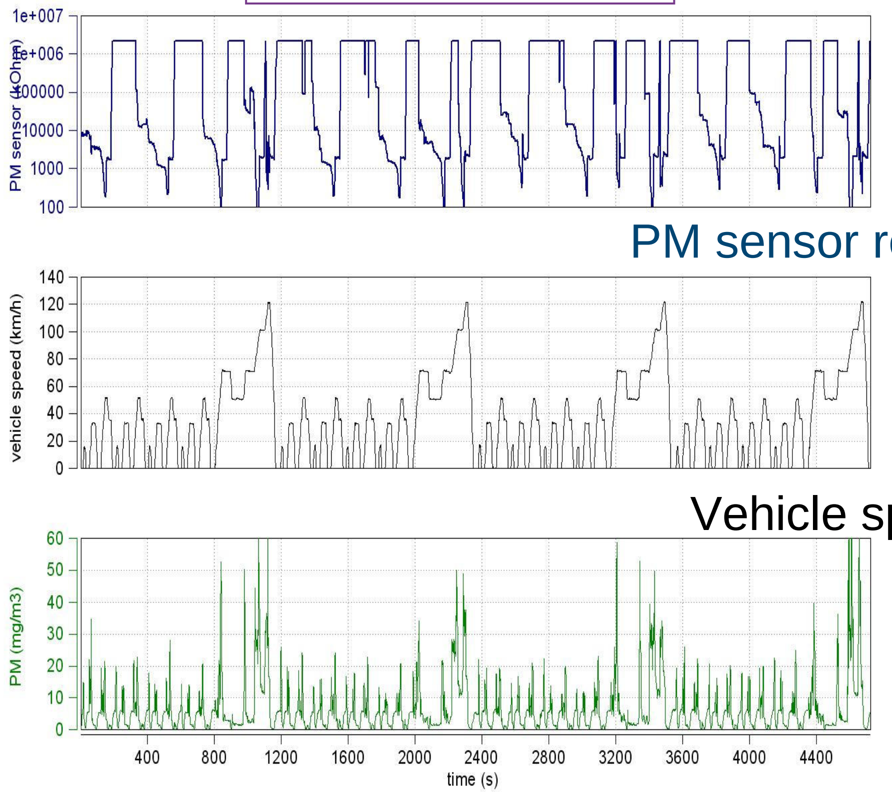
Instantaneous PM concentration
measurement by AVL 483 (MSS)

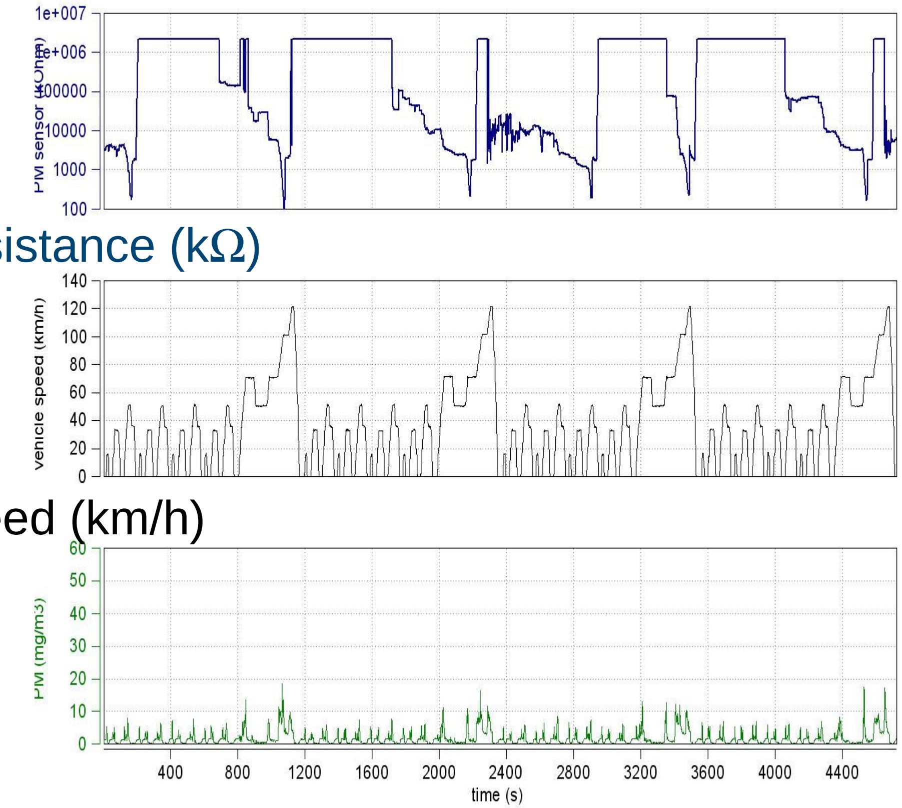
Vehicle evaluation on chassis dyno

No DPF
PM 15.2 mg/km

4 successive hot NEDC driving cycles

Slightly damaged DPF
PM 4.6 mg/km





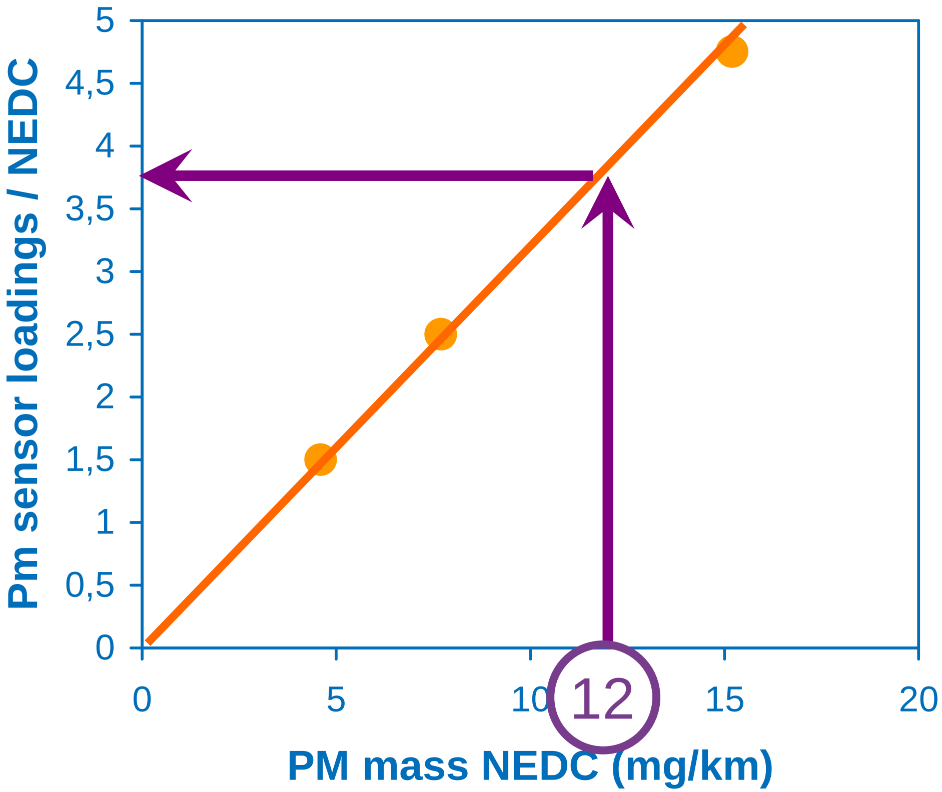
PM sensor resistance (kΩ)

Vehicle speed (km/h)

PM (mg/m^3)

Vehicle evaluation on chassis dyno

- PM sensors loading frequency function of the PM mass



➪ PM sensor loading frequency proportional to PM mass

➪ PM sensor able to detect low PM level (~ 4 loadings during NEDC @ 12 mg/km)

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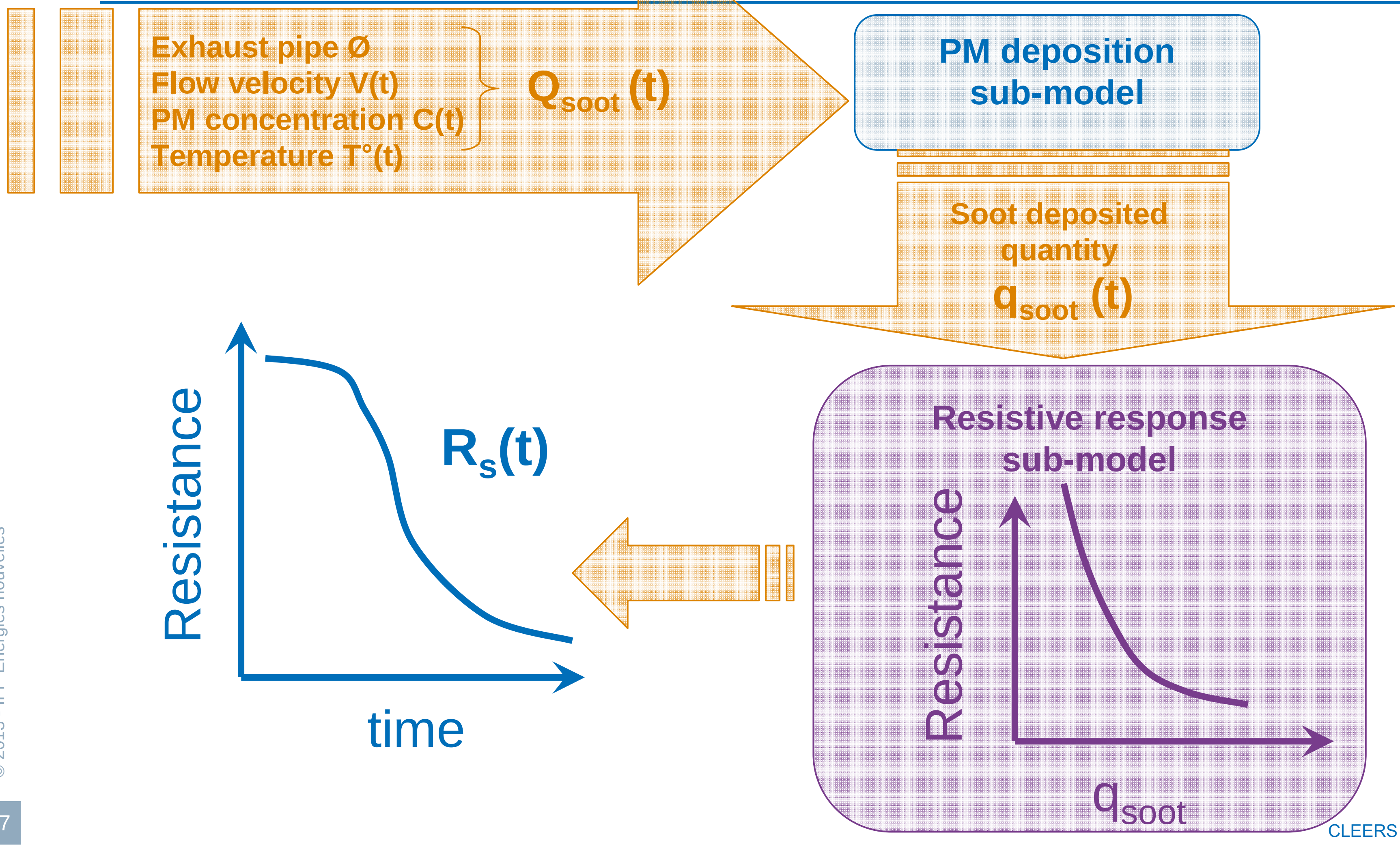
PM sensor response modeling

- Why
  - To analyze the effects of flow and PM sensor design parameters
  - To be used in model-based DPF on-board diagnostic algorithms (both model-based and non model-based diagnostics algorithms developed at IFPEN)

- How: by coupling two sub-models
  - PM deposition on the sensing zone
  - Resistive response according to PM quantity deposited over the sensing zone

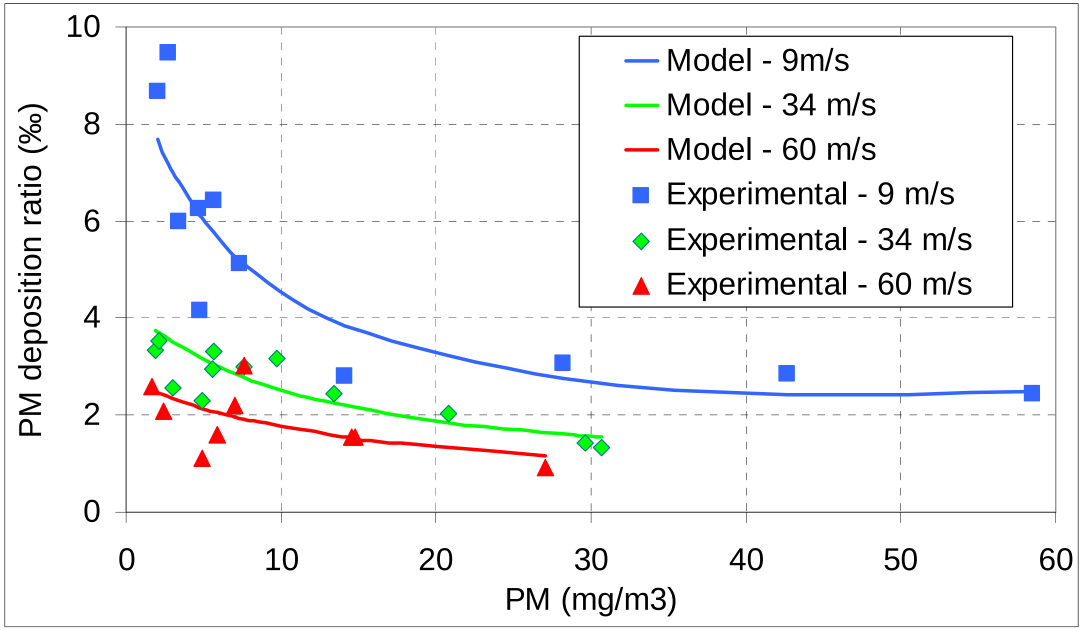
PM sensor response modeling



PM sensor response modeling
PM deposition ratio sub-model

- PM deposition ratio (Dr) is a function of flow velocity and PM concentration

$$Dr = A_0.(1 + A_1.V + A_2.C + A_3.V.C)$$

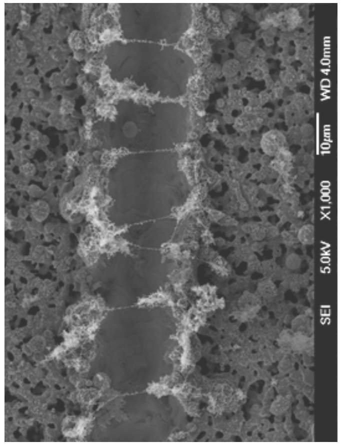


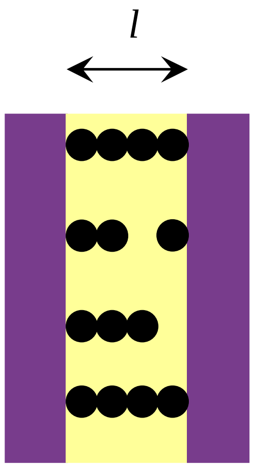
⇨A_1, A_2, A_3 calibrated from stabilized test results

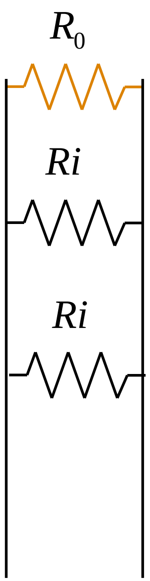
⇨A_0 calibrated from either stabilized or transient test results

PM sensor response modeling
Resistive response sub-model

- Particles in a bridge are series resistors and bridges are resistors connected in parallel







$$R_i = \frac{4.\rho.l}{\pi.Nb.D_m^{\ 2}}$$

$$1/R_s = 1/R_0 + \sum 1/R_i$$

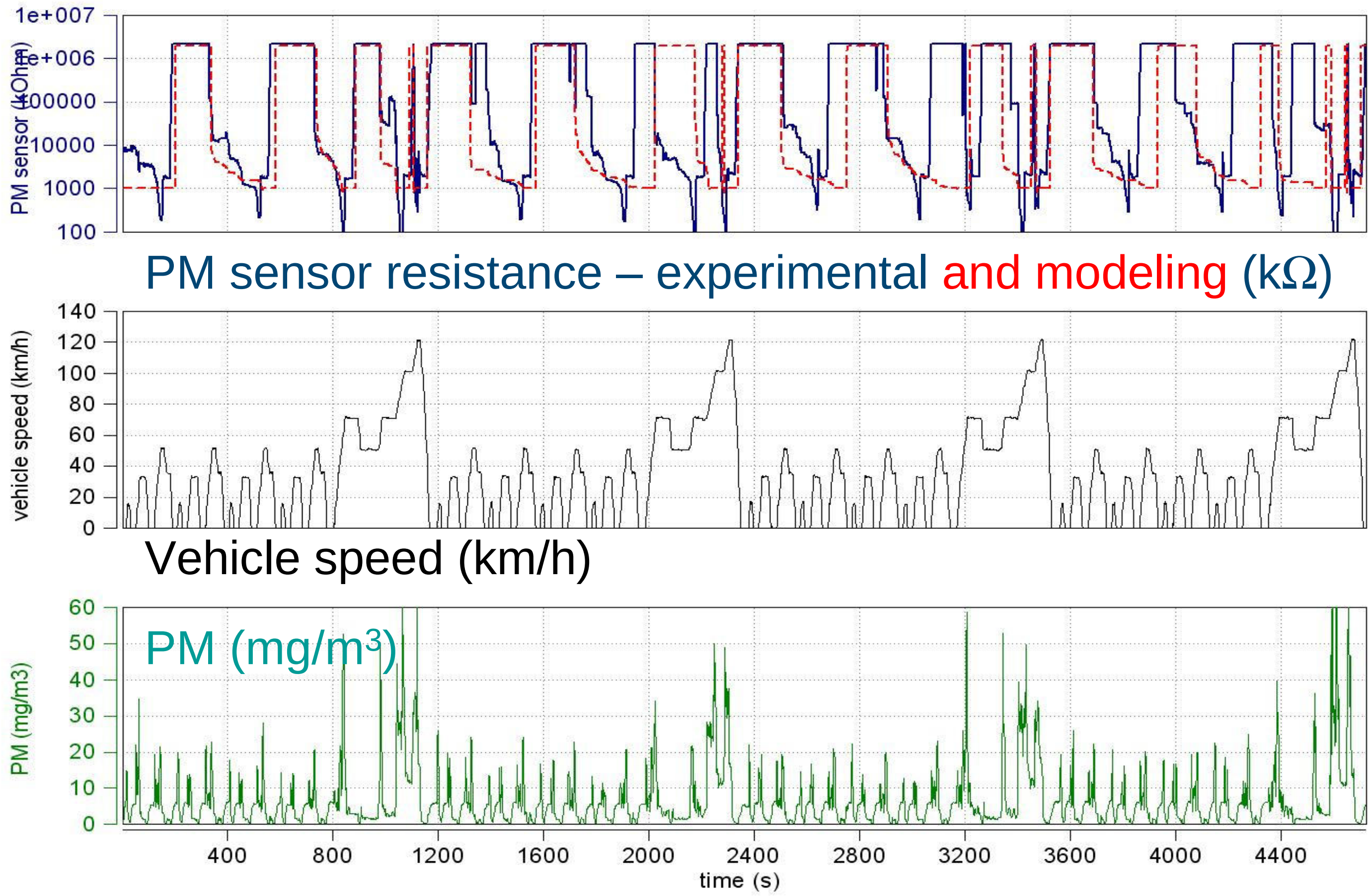
PM

D_m : mean diameter

ρ : resistivity (no specific data available, calibrated parameter from either stady state or transient test results)

PM sensor response modeling

No DPF – Hot successive NEDC - PM 15.2 mg/km

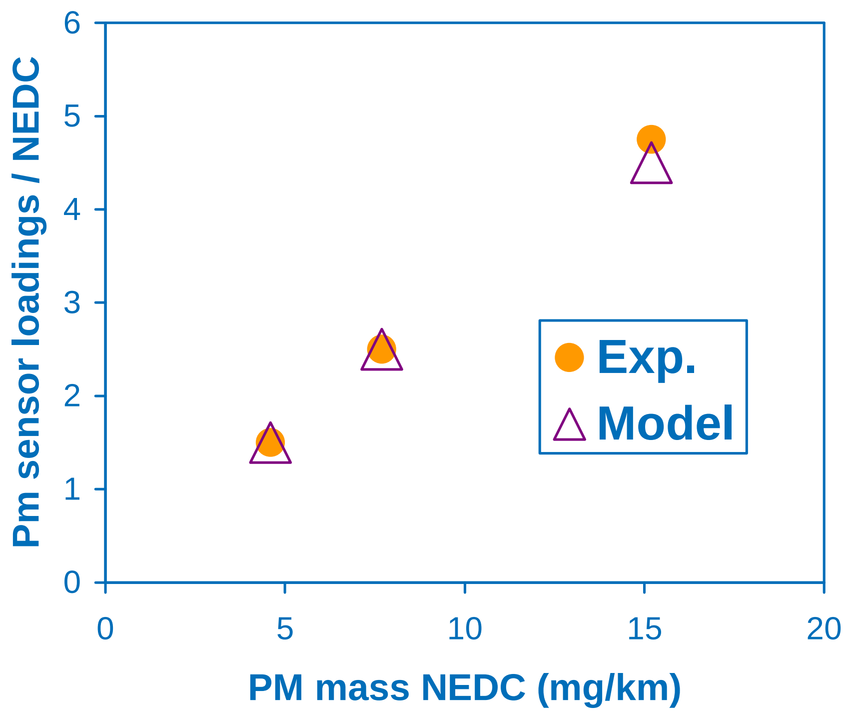


A_0 and ρ calibrated from this reference test

⇨ Good accordance with experimental data

PM sensor response modeling

- Application of the model for various DPF failure levels



➪ Accurate prediction of the PM sensor loading frequency whatever the DPF failure level

➪ Model evaluation for others driving cycles to be done

Conclusion

Tools used to develop a new resistive PM sensor

- 3D-CFD simulation
  - to better understand the particle deposition processes
  - to optimize the sensor collecting tip design
- Development of a specific particulate test rig
  - easy and independent control of flow velocity, temperature, PM concentration and nature (synthetic or engine soot)
  - sensor response analysis and results in accordance with engine tests
- Engine test benches and vehicles
  - sensitivity validation in steady-state and transient conditions

Conclusion

This on-board PM sensor demonstrated its strong ability to detect DPF malfunction or failure as required by the future OBD standards

- High sensitivity to low PM levels, complying with the 12 mg/km European OBD threshold limit (Euro 6.2 in 2017)
- Nearly continuous DPF monitoring despite a basic "cumulative process"
- Model of PM deposition rate and sensor resistance response developed and validated in both steady state and transient (NEDC cycle) conditions

Outlook

- Validation of DPF failure diagnostic algorithm in real life conditions
  - SAE paper 2013-01-1334 to be presented next week at SAE World Congress
- Durability tests under way
  - aging: 600 h, 2400 regenerations achieved so far on an engine
  - poisoning: from fuel and lubricant additives
- Evaluation of PM sensor response to particulate number
  - Diesel engine
  - GDI engine (GPF developed to comply with future PN legislation)

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