Experimental and Numerical Investigations of Particulate Formation and Oxidation Mechanisms

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INTRODUCTION

- **GOAL: Understanding the formation and oxidation of particulate matter in common rail diesel engines**
- **Investigations:**
  - Measurements in a constant volume, High Temperature and Pressure Cell (HTPC)
    - 2 Color Pyrometry
    - Back Diffused Laser
  - Development of a Virtual Soot Sensor
    - Fast models for online prediction of soot emissions
    - AVL Micro Soot Sensor for validation
  - 3-D Implementation of a formation and oxidation model
    - Development of a sampling valve for in-cylinder validation data

INTRODUCTION

High Temperature, High Pressure Cell

Optical investigations under engine-like conditions

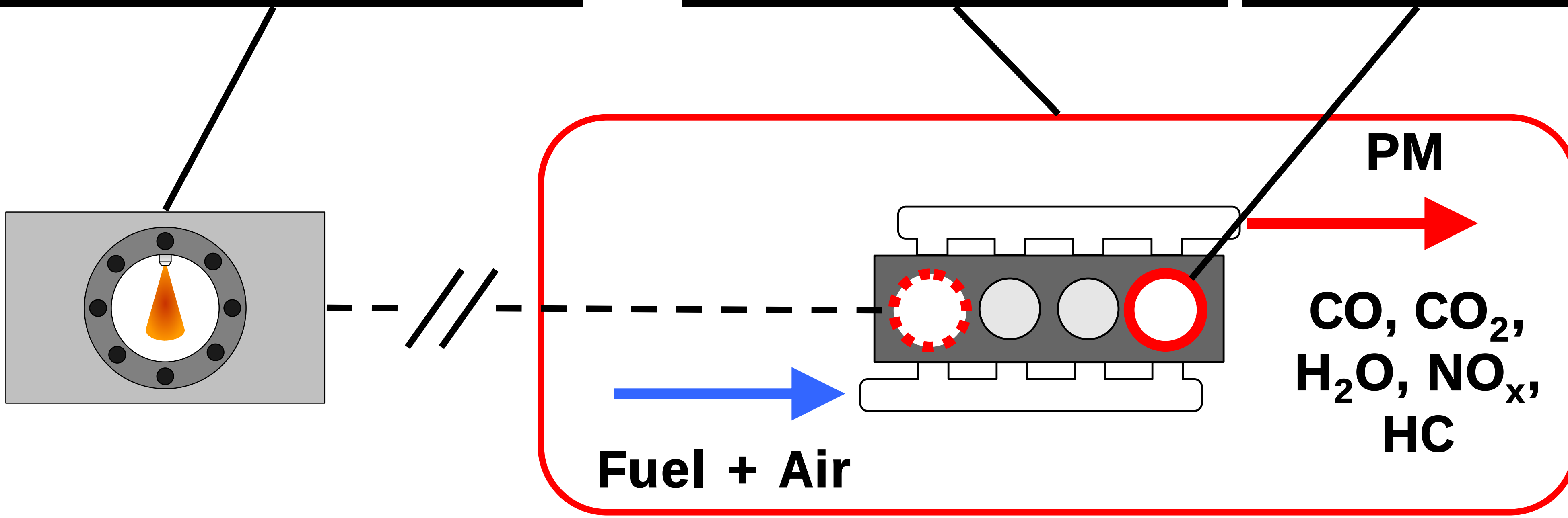
Virtual Sensor

PM Measurements and fast modeling

3D CFD

and

In-Cylinder Sampling



HIGH TEMPERATURE AND PRESSURE CELL (HTPC)

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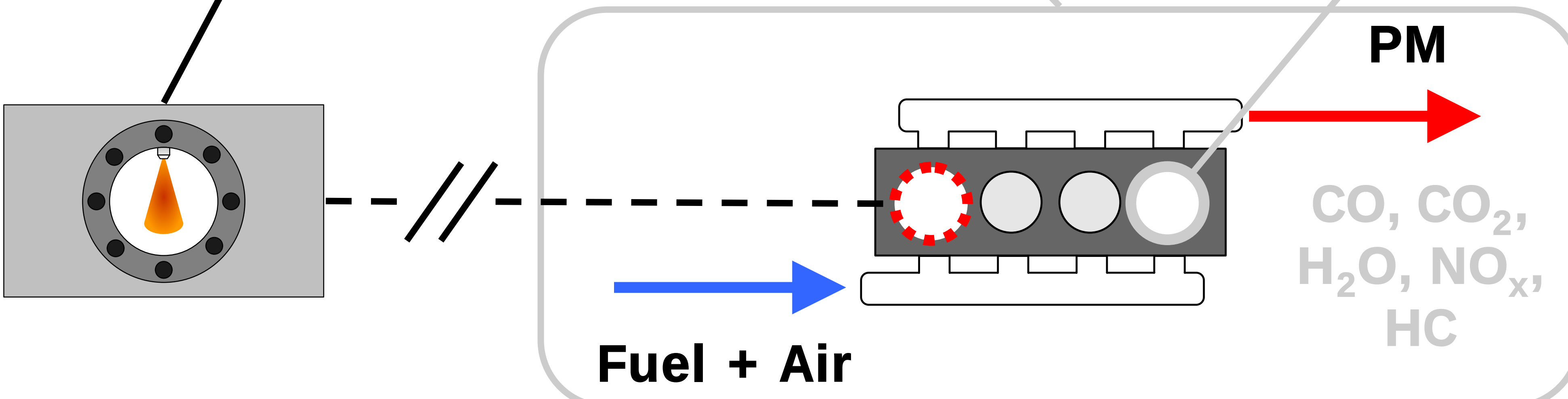
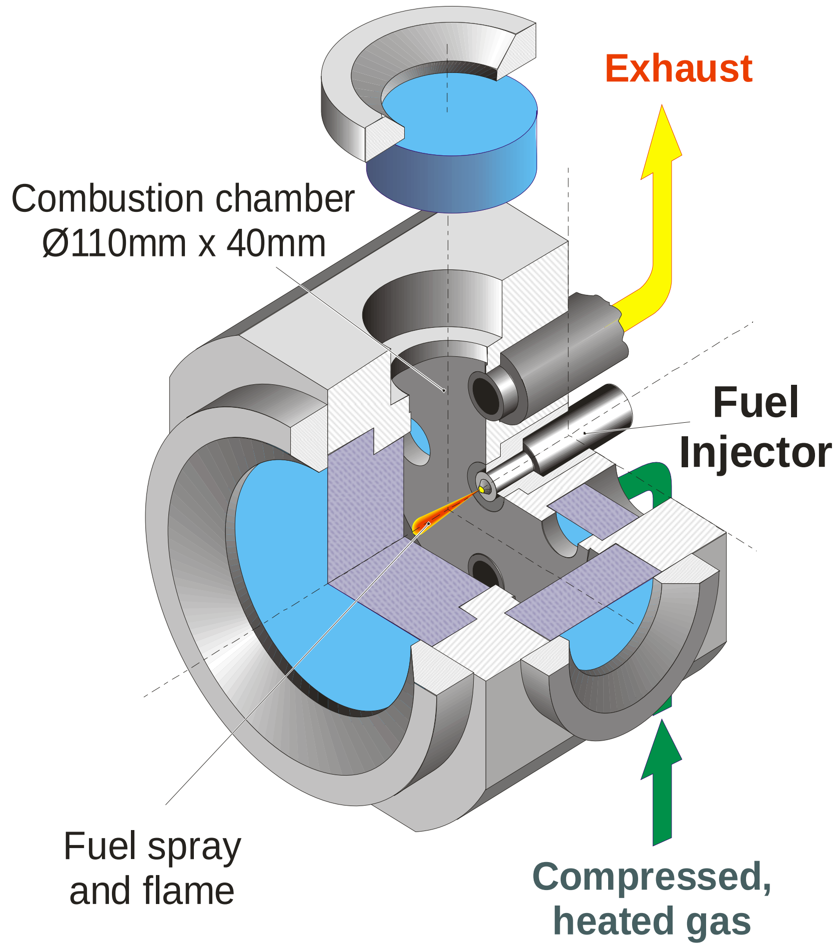


HTPC

Overview

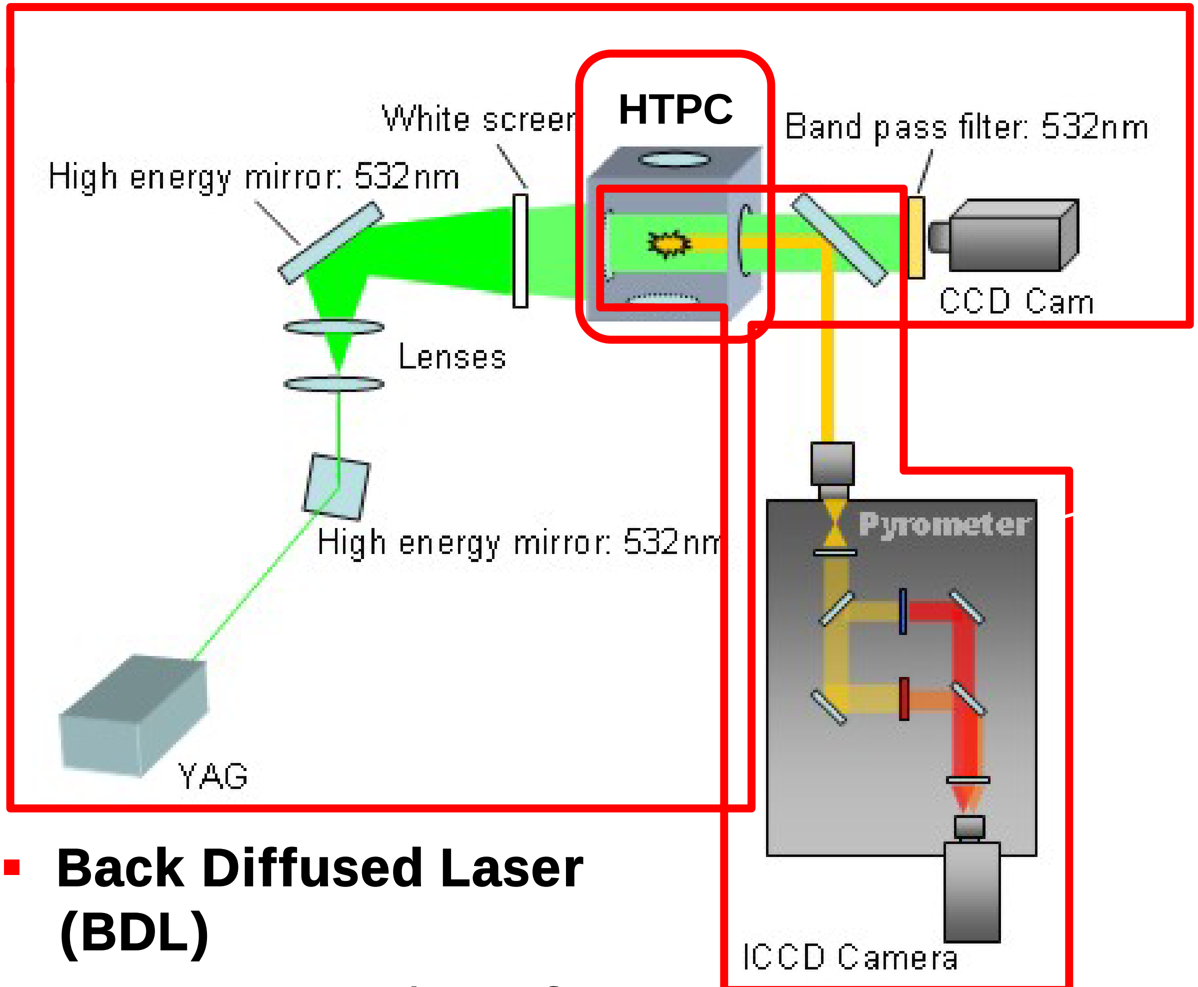


- **Investigate spray and combustion phenomena under diesel-like conditions**
- **Optical access through 4 sapphire windows**

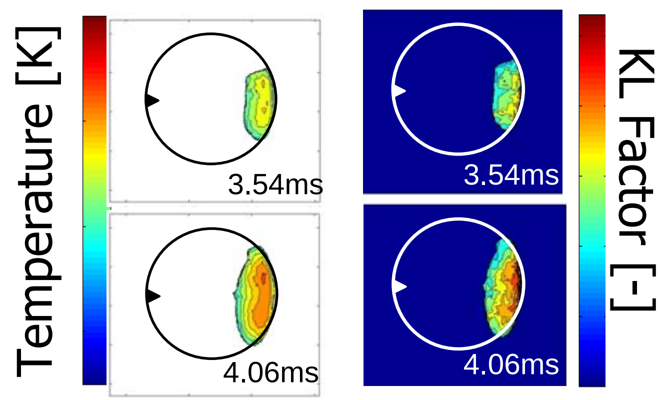
Chamber Volume	~0.5L
p_{cell} prior to combustion	< 80bar
p_{cell} after combustion	< 250bar
T_{cell} prior to combustion	< 800K

HTPC

Instrumentation



- **Combustion light and pressure**
  - Energy release rate
  - OH (λ = 313nm)
  - Soot (λ ~ 600nm)
- **2-color Pyrometry**
  - 2-D Soot temperature
  - 2-D KL factor

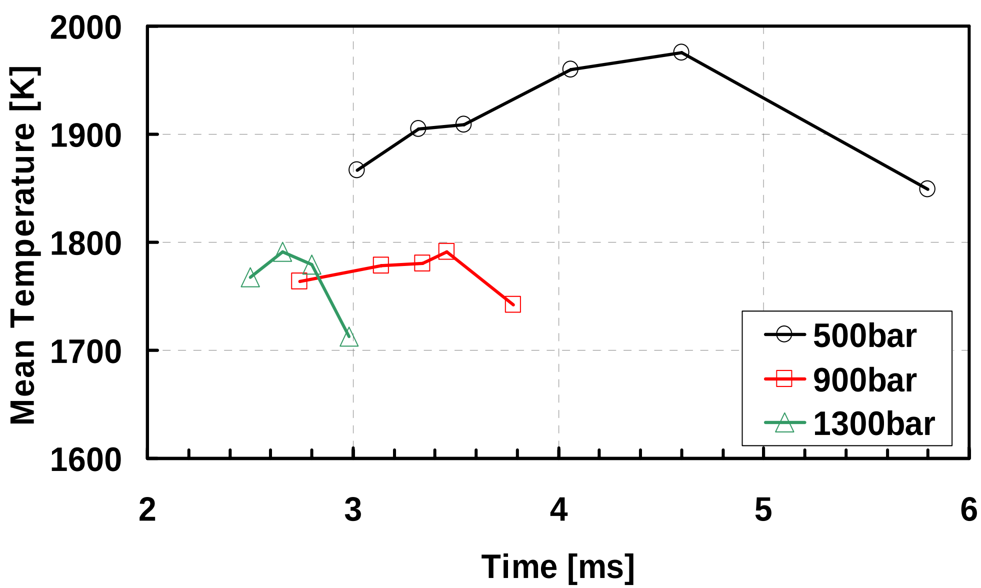


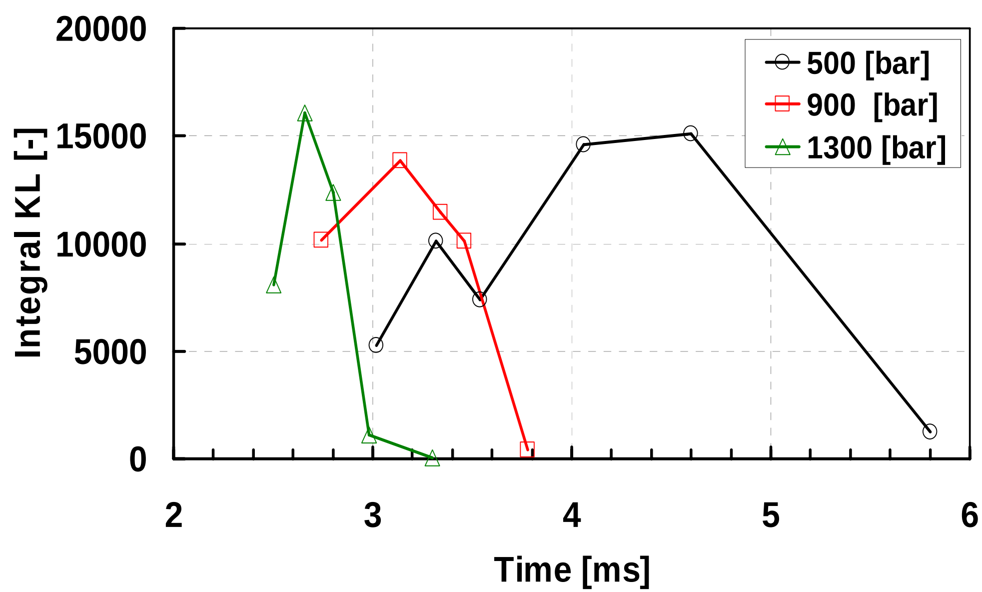
- **Back Diffused Laser (BDL)**
  - 2-D soot volume fraction
  - Not discussed here

HTPC – SOOT PARAMETERS Injection Pressure Variation

- Injection pressure varied from 500…1300 bar
- Constant injected fuel mass
- T_{soot} and mean KL decrease with increasing p_{inj}
- Soot formation begins earlier with higher p_{inj}
- Maximum integral KL value remains approx. constant for all p_{inj}

p_{cell}	60 bar
T_{cell}	790 K
m_{fuel}	17.4 mg





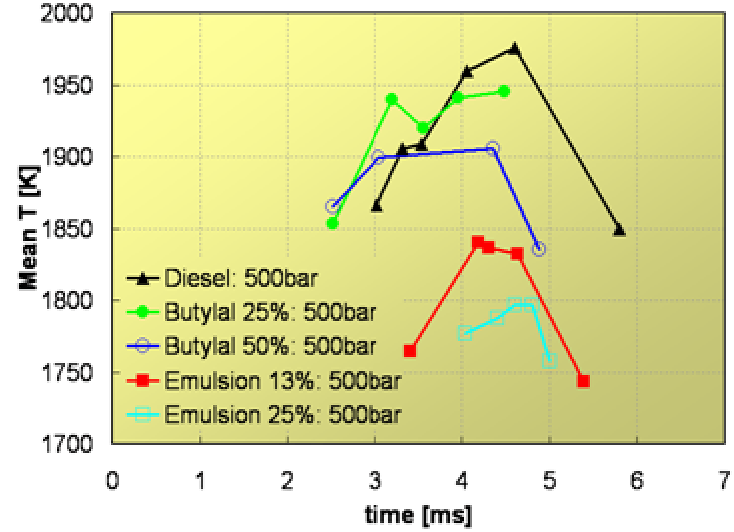
HTPC – SOOT PARAMETERS Fuel Composition Variation

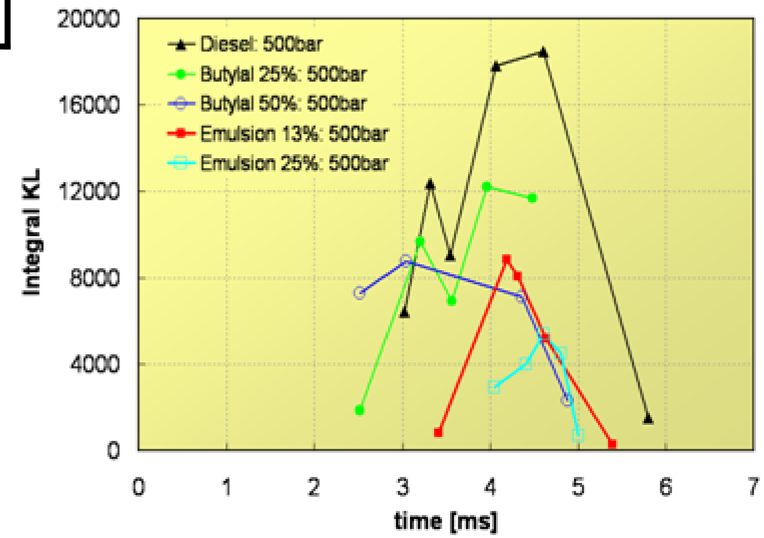
- **Investigated fuels**
  - Regular diesel
  - Diesel-butylal blends (25% & 50%)
  - Water-diesel emulsions (13% & 25%)
- **Constant injected energy content**

$C_4H_9\text{-}O\text{-}C\text{-}O\text{-}C_4H_9$

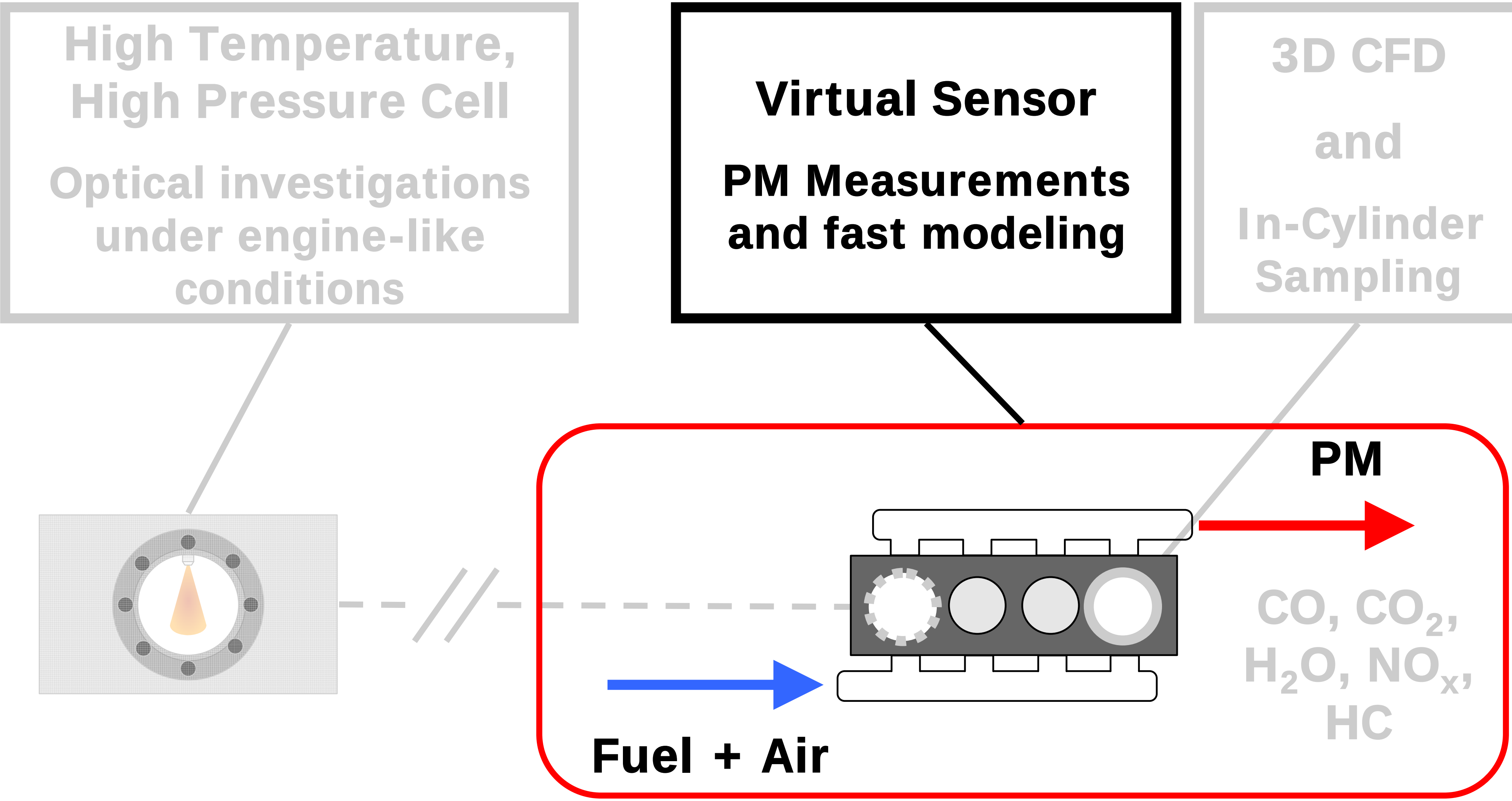
p_{cell}	60 bar
T_{cell}	790 K
p_{inj}	500 bar

- **Butylal results in:**
  - Decreased integral KL through:
    - Reduced soot formation
    - Enhanced oxidation (additional O_2)
- **Water emulsions result in:**
  - Even lower soot temperatures and integral KL through:
    - Enhanced mixing ("micro-explosions")
    - Increased O_2 availability
- **See poster #36 for details**





VIRTUAL SOOT SENSOR (VSS)



VIRTUAL SOOT SENSOR (VSS)

Overview

GOAL: Development of a fast model* for the prediction of engine-out soot emissions, based on information available from a production engine.

- **Model development**
  - Future reduction of existing phenomenological model for faster calculation times and inclusion of transient effects
  - Parameter optimization carried out using evolutionary algorithms
- **Validation measurements**
  - AVL Micro Soot Sensor and Dekati Fine Particle Sampler
  - Taken on a common rail, passenger car diesel engine
- **Today: Optimization and validation of "slow" (~1s) steady state model (basis of VSS)**

*Ideally real-time: $t_{calc} \sim x10^1$ [ms]

VIRTUAL SOOT SENSOR (VSS)

Soot Model

$$\frac{dm_{Soot}}{d\varphi} = \frac{dm_{Soot.Form}}{d\varphi} - \frac{dm_{Soot.Oxid}}{d\varphi}$$

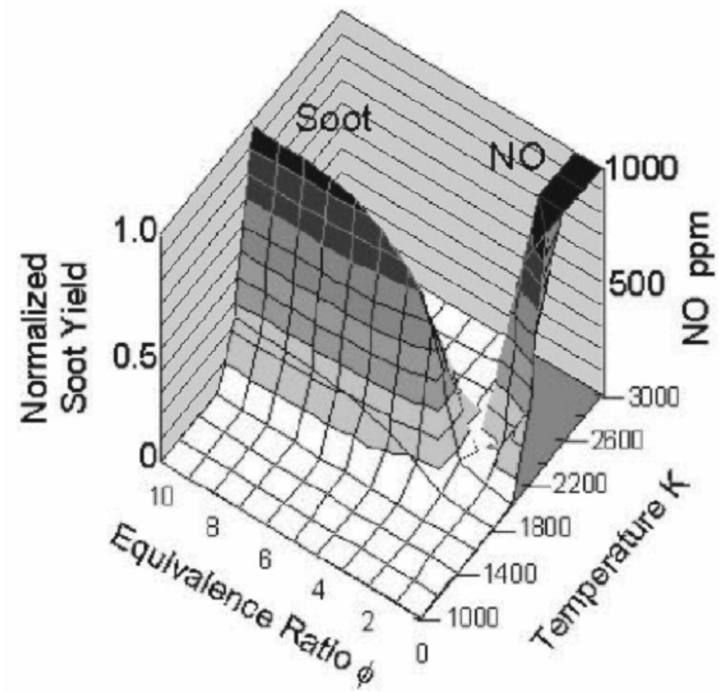
$$\frac{dm_{Soot.Form}}{d\varphi} = A_{Form} \cdot \frac{dm_{Fuel.Diff}}{d\varphi} \cdot \left[\left(\frac{p_{cyl}}{p_{ref}} \right)^{n_1} \cdot f\left(T_{Form}, \phi_{Form}\right) \right]$$

$$\frac{dm_{Soot.Oxid}}{d\varphi} = A_{Ox.O_2} \cdot \frac{1}{\tau_{char}} \cdot \left(m_{Soot}\right) \cdot \left(\frac{p_{O_2}}{p_{O_{2,Ref}}} \right)^{n_3} \cdot e^{-\frac{T_{A.Ox.O_2}}{T_{Ox.O_2}(\lambda_{Ox})}}$$

Parameters requiring optimization

- **Calculation requires:**
  - $p_{cyl}(\varphi)$, $m_{inj}(\varphi)$,...
  - Thermodynamic analysis, including mass fraction burned history (WEG)
- **1 Point: ~1 sec. calculation time**

See Warth (2005) for details

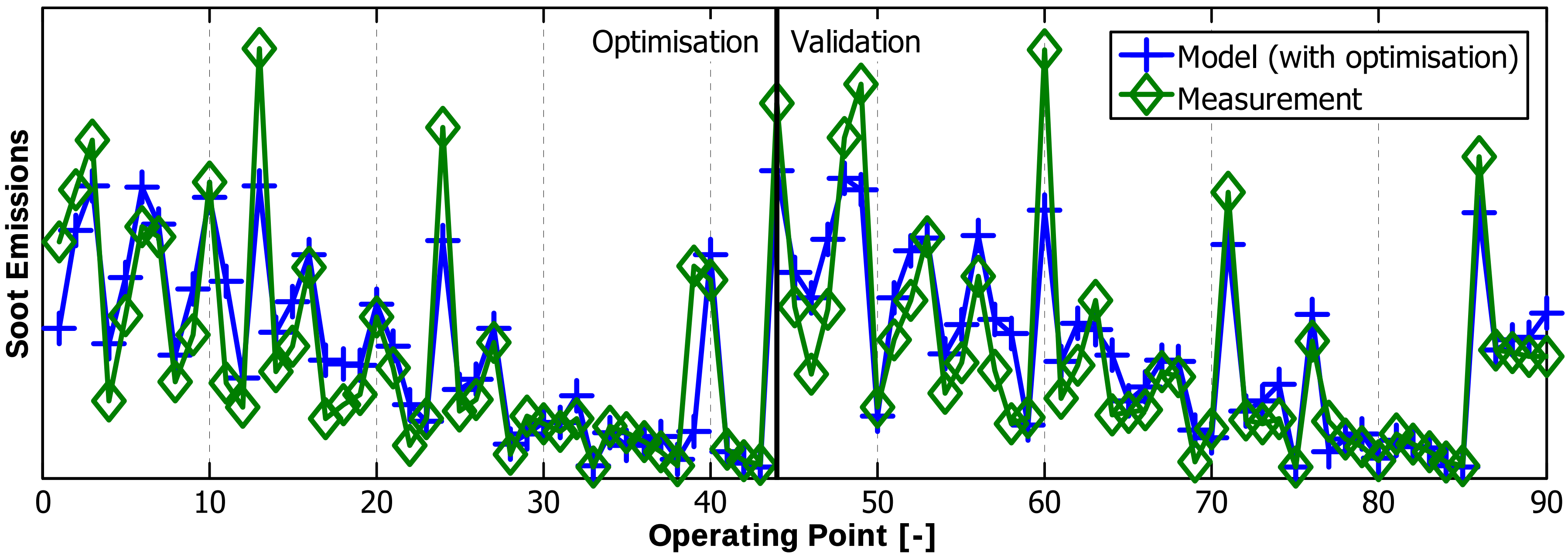


Akihama et al.
(SAE 2001-01-0655)

VIRTUAL SOOT SENSOR (VSS)

Preliminary Results

- Existing model optimized using evolutionary algorithms for steady state engine operation
- Optimization is dependant on fuel/engine combination
- Calc. time ~1 sec. / point
- Qualitative and quantitative trends reproduced in validation
- Extreme soot emissions not well reproduced by model
- Only representative formation and oxidation zones are considered



3D CFD – SOOT MODELLING

High Temperature, High Pressure Cell

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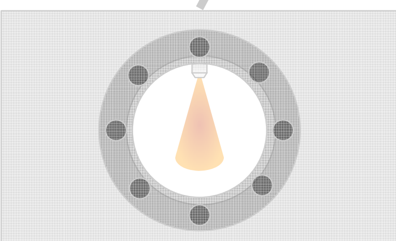
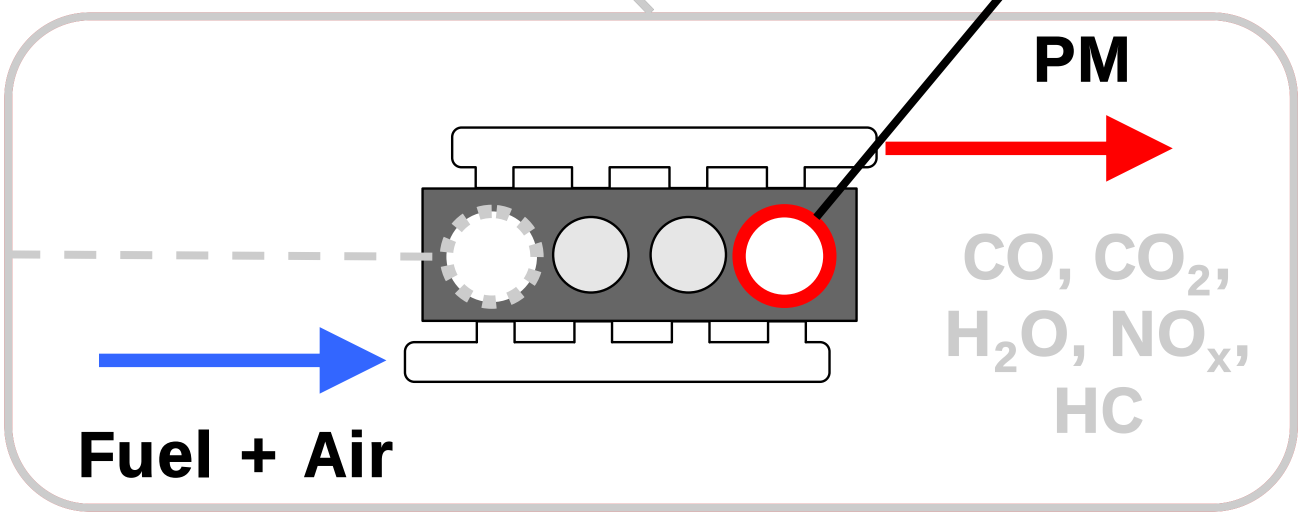


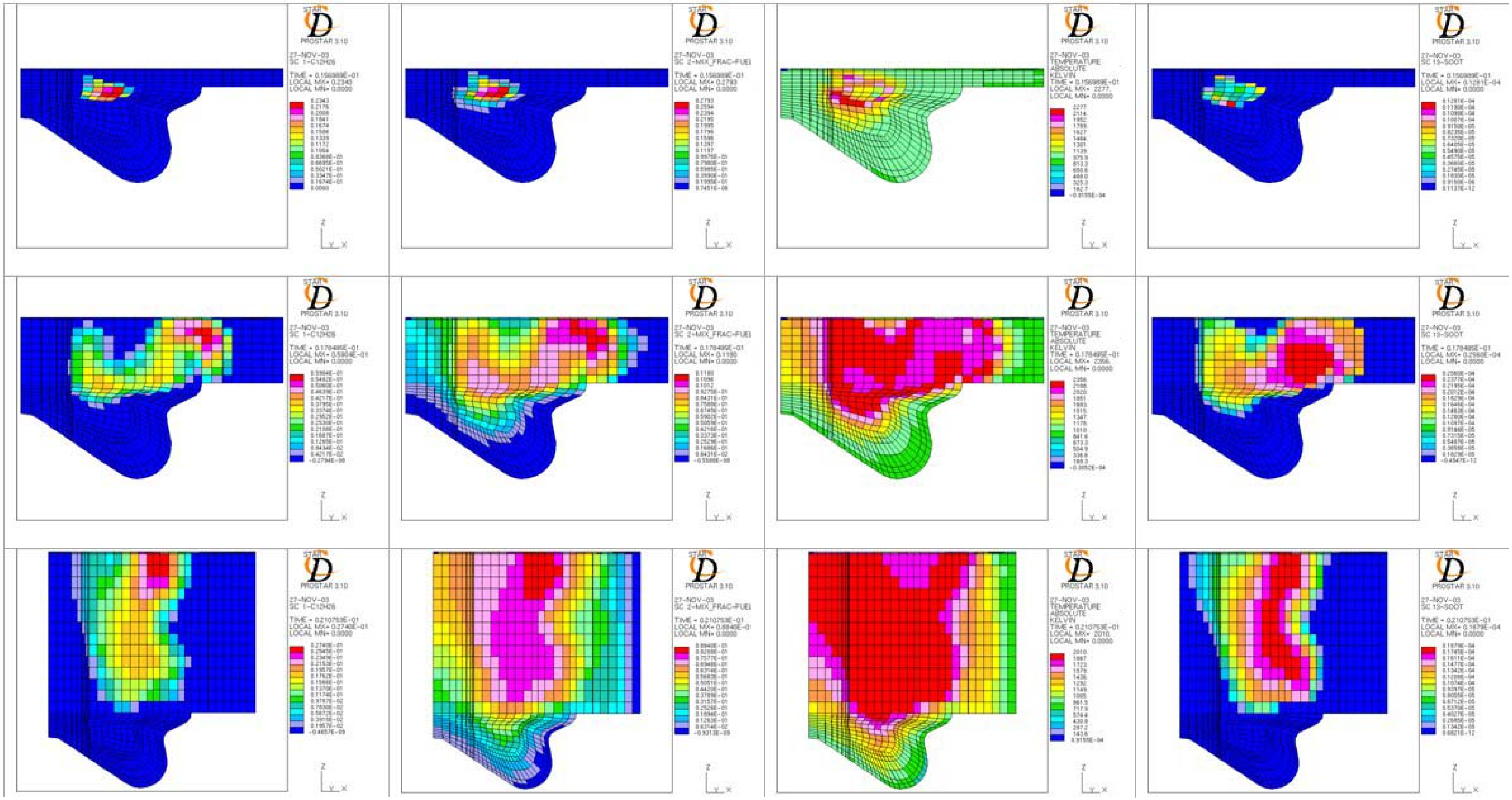


3D CFD

Temporal and Spatial Evolutions

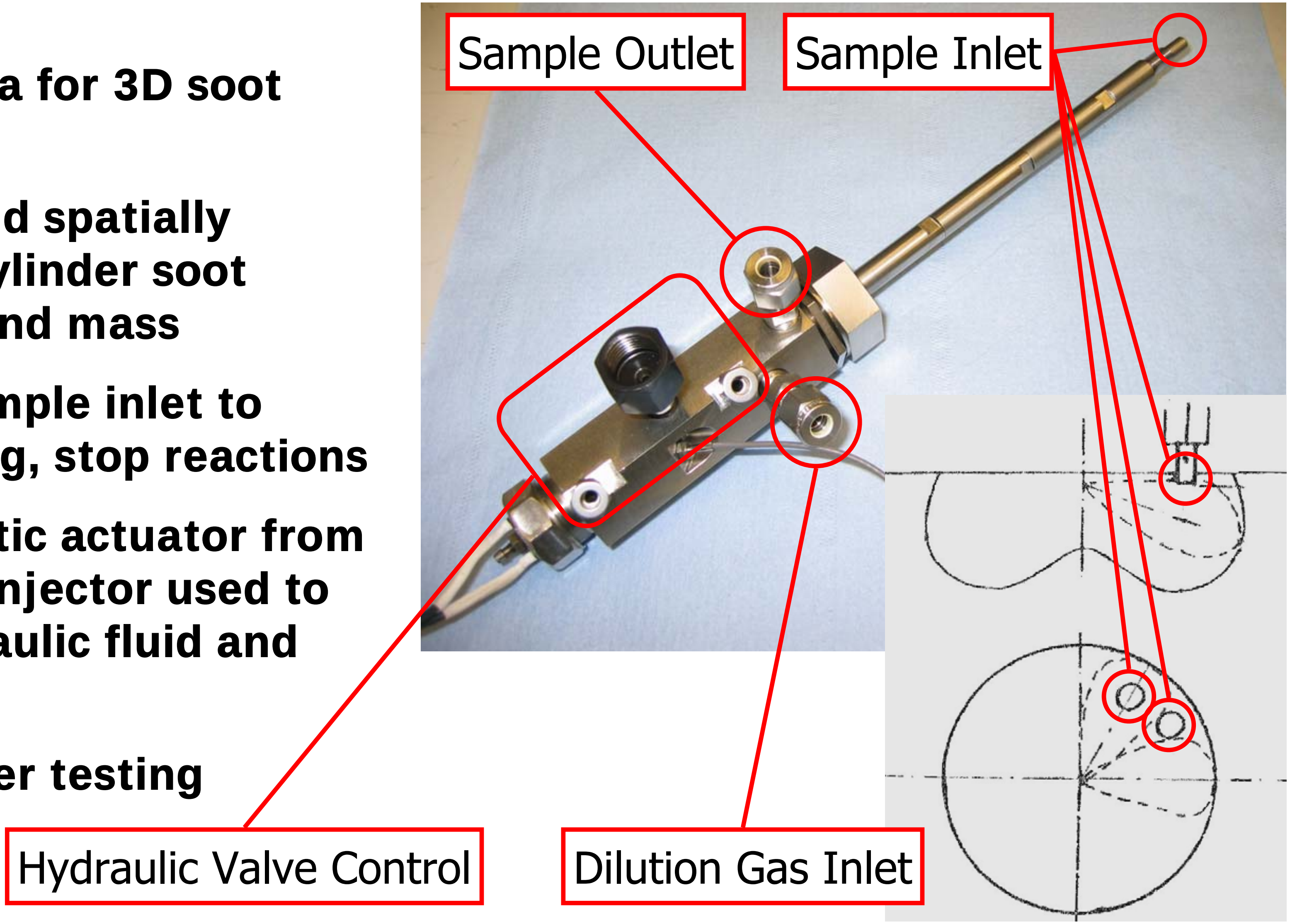
Liquid Fuel Concentration | Gaseous Fuel Concentration | Temperature | Soot Concentration

Crank Angle [°CA aTDC]: 10°, 30°, 60°



3D CFD – MODEL VALIDATION In-Cylinder Sampling

- **Validation data for 3D soot model**
- **Temporally and spatially resolved, in-cylinder soot composition and mass**
- **Dilution at sample inlet to provide cooling, stop reactions**
- **Electromagnetic actuator from common-rail injector used to regulate hydraulic fluid and needle valve**
- **Currently under testing**



SUMMARY

GOAL: Understanding the formation and oxidation of particulate matter in common rail diesel engines

- **HTPC: Two Color Pyrometry**
  - Influence of fuel and injection parameters on soot formation and oxidation
- **VSS: "Fast" Soot Modeling**
  - On-line determination of soot emissions using fast phenomenological models and evolutionary algorithms for parameter optimization
- **3D CFD: In-Cylinder Formation and Oxidation**
  - Calculation and measurement of temporally and spatially resolved soot distributions

ACKNOWLEDGEMENTS

BFE
OFEN
UFE
SFOE

Forschungsvereinigung
Verbrennungskraftmaschinen

FVV

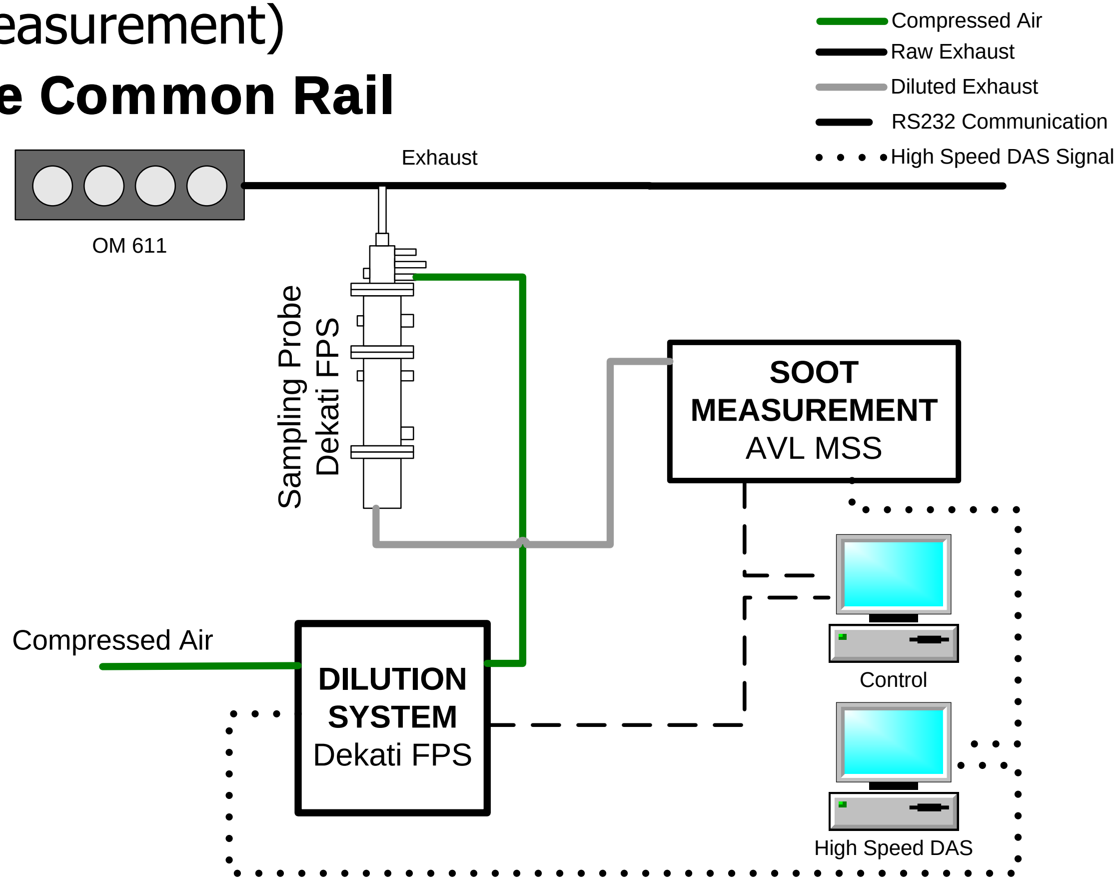
QUESTIONS?

VIRTUAL SOOT SENSOR (VSS)

Measurements

- **Steady state and transient soot emissions for model validation and optimization**
- **Dekati Fine Particle Sampler** (Dilution)
- **AVL Micro Soot Sensor** (Soot Measurement)
- **Carried out on a representative Common Rail diesel engine**

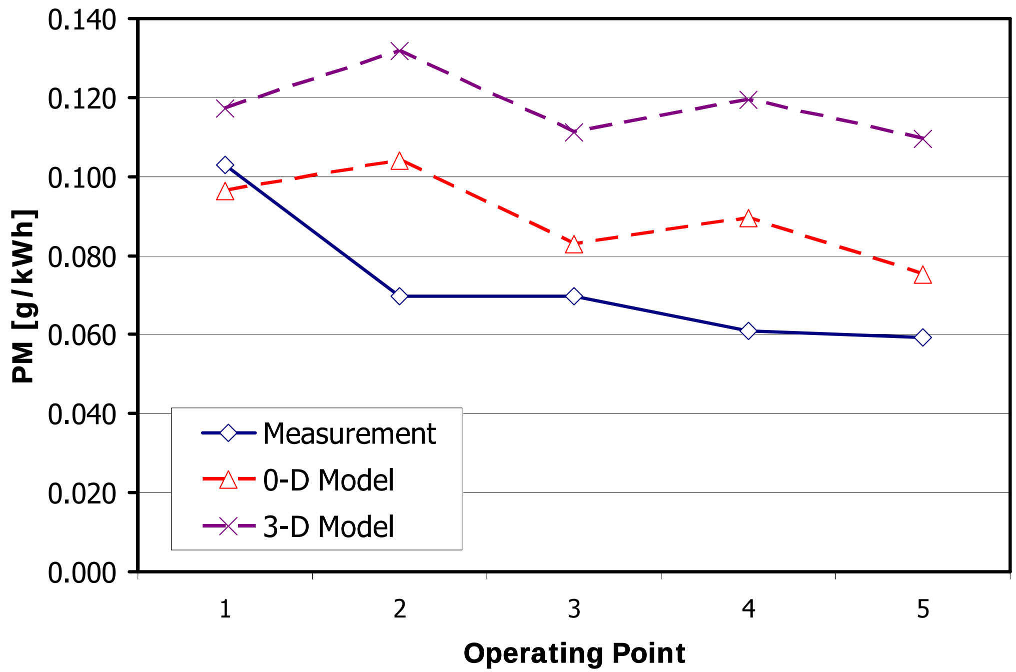
DaimlerChrysler OM611	
Displacement [l]	2.15
Number of Cylinders [-]	4
Valves/Cylinder [-]	4
Bore [mm]	88.0
Stroke [mm]	88.4
Compression Ratio [-]	19:1
Injection Pressure [bar]	500 - 1350



3D CFD

Soot Modeling Overview

- Implement phenomenological soot model for 3D calculations
- Apply the phenomenological soot model locally in each cell (during post-processing)
- Summation of soot mass in all cells gives total soot mass
- Both “hot” and “cold” soot are included, as many cells are considered
- Soot model requires separate parameter optimization for 3D application



- Comparison with gravimetric measurements from a single cylinder HD engine