Influence of Engine Operating Parameters on Physical and Chemical Properties of Emitted Soot Particles

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Motivation

Physical and chemical properties of soot particle emissions change with engine operating conditions [1-9]

- primary particle size
- oxidation behavior
- VOF / EC
- BET surface area
- morphology
- graphitization
- reactive groups
- toxic and inflammatory potential

→ **Influence on environment and human health**

→ **Consequences for catalytic aftertreatment**

[1] Su et al., 2008, [2] Su et al. 2004, [3] Jacob et al. 2003, [4] Ghzaoui et al. 2003, [5] Kennedy 2007, [6] Müller et al. 2005, [7] Wittmaack 2007, [8] Stratakis et al 2003, [9] Lapuerta et al. 2007

Motivation – Engine Sequence of Events

Can we correlate combustion to emitted particle characteristics ?

Injection

pressure,
timi g, quantity

Bound cond.

fuel,
temp
engi

Mixture formation

evaporation,
tumble a d swirl
motio quid and
fuel
tion, 3D

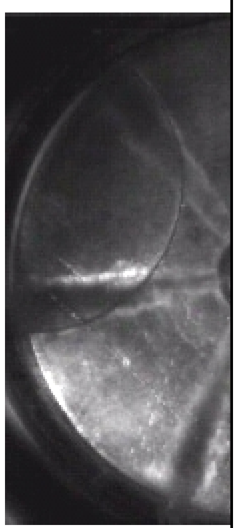
Combustion

Co l flame,
hom eneous-,
pr xed-,
d n
co n

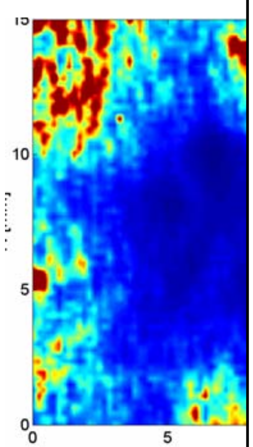
Engine-out emissions

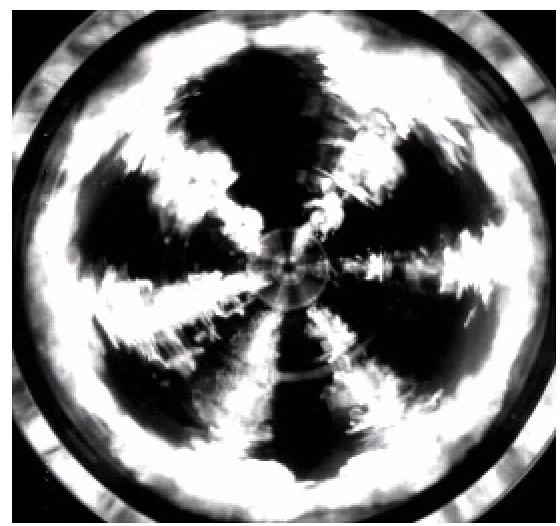
n

n



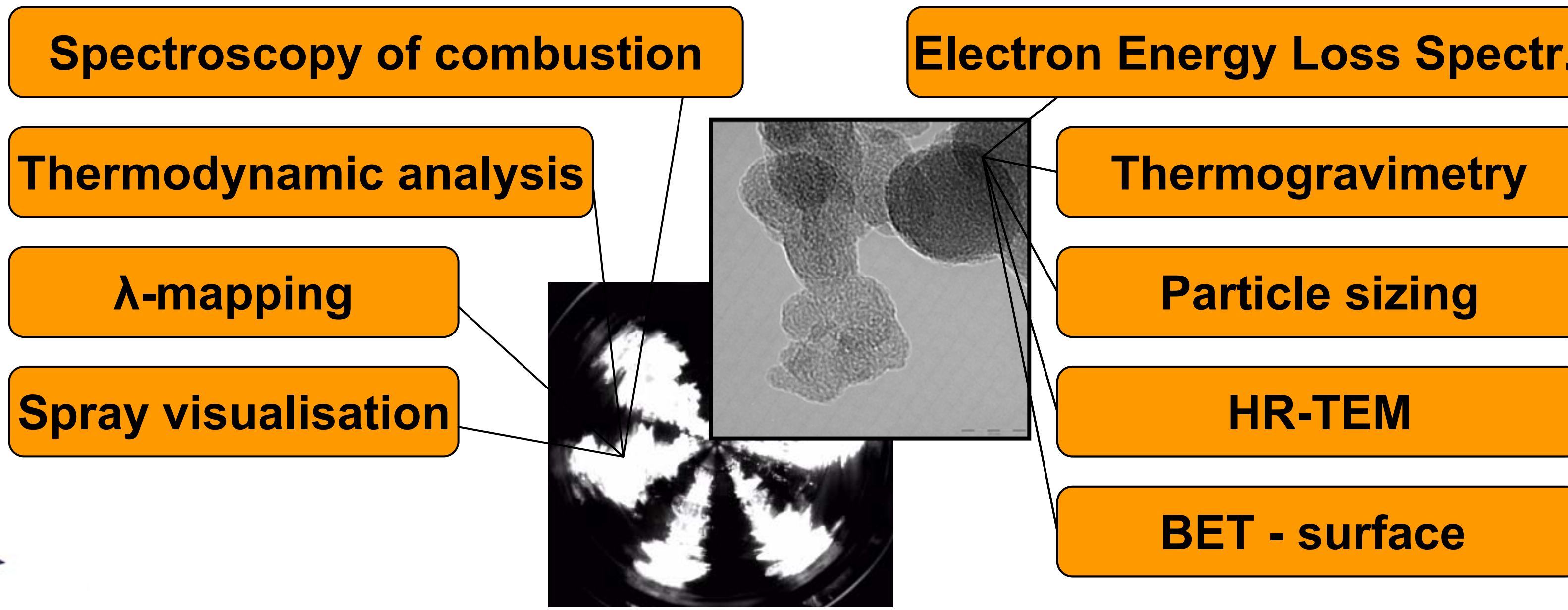
λ at start of





Measurement program and techniques

Simultaneous in-cylinder and engine-out measurements for a variation of engine operating parameters



Engine measurements

- Optically accessible single-cylinder test engine
- Engine dyno: Audi 3.0 l V6-TDI engine (EURO 4)

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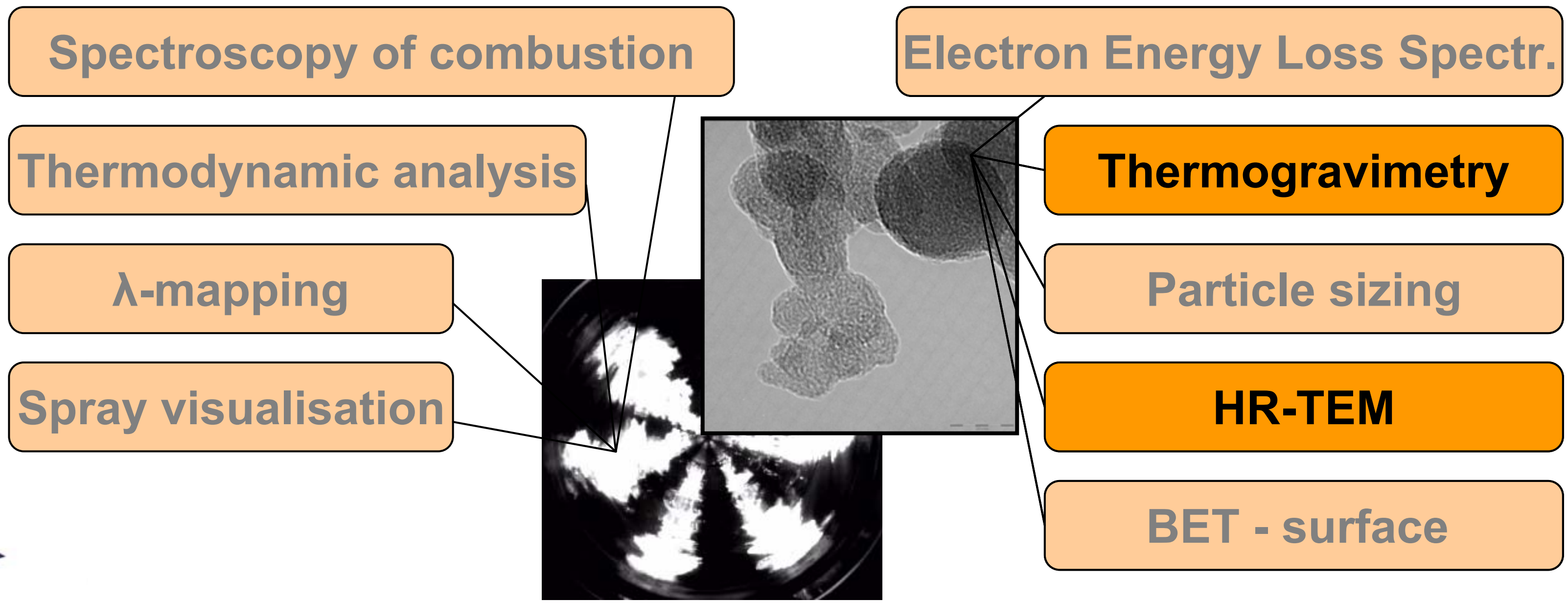


Engine measurements

Engine dyno: Audi 3.0 l V6-TDI engine (EURO 4)

Dynamometer measurements

Engine: Motored Audi V6 TDI (EURO 4) on a dyno test bench

Tailpipe soot sampling

- direct sampling for HR-TEM measurements
- diluted sampling on quartz glass filters for thermogravimetry

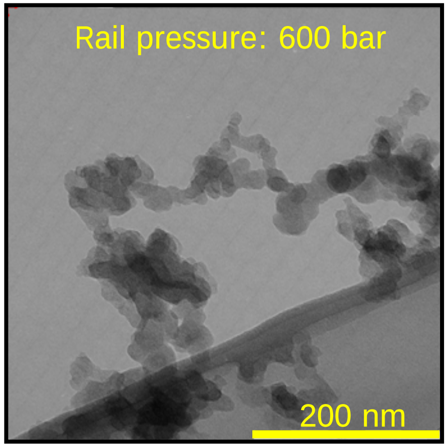
Operating conditions

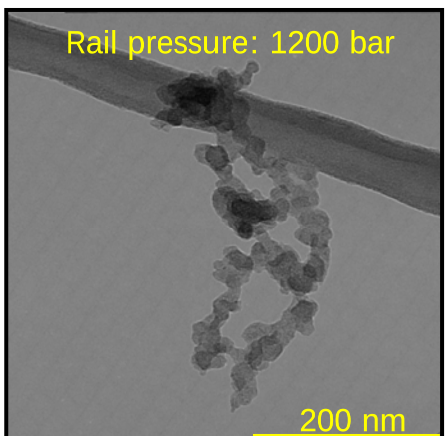
- Static operating conditions for all measurements
- Variation of rail pressure, torque and air/fuel-ratio ($\lambda = 1/\Phi$)

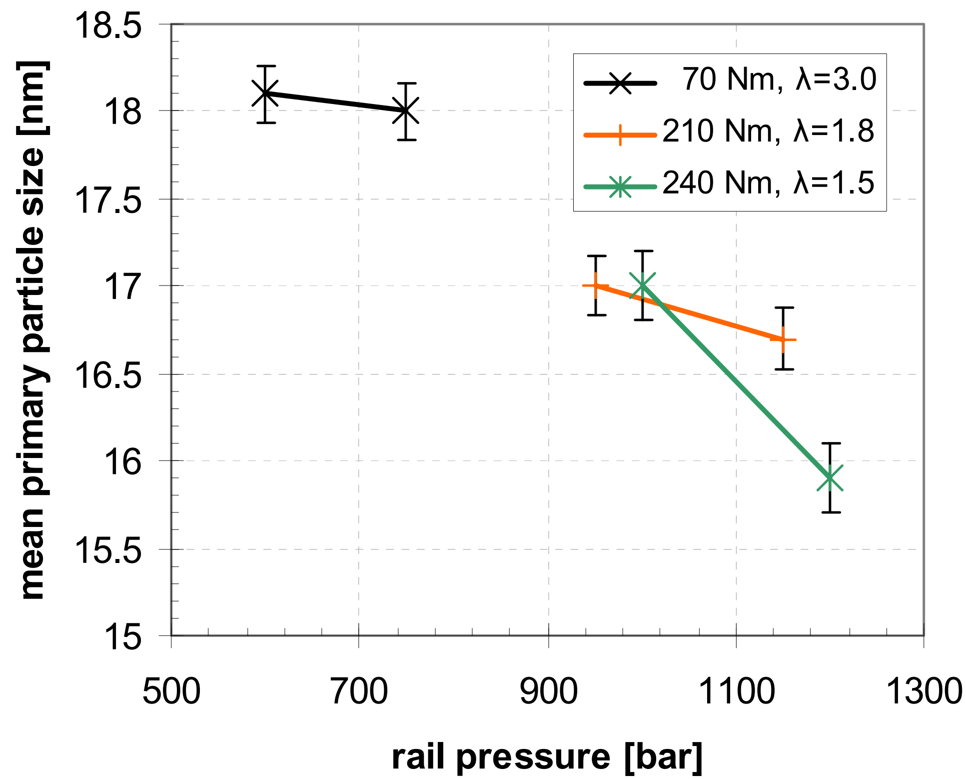
	OP1	OP2	OP3	OP4	OP5	OP6
Torque [Nm]	70	70	210	210	240	240
Rail pressure [bar]	600	750	950	1150	1000	1200
Air/Fuel ratio	3	3	1.8	1.8	1.5	1.5

Direct soot sampling for HR-TEM

Size determination of primary particles



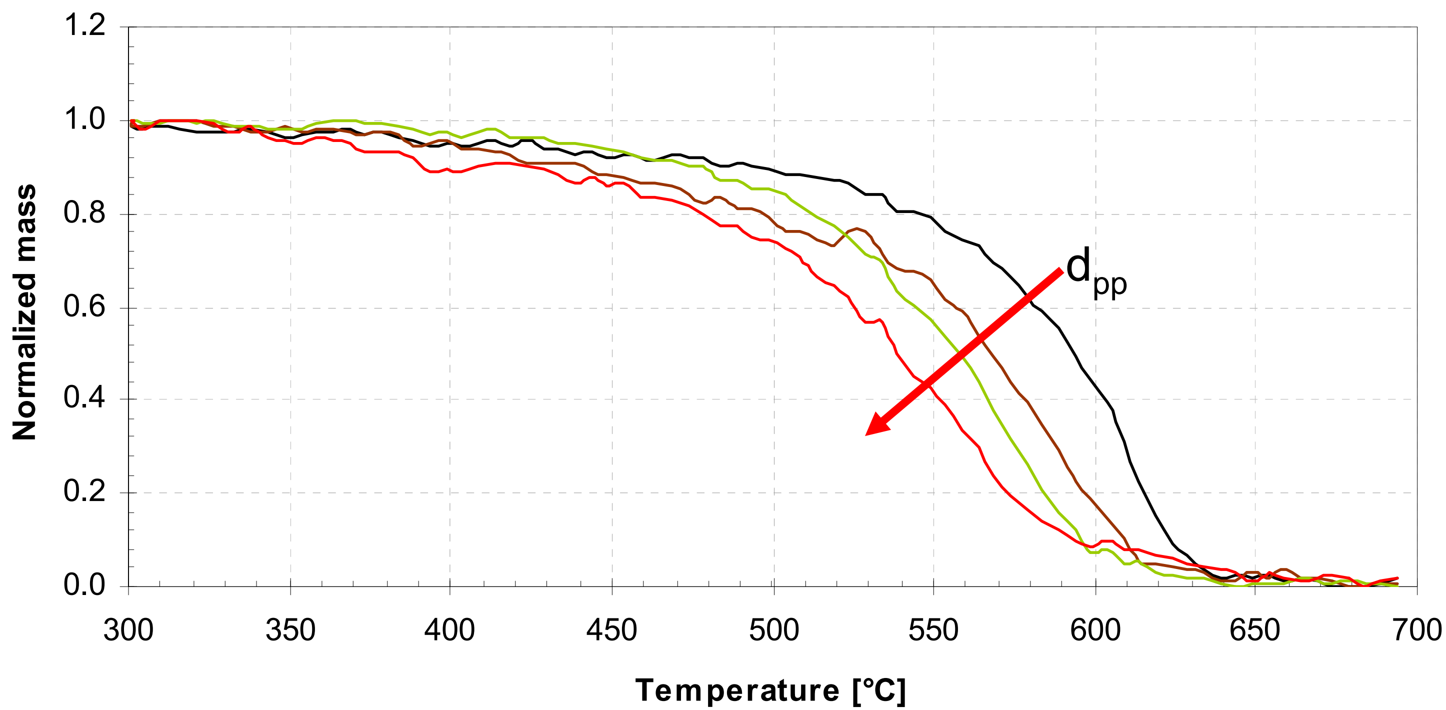




Thermogravimetry

Different oxidation behavior of dried soot samples

Drying in N_2 atmosphere, oxidation in air (150 ml/min, 10 K/min)



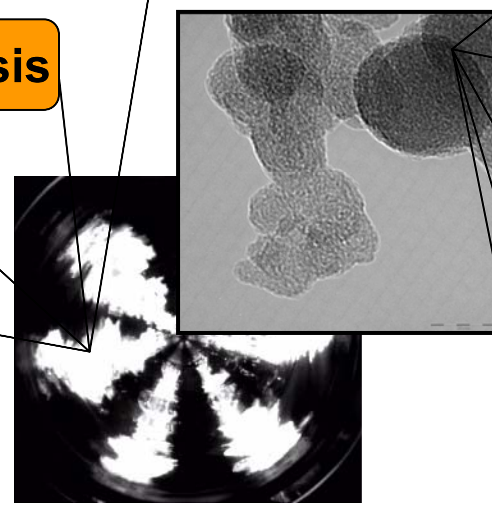
→ Faster oxidation for samples with smaller mean primary particle size

→ TGA results support HR-TEM primary particle sizing

Optical measurements

Changes in particle properties are related to the combustion

- **Spectroscopy of combustion**
- **Thermodynamic analysis**
- λ-mapping
- **Spray visualisation**



- Electron Energy Loss Spectr.
- Thermogravimetry
- Particle sizing
- **HR-TEM**
- BET - surface

Engine test objects

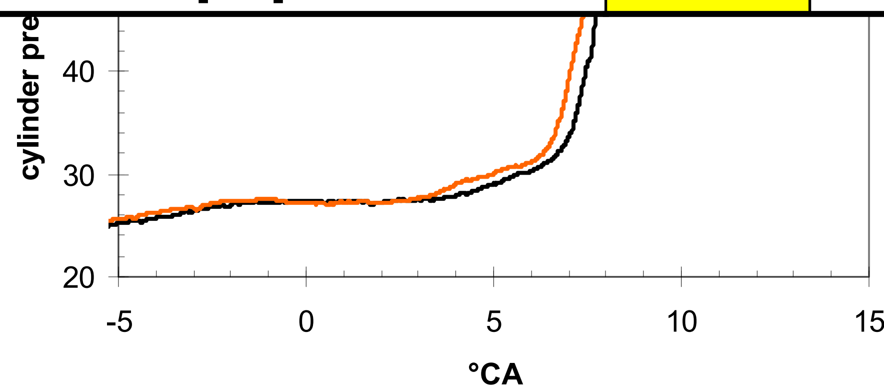
- Optically accessible single cylinder test engine

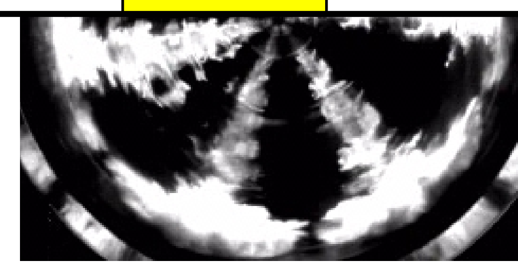
Optically accessible single cylinder engine

Engine operating conditions

Speed: 800 rpm / boost: 1.05 bar / SOI: -1.5 °CA

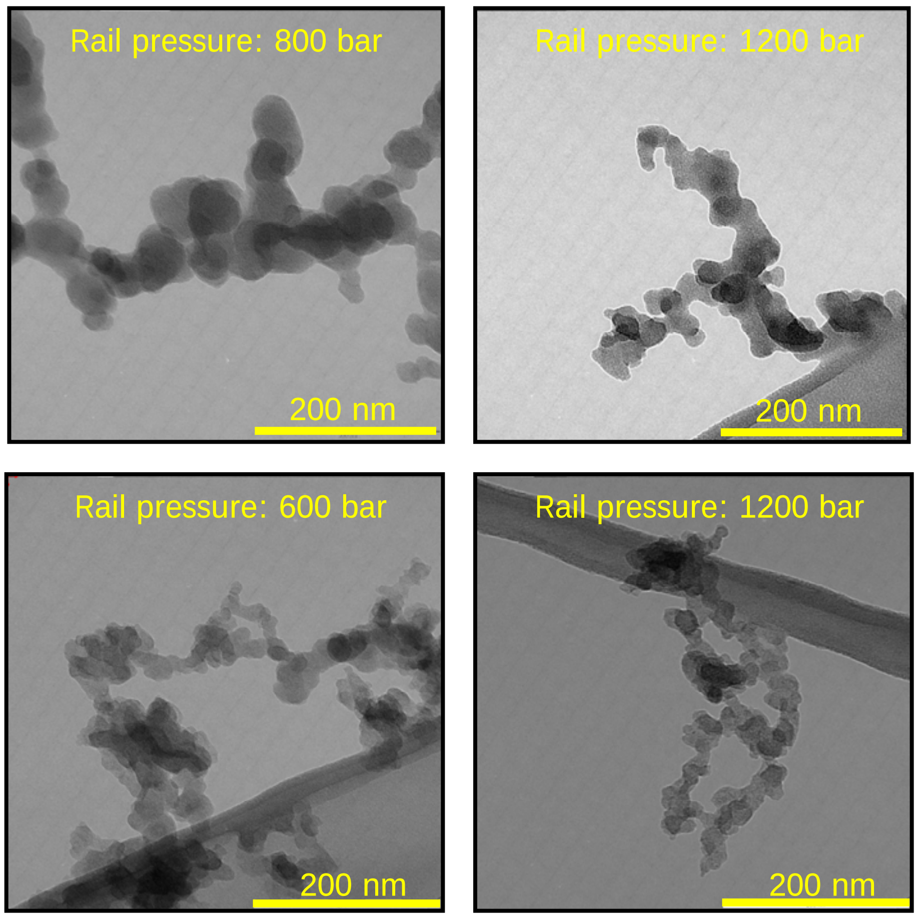
Operating point (OP)	OP1	OP2	OP3	OP4
Rail pressure [bar]	800	800	1200	1200
EGR-rate [%]	0	50	0	50
Pressure rise rate [bar/°CA]	30.8		18.1	
Ignition delay [ms]	2.1		2.0	
Maximum pressure [bar]	60.2		56.2	
Burntime [ms]	74		60	





Engine out soot analysis

Direct soot sampling in the tailpipe for electron microscopy



Primary particle mean size is reduced for increasing rail pressure

33.8 nm @ 800 bar

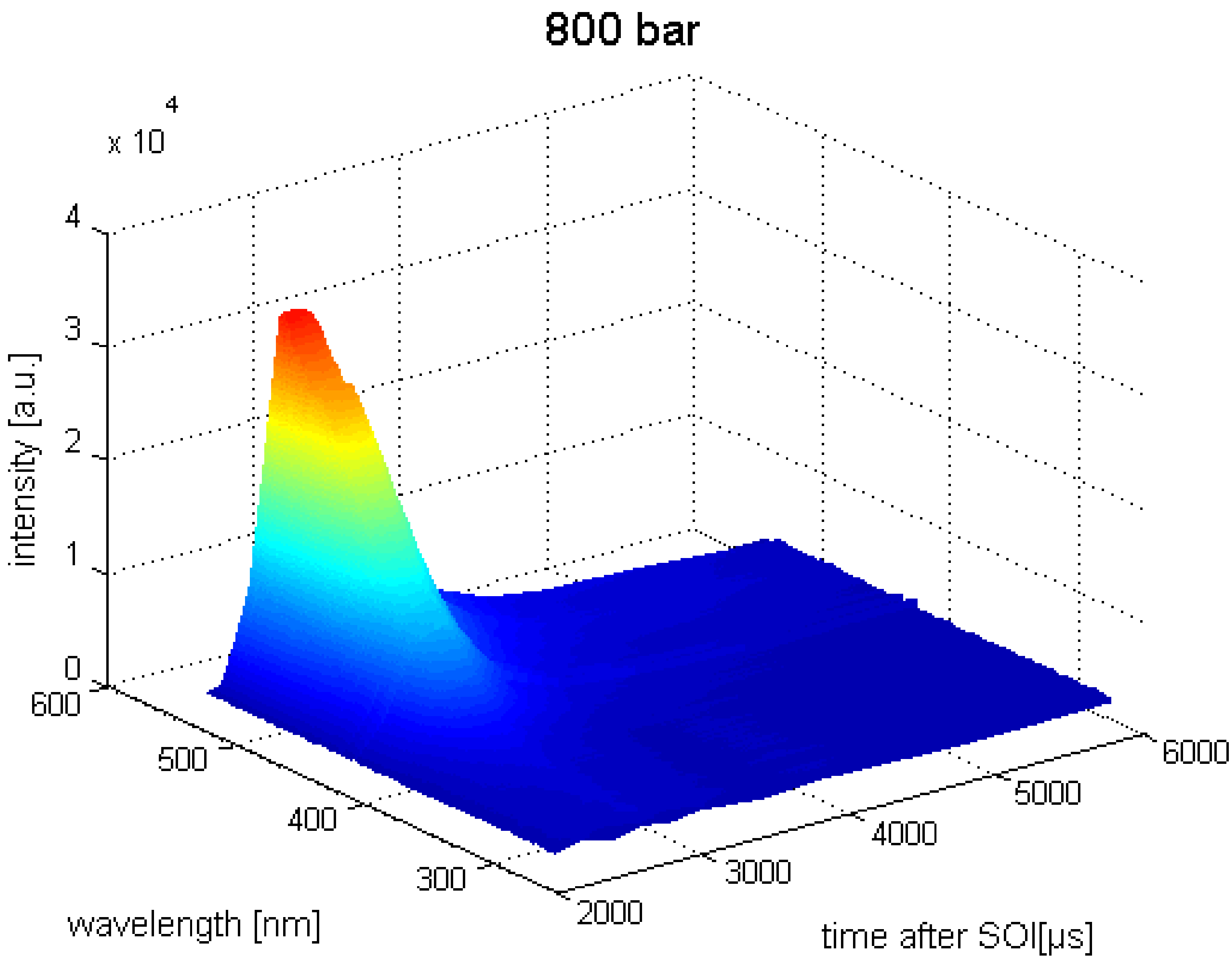
30.0 nm @ 1200 bar

Comparison to Audi V6 TDI engine

18.2 nm @ 600 bar

15.9 nm @ 1200 bar

Optical measurements: Spectroscopy



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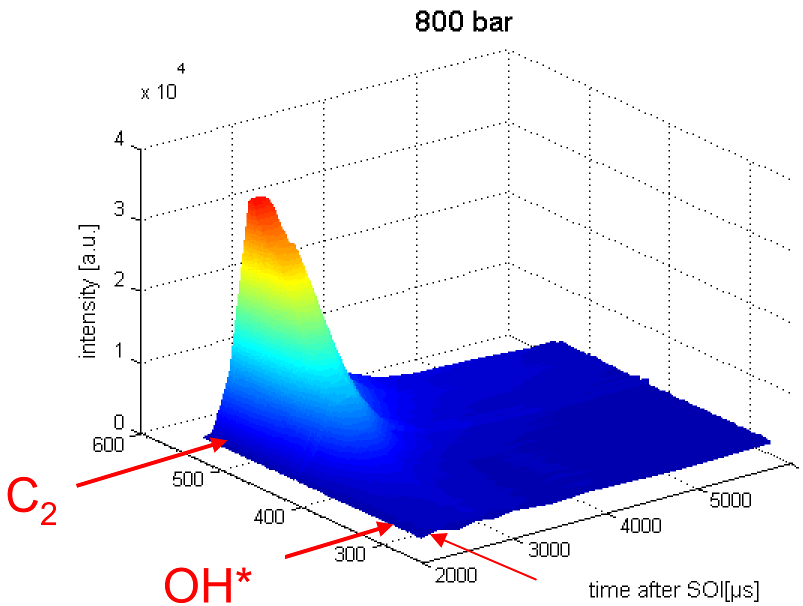
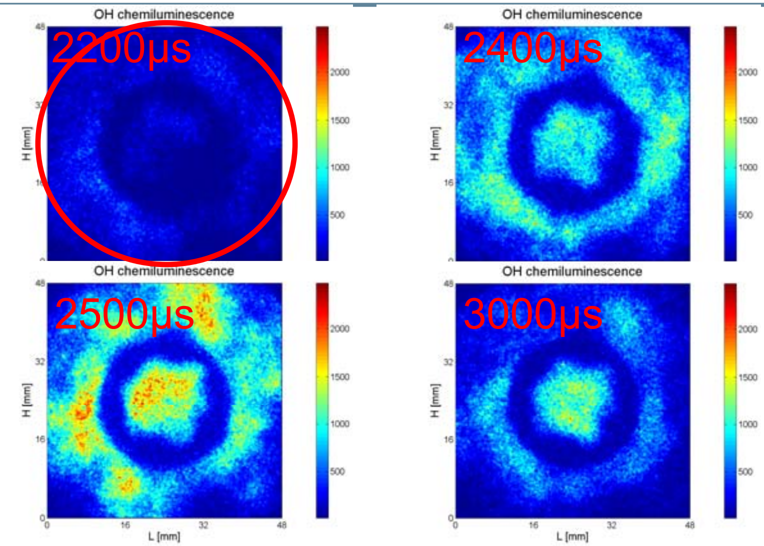
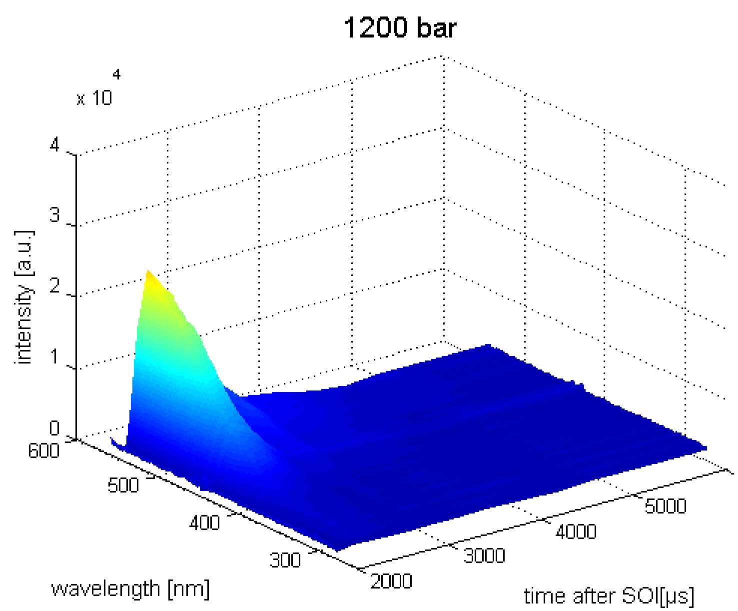
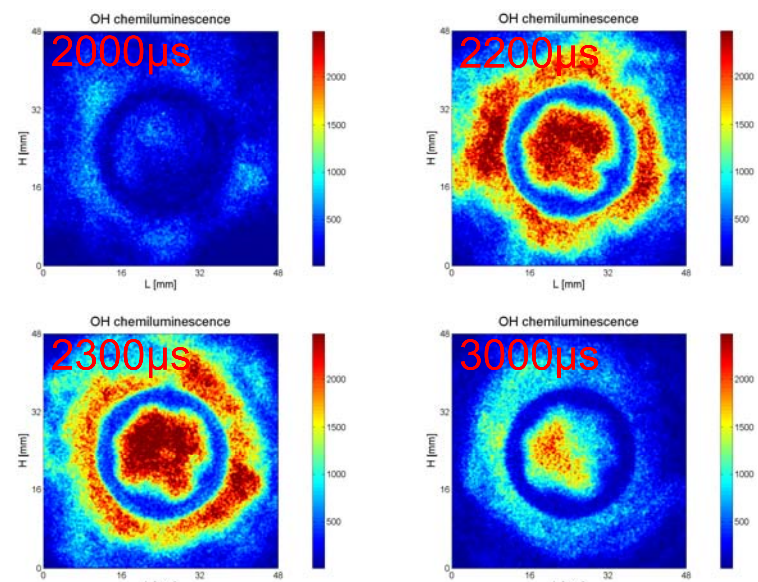
Optical measurements: Spectroscopy

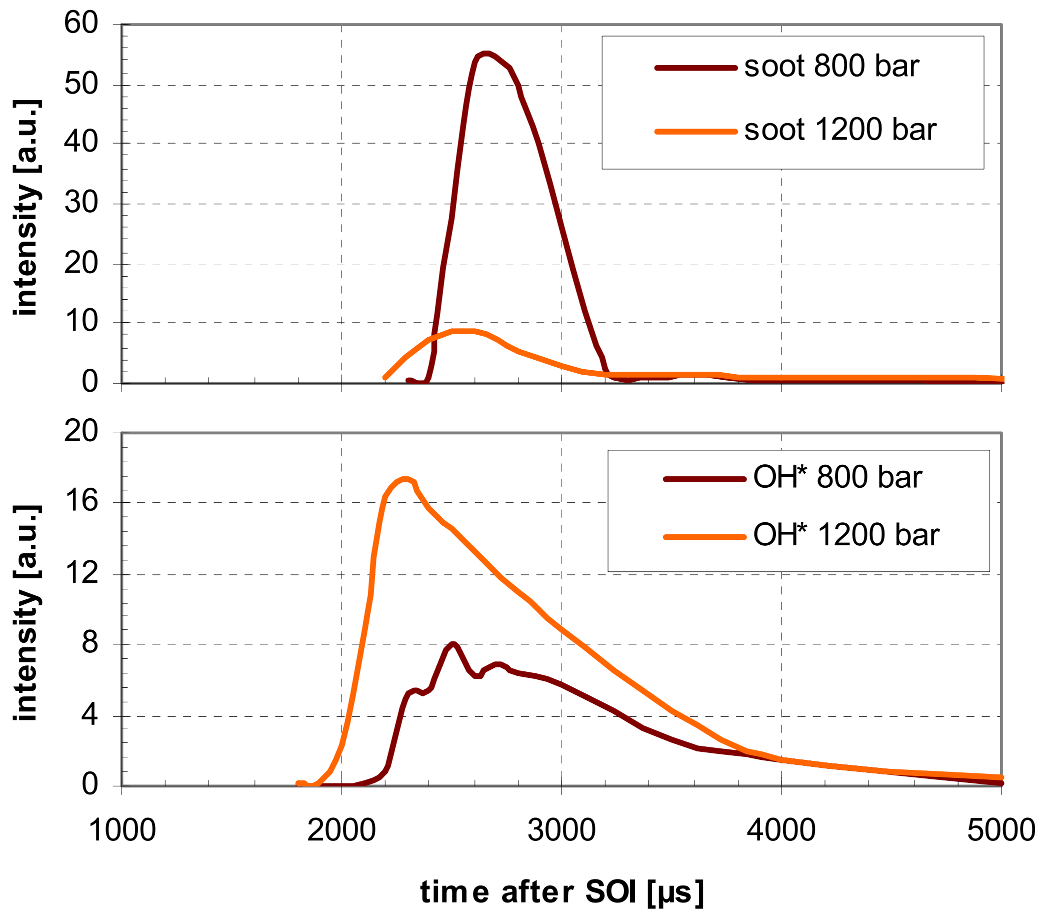








Optical measurements: Spectroscopy



[10] Angrill et al., 2000,
[11] Oh et al. 2006

Signal ratio of soot luminescence (at 550 ± 10 nm) to OH* (308 ± 10 nm) chemiluminescence varies

→ Different rail pressures cause changes in mixture formation

Results: optically accessible single cylinder

Similar trends for both engines

→ Increasing rail pressure reduces mean primary particle size.

→ Soot with smaller primary particles has a faster oxidation behavior.

For 1200 bar rail pressure optical investigations have revealed

→ lower intensity of soot luminosity

→ increased OH* concentration

→ differences in mixture formation

Conclusion and Outlook

→ Results have shown that engine operating conditions influence properties of engine-out soot particles.

→ Optical measurements are useful to analyze the differences in combustion.

→ A combination of optical, physical and chemical techniques can be used to correlate combustion to soot properties.

Current and future work includes

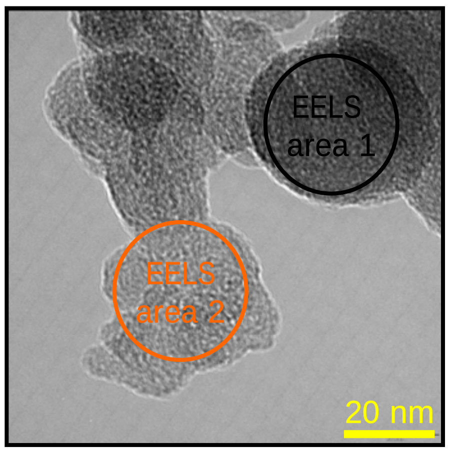
- extended study of important engine operating parameters
- additional analysis of mixture formation, EELS, total soot emissions and BET surface area
- study on toxic and inflammatory effects

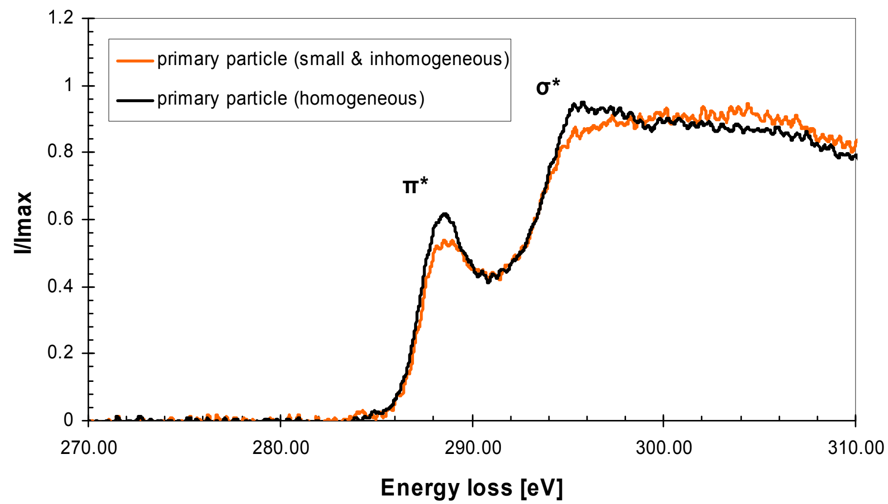
Thank you for listening

Questions ?

We like to thank

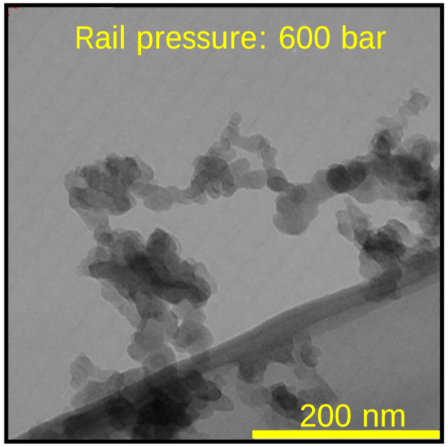
- The German Research Foundation for financial support
- C. Liebscher, Lehrstuhl für Metallische Werkstoffe, HR-TEM
- N. Müller, Lehrstuhl für Chemische Verfahrenstechnik, Bayreuth Engine Research Center,TGA

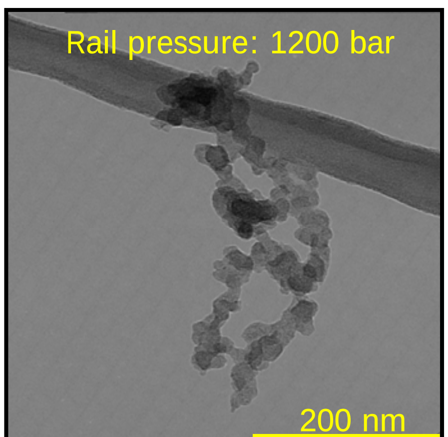

EELS
area 1
EELS
area 2
20 nm


primary particle (small & inhomogeneous)
primary particle (homogeneous)
σ*
π*
I/Imax
1.2
1
0.8
0.6
0.4
0.2
0
270.00
280.00
290.00
300.00
310.00
Energy loss [eV]

Direct soot sampling for HR-TEM and EELS

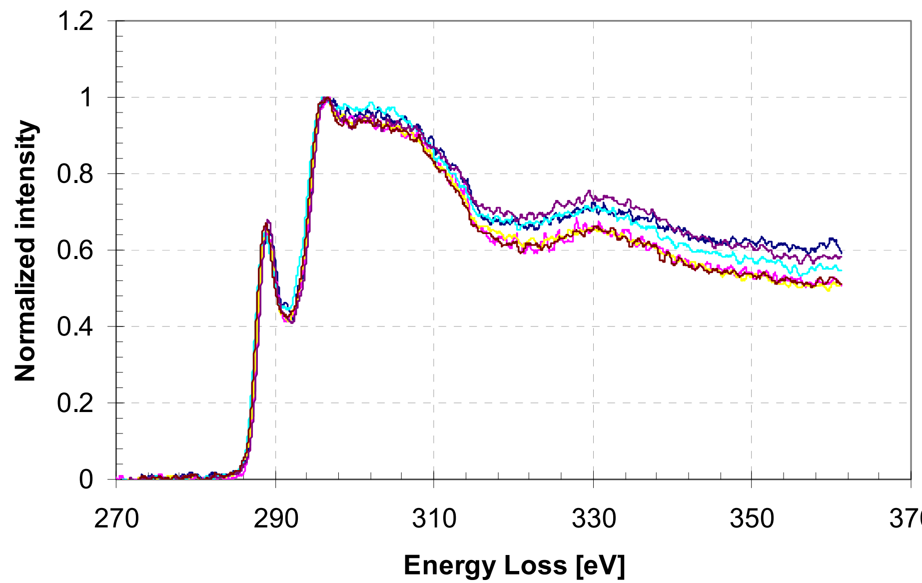
Engine operating conditions for the tail pipe soot sampling





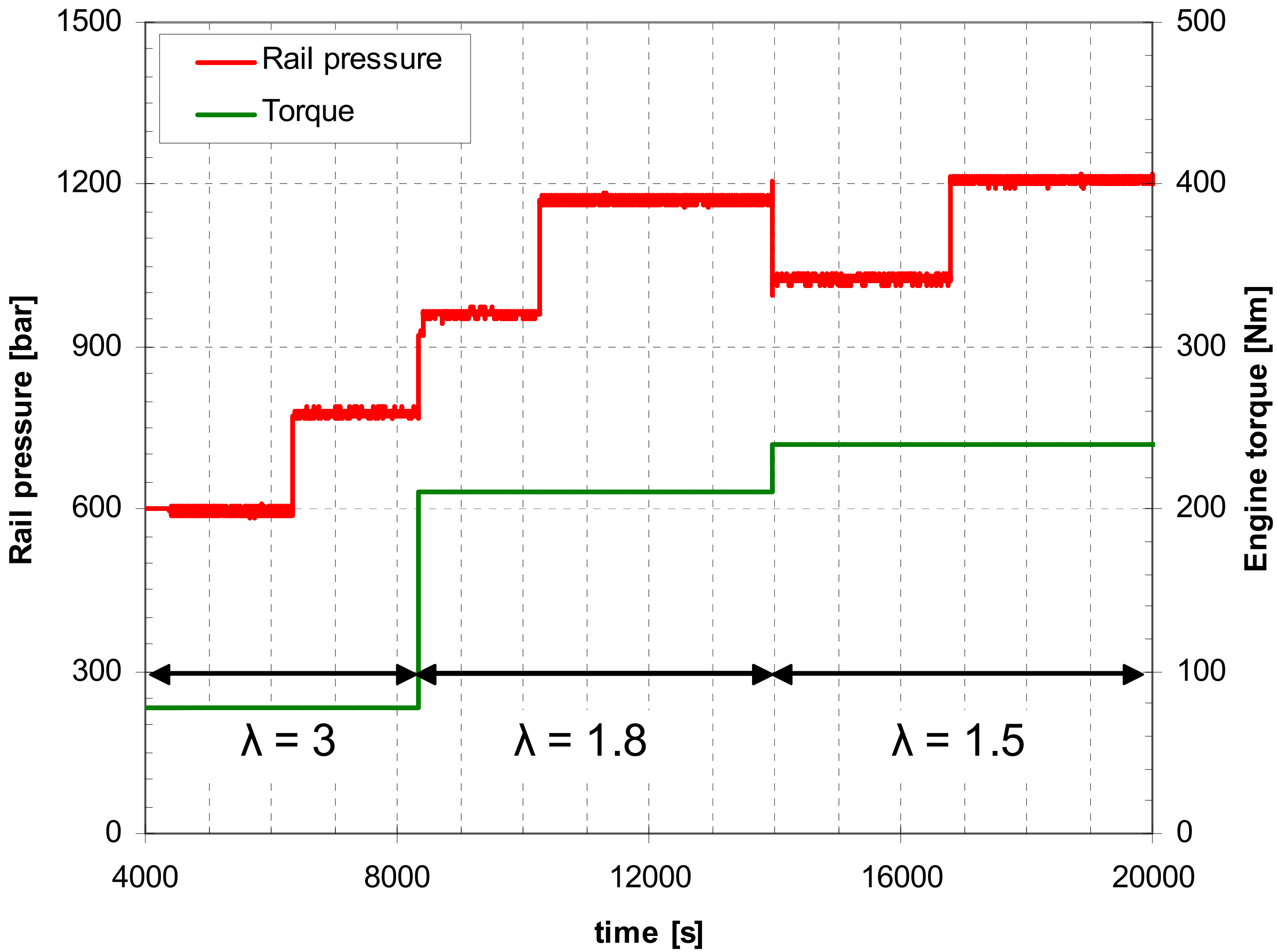
→ Size determination of primary particles

→ EELS measurement of agglomerates



Operating Conditions

Engine operating conditions for the tail pipe soot sampling



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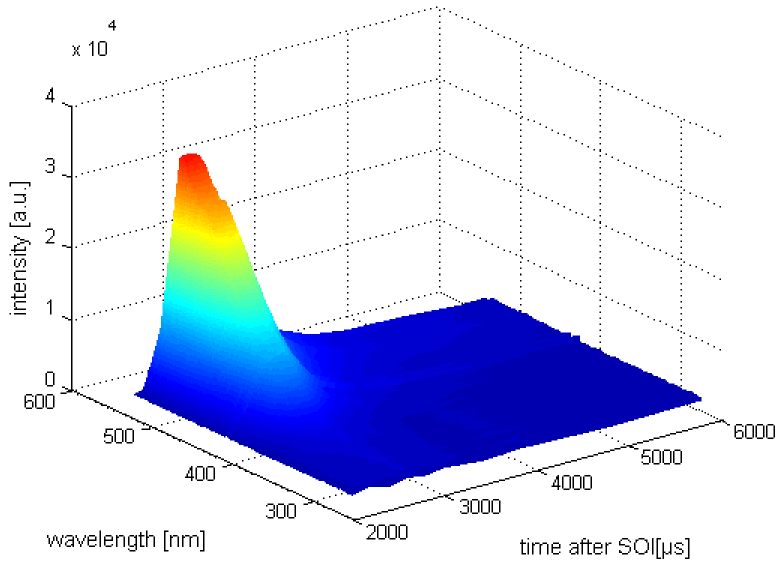
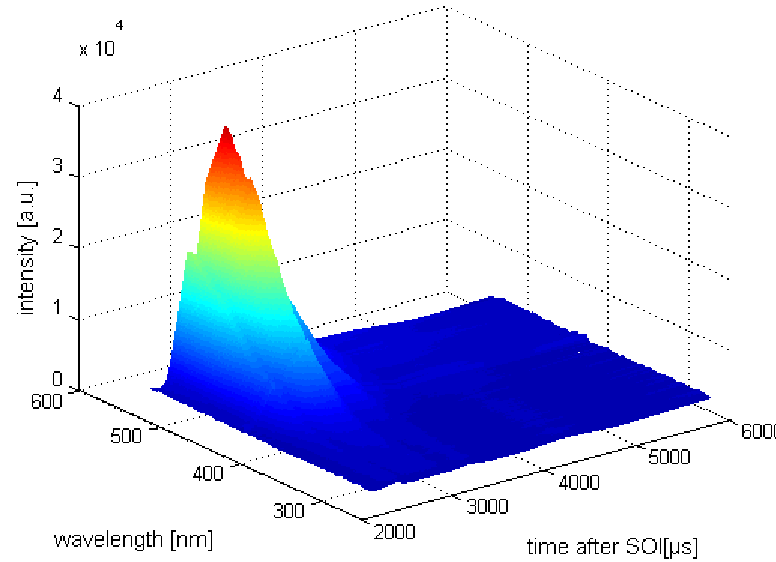
Optical measurements: Spectroscopy

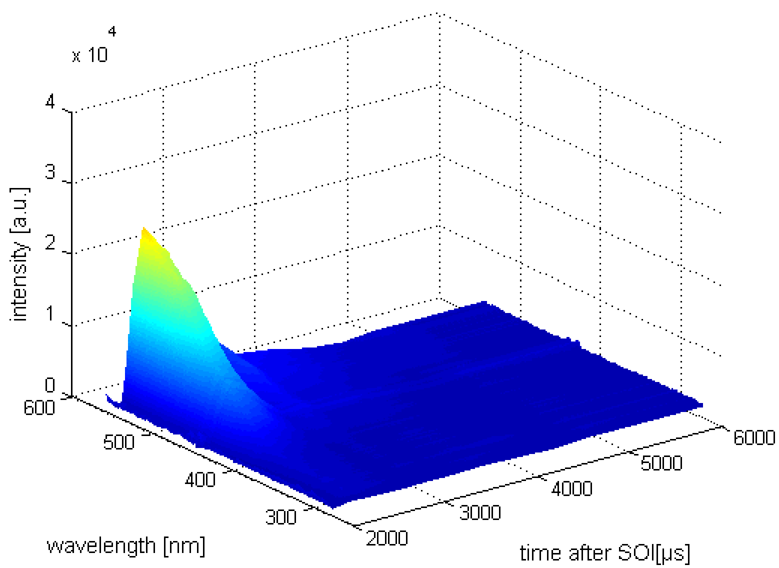
800 bar



800 bar / EGR



1200 bar



1200 bar / EGR