AVL

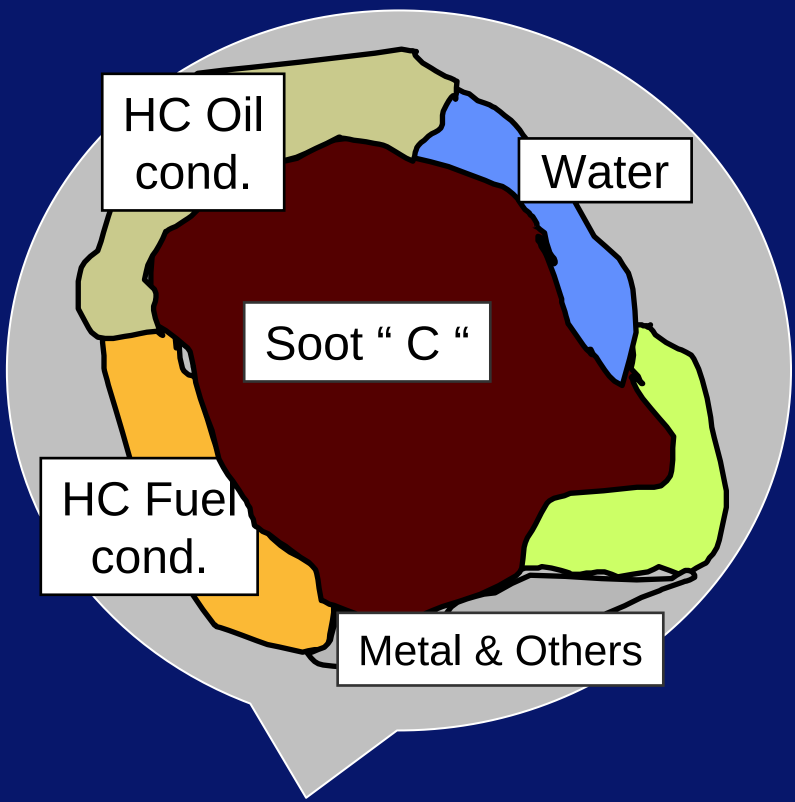
# Notes on „Soot“ Measurement of Diesel Engines


**Wolfgang Schindler**
**Wolfgang Singer**

AVL List GmbH, Graz, Austria

# Why bother about Soot Measurement ?

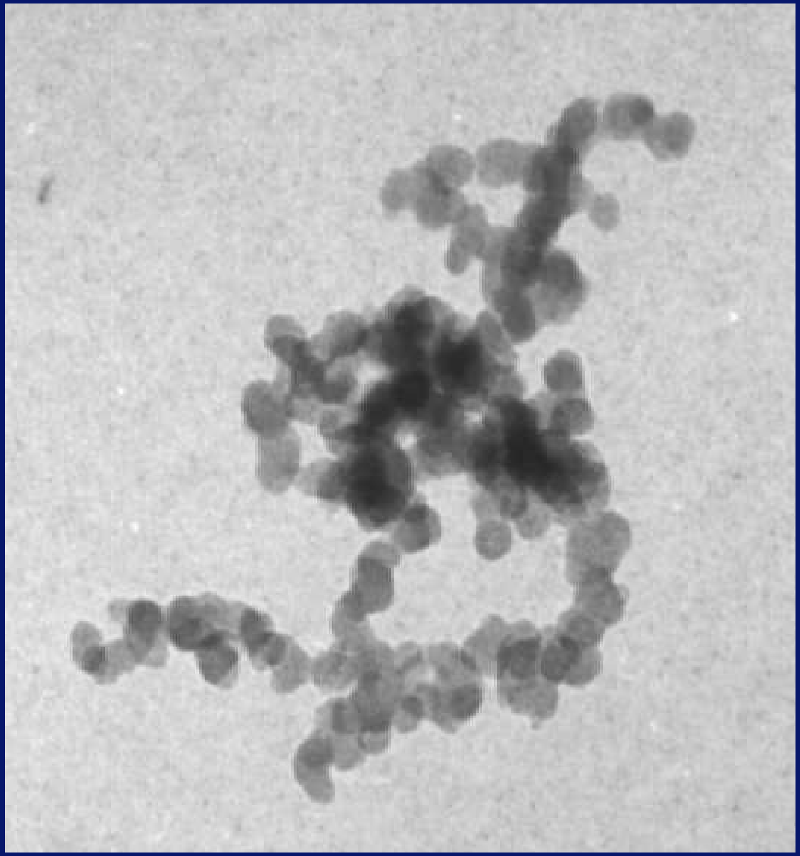
AVL




Gravimetric measurement of
total particulate mass
after partial-flow or full-flow dilution

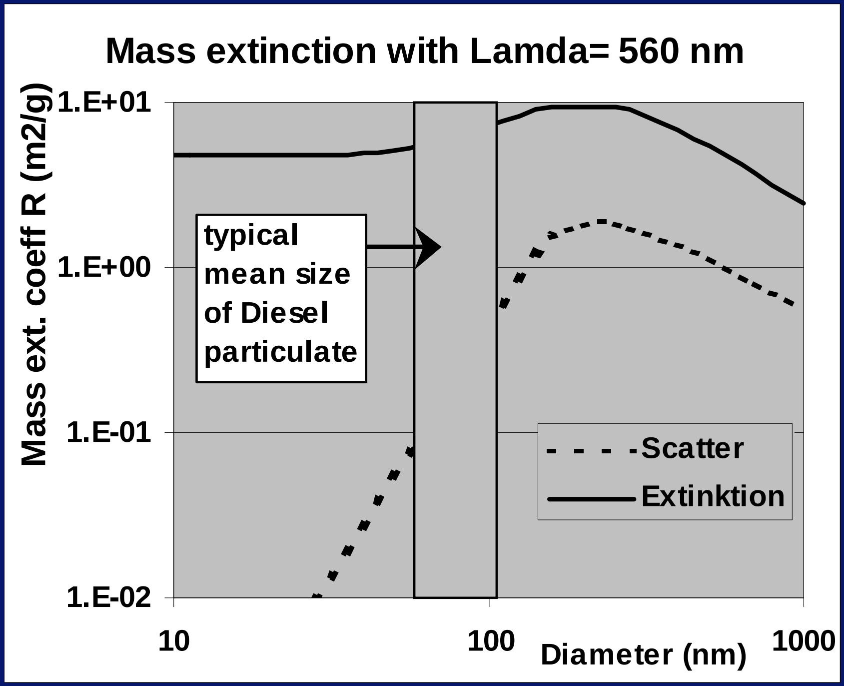
- **The measurement of "Soot" is a widely accepted method in Engine R&D since several decades.**
- **It provides information about the quality of the combustion process**
- **PMP has decided that agglomeration mode particles should be counted - Such particles typically consist of "soot" in Diesel exhaust**
- **There is some evidence that soot is more relevant with regard to health concerns than the homogeneous, volatile "Nanoparticles"**

# Properties of Soot from Diesel Engines



- **Soot is a combustion product. ("Carbon black" is no "soot").**
- **Soot consists of "Carbonaceus Particles"**
- **Soot has a combustion temperature in air of >450 °C, it is not volatile or liquid. (compare the measuring proposal of PMP)**
- **The size is mainly in the "agglomeration mode" range, the structure irregular (fractal dimension 1.8 to 2.5)**
- **Soot is "really black"**

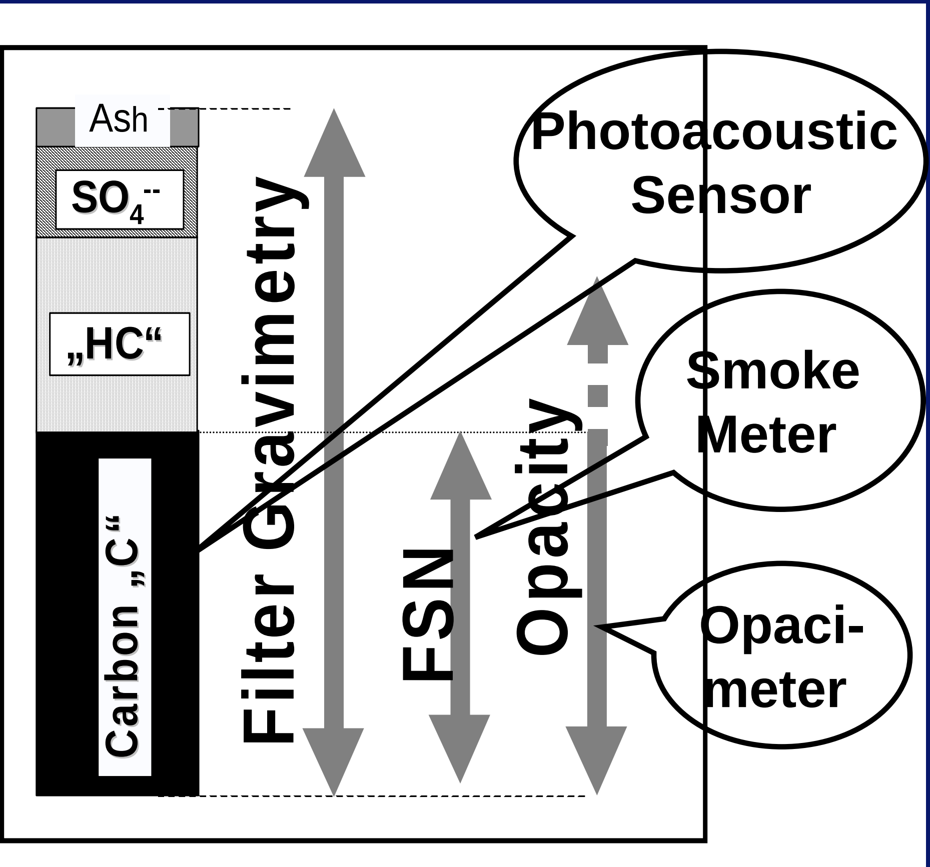
# Methods for Diesel Soot Measurement




- **Analysis of filtered Diesel Particulates**
  - **chem. extraction**
  - **thermogravimetry**
  - **Coulometry**
- **PMP method:**

  **Thermodesorption and particle counting**
- **Via its optical properties:**
  - **The mass extinction coefficient of Soot is nearly constant for D < 100 nm**
  - **The scattering coefficient goes with $D/\lambda^{-4}$**

# How well can various systems measure Soot Mass?



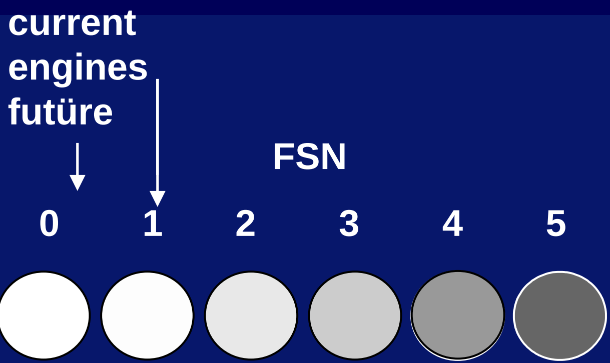

## Criteria:

- accuracy - selectivity - measuring artefacts
- concentration:
  - resolution, detection limit
  - dynamic range
- repeatability, reproducibility
- time resolution

## Target:

**to assess the physical limits of various methods and the practical problems encountered when measuring Diesel Soot.**

# “Filter Smoke Number (FSN)” Measurement

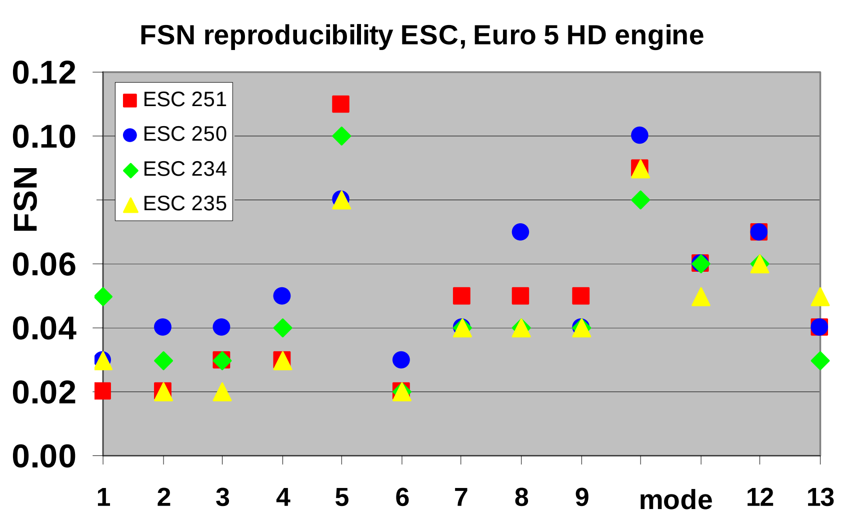



- **Advantages:**
  - **Simple method, proven reliability, widely used in R&D**
  - **Selectivity: for soot content >15%, FSN is clearly related to Soot concentration**
  - **Detection limit: with high sampling volume 20 µg/m³** or **0,002 FSN achievable**
    **⇒ dynamic range > 1: 10000 (concentration)**
  - **Repeatability: 5% achievable (see below)**
- **Challenges:**
  - **Due to the simplicity of the method it is often used uncritically without observing the basic principles of particle measurement.**
  - **A <u>realistic theory</u> of the relation between FSN and Soot concentration does not exist**
- **Drawback:**
  **time resolution >10 sec by principle**

# FSN measurement: Challenges

## Influences to FSN Measurement:

- Sample Conditioning. FSN is measured from the raw exhaust ⇒ concentrations are high, particle deposition is of considerable concern.
- Hangup after measurement of large FSN: purging is required to avoid re-entrainment during “white level determination” ( <2 μg allowed !)
- Filter paper: if two different filter papers, at opposite ends of the ISO 10054 specification band are used, results may vary by >20%. (AVL makes a special paper check to guarantee ± 5%).
- Soot content: in aerosols with a very small soot core (<15% by mass) “the absorption coefficient is increased”




**If measurements are carried out carefully, even the emissions of a Euro 5 HD engine can be measured reproducibly.**

# Opacity Measurement


- **Advantages:**
  - Good time resolution, ≤ 0.1 sec
  - Theoretically well defined ( for fixed R)
  - Detection limit: k = 0.002 $m^{-1}$ corresponding to ≈ 300 µg/$m^3$ (sufficient for non-trap engines)
- **Challenges:**
  - To achieve a stable “Zero” value $I_0$
  - The mass extinction coefficient R of soot is slightly size dependent (typical uncertainty ± 20%)
  - The influence of $NO_2$ on the signal is substantial,
    the influence of HC and $SO_4$ only at high concentrations
- **Drawback:**
  - At the current stage the technology is at its limits

# Challenges for good Opacity Sensitivity

$I/I_0 = e^{-k \cdot L} = (1 - N/100)$

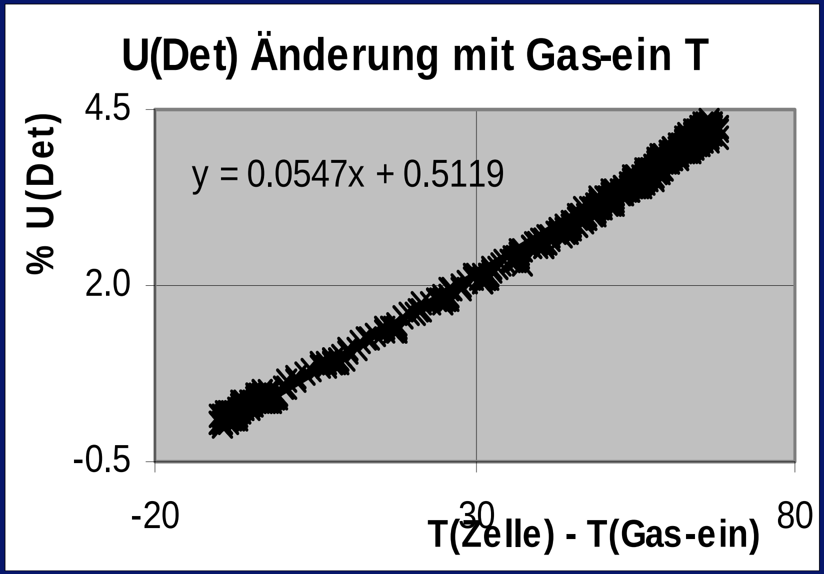
N [%] Opacity

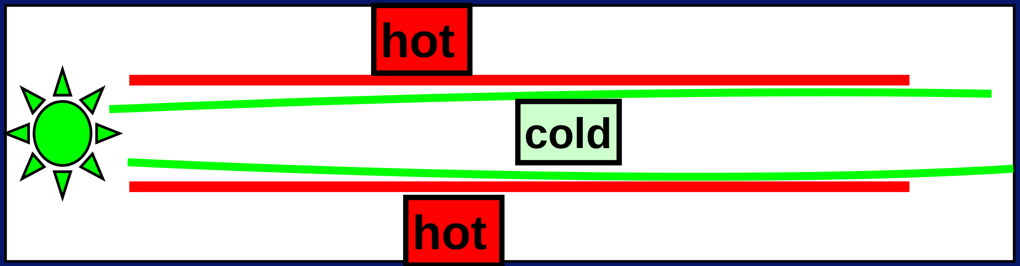
k [$m^{-1}$] Absorption

**Good resolution in k is achieved if:**

- $I_0$ is stable
- The measuring length L is large

**To some extent the two requirements contradict each other:**



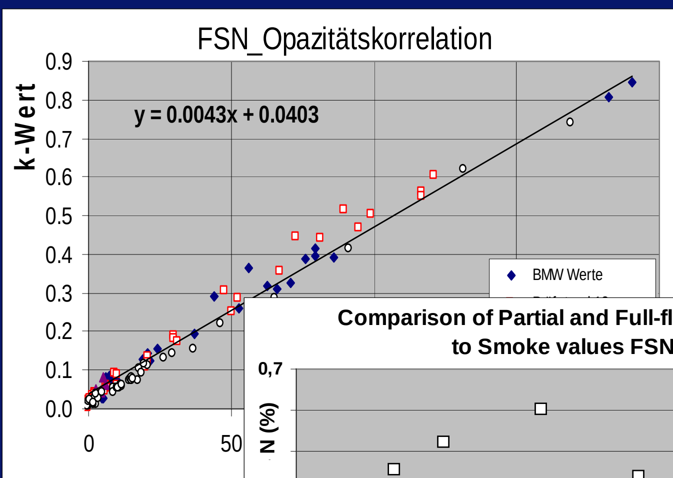

If the temperature of gas and chamber walls are not stable, the thermal lens („mirage effect“) changes $I_0$

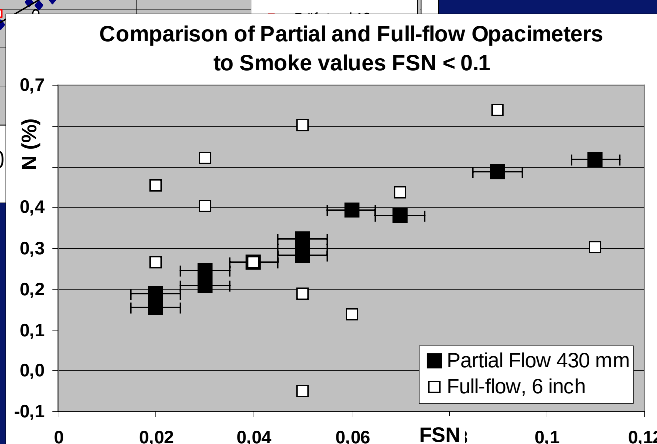
Temperature changes of 1.5 °C result in an $I_0$ change of 0.1%

# "Accuracy" - is Opacity related to Soot?

**In other words: is**
**k (m^-1) = R · Conz (mg/m³)**
**with <u>konstant</u> R?**

$$k\,(m^{-1}) = R \cdot Conz\,(mg/m^3)$$




## Quantities influencing R:

- Particulate size.
- Particulate composition: (HC and $SO_4$)

## <u>Practical experience:</u>

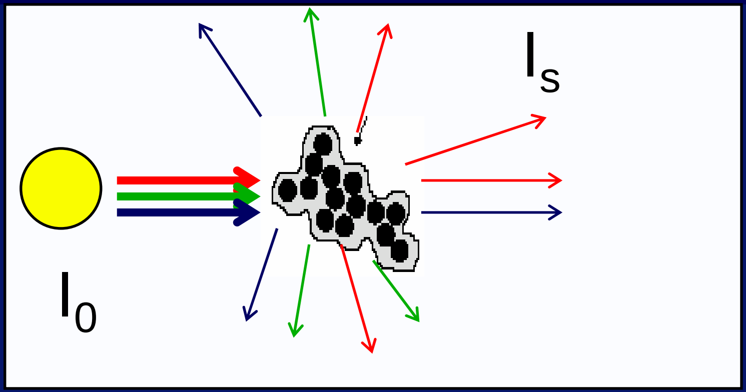
**A constant (± 20%) relation between Opacity and Soot is given if:**

- $NO_2$ concentration is < 100ppm
- The particulates consist to less than 50% of HC and $SO_4$
- The exhaust temperature in the measuring chamber is ≥ 100°C
- The particle size is in the "typical" Diesel exhaust accumulation mode range

**The Particulate size dependence of R decreases with increasing λ**

**-> IR extinction (drawback: R decrease with increasing wavelength)**

# How about light Scattering?




$$I_S = Fkt(\vartheta, \varphi, d/\lambda, n, ff)$$

with $n = m+ik$,

$ff$ = form faktor

$$I_S \propto d^{-6}$$

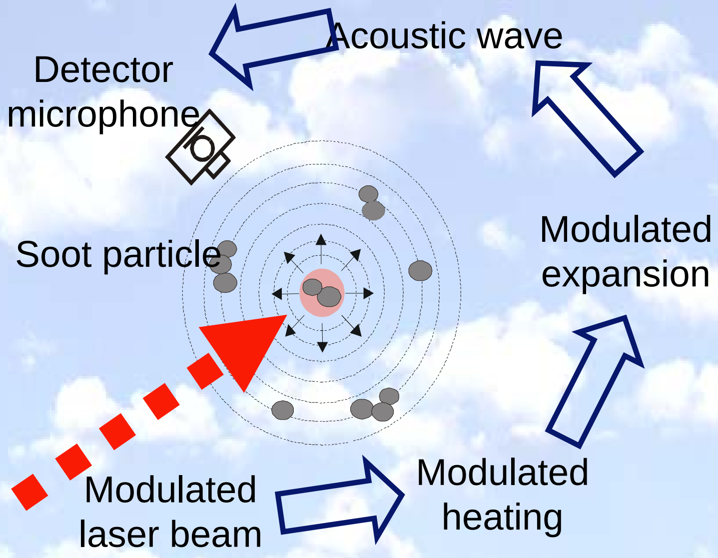
**In Principle:** The measurement of $I_s$ at different $\vartheta$, $\varphi$ and at different $\lambda$ can yield a wealth of information about size, size distribution, number, shape.....

**In Practice:**

- Single particle scattering: with reasonable effort the lower size limit is ≈ 100 nm due to low scattering intensity.
- Multi particle scattering: large particles dominate the Signal.
- Multi-wavelength and -angle scattering: the addition of measuring uncertainties introduces ambiguities into the data evaluation.

⇒ A robust and accepted light scattering instrument has not made its way to the market despite substantial and repeated effort in the last 20 years

# Photoacoustics - AVL Micro Soot Sensor



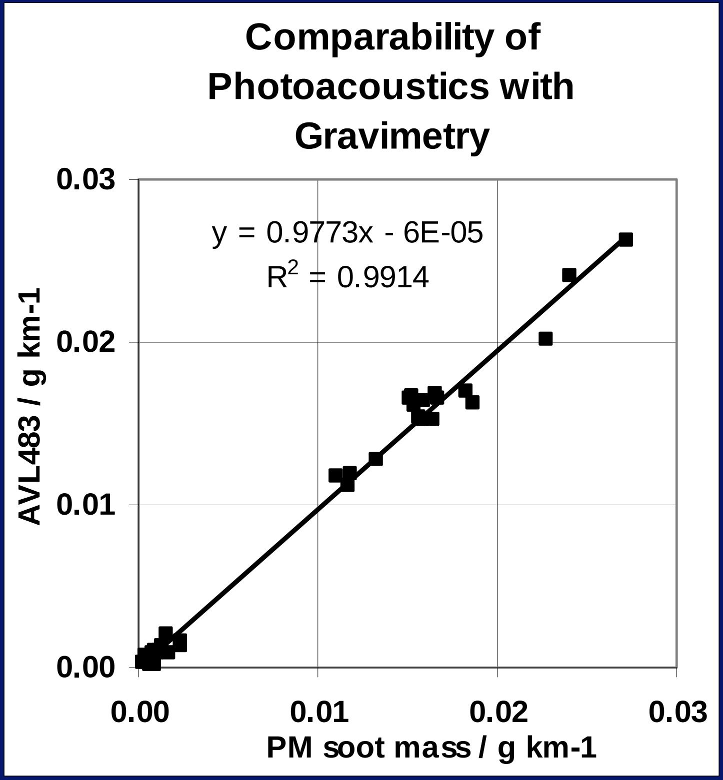

- Periodic heating by a modulated laser beam and subsequent cooling generates an acoustic signal that is detected by a microphone

- Advantages:
  - Sensor is "directly" sensitive to soot concentration
  - high sensitivity (detection limit < 10 µg/m³)

- Challanges:
  - signal evaluation at low concentrations
  - repeatability / reproducibility / calibration
  - currently for diluted exhaust only

# Accuracy: Selectivity, Linearity and Comparability

- **Selectivity:**
  **No cross-sensitivity from typical or untypical exhaust gases, if the proper near IR Laser wavelength is used ($H_2O$, HC, $SO_4$, $NO_2$....).**




Courtesey V. Scheer, FFA

Research & Advanced Engineering

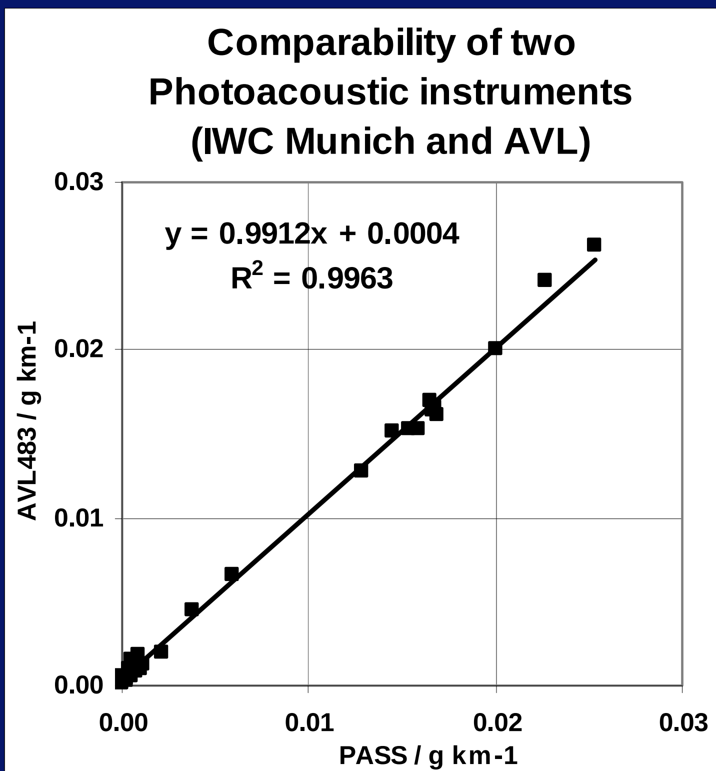
- **Linearity:**
  **Due to the physical principle the signal is linear with soot concentration**

- **Comparability:**
  **According to experience in various laboratories the signal is comparable to the soot determined with gravimetric soot mass determination**

# Reproducibility, Repeatability, Calibration

- ## Reproducibility:

The near IR frequency of the laser used guarantees, that D/λ is small for typical Diesel particulates.
Therefore the mass extiction coefficient R is nearly constant




Courtesey V. Scheer, FFA
Research & Advanced Engineering

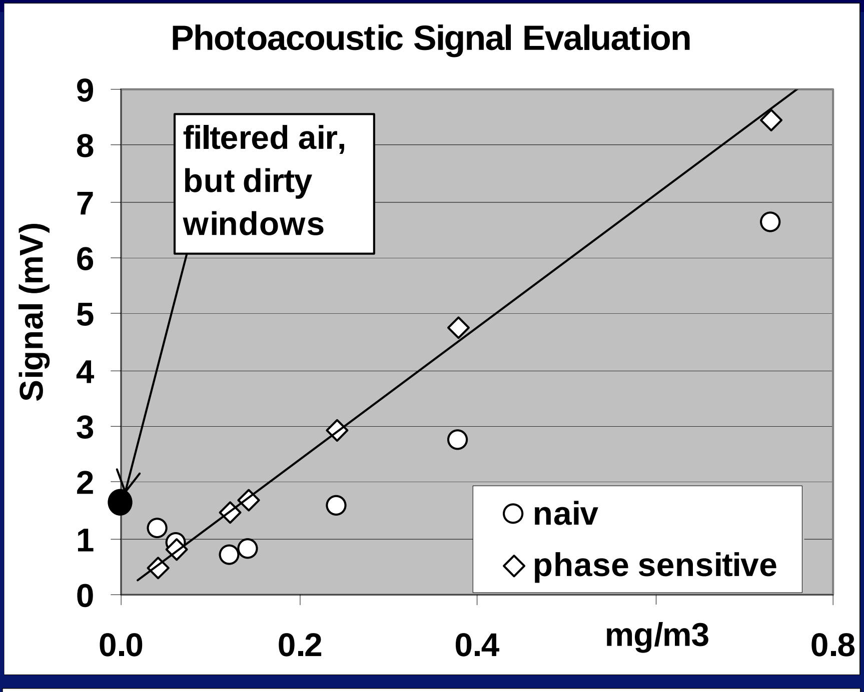
- ## Repeatability:

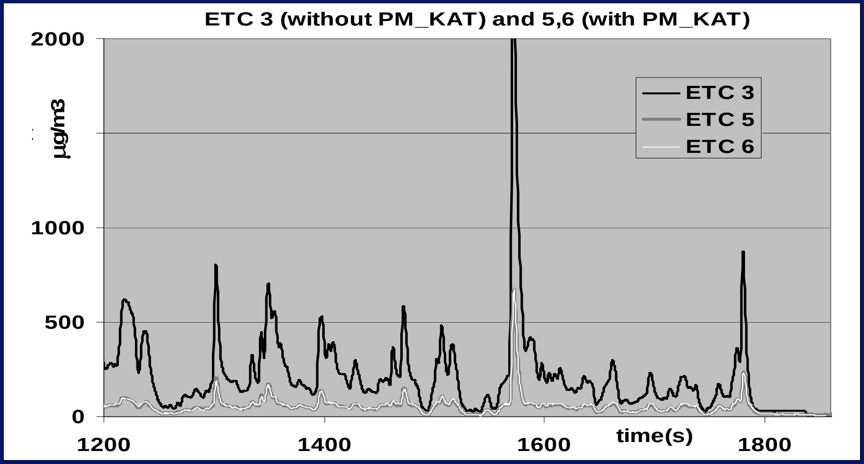
The experiments show that two photoacoustic systems of different build and different calibration methods show equal results

- ## Calibration:

Calibration must be performed in comparison to gravimetric methods. However, the calibration factor in the „PASS“ has not been changed in the last 2 years, and yields the same results as the AVL Micro Soot Sensor

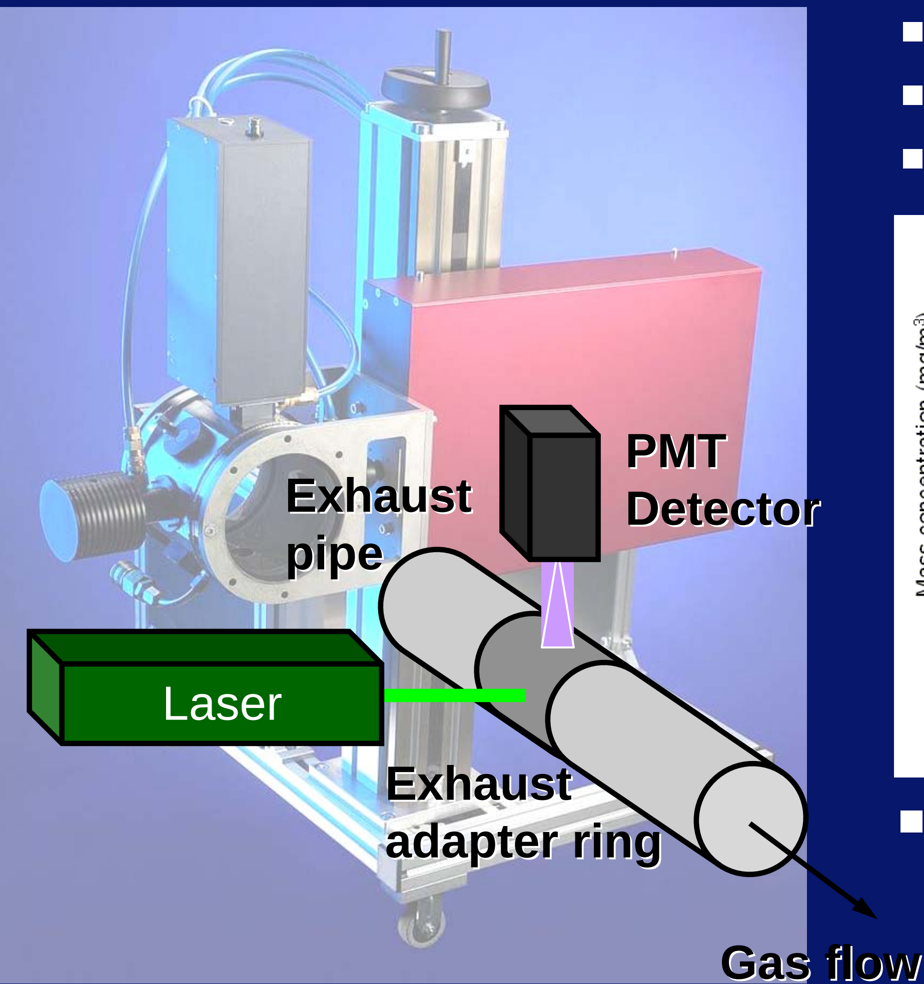
# Resolution (concentration, time)



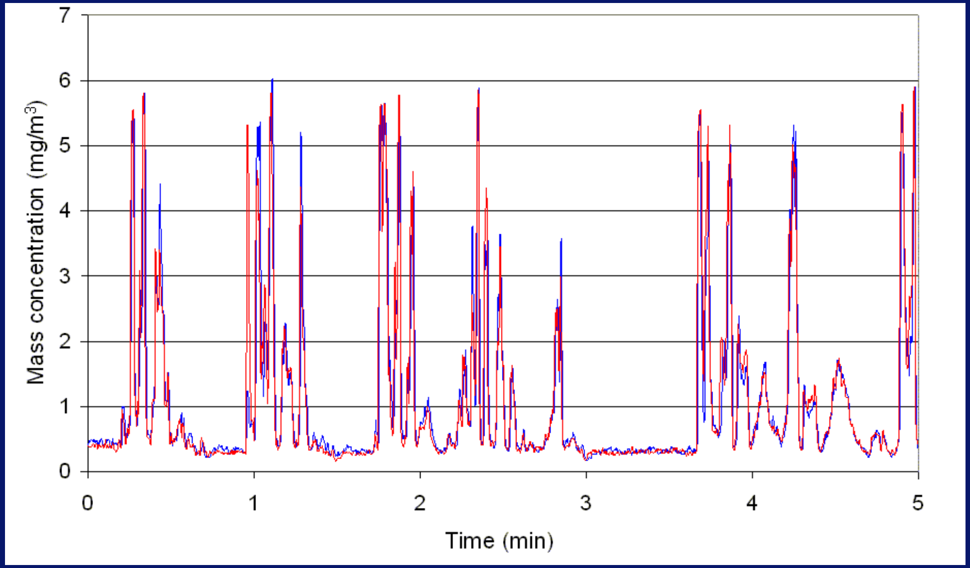




- **Resolution:**
  **Challenges: Good resolution (below 10 $\mu g/m^3$) can be obtained by:**
  - Signal evaluation with high frequency selectivity
  - Low noise in the gas path
  - Correct signal evaluation, subtracting the baseline signal from sooted windows phase-corrected
- **Dynamic range:**
  **Photoacoustics allows a dynamic range of 1: 10000 (important to detect peaks on low background**
- **Time resolution:**
  **1 sec $\tau_{90}$ is easily achievable, better time resolution currently sacrifices concentration detectivity**

# Laser Induced Incandescence (LII)



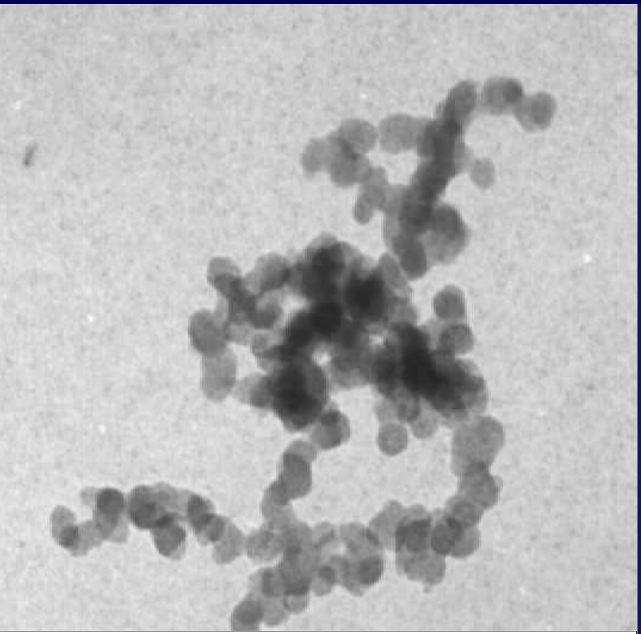

- High sensitivity for ultra-low emission
- good time resolution for transient testing
- In-situ raw exhaust gas measurement

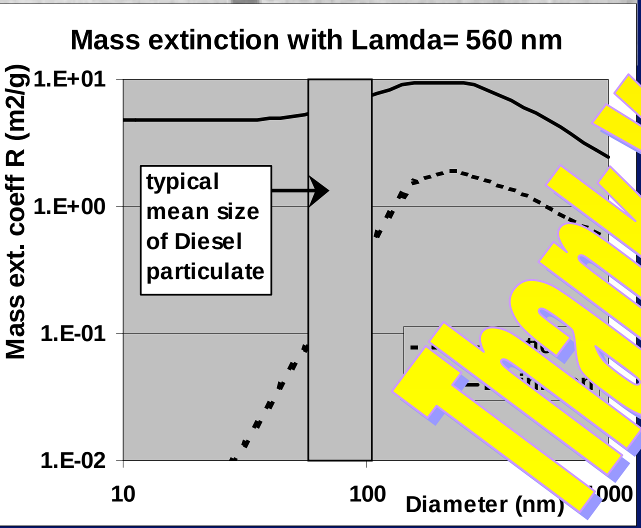



- **However:**
  - substantial costs, due to expensive laser
  - serious laser hazards

# Summary

AVL






- Several Methods exist to measure Soot on the basis of its strong absorption coefficient
- If these methods are used with attention and some basic knowledge about particulate measurement they can give reliable soot data
  - even for very low soot concentration in the exhaust
- The method proposed by PMP for measuring particles seems feasible - the interlaboratory exercise has not yet started - but practically it measures only the soot fraction of the Diesel exhaust
- A second thought on mass-proportional soot measurement methods as a viable alternative seems appropriate.

Thank You for your attention