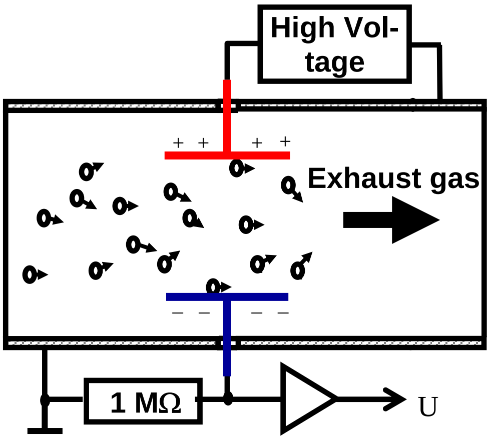
Prof. Dr.-Ing. Günther Hauser, 38640 Goslar, Oberer Triftweg 33, Tel.: 05321-23674, Fax.: -1245
Öffentlich bestellter und vereidigter Sachverständiger für Technische Akustik und Elektronische Messtechnik

Smoke particle sensor for on-board diagnoses and high sensitivity measurements

Abstract: This sensor uses the capability of carbon particles to be electrically charged. By means of a very high static electrical field the particles are attracted by Coulomb forces and touch statistically the negative or positive electrode of a capacitor incorporated into the main exhaust gas flow. During this procedure electrical charge is transported out of the capacitor. One electrode is connected to a high voltage supply of 1500 V, the other is connected to ground in series with a high ohmage resistor of min. 1 MΩ. As the high voltage stays constant the changes of charge cause a current which RMS value represents the quantity of smoke particles. This current is converted by the resistor into a voltage and then amplified. The received signal is also depending on the gas flow speed which can be calculated by measuring the gas temperature the intake air mass and the fuel mass of the diesel engine. For high accuracy measurements the exhaust gas has to be sucked through a bypass in order to receive a constant gas flow. Other parameters are the size of the capacitor area the shape of the capacitor electrodes and of cause the value of the voltage. The voltage stays approximate 50 % beyond the spark event. For a voltage of 1500 V the distance between the capacitor blades measure 3 mm. The size of the capacitor blades measures app. 1,5 x 3 cm. To avoid interference from vibrations of the capacitor blades a low-pass filter with a cut-off frequency of e.g. 200 Hz is necessary. A stiff construction of the blades will raise the resonant frequency to much higher values and lower the influence to the signal. For onboard measurements this edge frequency has to be lowered to 10 Hz because of gas flow oscillations inside the exhaust silencers and pipes. The rise time of the signal (without low pass filter) allows the measurement of individual cylinder smoke emission when mounted near the manifold of the engine.

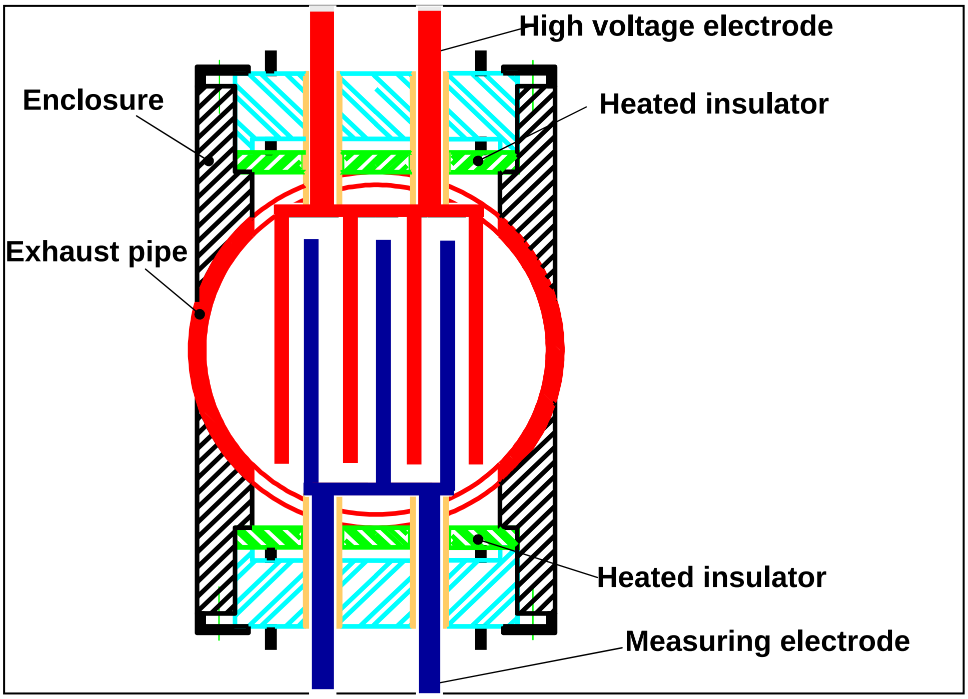
1. Methodology of Operation



The property of carbon, leading electrical current, is used for the transportation of electrical charge. Therefore a high electrical field is implemented inside the exhaust gas tube by means of capacitor blades with a distance of 3 [mm] and a high voltage of 1500 [V]. Whilst the particulates pass this capacitor they are attracted by Coulomb forces on to the blades and, during statistically touching them, they will be charged. As they have then the same polarity as the electrode itself they move away following the exhaust gas flow. The charging procedure and the transportation of charge produce an electrical current which causes a voltage difference along the high ohmage resistant. The RMS value of this voltage is the measure of the quantity of particulate. At low gas flow the quantity of charge exchanges is much higher than at high gas flow. Therefore the gas flow must be known in order to calculate the smoke concentration of the Exhaust gas.

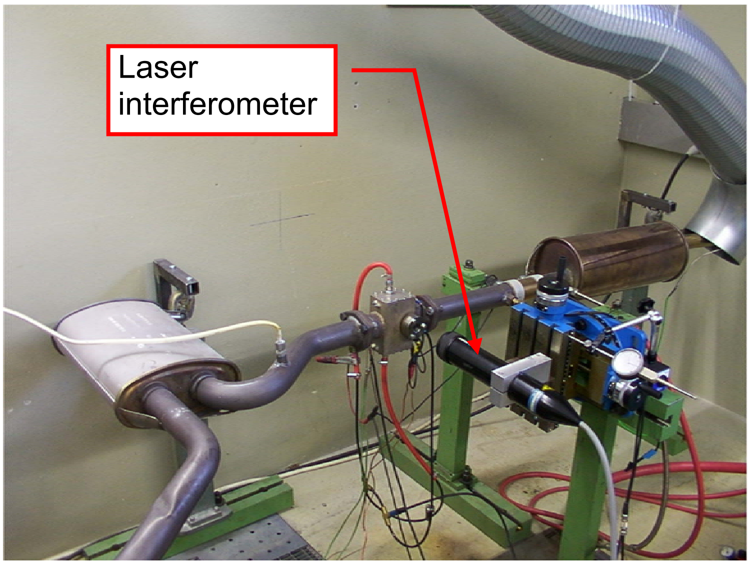
After the combustion process the smoke particles have a more or less individual electrical charge which has no effect to the measuring results because the electrical field is extremely low in comparison with the field inside the capacitor.

2. Construction principle of the Charge- Sensor



The most important part of the sensor construction consists of the electrode shaft heating. It is necessary to keep the isolation resistant within the range of 10 [MΩ].
It was found out, that a temperature of 200 [°C] is sufficient to keep the insulators clean of smoke particulates.

3. Charge- Sensor at test bench operation

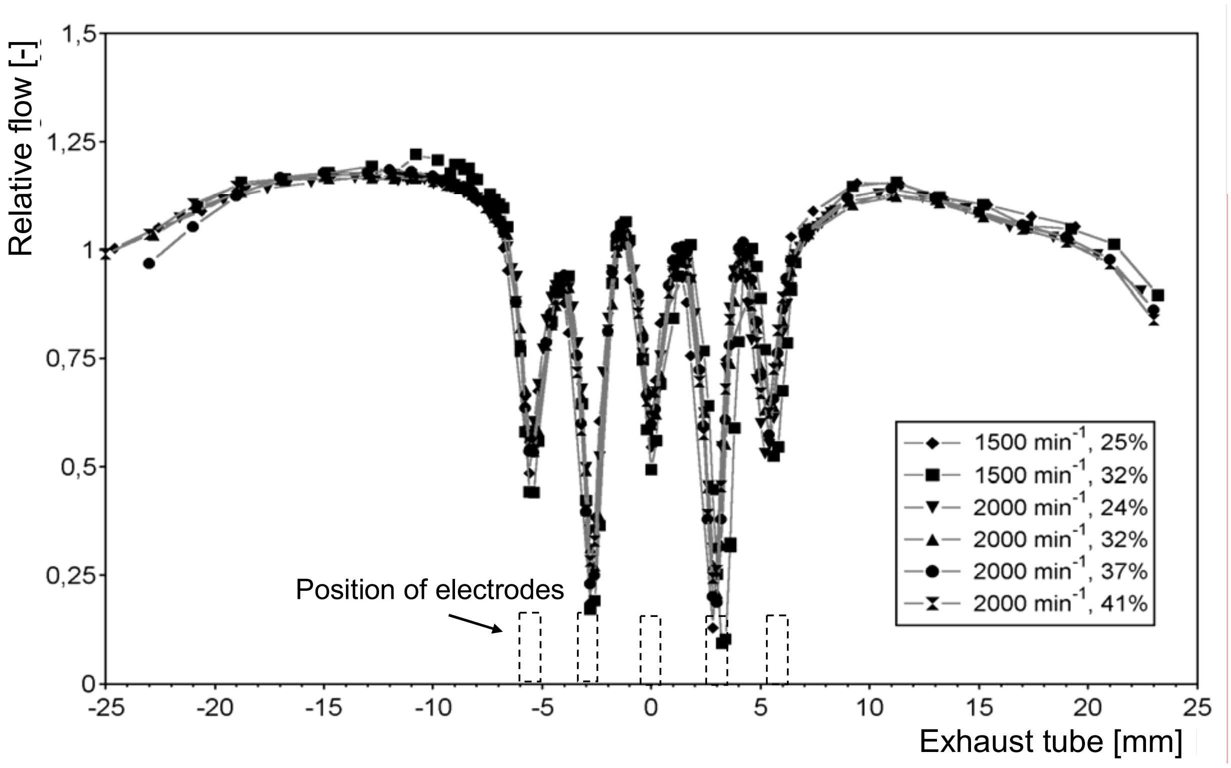


The photo shows the Charge-Sensor used for on-board diagnosis.

As the smoke signal is depending on the gas flow it has to be investigated, if the flow profile stays equal during all flow speeds including the gas pulsations. Through a plane glass window, kept clean by compressed air, the profile was measured in small steps across the exhaust tube.

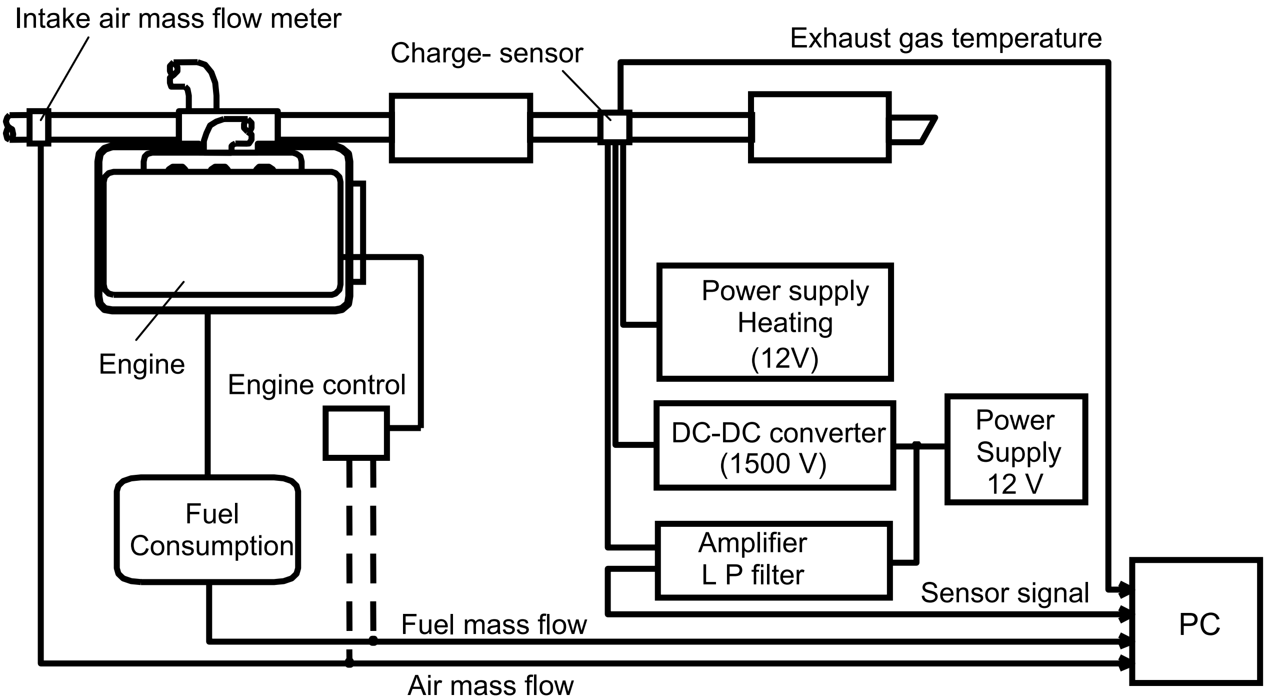
The result is shown in the next graph.

4. Gas flow profile through electrode blades



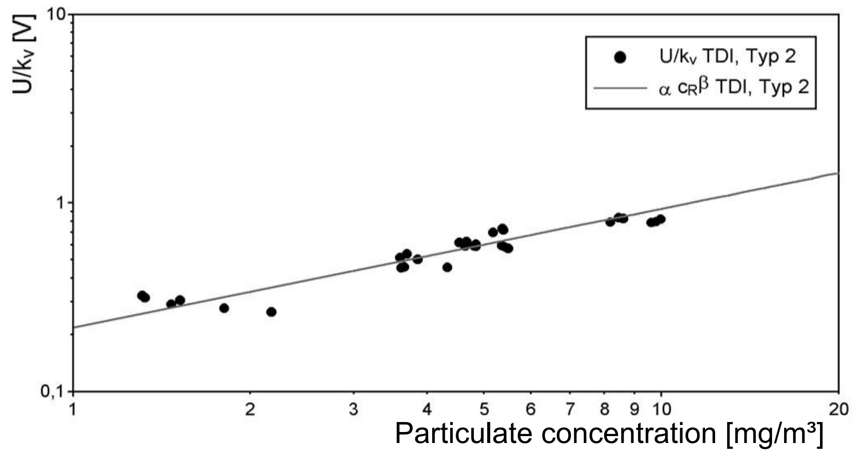
The exhaust tube of 50 [mm] diameter was scanned across for a range of engine speeds an engine loads. The measured results had to be normalized in order to see the profile at different gas flow speeds. Even at the positions of the electrode blades inside the tube the profile stays constant. This is the necessary condition for on board measurements of high accuracy.

5. Complete system for on- board operation



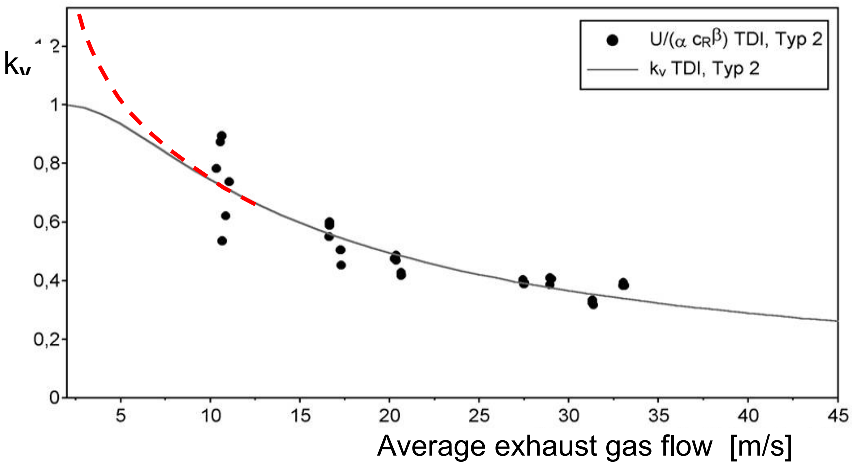
The gas flow speed has to be derived from the air intake mass flow, the fuel mass flow, the exhaust tube diameter and the temperature at the sensor position. If the sensor is mounted near the manifold, additionally the gas pressure value is necessary. The flow parameters are principally available from the engine management. In this case these parameters had to be measured separately. But, according to the input parameters and power supply, the charge-sensor can be used as on-board diagnostic system in vehicles. For the calculation of the smoke particle concentration in the exhaust gas the equation of the gas flow influence has to be derived. As at time there was no possibility to measure the gas flow speed directly an indirect method was used.

6. Design of the mathematical model



$$U = k_v \, \alpha \; c_R^{\,\beta}$$

If in the graph aside U/kv is regarded and the particulate concentration is known the straight line shows the behaviour of the model parameters α and β. As the graph has double logarithmic scaling the equation above can be described.



$$k_v = (1 - e^{\kappa / v})$$

If the other parameters are kept constant and the gas flow speed varies against the particulate concentration the curve shows the shape of an e- function.

Later experiments with bypass measurements and controlled gas flow speeds down to 0,5 [m/s] have result in the red line.

U: Sensor signal [V]
v: Exhaust gas flow [m/s]
c_R: Particulate concentration [mg/m³]
k_v: Gas flow weighting factor
α, β, κ: Model parameter

7. Measuring Errors

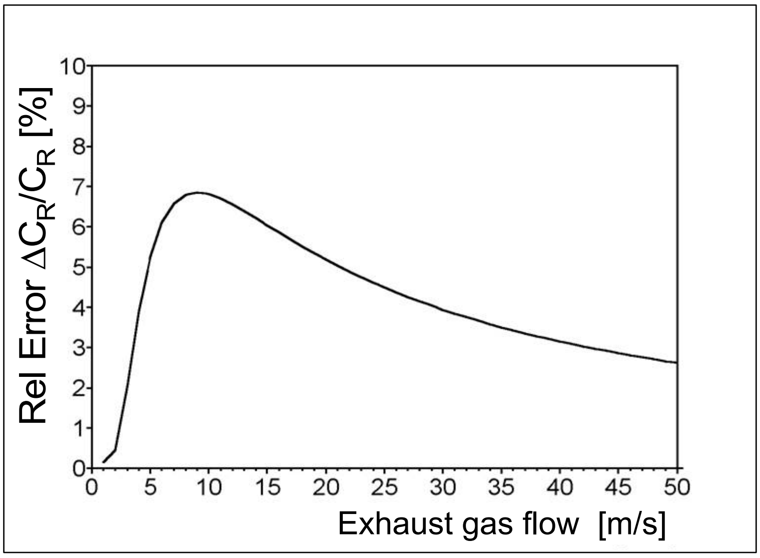
The mathematical calculation of the smoke particulate concentration finally follows the equation:

$$c_R = \left(\frac{U}{\alpha\,(1 - e^{\kappa/v})} \right)^{\frac{1}{\beta}}$$

c_R: calculated particulate concentration
U : Charge- sensor signal [V]
v : Exhaust gas flow [m/s]
$\Delta U/U$: ±0,1% accuracy of amplification
Δv: ±1,0 m/s accuracy of flow measurement

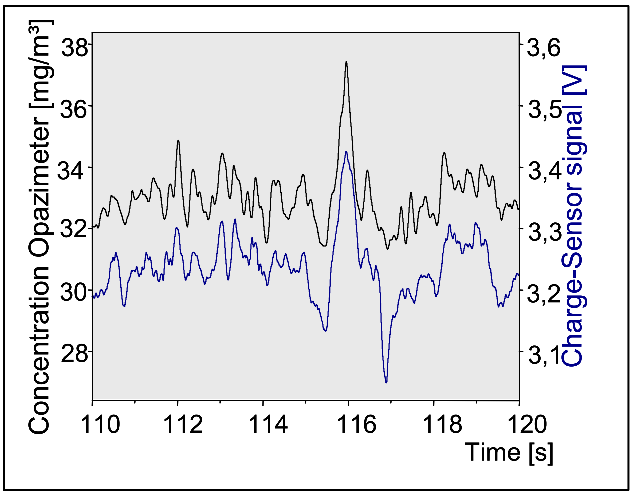
This function was used to calculate the error propagation in order to get information about the accuracy of the smoke particulate concentration.

$$\frac{\Delta c_R}{c_R} = \sqrt{\left[\frac{\Delta U}{U}\frac{U}{c_R}\frac{\partial c_R}{\partial U}\right]^2 + \left[\frac{\Delta v}{c_R}\frac{\partial c_R}{\partial v}\right]^2}$$



The graph aside explains that the error depends on the gas flow speed. That means that for highly accurate measurements it is recommended to use a bypass procedure with low and constant gas flow speed.

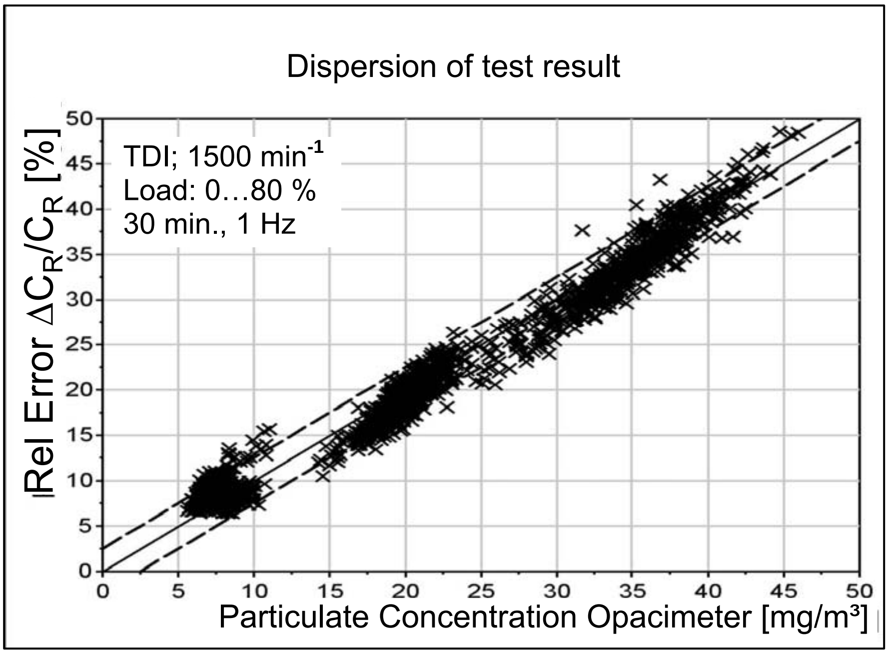
8. Dynamic behaviour



The graph shows a cut-out of a constant particulate emission. The dynamic behaviour was compared with the analogue output of an opacimeter. It can be remarked that both curves have nearly the same structure though they result from completely different methodologies.

Prof. Dr.-Ing. Günther Hauser, 38640 Goslar, Oberer Triftweg 33, Tel.: 05321-23674, Fax.: -1245
Öffentlich bestellter und vereidigter Sachverständiger für Technische Akustik und Elektronische Messtechnik

9. Dispersion error of test results



Designing a new technology it is always necessary to verify the results with known and standardized procedures as the opaqueness method.

It can be seen that, though different methods, the linearity shows a good result. The dispersion between both technologies differs by ± 5 %. It has to take into account, that this dispersion also includes the dispersion of the used opacimeter and the instability of the TDI-engine as smoke particulate emitter. The curve above was created by operating the engine at constant speed measuring at a time rate of 1 [s] for a duration of 30 [min] at each load.

10. Cross sensitivities

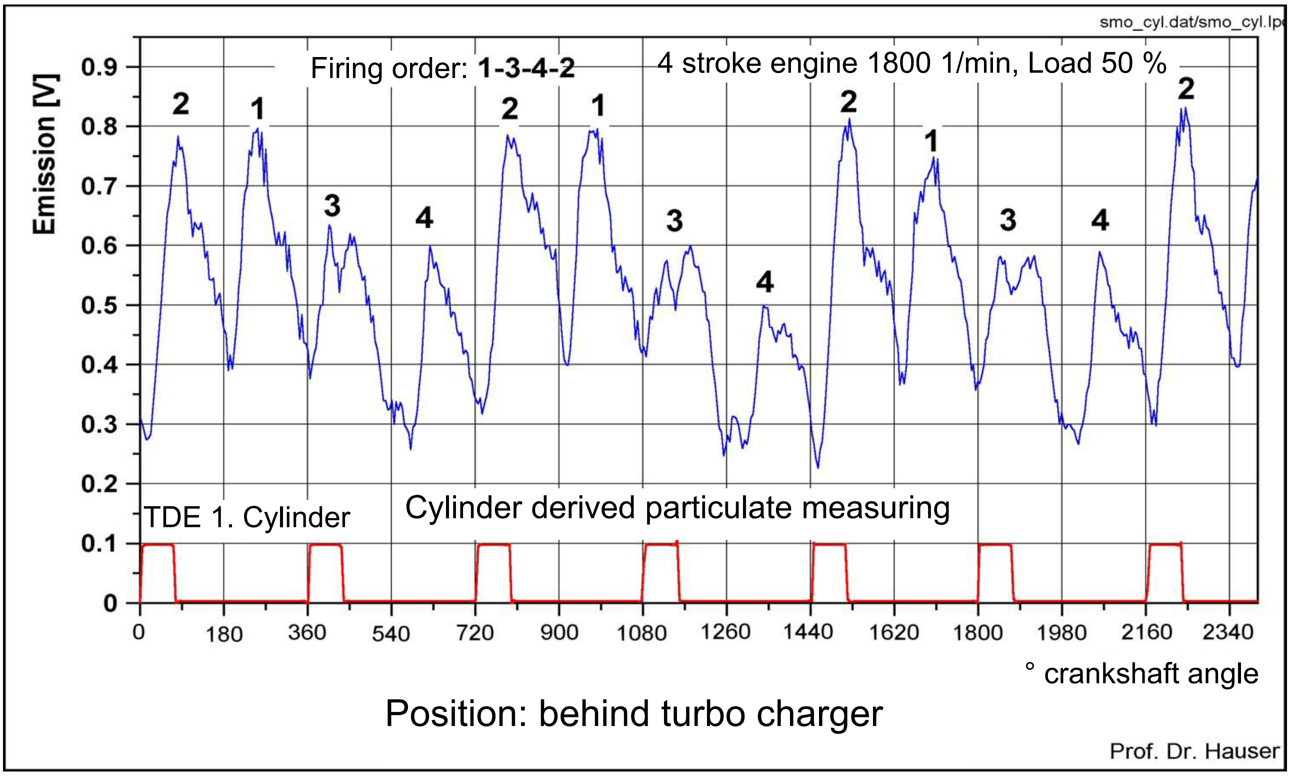
In the first approach the cross sensitivities are regarded within the measuring range down to 1 mg/m³.

Parameters		Behaviour		Solution
Exhaust gas flow	⇒	non linear	⇒	mathematical equation
Exhaust gas temerature	⇒	indirect influence by means of changing the gas flow		
Vibration	⇒	resonance frequency of electrode blades	⇒	Low pass filter in combination with high stiffness of the electrodes
Exhaust gas humidity	⇒	no effect down to concentrations of 1 mg/m³		

The table above summarizes the tested effects and incorporated solutions. For on-board operation in a vehicle the problems during the warm-up situation have to be investigated. Probably a hold-off-time of approximate 5 [min] has to be taken into account until the insulators temperature of 200 [°C] is reached. As a high isolation resistant is necessary an automatic isolation measurement should be incorporated before the smoke measurement begins. Principally it can be expected that these ore similar problems could be solved during the next step of development.

11. Other possible applications

By means of the methodology of the charge sensor the rise time is very short. Just for a test the sensor was mounted behind the exhaust manifold to see the reaction.



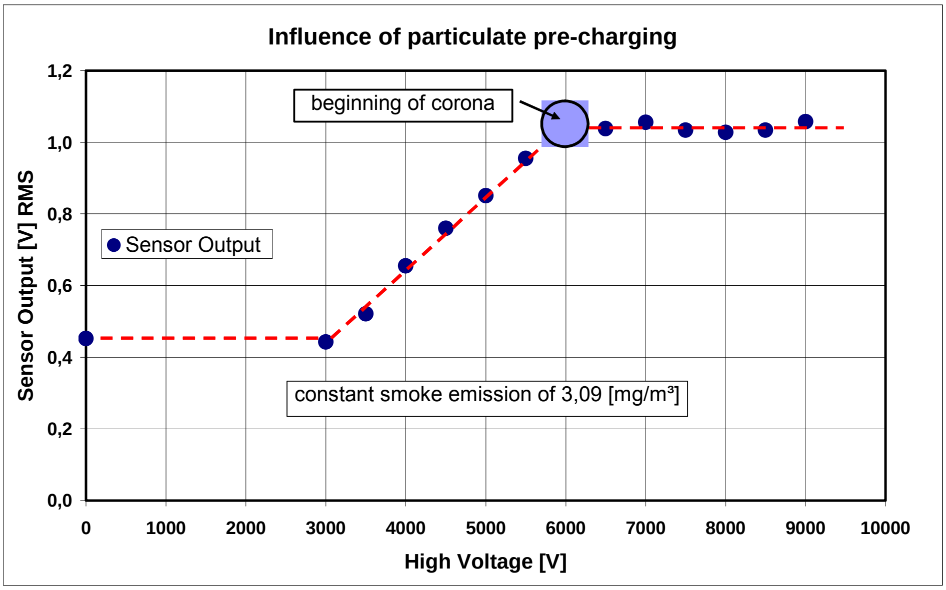
This measured result makes no sense as long as the cylinder derived exhaust gas speed is unknown. On the other hand no signal could be measured if no particulate was there. This is a possible approach to another field of engine control and monitoring.

12. Optimization of the charge- sensor

The described stage of development was documented by a thesis at the University of Clausthal and meanwhile settled as a patent Nr. DE 198 17 402 C1 on 30.09.1999 .

During the last months many tests and procedures have been made to raise the signal strength and the signal to noise ratio as well. The reason was to minimise the dimensions of the charge sensor in order to implement the device like a lambda sensor.

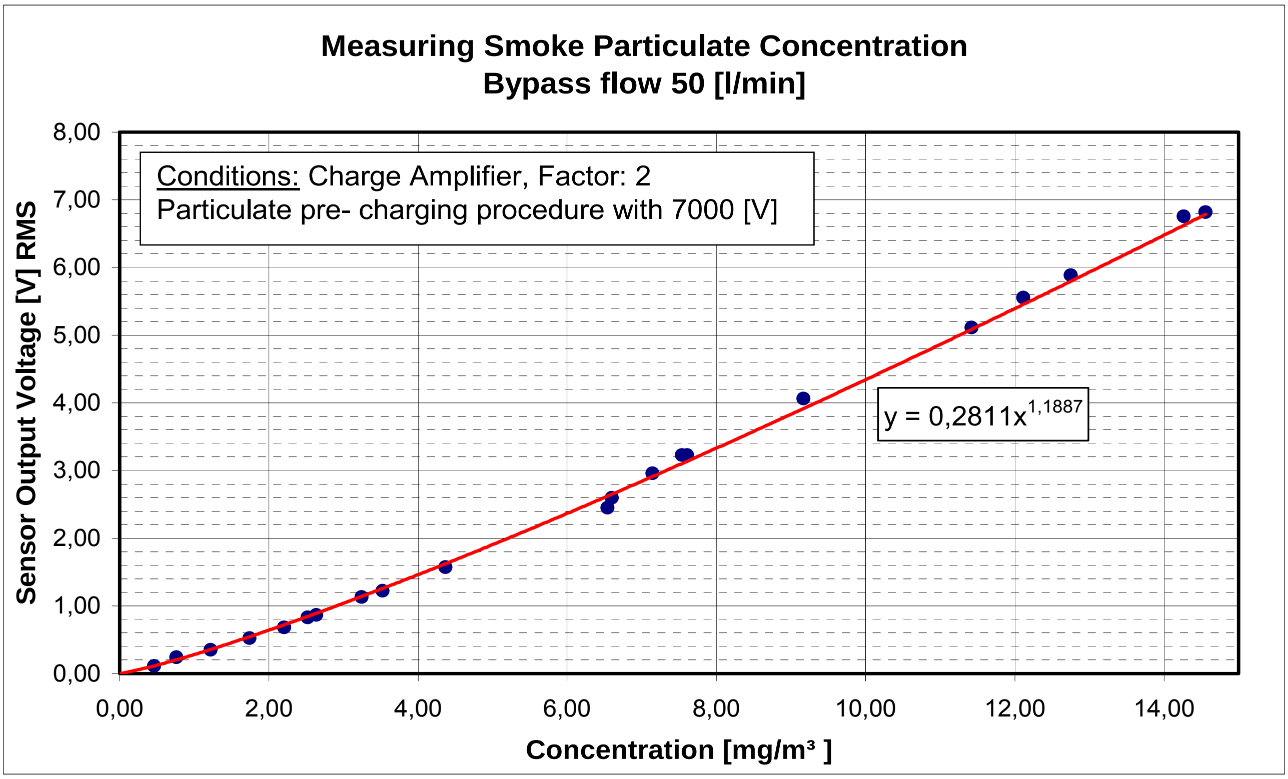
The first approach was to pre-charge the particulates before they pass the charge sensor. The result is shown in next diagram.



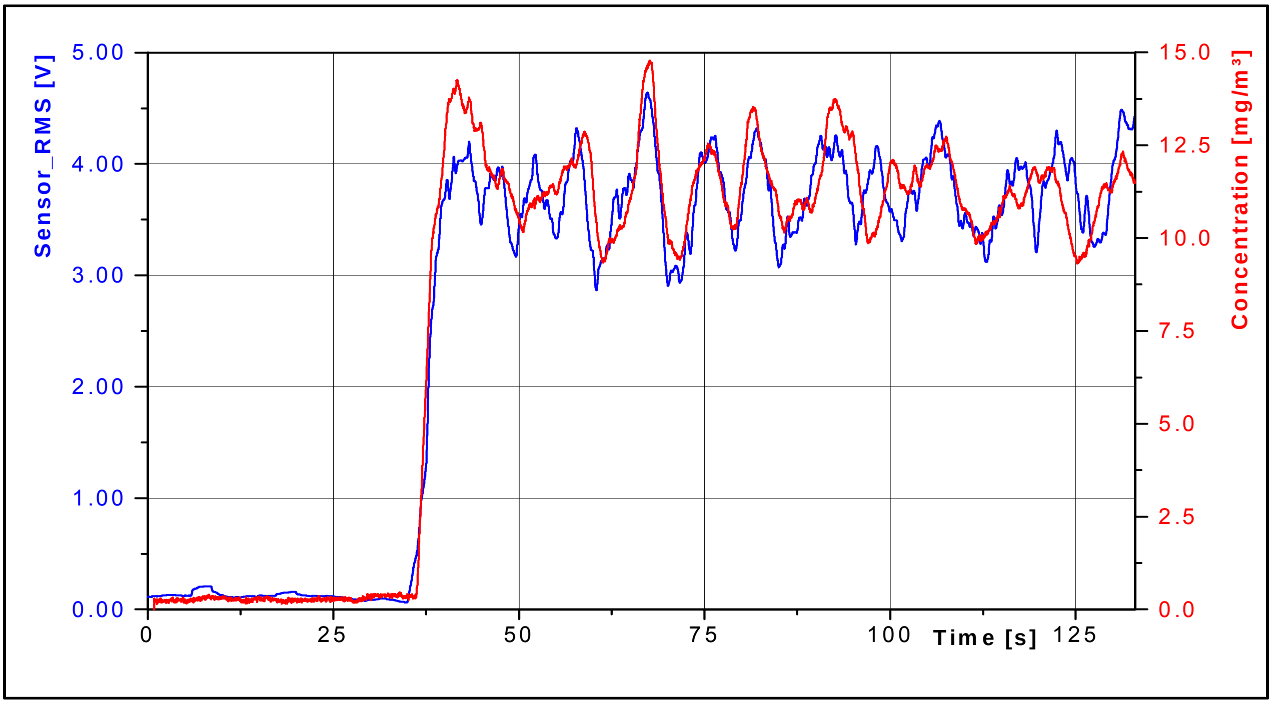
All parameter ware hold constant whilst the pre-charge electrode was activated stepwise.

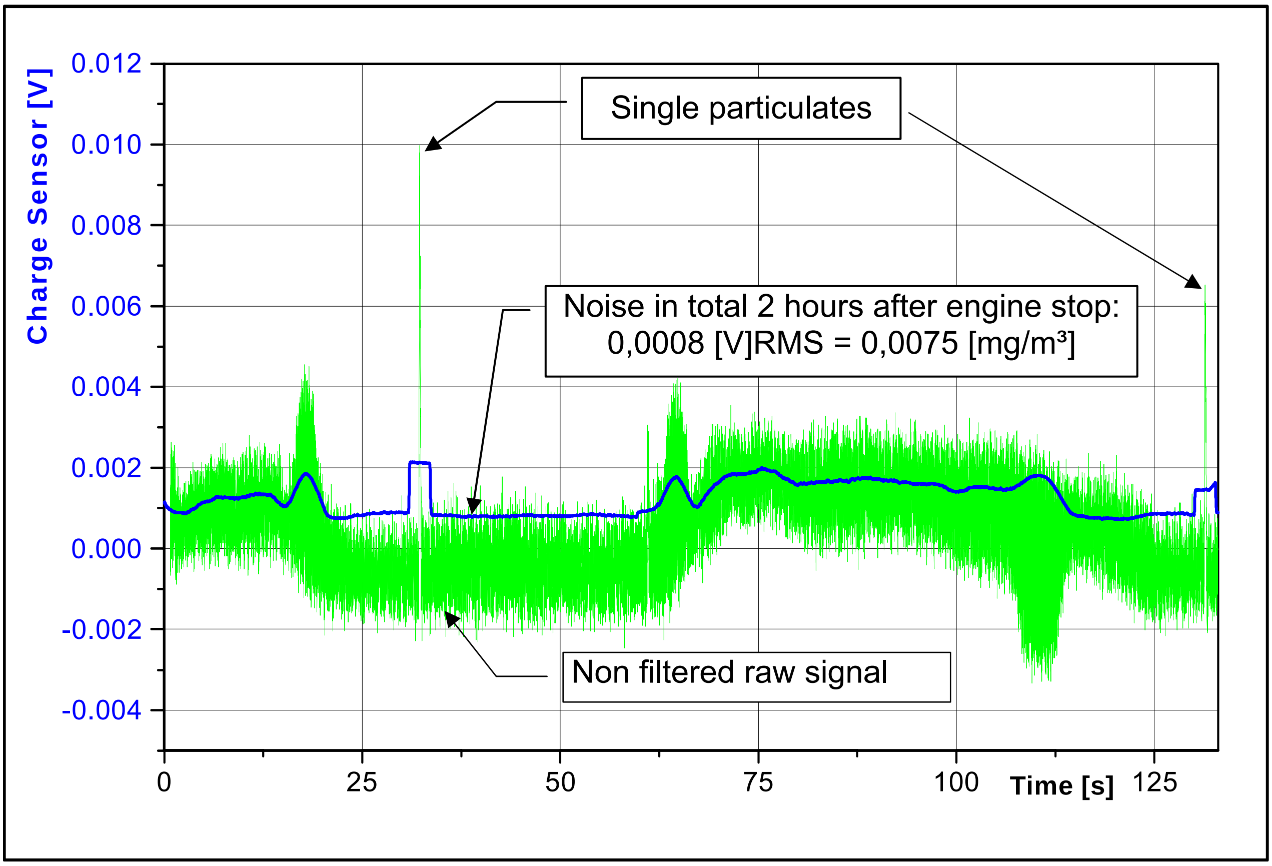
The sensor output rises linear with the pre-charge level until the corona occurs. Finally 1.05 [V] were reached at a smoke concentration of 3,09 [mg/m³] only.

By introducing a charge amplifier which transmits also the DC value of the charge signal it is now possible to measure the charge procedure directly without the influence of the cable and sensor capacities, because the measuring part of the sensor capacitor stays always at zero volt. The high sensitivity opens the possibility to reduce the capacitor area down to 2 [cm²].



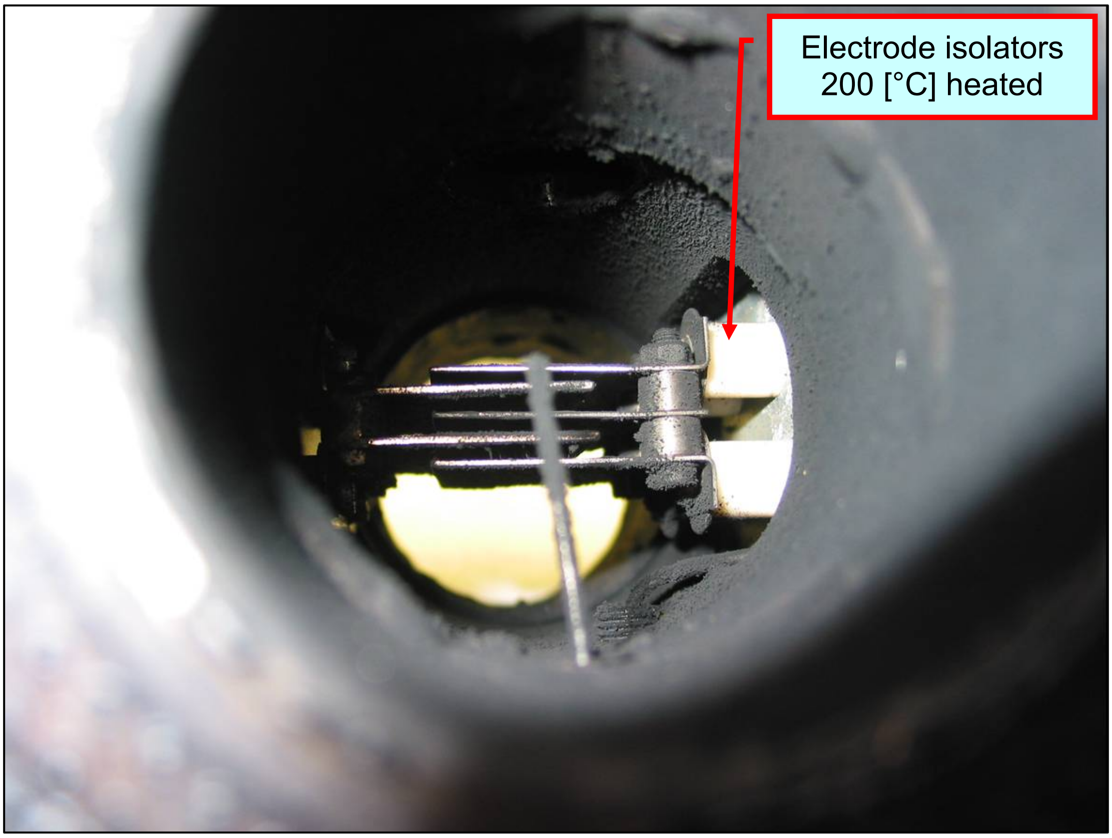
The result represents a clear exponential function which equation can be used to linearize the Sensor signal. Next graphs show the jump answer to a smoke burst and the noise in total at fully operating system.





The diagram above shows the state-of-the-art of today in point of view signal strength and signal-to-noise ratio. There is still some potential of optimisation according to the later use of the charge-sensor that means for high precision measuring or for on-board diagnoses.

13. Long-time behaviour of the Charge- Sensor in operation

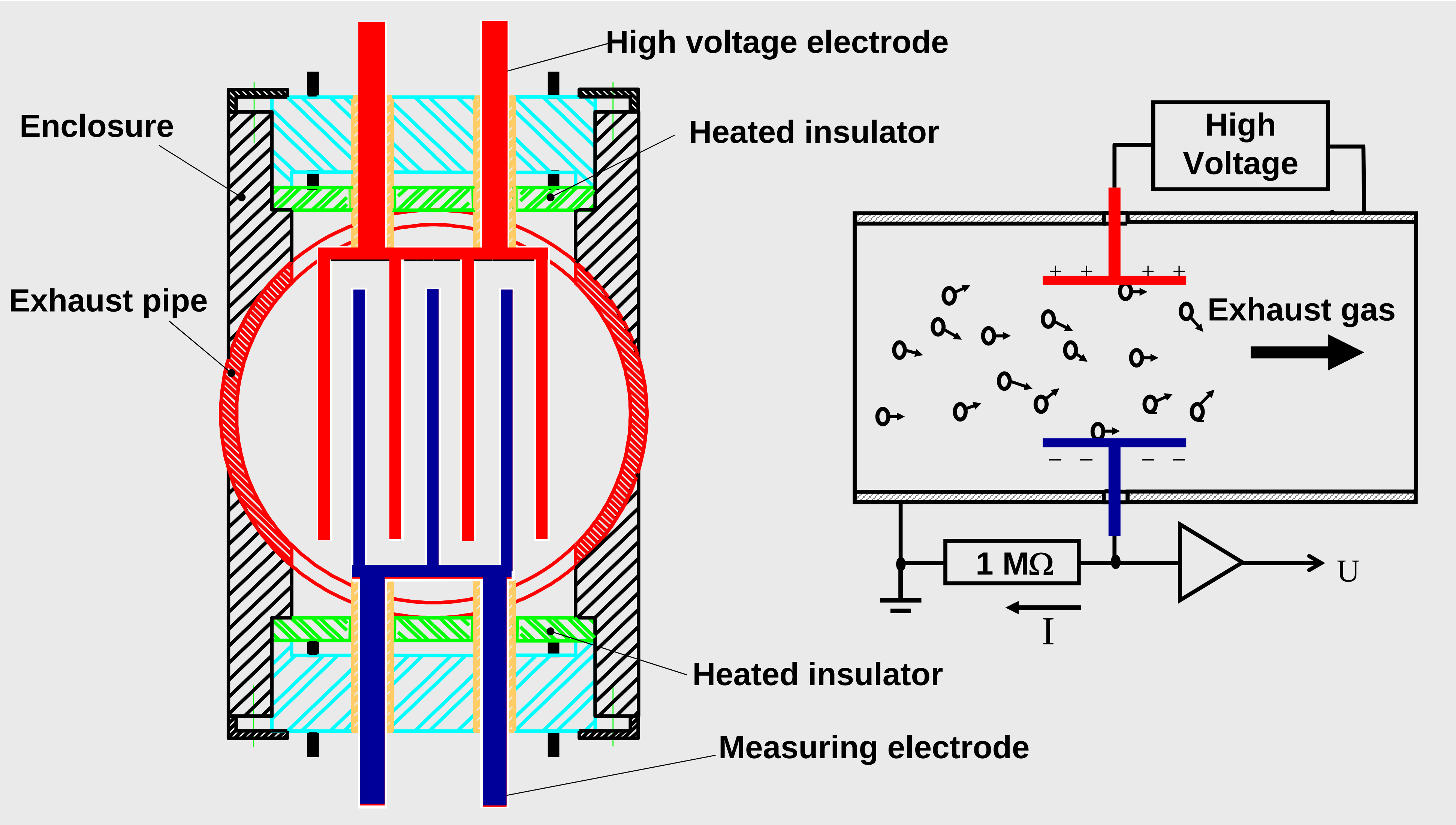


Smoke particle sensor for on-board diagnoses and high sensitivity measurements

Fachhochschule
Braunschweig/Wolfenbüttel
Prof. Dr.-Ing. Hauser

LOGISTIKZENTRUM CLE

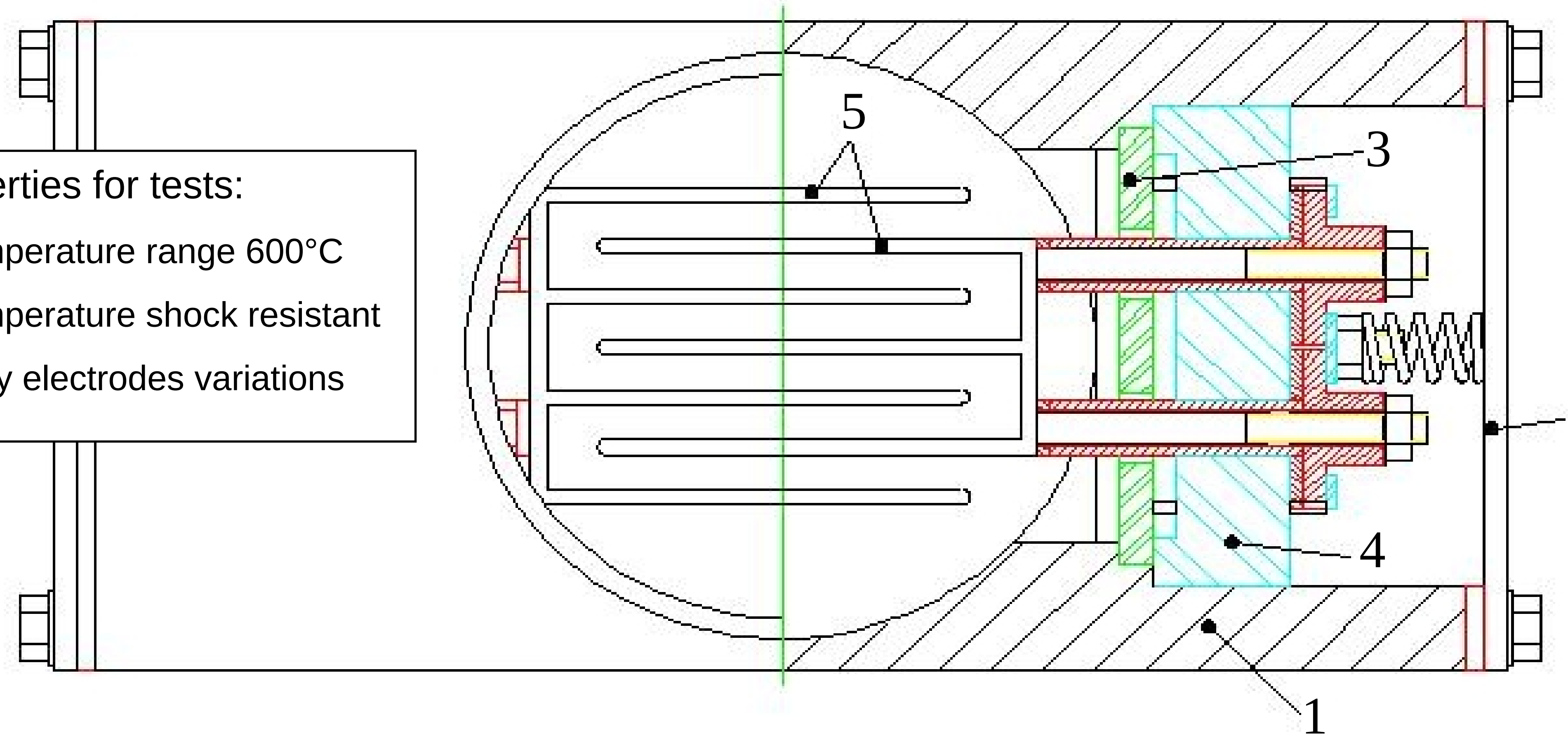
Methodology of Operating



Construction of test device

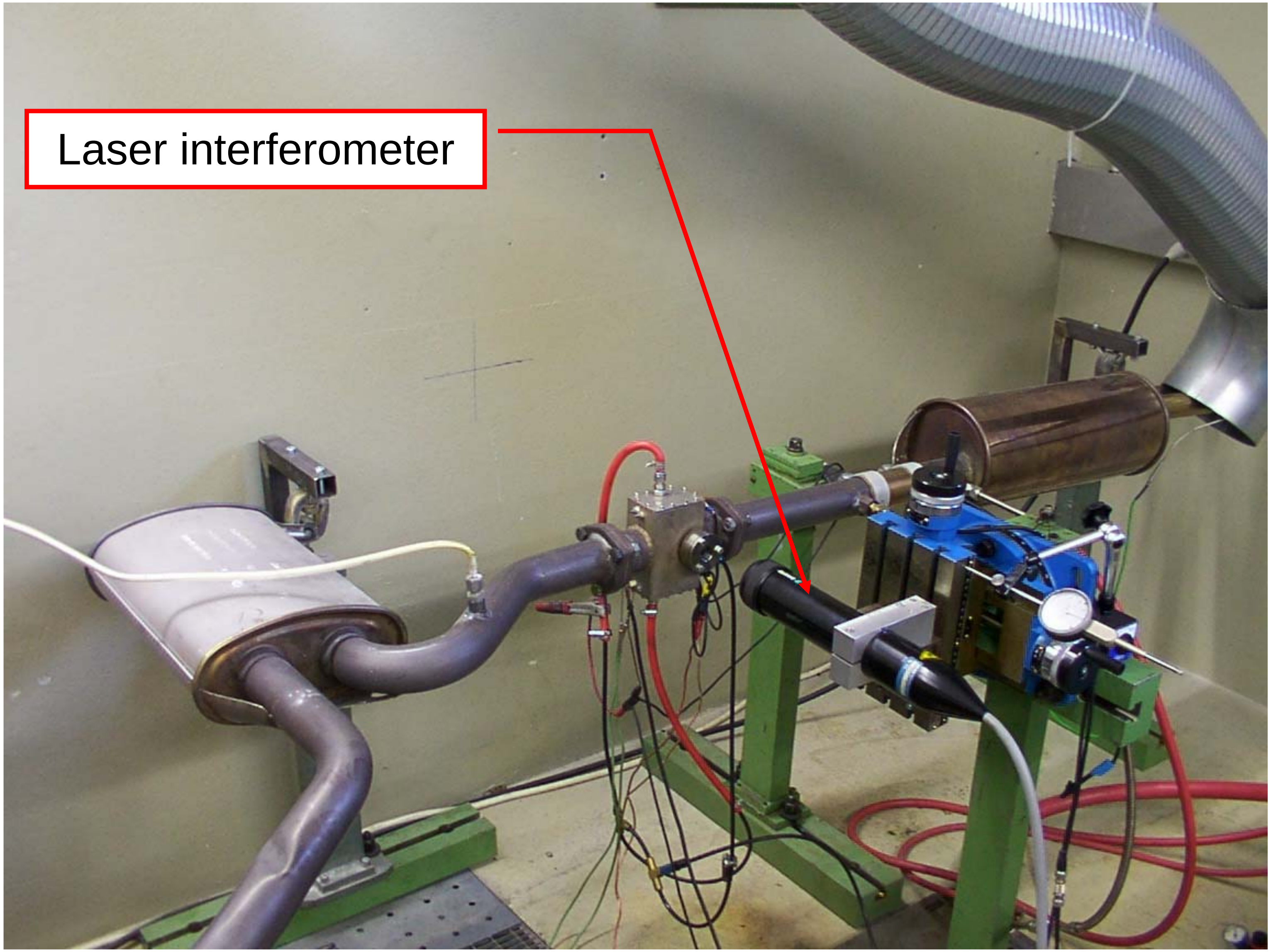
Properties for tests:

- Temperature range 600°C
- Temperature shock resistant
- Easy electrodes variations

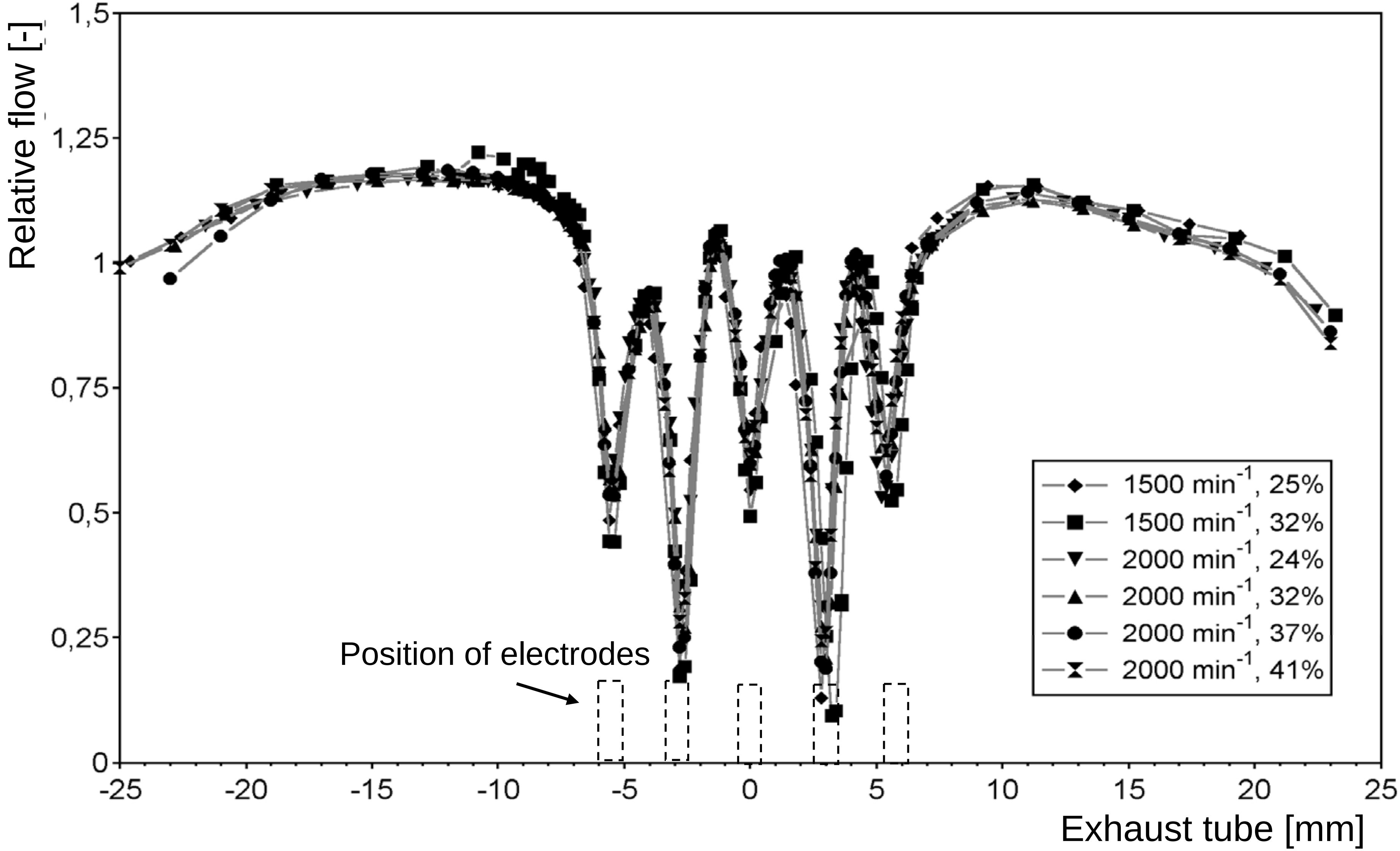


1: Enclosure, 2: Cover, 3: Ceramic heater, 4: Mounting plate, 5: Electrodes

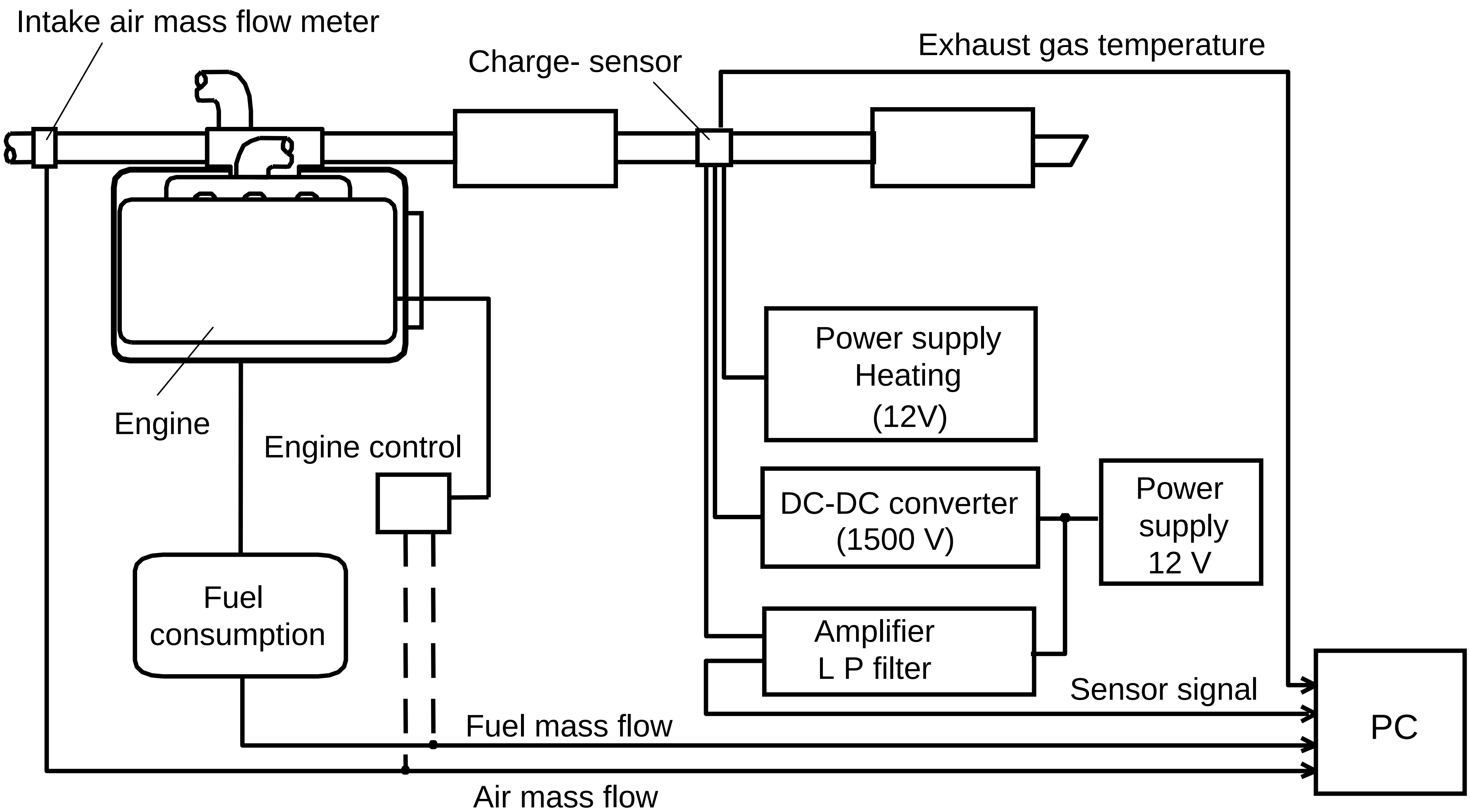
Charge- Sensor test bench operation



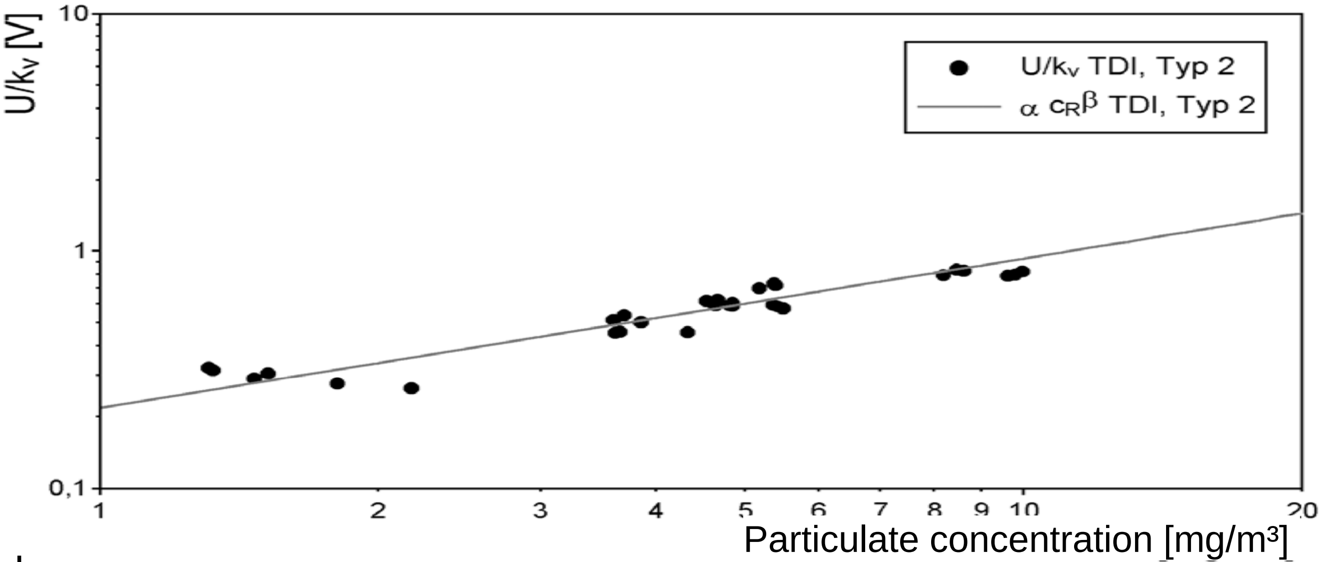
Gas flow profile through electrode blades

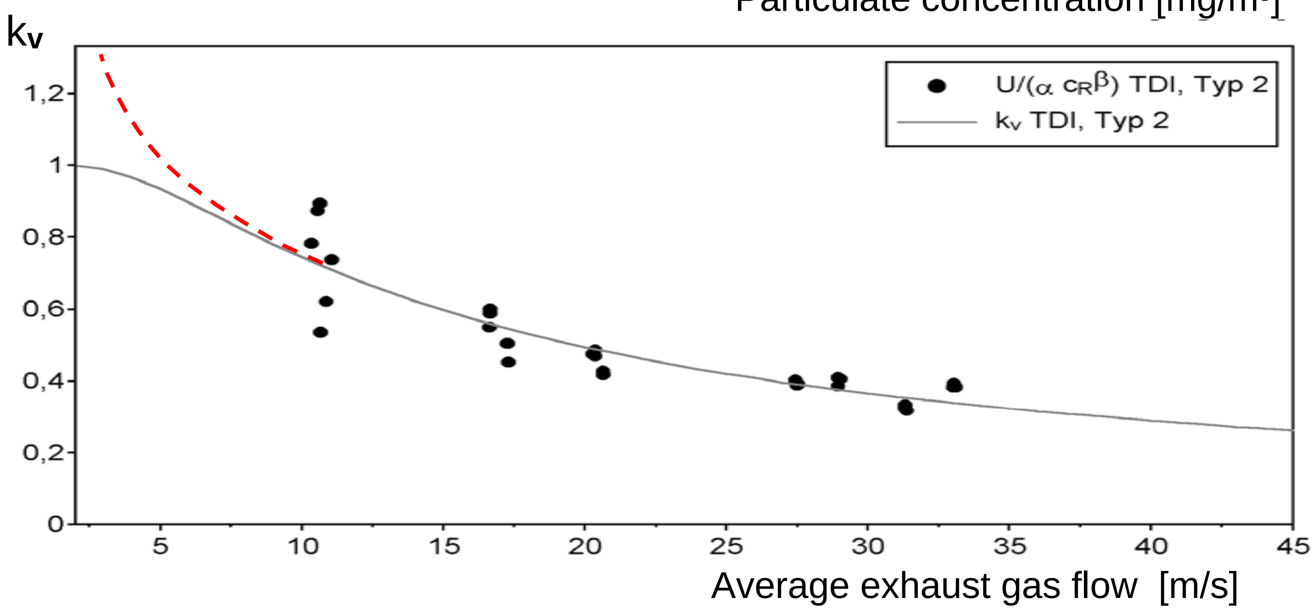


Complete system for on-board operation



Design of the mathematical model





$$U = k_v \, \alpha \; c_R{}^{\beta}$$

$$k_v = (1 - e^{\kappa / v})$$

U: Sensor signal [V]

v: Exhaust gas flow [m/s]

c_R: Particulate concentration

k_v: Gas flow weighting factor

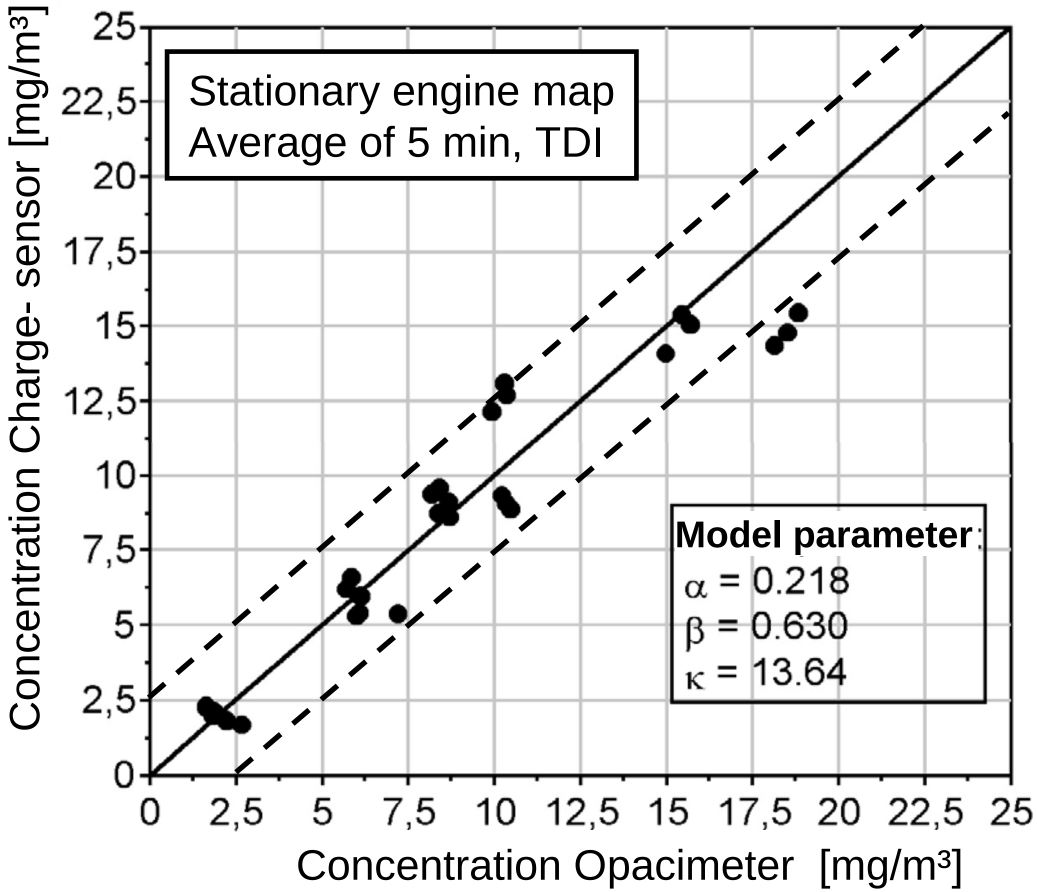
α, β, κ: Model parameter

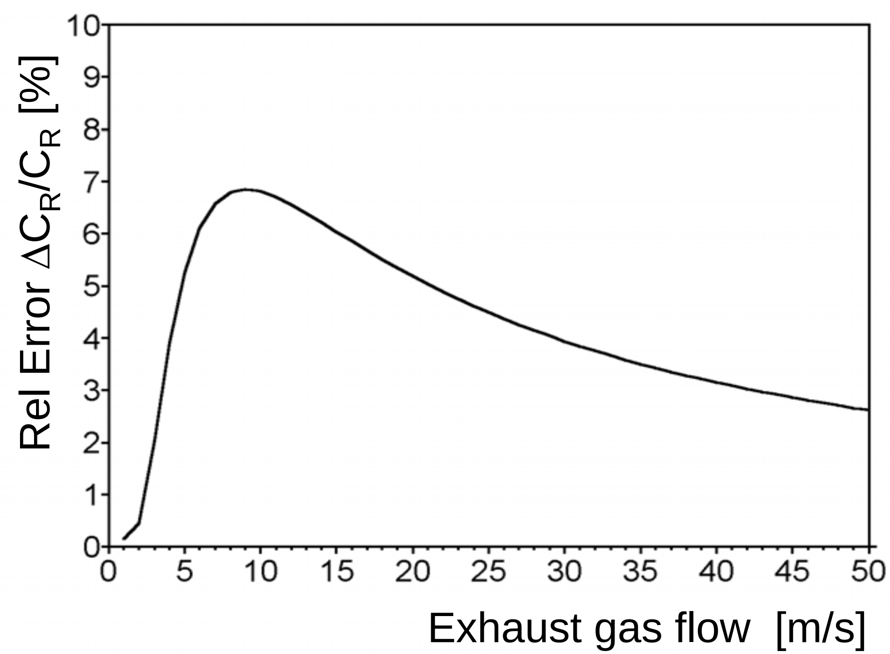
Measuring errors

$$c_R = \left(\frac{U}{\alpha\,(1 - e^{\kappa/v})} \right)^{\frac{1}{\beta}}$$

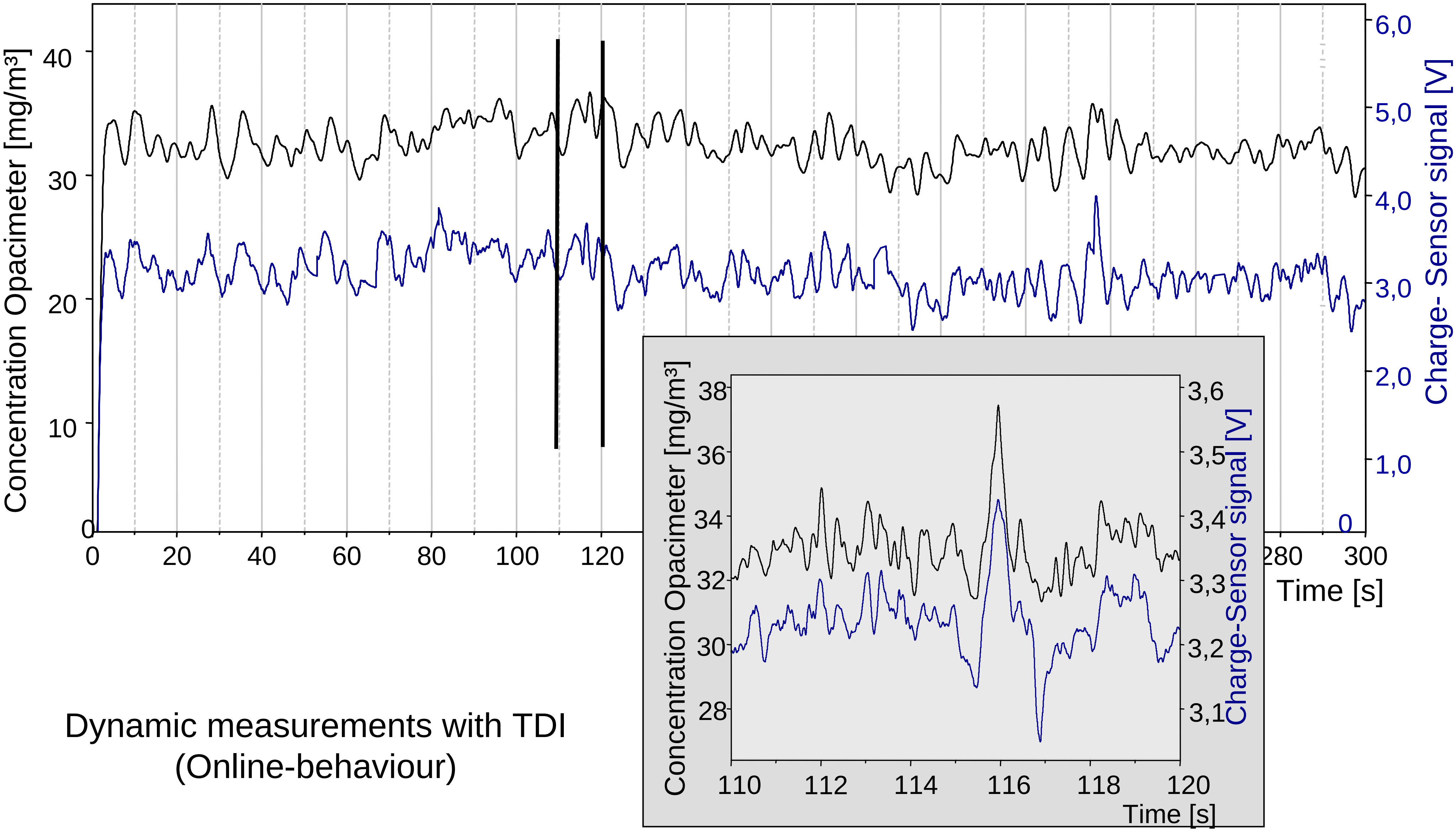
$$\frac{\Delta c_R}{c_R} = \sqrt{\left[\frac{\Delta U}{U} \frac{U}{c_R} \frac{\partial c_R}{\partial U} \right]^2 + \left[\frac{\Delta v}{c_R} \frac{\partial c_R}{\partial v} \right]^2}$$

c_R: calculated particulate concentration
U : Charge- sensor signal [V]
v : Exhaust gas flow [m/s]
$\Delta U/U$: ±0,1% accuracy of amplification
Δv: ±1,0 m/s accuracy of flow measurement



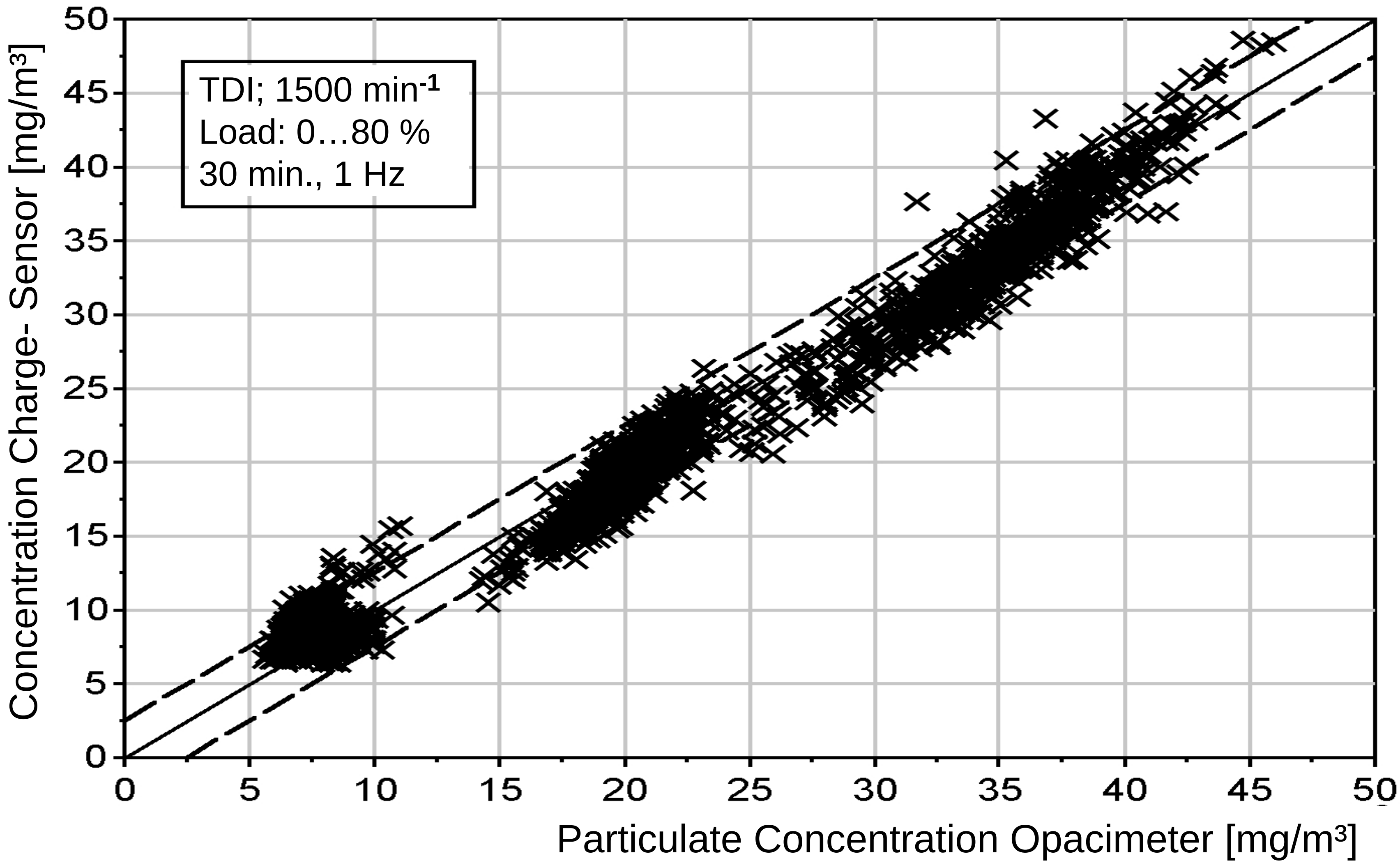


Comparison: Charge-Sensor — Opacimeter



Dynamic measurements with TDI
(Online-behaviour)

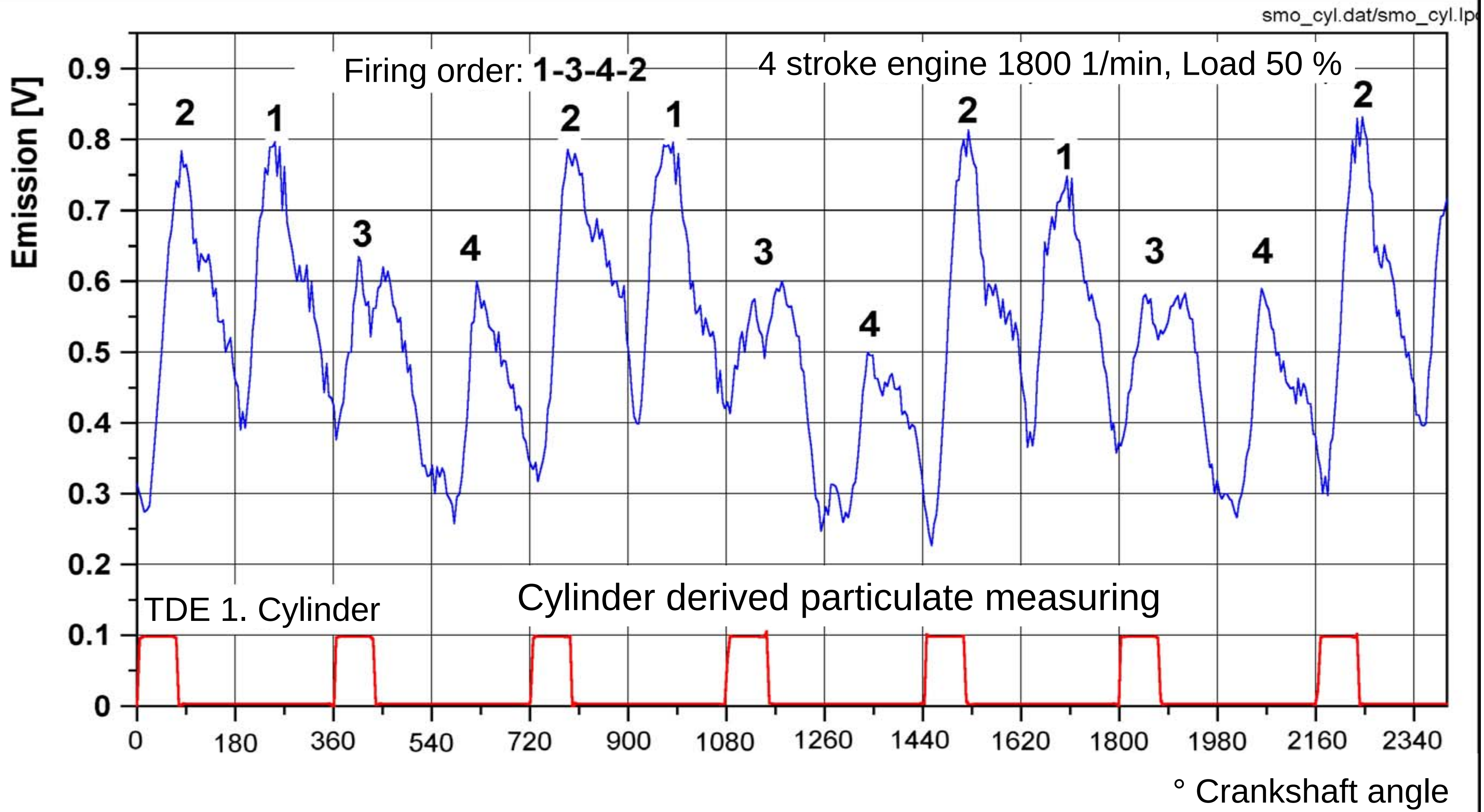
Dispersion of test results



Cross- sensitivities

Parameters		Behaviour		Solution
Exhaust gas flow	⇒	non linear	⇒	mathematical equation
Exhaust gas temerature	⇒	indirect influence by means of changing the gas flow		
Vibration	⇒	resonance frequency of electrode blades	⇒	Low pass filter in combination with high stiffness of the electrodes
Exhaust gas humidity	⇒	no effect down to concentrations of 1 mg/m³		

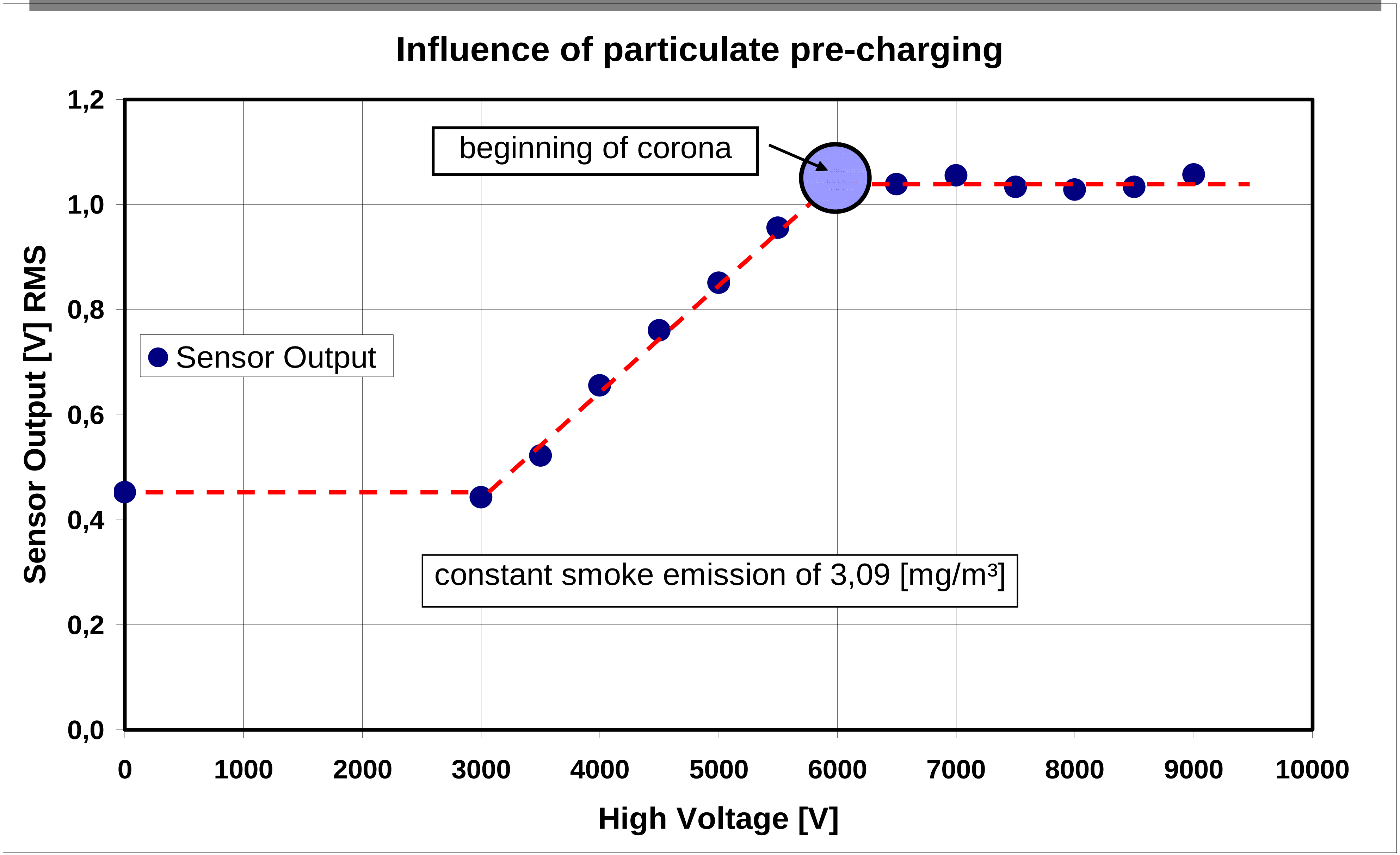
Annother possible application



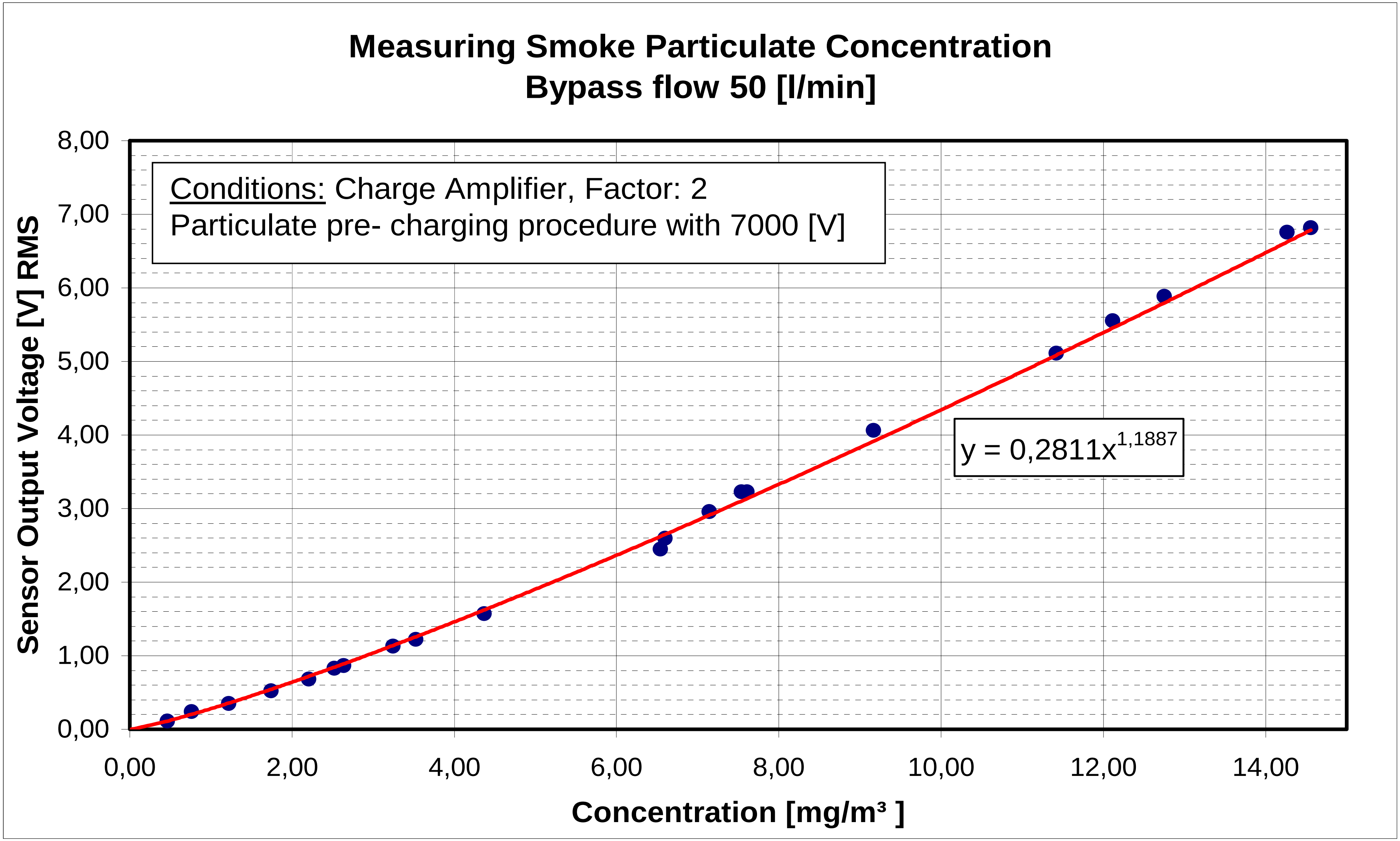
Position: behind turbo charger

Prof. Dr. Hauser

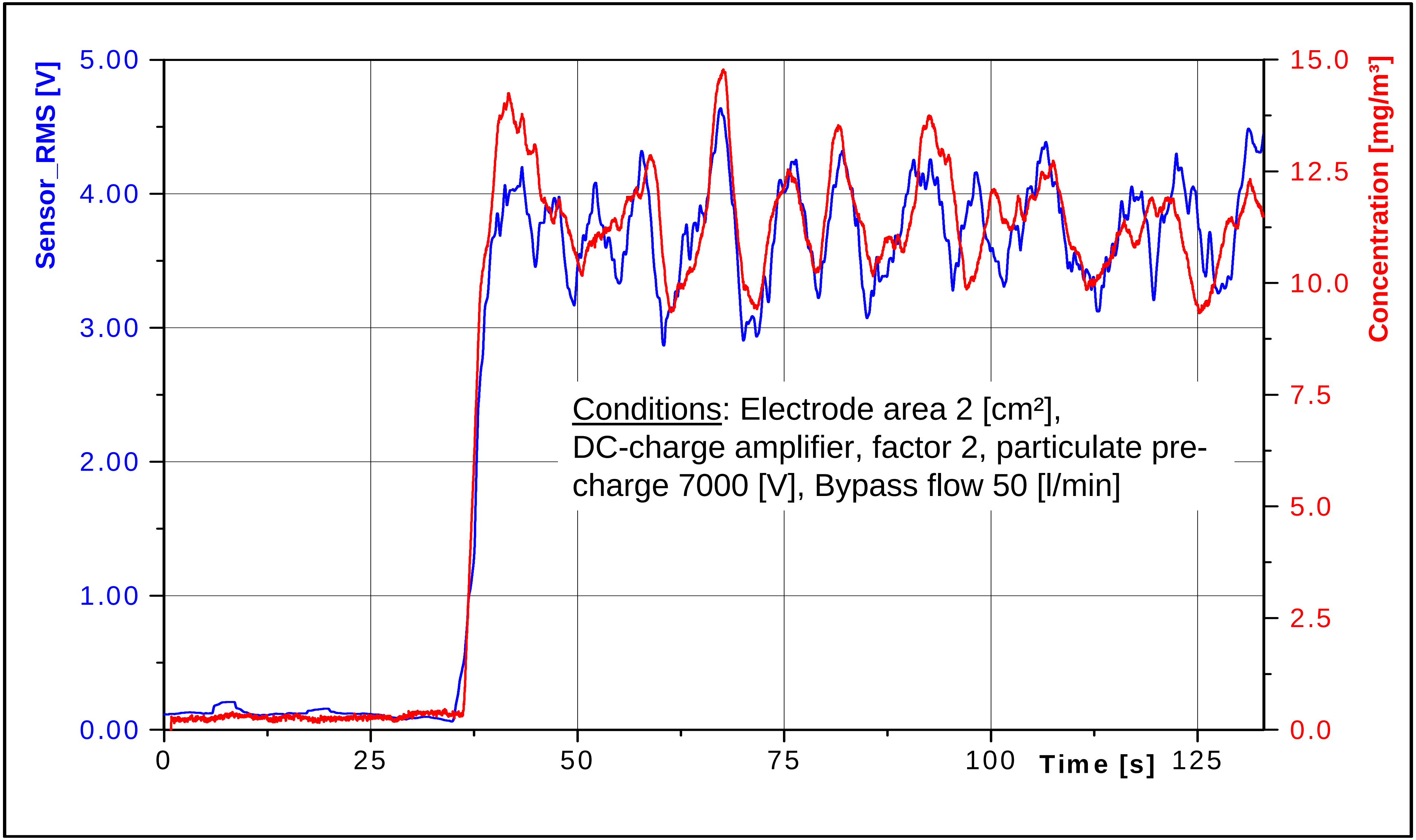
Optimization of charge- sensor



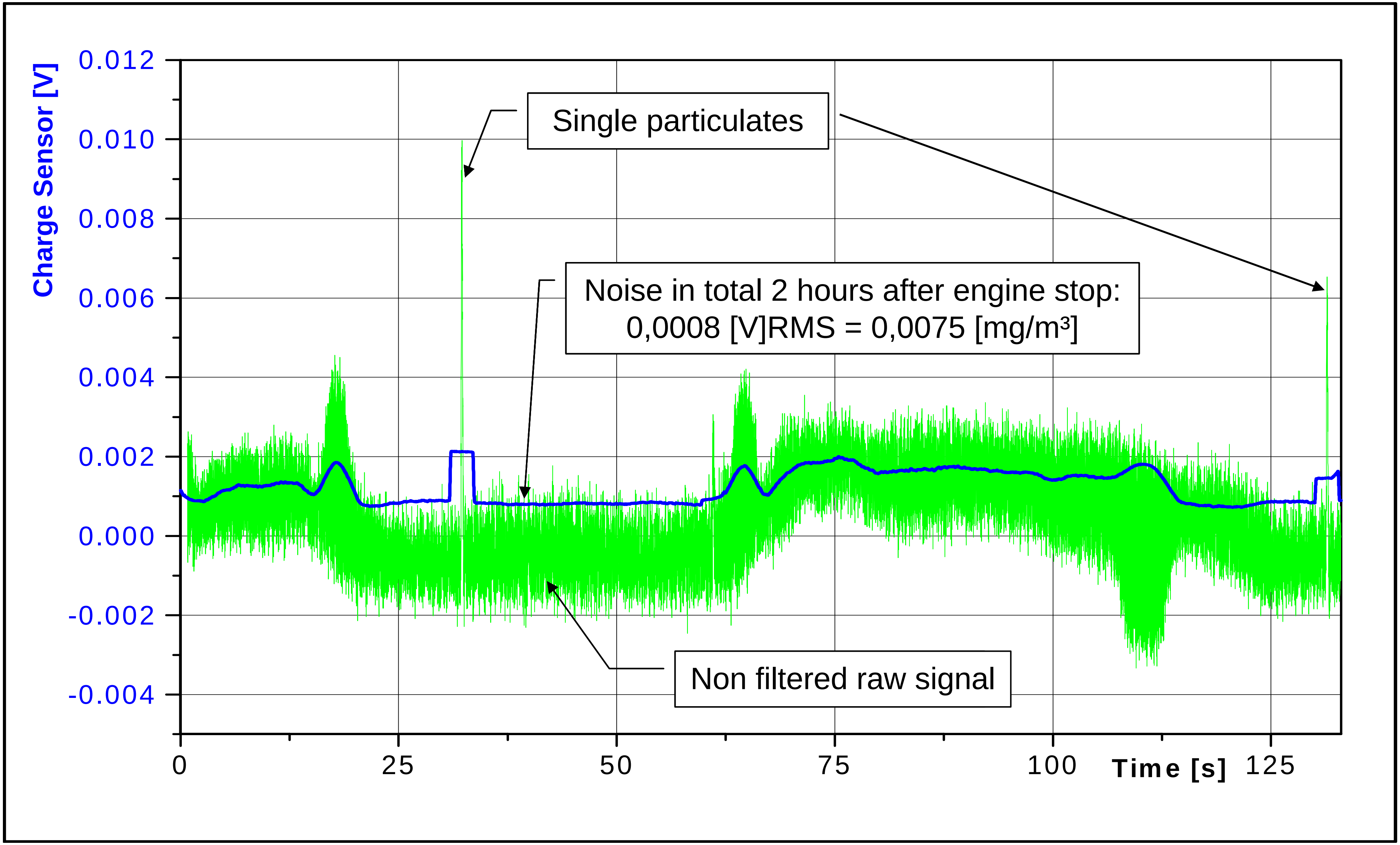
Optimization of charge- sensor



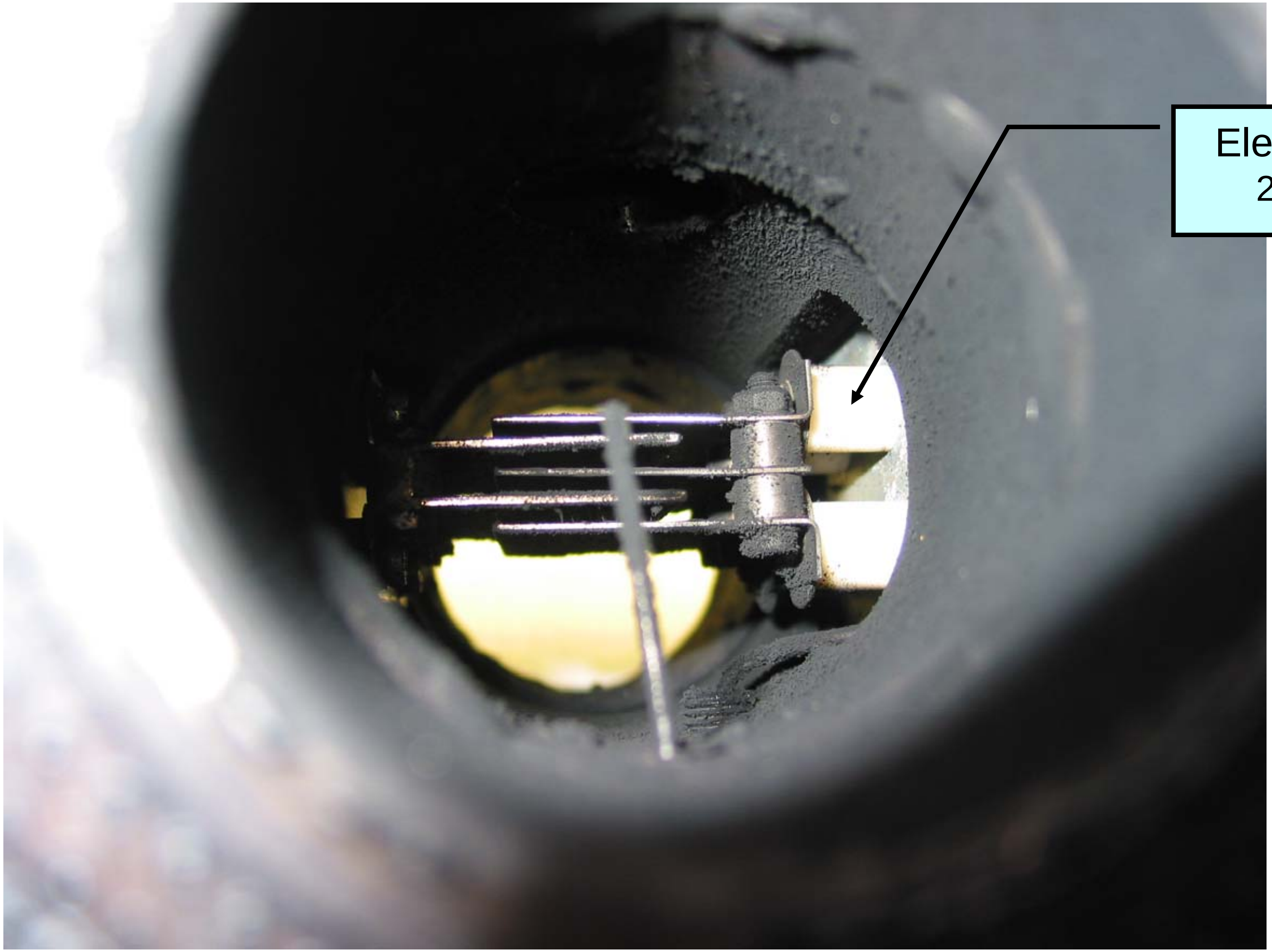
Optimization of charge- sensor output



Total noise of the complete system



Operating behaviour of the charge-sensor



Electrode isolators
200 [°C] heated

Future planning

I am looking for partners who are seriously interested to implement this new smoke measuring technology into high-end equipment and / or on-board diagnosis procedures.