Validation of Novel Light Scattering Sensors for Soot Opacity and Soot Mass

A.Nowak

M. Hildebrandt, G. Lindner, A. Jordan-Gerkens,
A. Kuntze, S. Pratzler, N. Böse,
V. Ebert

Outline of presentation

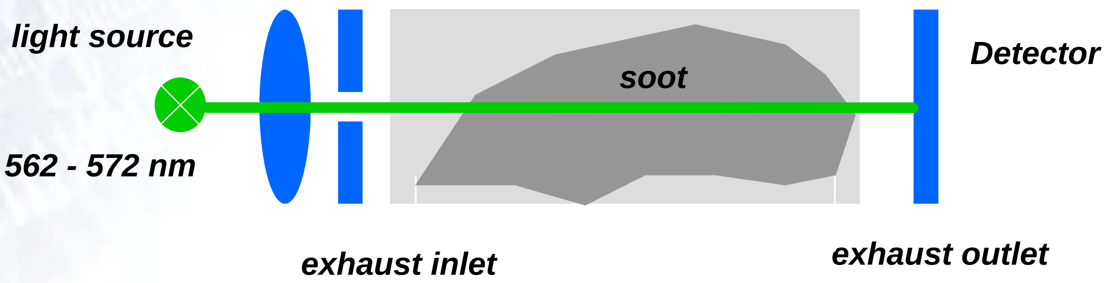
PTB

- Legal bases and framework for soot opacity
  - In Europe and Germany
- Research project
  - Challenges and objectives
  - New method for measurement of soot opacity and soot mass concentration
  - Experimental setup for validation and special dilution system
- Results of research project
  - Correlation for high soot concentration
  - Correlation for low soot concentration
- Conclusion

Legal Bases in Europe for Opacity

Periodical emission control of vehicles

- *European Commission Directive 2010/48/EU*
- *Vehicles with type approval since 2006: On-Board-Diagnostic*
- *Older vehicles: regular - particle emission controlled via opacimeter*



- *Measuring the opacity N (in %) or the light absorption coefficient k (m^{-1})*

$$N = 1 - \frac{I}{I_0}$$

Light intensity with smoke (I)

Light intensity without smoke (I_0)

$$k = \frac{1}{L_A} \ln\left(\frac{I}{I_0}\right)$$

effective optical path length (L_A)

- *Maximum limit for exhaust of modern engines: k = 1,5 (error limit ± 0,3)*

Framework for vehicle inspection in Germany

- *Type approval of opacimeters required verification ordinance 18.9 at PTB*
- *Traceability of reference opacimeter to the SI via optical filters that are calibrated at PTB*
- *Verification in the field via calibrated optical filters*

Points of criticism since years:

- *Insufficient resolution of type approved opacimeter*
- *k = 0,5 (± 0,3) as lower limit is too high in contrast to the regular motor type approval (k < 0,3)*
- *No signal when measuring exhaust of modern diesel engines with particle filters*

Research project with ASA[1]-association

- Project duration: 3 years (finished in Nov.2013)

- Goal:
  - Development of a metrological background for future type approvals of new soot sensors based on light scattering

- Challenges:
  - German verification act requires devices to measure the opacity and the light absorption coefficient
  - Indication on the screen of devices must be k in m^{-1} or N in %
  - Verification method in the field should be similar to transmission filters (easy to use, traceable)

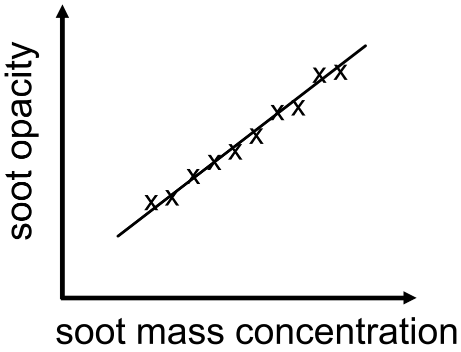
[1] **Bundesverband der Hersteller und Importeure von Automobil-Service Ausrüstungen e.V.**

PTB – ASA Research cooperation

Objectives

- *Traceable and improved correlation between soot opacity and soot mass concentration are needed for the novel devices → experimental validation!*

opacimeter



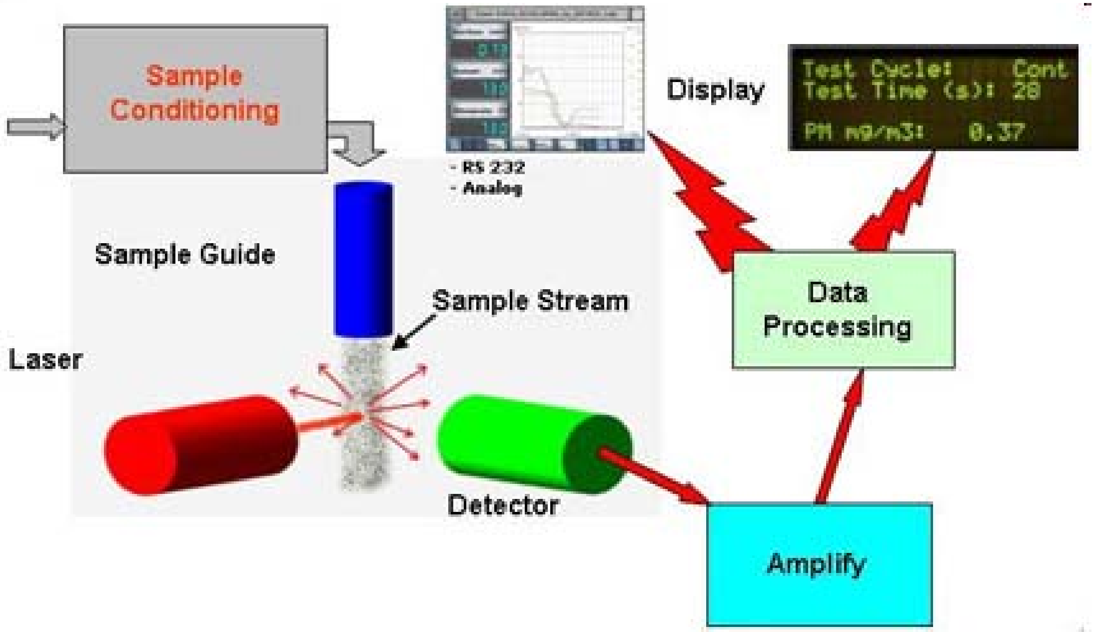
light scattering soot sensor

- *Investigate if a general correlation between the soot opacity and the soot mass concentration*
  - *for different particle sizes / particle number size distributions*
  - *for different light scattering sensor types*
  - *for improved uncertainty*

PTB-ASA research cooperation
New method for particle measurement: light scattering

Basic physical concept :

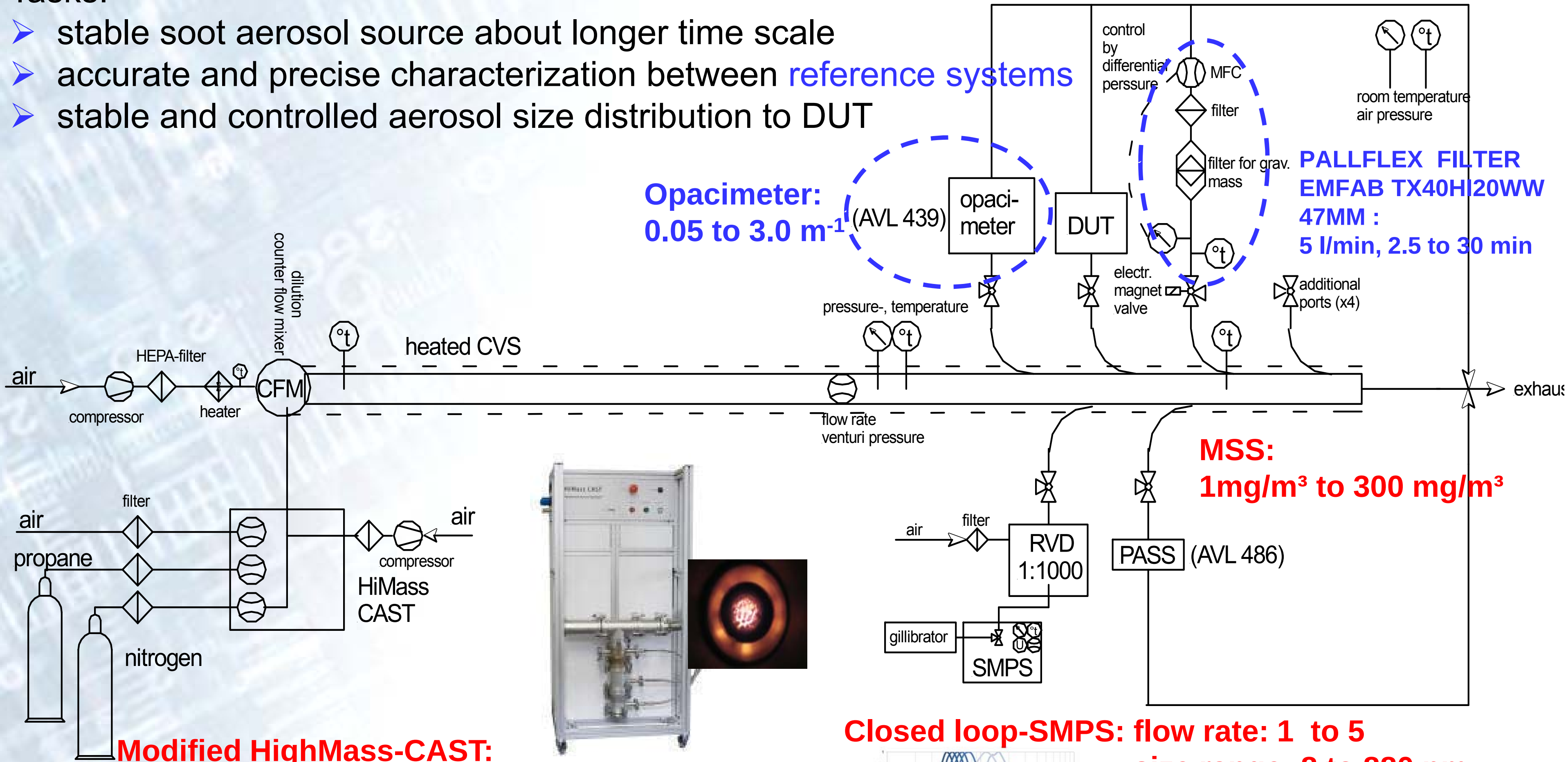
- *The Mie Theory for light scattering*
  - *Light is scattered by small particles*
  - *Scattered light intensity and angle distribution depends on the sensor angle between laser beam and detector*
  - *Detected signal of sensors depends on particle size, shape and number concentration*



- *Typically, higher sensitivity than opacimeter at low particle concentrations*

Experimental Setup for Research Cooperation

Tasks:
- stable soot aerosol source about longer time scale
- accurate and precise characterization between reference systems
- stable and controlled aerosol size distribution to DUT



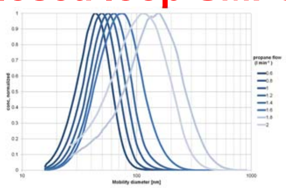
Opacimeter: 0.05 to 3.0 m^{-1}

PALLFLEX FILTER EMFAB TX40HI20WW 47MM : 5 l/min, 2.5 to 30 min

MSS: 1mg/m³ to 300 mg/m³

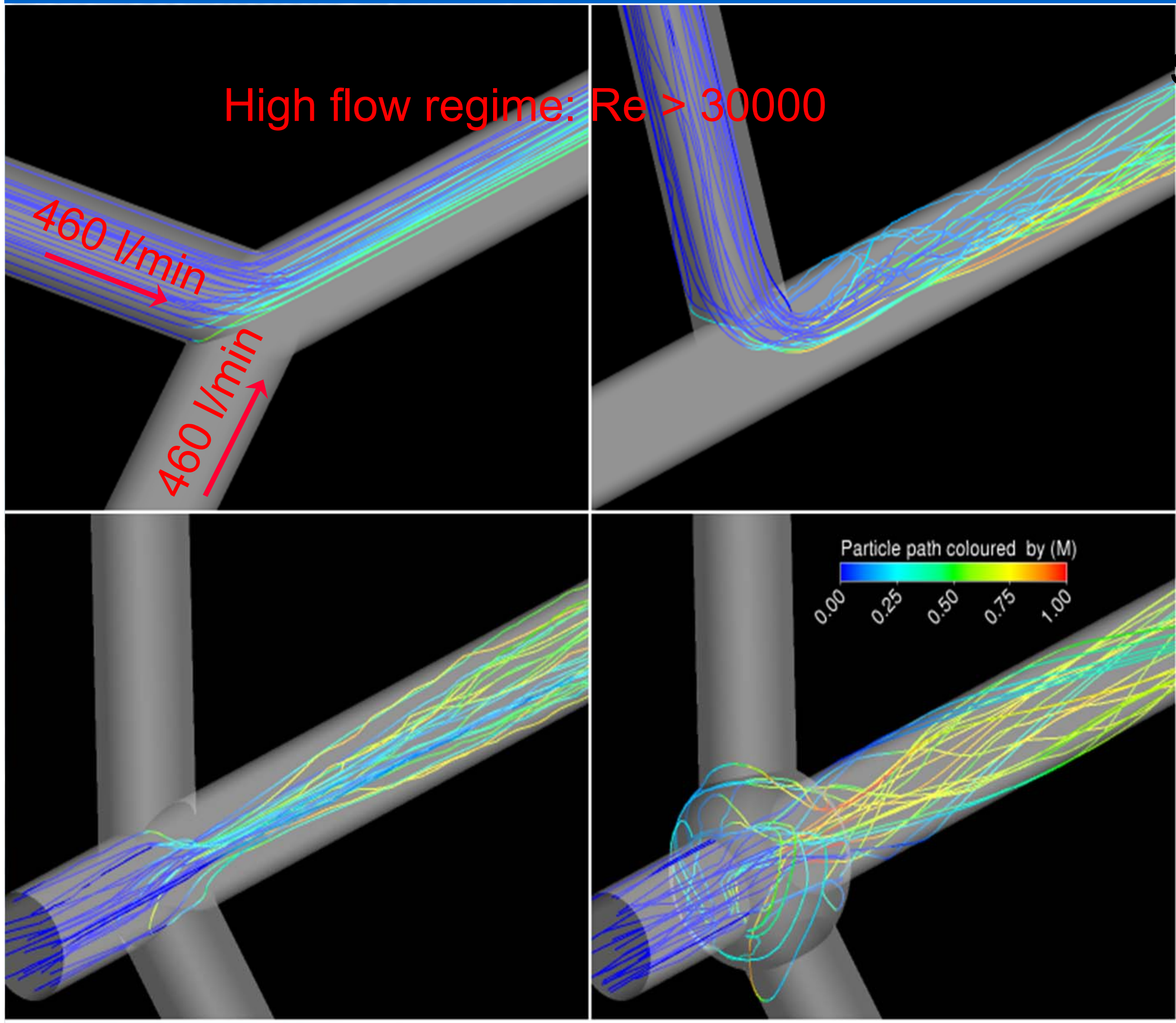
Modified HighMass-CAST:
approx. 460 l/min
10^5-10^8 part./cm³
1 mg/m³ to 500 mg/m³
70 to 220 nm, monomodal

Closed loop-SMPS: flow rate: 1 to 5
size range: 8 to 880 nm



Special Dilution System – CFD Simulation
PTB internal Cooperation

PTB



Simulation of particle trajectories

A boundary layer and a developing of string jet could only be avoided by the sphere

→ Best results for aerosol mixture by a counter flow mixer, especially for the geometry of the sphere

Overview of parameter for intercomparison workshop

PTB

- Gravimetric soot mass (m_1) via filter loading
- Online optical soot mass (m_2) via MSS AVL 483
- Light absorption coefficient (k) via reference opacimeter AVL 439 (k in m^{-1})
- Particle number size distribution via non-commercial SMPS (→ Mean Dp, nm)
- CVS tunnel parameter (T, flow)

Number of participants and DUTs	Number of measured points	Analyzed data of intercomparison workshop
6 (14)	117	k, m_1, m_2, Dp, CVS

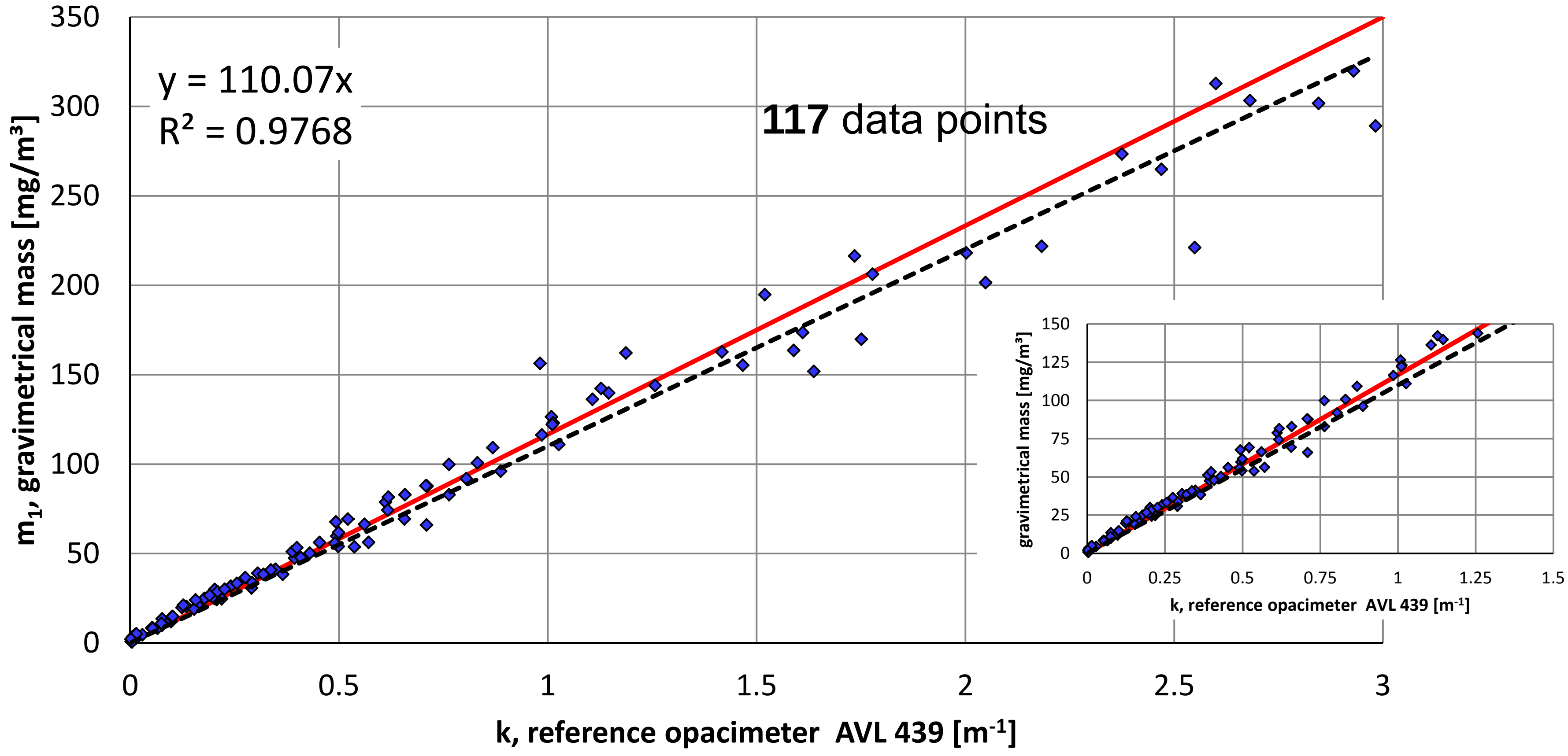
→ Average means values of all parameters are predefined by gravimetrical filter loading time

→ Only measurements for stationary conditions (no dynamical response check)

Results of intercomparison workshop PTB internal traceable systems

PTB

- Very good correlation for reference systems could be observed about 3 orders of magnitude for k and m_1

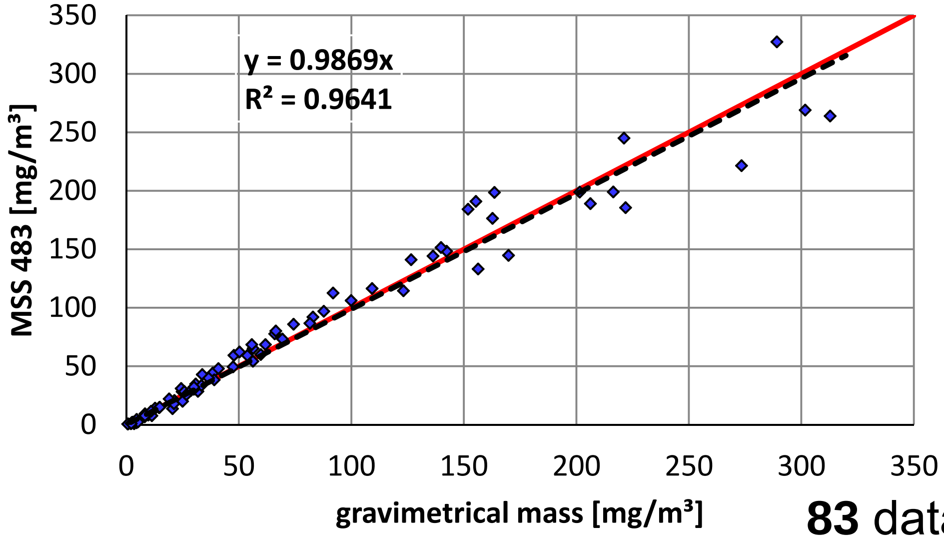


About stability of setup: see Poster Session 5: Instrumentation, no. 40: Margit Hildebrandt

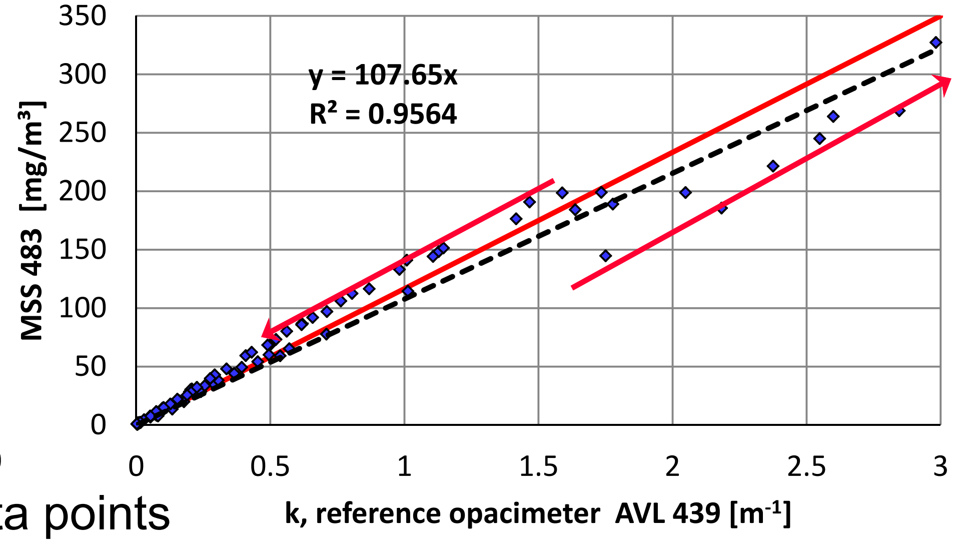
Results of intercomparison workshop
PTB internal systems

PTB

- Also very good correlation could be observed for gravimetric soot mass vs. optical soot mass (MSS 483)
- For correlation between optical soot mass and reference opacimeter are some discrepancy for the slope of the linear correlation



83 data points

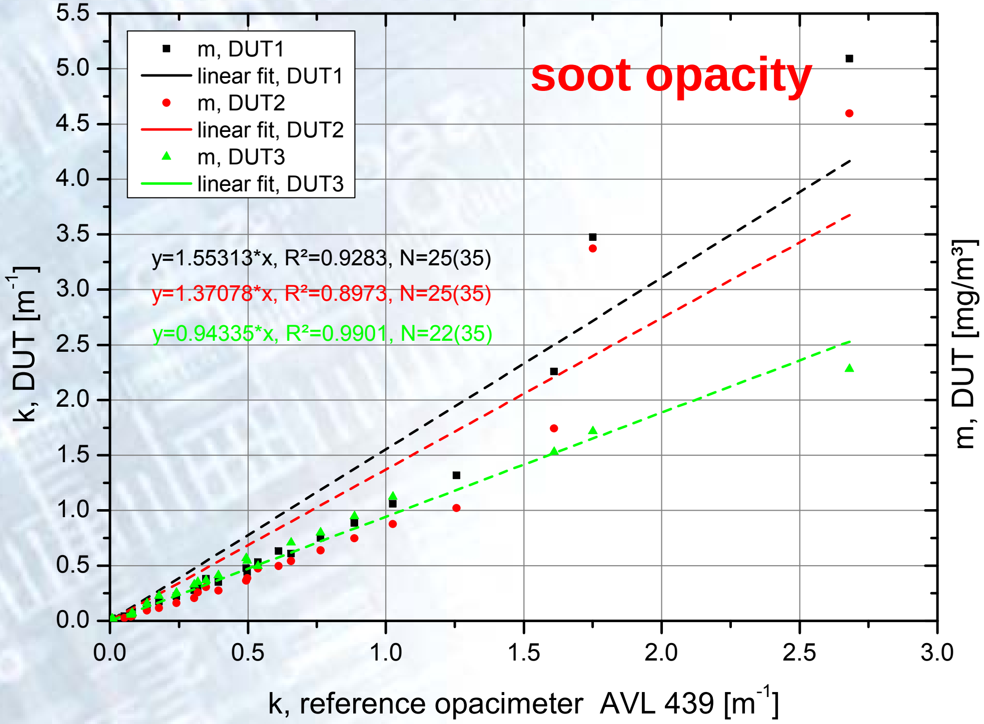


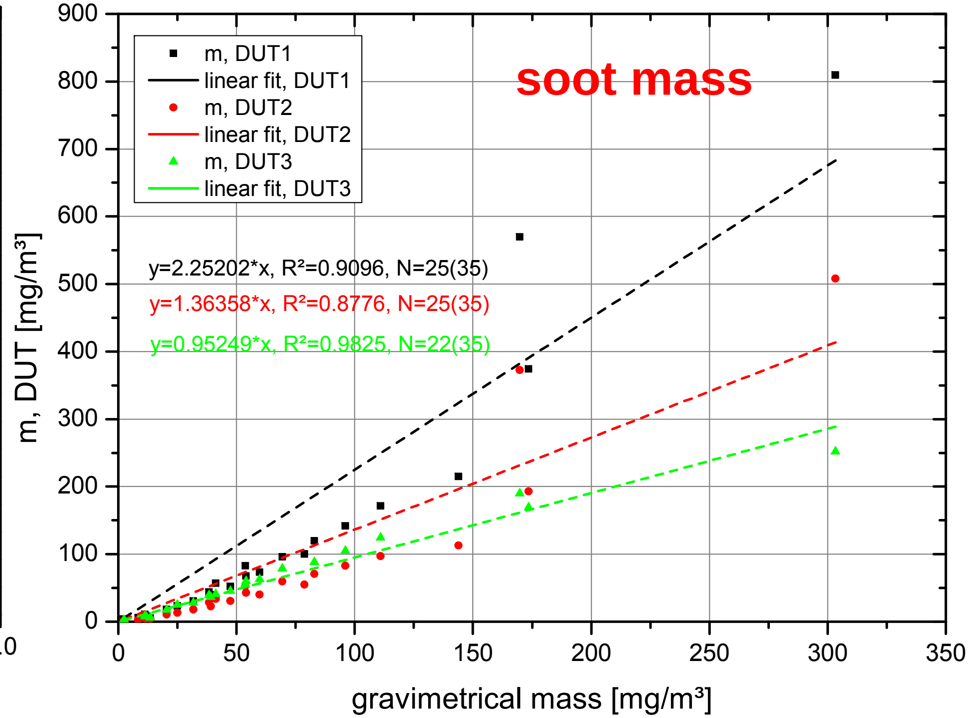
Less data density for MSS, because of leakage in measuring cell for two days

Results of intercomparison workshop
reference systems vs. new sensors for high soot loading

PTB

- Quite different deviation for DUTs could observed, one device with very good correlation (master device?)

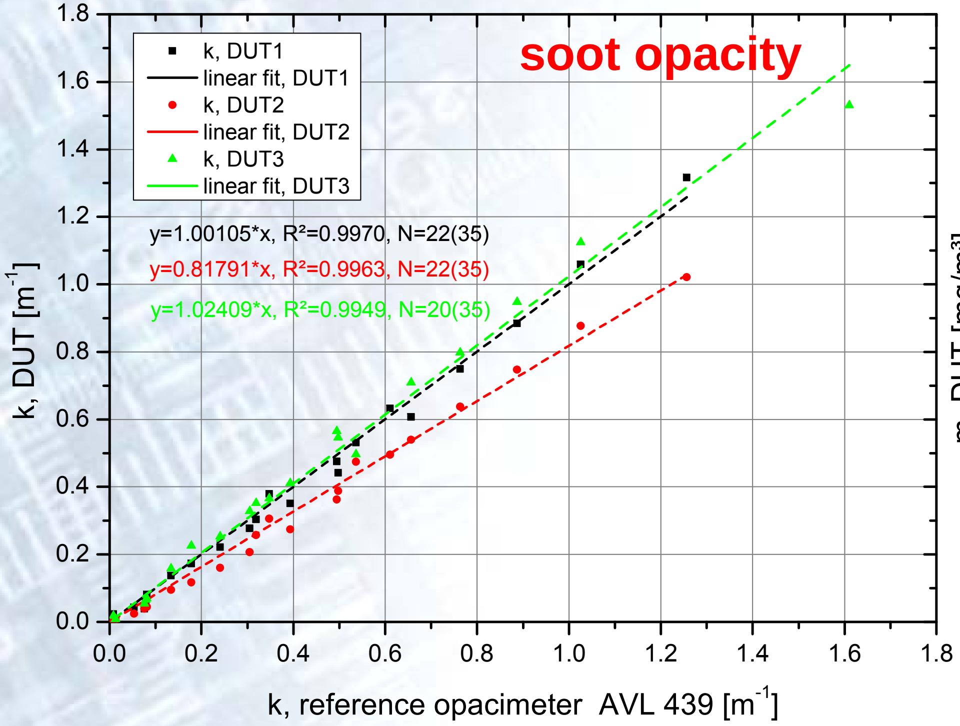


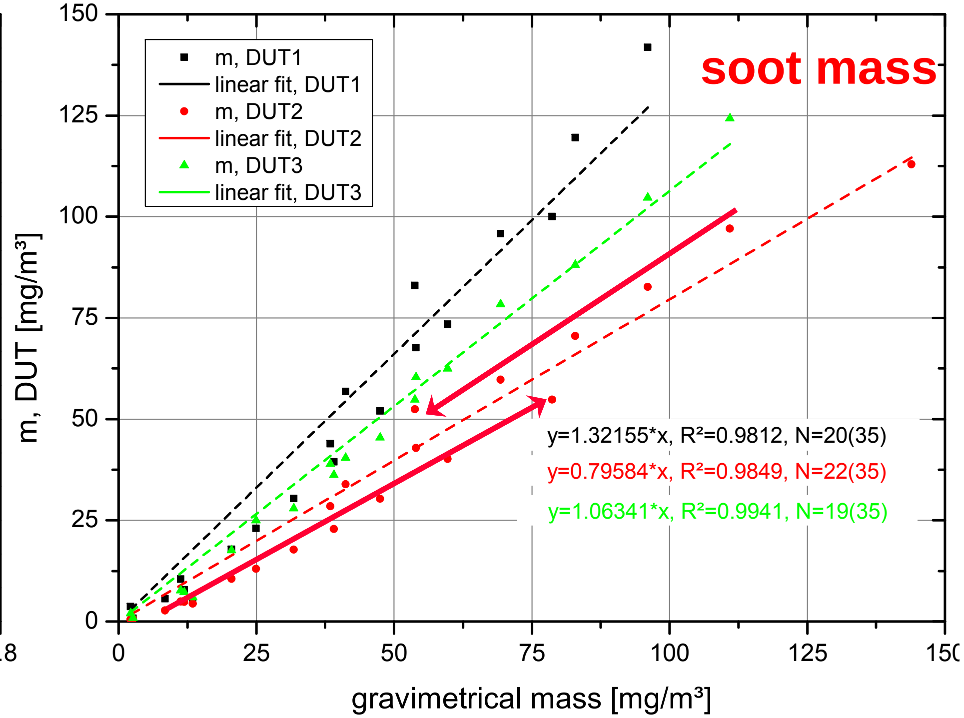


→ Higher variance of data points for m > 150 µg/m³ and k > 1.6 m^{-1} stronger variance as well as very rare data points

Results of intercomparison workshop
reference systems vs. new sensors for low soot loading

- For data points for m < 150 µg/m³ and k < 1.6 m^{-1} could observed very good correlation, especially for k





→ For m were observed different slopes for the linear correlation in different directions

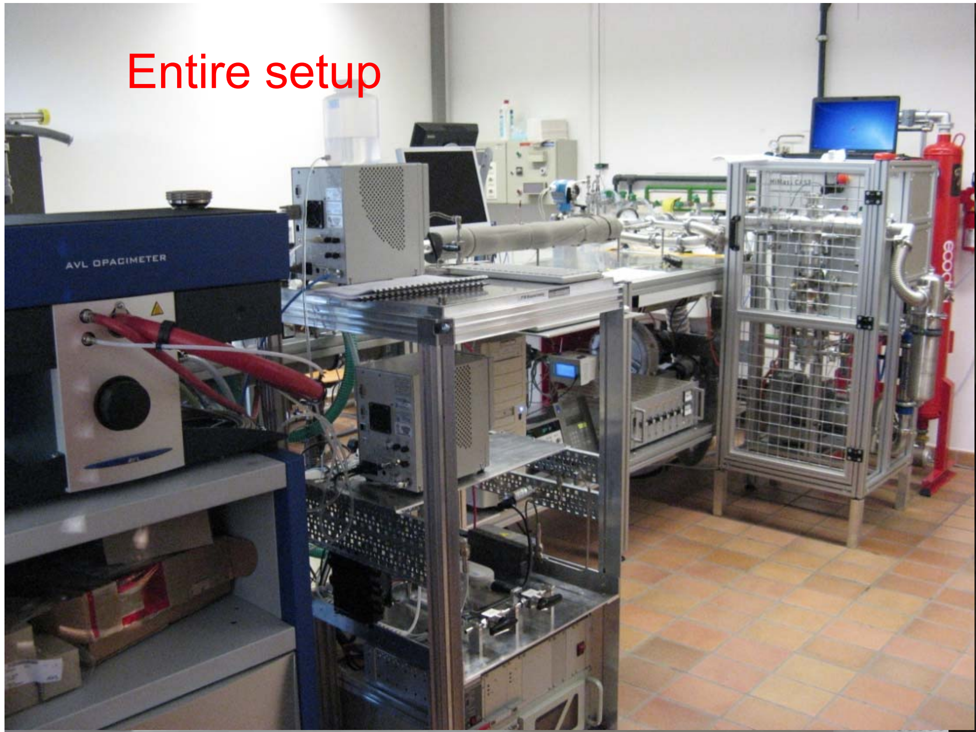
Conclusion

PTB

- A new stable soot reference source was installed at PTB for a large range of soot mass concentration
- The new light scattering sensors are a 100xmore sensitive than commercial opacimeter on the market for vehicle inspection
- In general, the correlations with respect to light absorption coefficient showed for low soot concentration ($k < 1.6\ m^{-1}$) significantly better results than for high soot concentration ($k > 1.6\ m^{-1}$)
- For k < 1.6 mostly very good correlation coefficient were determined between 0.98 to 0.99 for all devices
- Just few sensors with good correlation for soot mass during these campaign, especially below 150 mg/m^3

→ So far, no universal calibration method according to verification ordinance 18.9 is available to validate the sensors during field measurements → no type approval

Thanks for your attention


Entire setup
AVL OPACIMETER

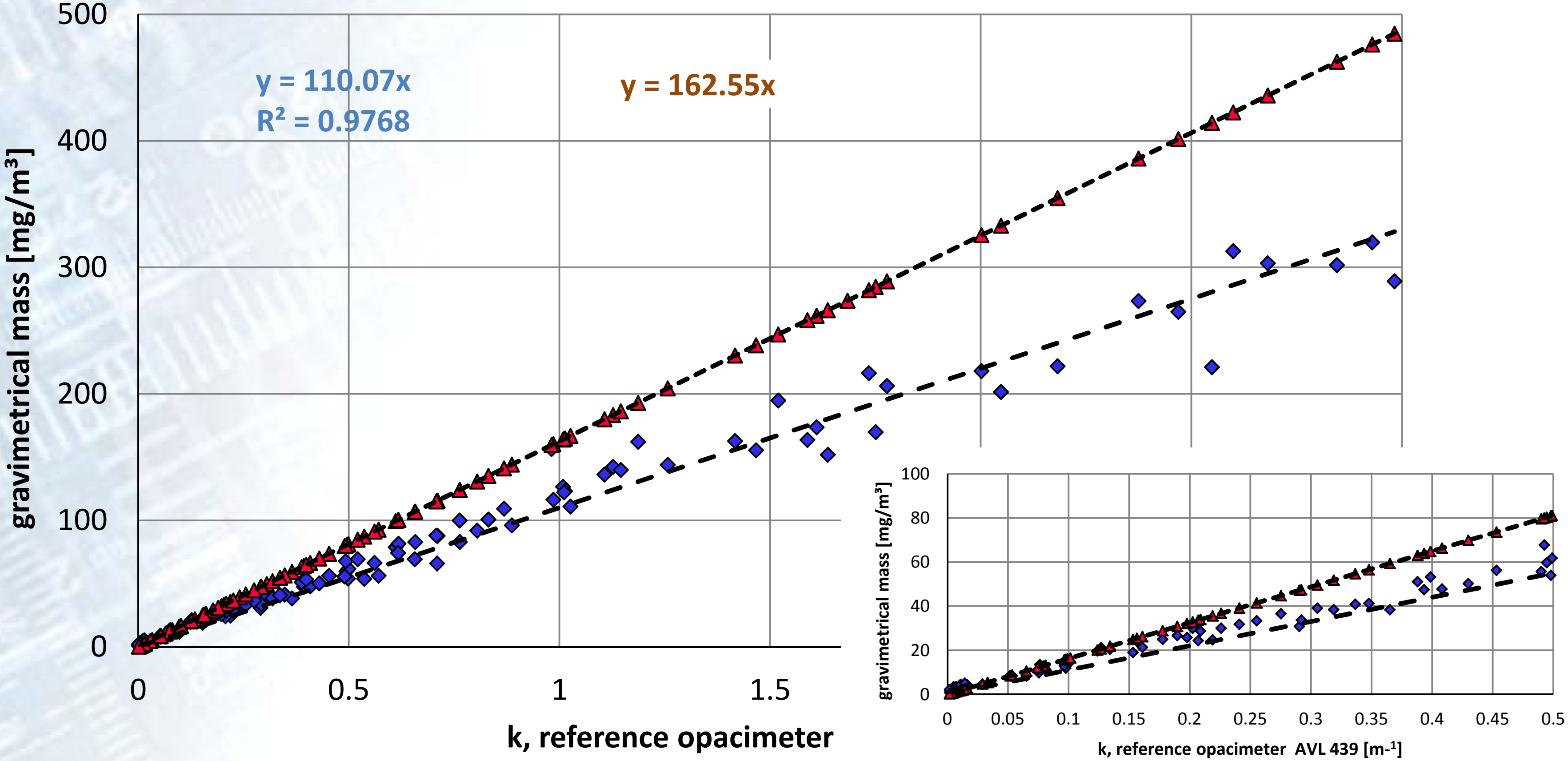

Counter flow mixer


Scale with filters
METTLER
METTLER AT261 DeltaRange
FACT


Gravimetrical unit
mks
MASS-FLO CONTROLLER
FLOW

Outlook: Link to real soot data (MIRA report[1]) Fitted linear correlation vs. measured data

- The linear fit of the MIRA report was used to calculate the MIRA soot mass based of the k-values of the intercomparison workshop → Implementation of conversion factor is needed



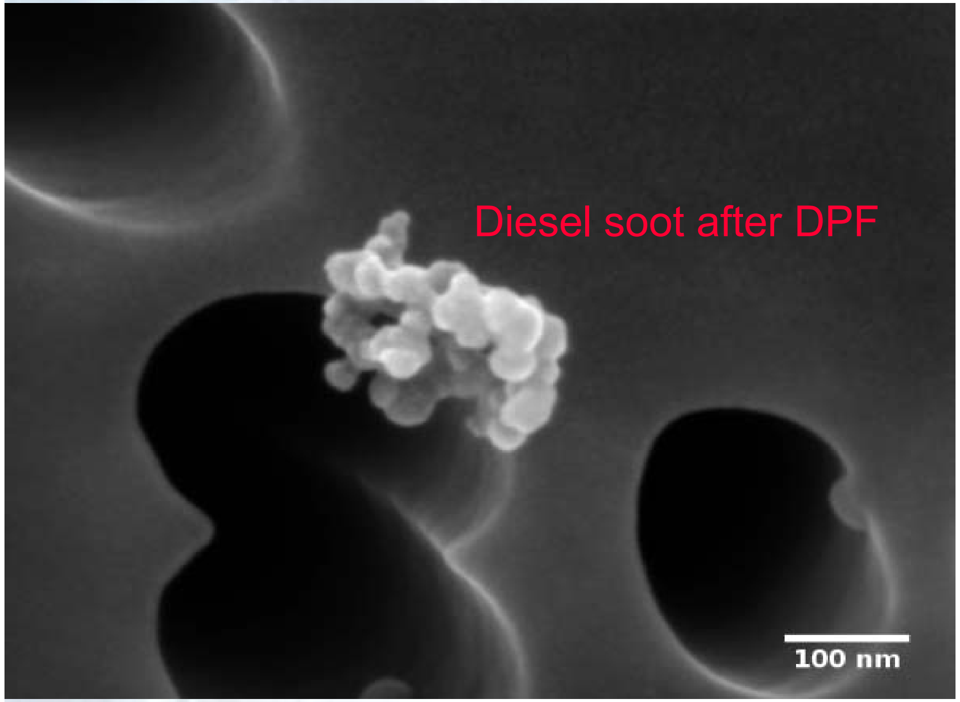
[1] A. E. Dodd und Z. Holubecki im MIRA – Report No. 1965/10, Nuneaton (1965).

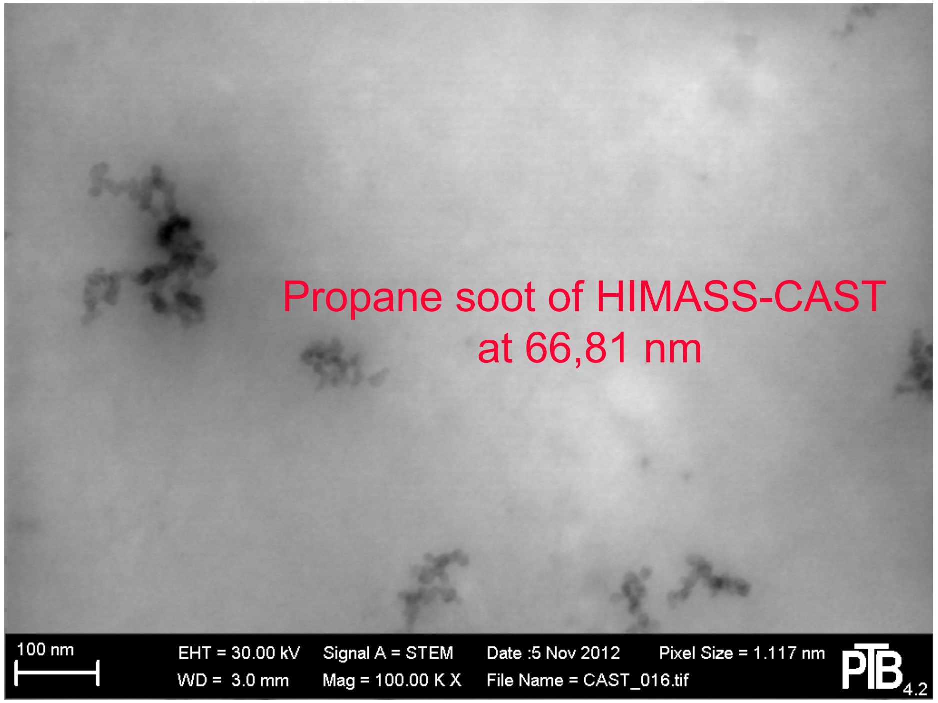
Outlook: Link to real soot data
Difference between diesel and propane soot

PTB

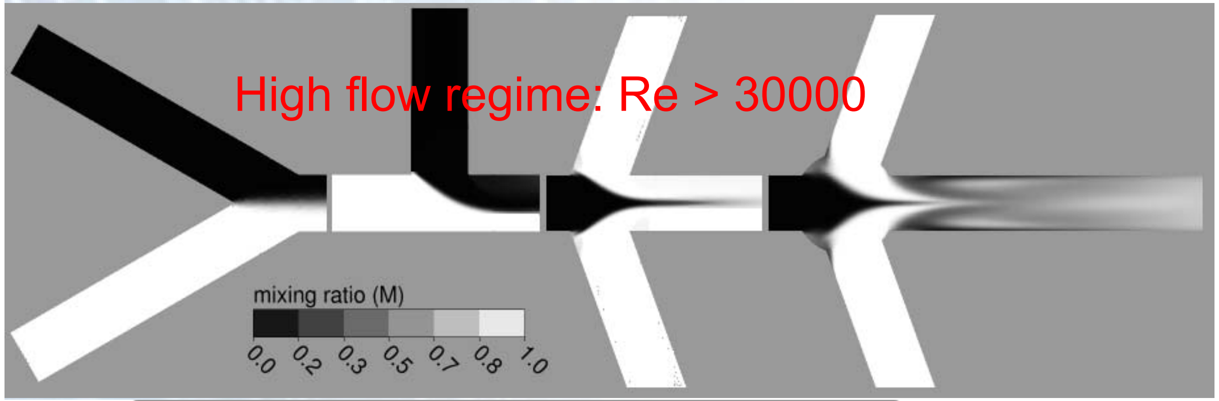
- TEM analyze showed more clustered structure for diesel soot than propane soot (longer aggregates) → Differences in density
- Effect on optical parameter like refraction index, primary particle sizes, fractional dimension
- Influence of relative humidity in the exhaust

→ Further research project is needed

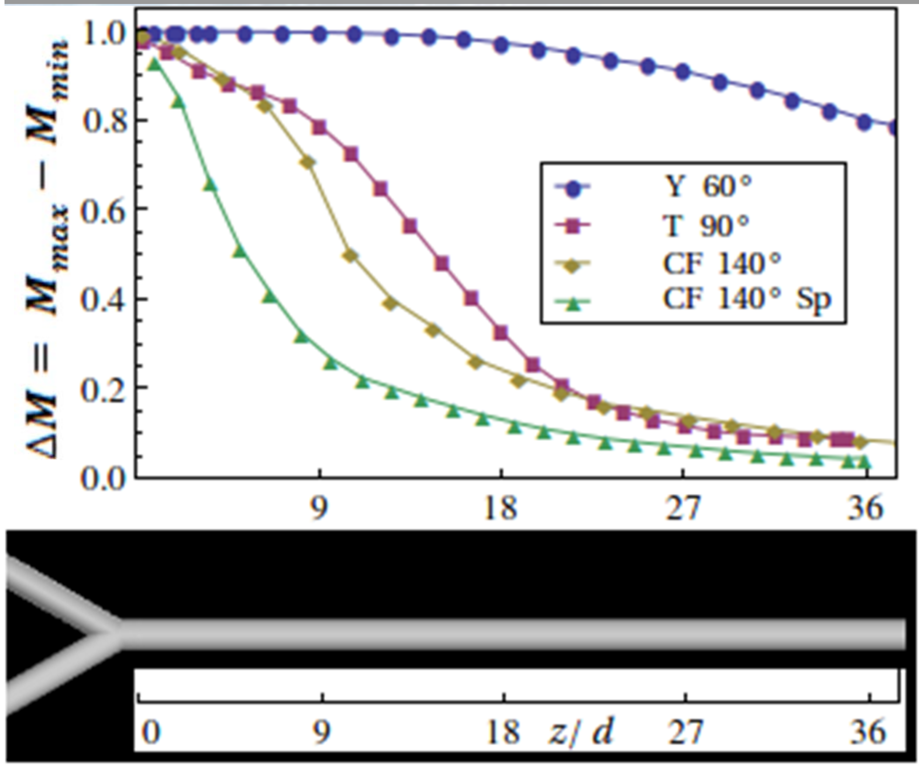




Special Dilution System – CFD Simulation
PTB internal Cooperation



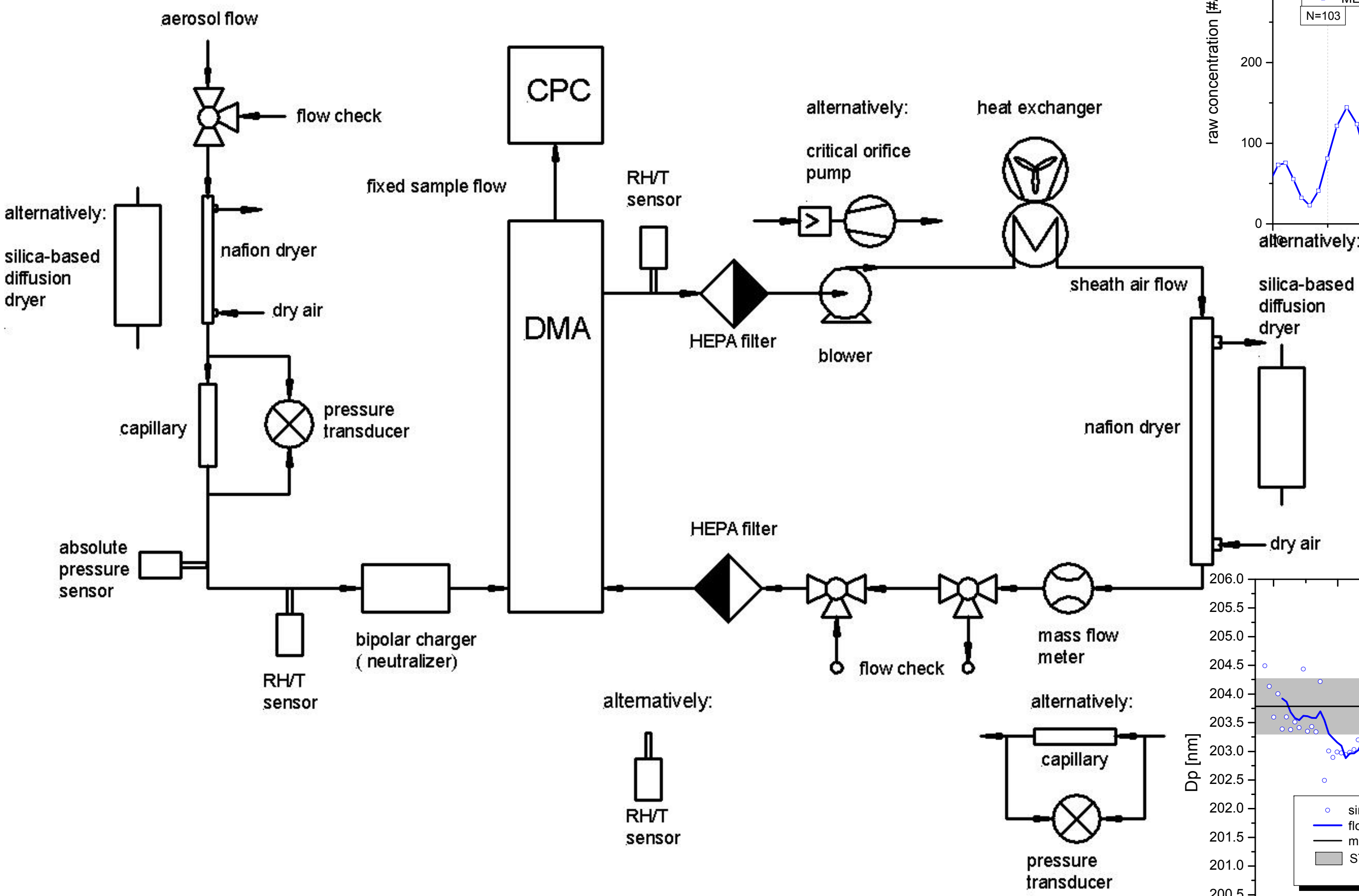
Side view of different geometries for the mixing ratio of two gases (white for dilution air at 0.0 for 450 l/min and black for CAST exhaust at 1.0 for 450 l/min)

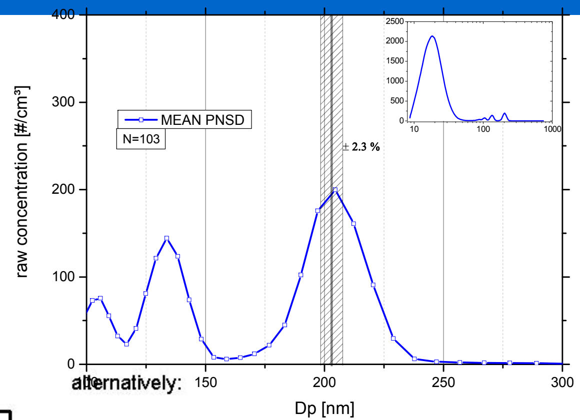


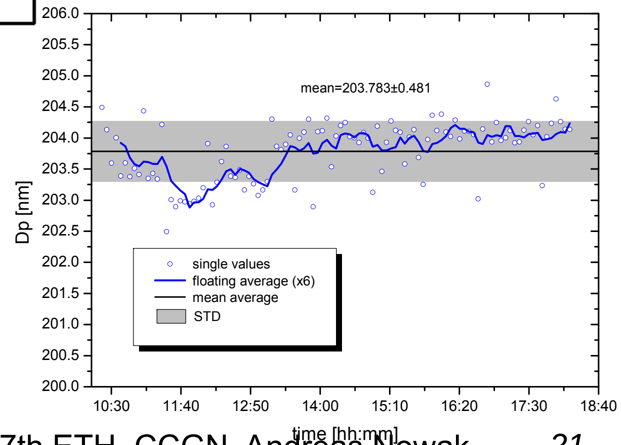
Quantification of mixing process behind the mixing unit about $\Delta M = M_{max} - M_{min}$

→ Best results for gas mixture by a counter flow mixer including a sphere

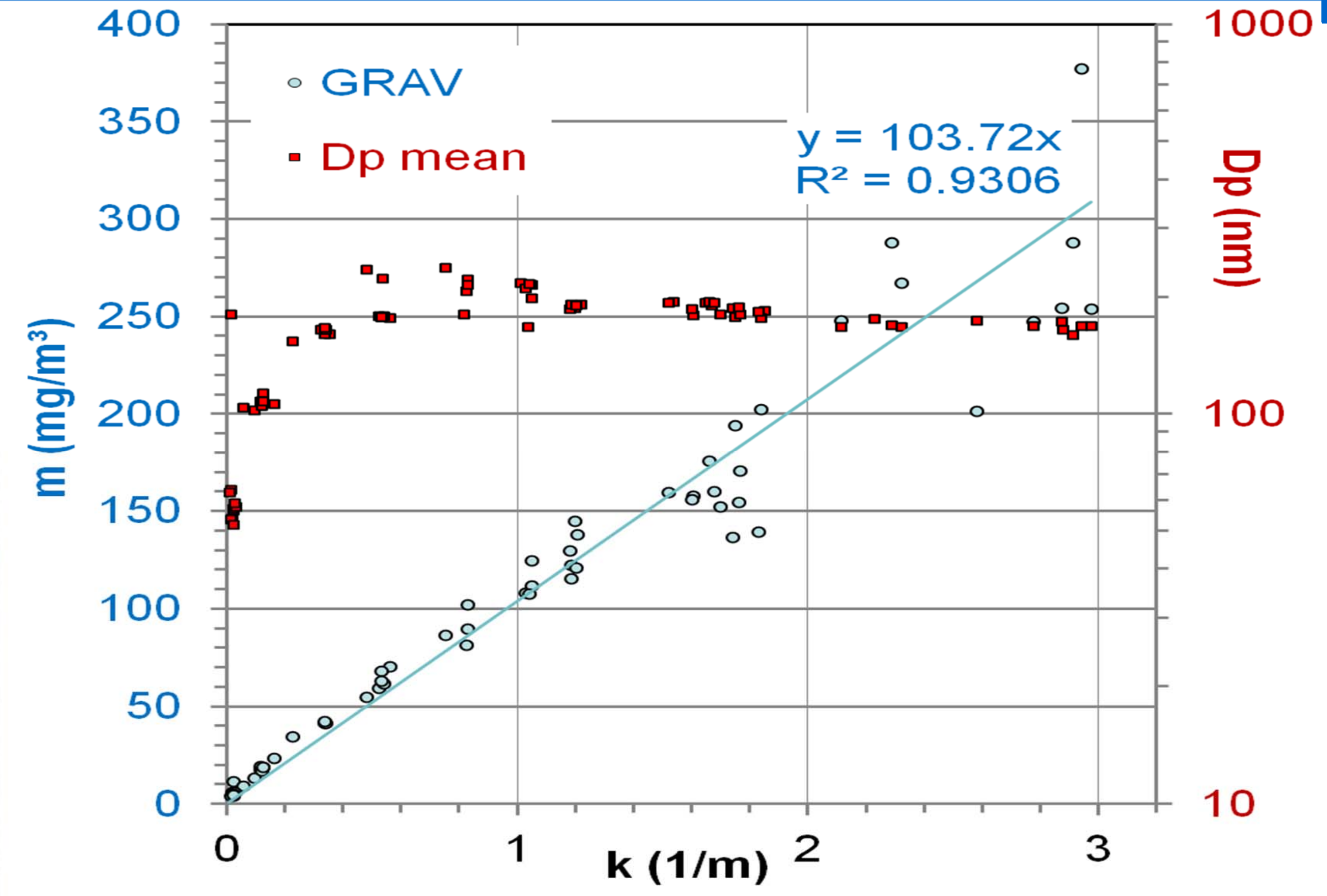
Non – commercial SMPS system







k vs. m vs. Dp,mode diameter



Comparison between k- value of reference opacimeter (AVL 439) and mass concentration from gravimetrical mass and Gaussian fit parameter of PNSD for mode diameter