Performance of the LI²SA-Soot-Sensor for ultra-low concentration levels in comparison to conventional PM measurement methods

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INTRODUCTION

Especially sensitivity is one of the most important features of suitable measurement systems for future engine and exhaust gas aftertreatment concepts. Besides the sensitivity and limit of detection which in future most likely has to be close to immission levels, some other important aspects like repeatability and ability of calibration have to be kept in mind. This is, however, not only a question of the measurement system alone. Conditioning of the unit under test, dilution and influence of sampling systems are very important issues in this context. Additionally, it has been shown that the nature of the measurement quantity itself exhibits the source for some significant instationarities. As a specific example, it has been shown that the total PM mass including volatiles is much more fluctuating than the solid PM fraction, e.g., like the EC mass emission.

In this contribution these aspects are discussed in detail for the LI²SA system, relying on time-resolved laser-induced incandescence in comparison to conventional methods. The technique evaluates thermal radiation of soot particles after rapid laser heating and has been shown to be selective just on the EC component of the PM emission. Consequently, as the appropriate calibration tool the CAST Aerosol Standard together with coulometric analysis of the aerosol is favoured.

RESULTS

Experimental results are presented for different vehicles and engines with advanced aftertreatment and combustion concepts within different driving cycles, both under stationary and transient conditions. Especially engine concepts with emission levels well below Euro IV have been in the focus of the presented trials. These are including engines with DPF systems (PSA FAP and heavy duty CRT system) as well as gasoline direct injection (GDI) concepts. The repeatability of the results at those low emission levels has been determined and compared for the gravimetric method (standard and US2007), the CPC and the LI²SA system. The analysis of the variances shows a non-uniform behaviour: whereas the LI²SA and the CPC results for heavy duty applications are (dependent on the driving cycle) generally more repeatable than the standard and the US2007 gravimetry, the light duty measurements are strongly influenced by both, the driving cycle and also the combustion and aftertreatment concept and thus yield inconsistent results.

Especially for ultra low emission levels, achieved for heavy duty measurements, about 6 times greater values for the variance of the standard gravimetric method as compared to the LI²SA results have been obtained which most likely indicate that the volatile particle fraction is one of the main sources for measurement uncertainties. This is in particular remarkable as total filter loads below the suggested minimum of 0.5mg (for the 47mm filters) have been observed and the variance is considered not to be acceptable in this case. The solid fraction (the EC fraction in this case) has been proven to be much more repeatable. However, especially for the heavy duty CRT system some remaining fluctuations in the EC mass emission are clearly obvious, caused by the engine itself despite of carefully being conditioned.

CONCLUSIONS

The main conclusions drawn from these results are:

- There are principle limitations for the repeatability of all instruments. These are mainly given by fluctuations of the engine and/or the aftertreatment system, the test protocol employed and the sampling system. Further, even fluctuations given by statistical noise have to be considered for different measurement systems, like the CPC and also for the LI²SA system.
- Heavy duty measurements (on engine test benches) have been consistently shown to be much better repeatable than light duty measurements (on chassis dynamometers).
- The employed sampling system has an essential influence on the repeatability of gravimetric and CPC results, but not on the LI²SA results.
- Most likely, volatile exhaust components are one major source for measurement uncertainties, especially for the gravimetric method.

PERFORMANCE OF THE LI²SA SOOT SENSOR FOR ULTRA-LOW CONCENTRATION LEVELS IN COMPARISON TO CONVENTIONAL PM MEASUREMENT METHODS

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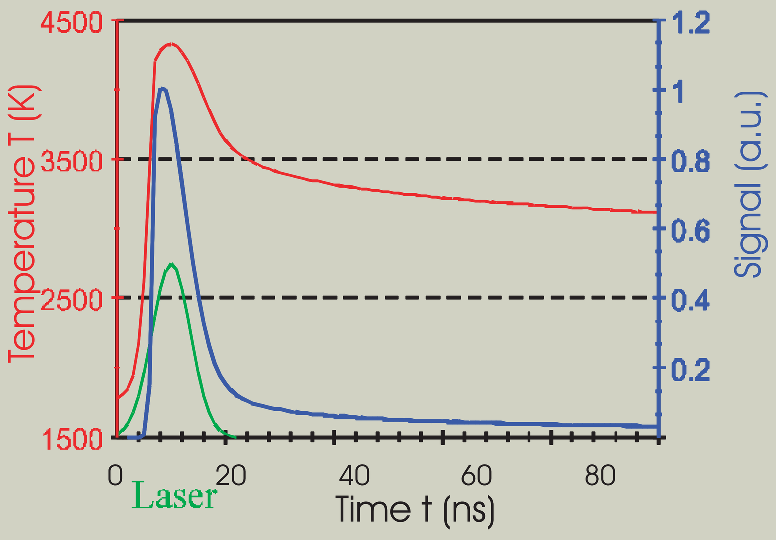
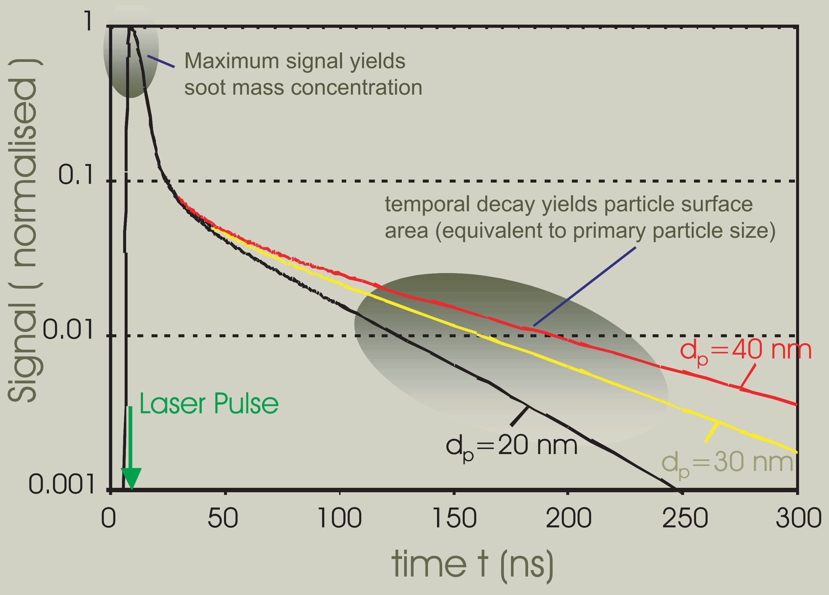
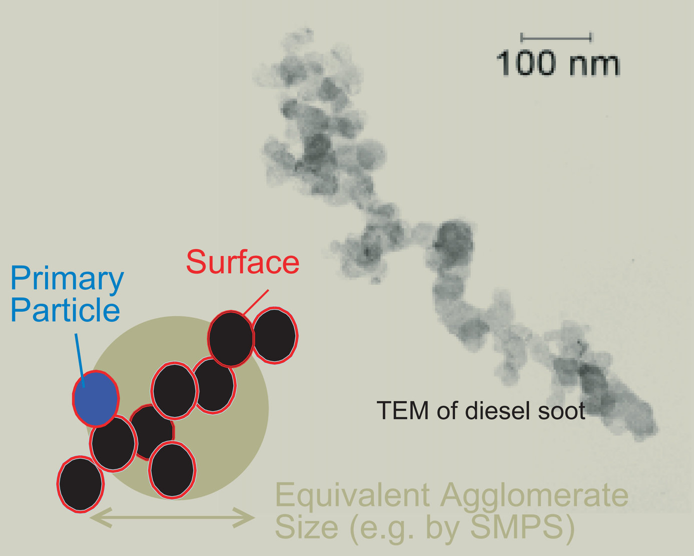
THEORY OF LASER-INDUCED INCANDESCENCE

Basic Principle

- Particle heating by means of a laser pulse to temperatures >4000K
- Optical measurement of enhanced thermal radiation by a highspeed photodetector



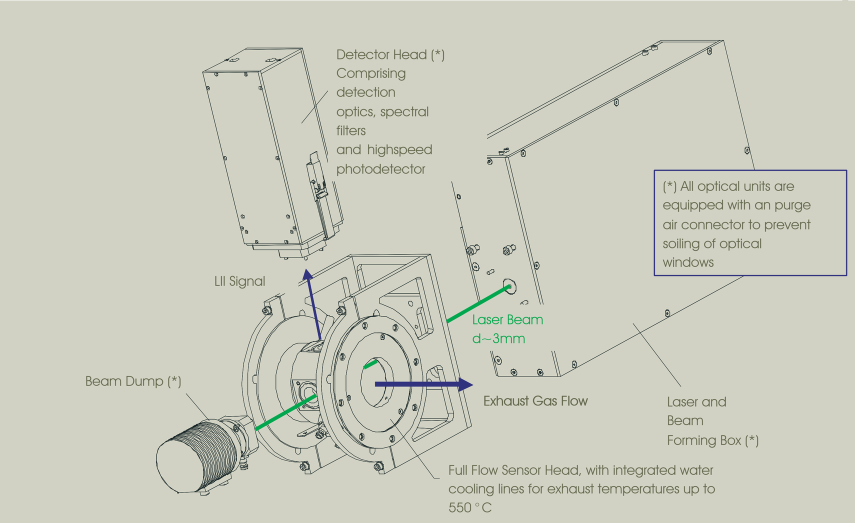




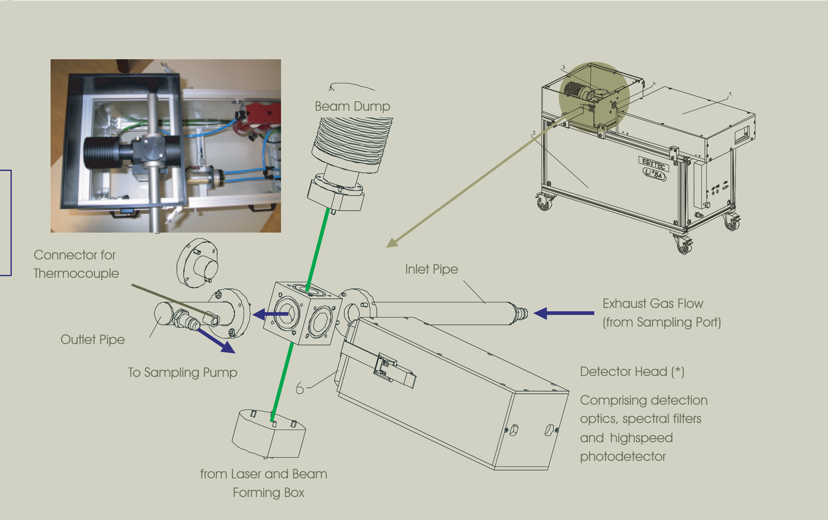
- Highly specific on Elemental Carbon (EC), no cross-sensitivities to other exhaust components
- No need for dilution to prevent particle condensation, raw exhaust gas measurements feasible

SENSOR CONCEPT

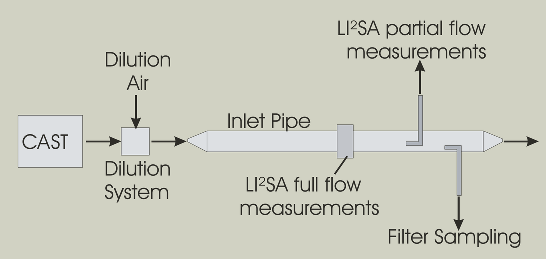
Full Flow Sensor Head

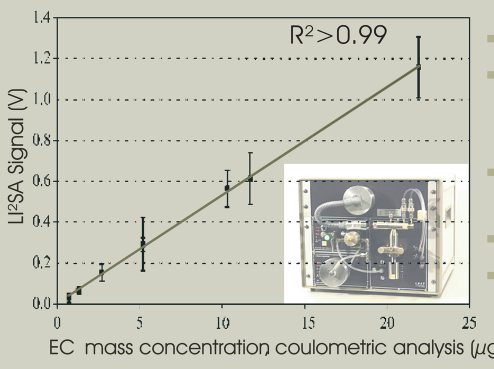


Partial Flow (CVS) Sensor Head



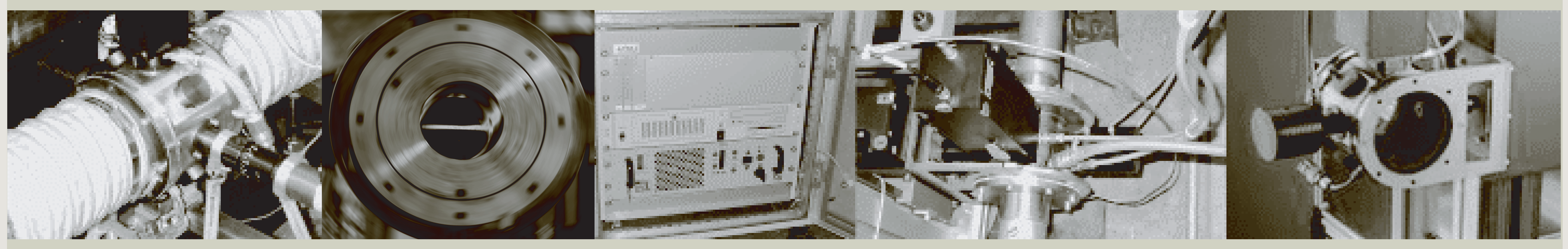
Calibration by coulometric analysis at CAST * Aerosol -Generator





- LII is sensitive on elemental carbon (EC) only
- → Reference is coulometric analysis (well established in working place and imission measurements!)
- Excellent linear correleation (error bars yield CAST fluctuations ~10%)
- Slope of curve yields system calibration factor
- High sensitivity of LI²SA system

* Matter Engineering AG

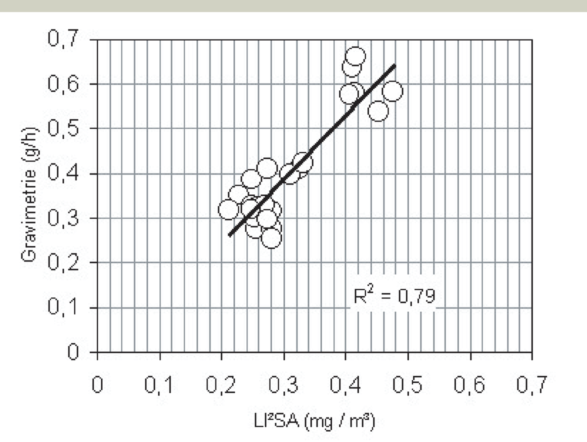


Performance characteristics

- simultaneous measurement of soot mass concentration (EC) and soot surface area / primary particle diameter
- High sensitivity below 10µg/m³ to meet future regulations
- High temporal resolution of up to 20Hz for analysis of extremely transient processes
- Flexible adaptation by availability of different detector heads
- CVS detector head for diluted or undiluted partial flow measurements
- Water-cooled detector heads for a direct application into the exhaust pipe (full-flow raw measurements, light duty and heavy duty versions) available
- Fully-automatic 'simply press button'-system - integrated LI²SoP Software Package allows operation with no need for further user interaction

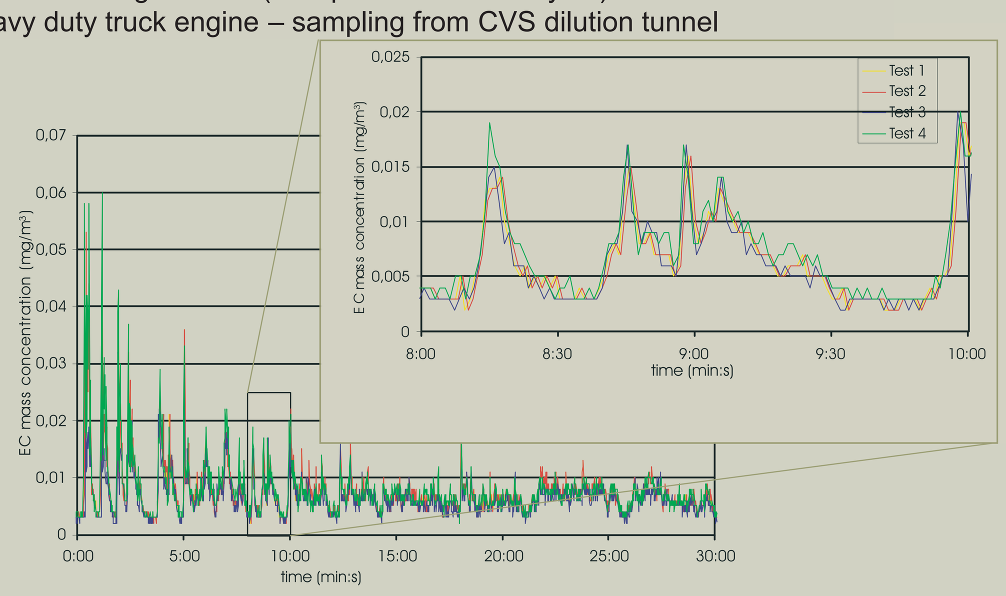
RESULTS

CRT equipped heavy duty engine (EURO III)



- Emission level not very stable (for total PM and EC)
- Filter loads (ETC test cycles) of 0.15 - 0.3 µg (recommended filter load >0.5 µg!)
- 0.0035-0.0055 g/kWh (<<EURO 4: 0.03 g/kWh)
- Moderate correlation coefficient caused by different metrics
- ~50% (variable) EC fraction of total PM

EC mass concentration during an ETC (European Transient Cycle) test of a CRT equipped heavy duty truck engine – sampling from CVS dilution tunnel



Repeatability of results (CRT equipped heavy duty engine (EURO III)

	LI²SA raw (mg/m³)	Standard Gravimetry (g/kWh)	2007 Gravimetry (g/kWh)	CPC (10^5/cm³)
WHTC 1	0.269	-	-	1.93
WHTC 2	0.250	0.0049	0.0070	1.82
WHTC 3	0.257	0.0056	0.0060	1.90
WHTC 4	0.269	0.0064	0.0054	1.90
WHTC 5	0.281	0.0048	0.0055	1.90
WHTC 6	0.281	-	0.0054	1.95
WHTC 7	0.275	0.0052	0.0051	2.09
mean value	0.2687	0.0054	0.0057	1.93
COV	4.03%	10.80%	10.71%	3.95 %

	LI²SA raw (mg/m³)	Standard Gravimetry (g/kWh)	2007 Gravimetry (g/kWh)	CPC (10^5/cm³)
ETC 1	0.276	0.0042	0.0054	-
ETC 2	0.248	-	-	-
ETC 3	-	0.0054	0.0065	-
ETC 4	0.274	0.0043	0.0040	1.86
ETC 5	-	-	-	-
ETC 6	0.256	0.0028	-	2.16
ETC 7	0.253	0.0031	-	1.99
mean value	0.2616	0.0040	0.0053	2.00
COV	4.40%	23.51%	18.74%	6.13 %

Other studies

UK PMP (HD)	LI²SA diluted	2007 Gravimetry	Standard Gravimetry	CPC
ETC	13.7%	8.5%	19.1%	26.2%
WHTC	12.0%	10.9%	20.4%	31.2%
FTP	4.6%	6.1%	22.0%	14.7%

Swiss PMP (HD)	LI²SA diluted	Standard Gravimetry	CPC
ETC	7.6%	20%	24%

Light duty measurements

	LI²SA raw (mg/m³)	COV	2007 Gravimetry (mg)	COV	Standard Gravimetry (mg)	COV	CPC (10^5/cm³)	COV
FTP Vehicle 1	0.352	12.49%	-	-	0.00349	17.74%	-	-
FTP Vehicle 3	0.128	50.85%	0.0514	14.95%	0.0570	19.03%	7.58	66.37%
FTP Vehicle 4	0.030	4.85%	0.1478	29.69%	0.2810	34.22%	0.40	14.21%
NEDC Vehicle 2	0.097	7.34%	-	-	0.0026	9.62%	82.4	14.60%
NEDC Vehicle 4	0.037	7.02%	0.0880	7.78%	0.0696	17.81%	0.37	7.83%

	work principle	Emission status	Aftertreatment
Vehicle 1	Diesel	Euro III, PM< Euro IV	CRT wit reagent
Vehicle 2	GDI	Euro III	EGR , TWC
Vehicle 3	GDI	Euro IV	EGR, TWC, N O_x storage
Vehicle 4	Diesel	Euro II, PM< Euro IV	autark DPF

Limit of Detection

German PMP (at RWTÜV, Essen, D)

CPC	(80nm, n~60 1/cm³)	0.23 µg/m³
Standard Gravimetry		4.5 µg/m³
LI²SA (raw)		5 µg/m³

Swiss PMP (at EMPA, Dübendorf, CH)

CPC	(80nm, n~4000 1/cm³)	15 µg/m³
Standard Gravimetry		189 µg/m³
LI²SA (diluted)		37 µg/m³

CONCLUSIONS

- LII is suitable for EC characterization of ultra low emission engines
- Principle limitations of repeatability for all instruments are given by:
  - fluctuations of the engine / aftertreatment system
  - influence of sampling system
  - and even signal statistics
- Heavy duty measurements (on engine test bench) are likely to be better repeatable than light duty measurements (on chassis dynamometer)
- Sampling system has essential influence on repeatability of CPC and gravimetric results, but not on LII results
- Most likely, volatiles are a major source for measurement uncertanties

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