Comparison of two Condensation Particle Counters for automotive applications using a combustion soot generator

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The Euro V regulations establish limits for the particle number concentrations in engine exhaust gas. The measurements of these particle number concentrations must be done by a standardized procedure, which specifies the dilution of the exhaust gas, the removal of the volatile aerosol fraction, and the use of a special Condensation Particle Counter (CPC) for the detection of particles. The standardization of the measurements is a work in progress in the frame of the „Particle Measurement Program" (PMP) of the UN-ECE GRPE. The requirements for such a PMP-CPC are mainly: (1) It must be a full flow CPC, (2) the accuracy against a traceable standard must be better 10%, (3) the CPC must have a linear response ($R^2 > 0.97$), (4) the T90 response time must be less than 5 s, and (5) the counting efficiency must be of 50 +- 12% for a particle diameter of 23 nm and > 90% for a particle diameter of 41 nm.

We have tested two commercial PMP-CPCs, namely the GRIMM model 5430 and the TSI model 3790, with the setup shown in Fig. 1. Since the characteristics of the soot particles are very similar to those emitted by combustion engines, a Combustion Aerosol Standard (CAST) soot generator (Jing Mini-CAST) was used for the generation of particles. A Vienna-type Differential Mobility Analyzer (GRIMM M-DMA) with a ^{241}Am Neutralizer was used to classify the particles. As a primary standard for particle number concentrations we have used a GRIMM Faraday Cup Electrometer (FCE), a GRIMM standard CPC with a minimum detectable particle size of 4.5 nm was used as additional reference and to monitor the contribution of multiple charged particles. Both FCE and reference CPC were operated with a temperature stabilized critical nozzle to maintain the flow rate with a high accuracy.

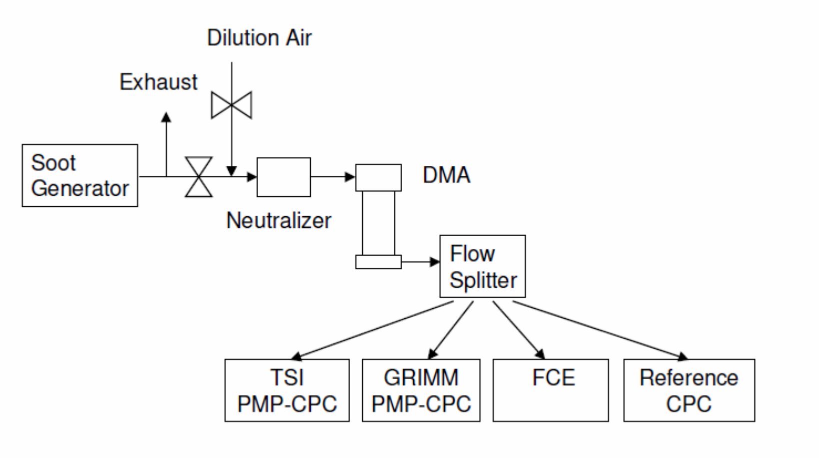

Fig. 1: Experimental setup for the comparison of the two PMP-CPCs.

Accuracy and linearity of the CPCs were determined with eight concentration steps including zero concentration for a particle size of 50 nm. The results, displayed in Fig. 2, indicate that the two tested PMP-CPCs are well within the specifications of the PMP regulations, both for accuracy and linearity. The two PMP-CPCs feature only minor differences with the GRIMM model showing a better accuracy and the TSI PMP-CPC a slightly better linearity.

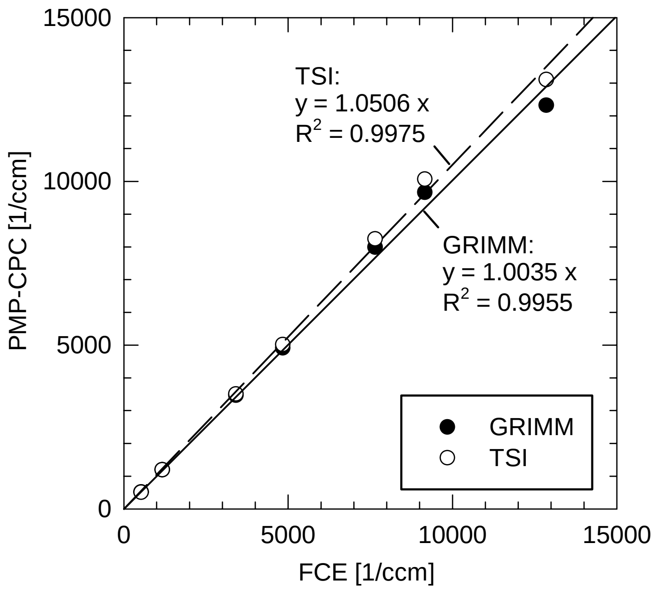

Fig. 2. Accuracy and linearity of the two tested CPCs.

Efficiency of the CPCs was alternately measured for 23 nm and 41 nm particles, each for two minutes, and the measurement was repeated 14 times to explore the reproducibility. The measured efficiencies, compiled in Tab. 1, refer to the ratio of number concentration measured by CPC and number concentration measured by FCE and constitute mean values and standard deviation from the 14 measurements.

Table 1: Efficiency of the tested CPCs. Values are in %.

	TSI PMP-CPC	GRIMM PMP-CPC	Reference CPC
23 nm	55.50 ± 0.09	59.84 ± 0.14	99.43 ± 0.11
41 nm	86.38 ± 0.44	93.59 ± 0.52	101.42 ± 0.61

The efficiency of the reference CPC, being essentially 100%, proves that the contribution of multiple charged particles was negligible during these measurements. Thus the combination of (1) a MiniCAST soot generator, adjusted to produce sufficiently low mean particle size and (2) a GRIMM DMA with a ^{241}Am Neutralizer constitutes a source of monodisperse particles suitable for the calibration of PMP-CPCs. The efficiencies of the two PMP-CPCs are within the range specified by the PMP regulations with the exception that the efficiency of the TSI the TSI PMP-CPC was slightly below the required limit of 90% for 41 nm particles.

The PMP regulations do unfortunately not specify all details for the tests of a PMP-CPC and hence slightly different results from different experimental setups must be expected. This comparison showed however that two commercial PMP-CPCs feature a quite similar properties despite the different test procedures used by the manufacturers.

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Contents

PMP Measurements

Experimental Setup

- ➢ Measurements were done at Volkswagen AG, Wolfsburg, March 17, 2009

Results

- ➢ CPCs: Accuracy, Linearity, Efficiency; additional tests with Electrometers

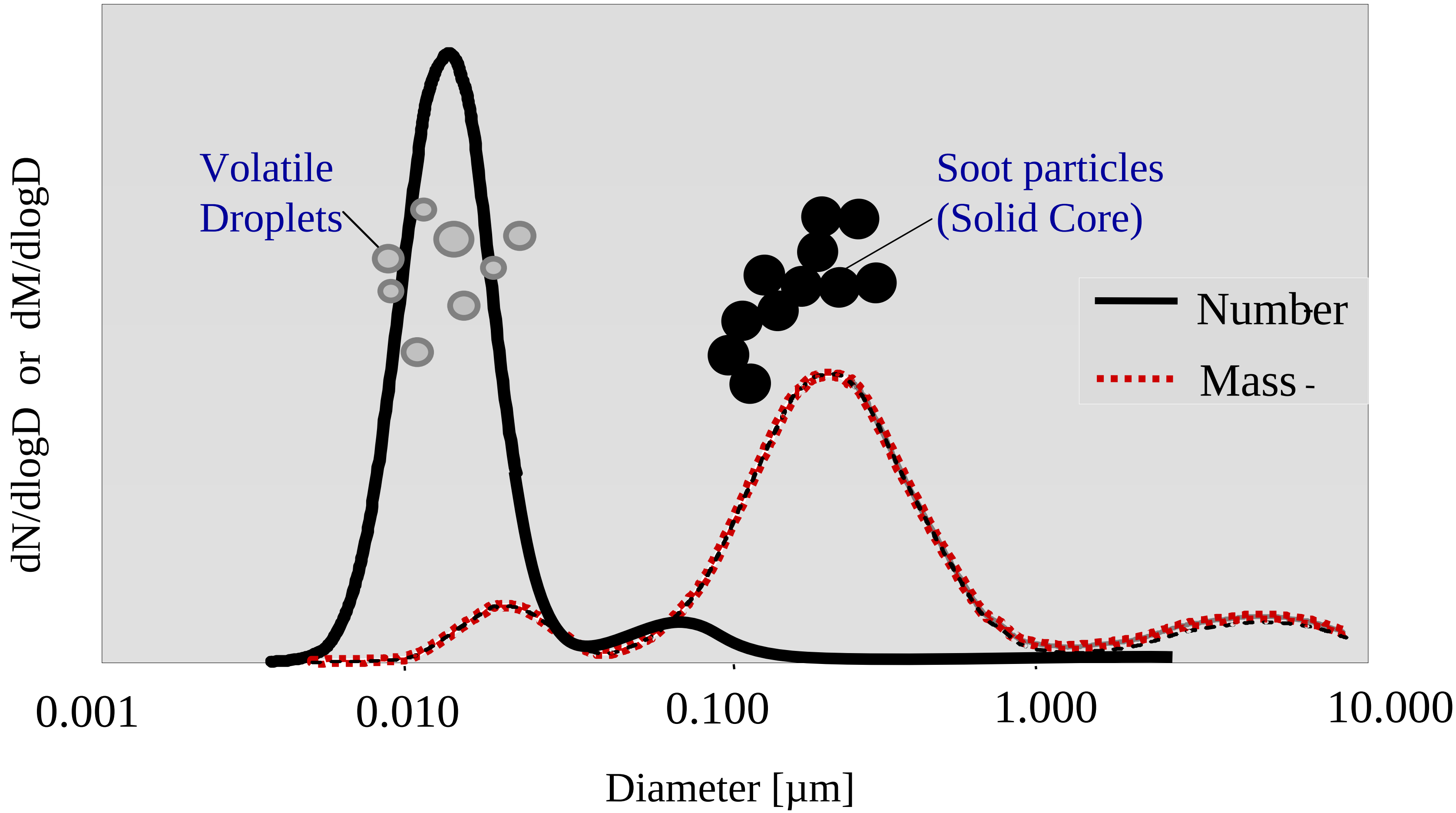
Summary

Euro5/6 Limits for passenger cars

	Diesel		Otto DI	Otto
Einsatzdatum	PM [mg/km]	PN [#/km]	PM [mg/km]	PN [#/km]
9/2009 EURO 5a	5	----	5	----
9/2011 EURO 5b	4,5 Geändertes Messverfahren	$6 x 10^{11}$ Neues Messverfahren	4,5 Geändertes Messverfahren	----
9/2014 EURO 6	4,5	$6 x 10^{11}$	4,5	**Wird bis spätestens 9/2014 festgelegt**

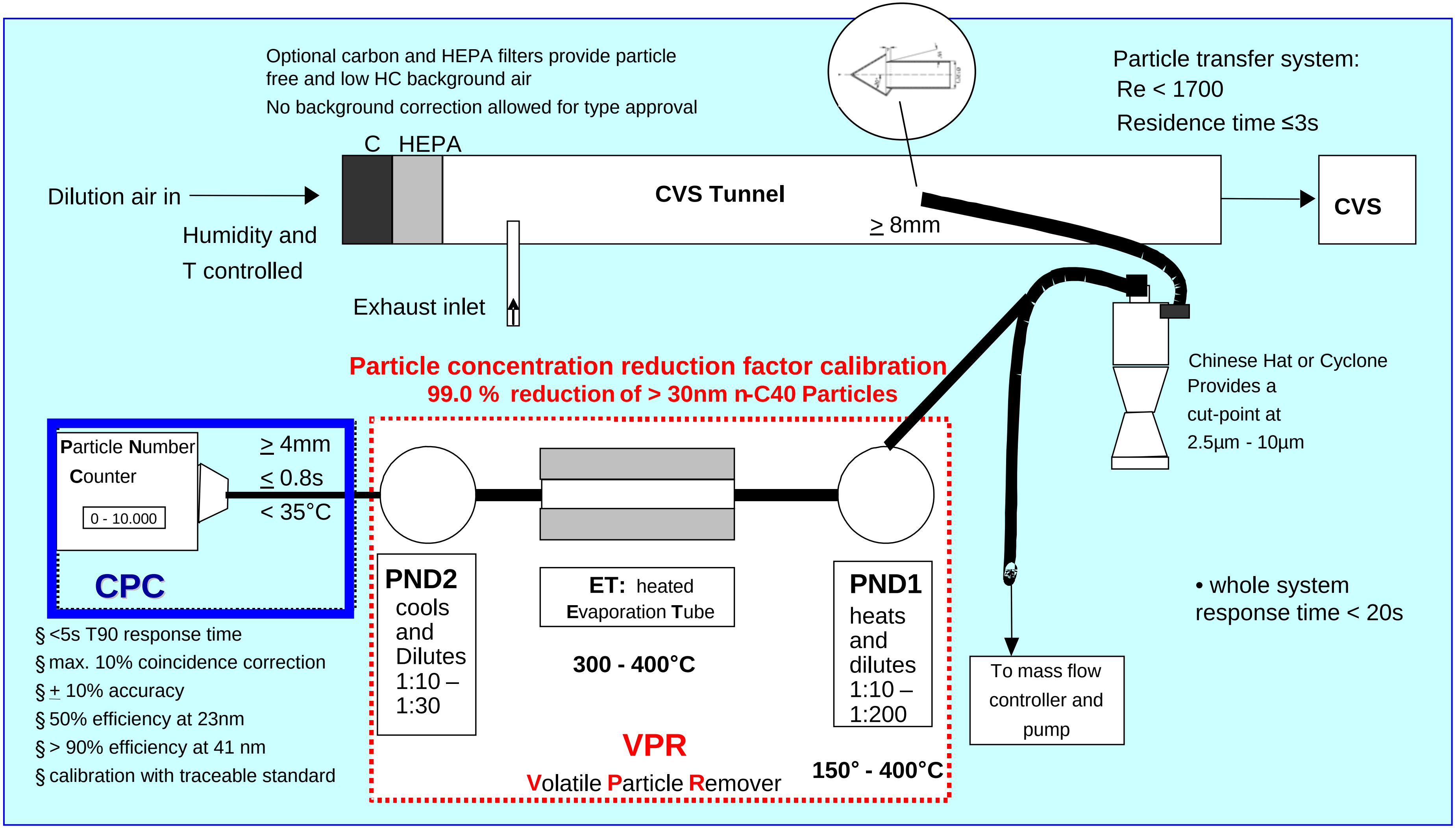
*Reg. (EC) 715/2007

Particle size distribution in engine exhaust gas



Source: Kittelson, 1998

Setup for PMP measurements



*ECE/Trans/WP.29/GRPE/2007/8/Rev.1 (Reg 83 Amendment Proposal)

Main requirements for PMP-CPCs

- full flow CPC.
- **Accuracy** against a traceable standard better 10%.
- The CPC must have a **linear response**.
- T90 response time less than 5 s.
- The counting **efficiency** must be:

  50 ± 12%   for a particle diameter of 23 nm,

  > 90%   for a particle diameter of 41 nm.

Instruments used in this study

PMP-CPC
TSI 3790

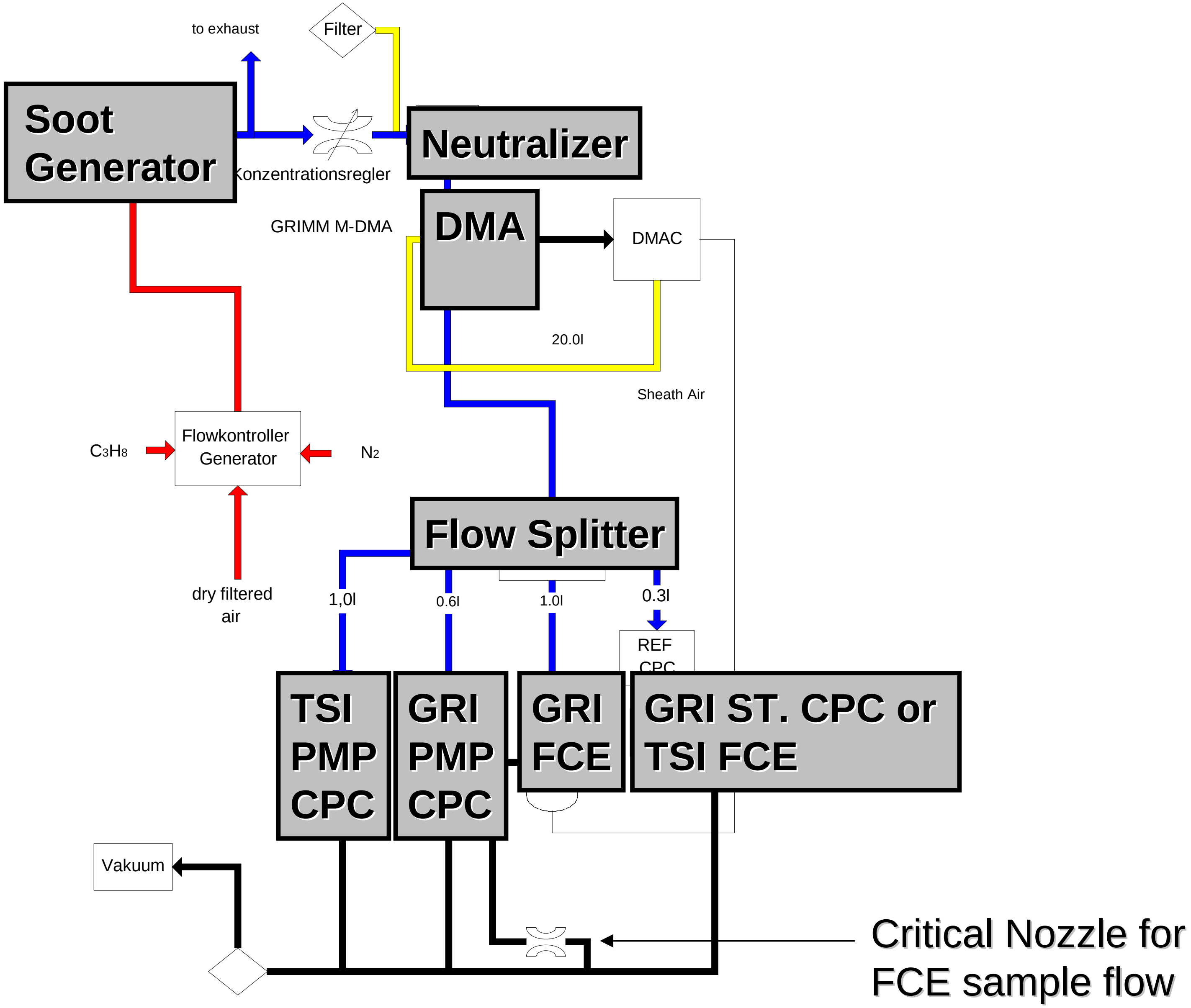
PMP-CPC
GRIMM 5430

DMA
GRIMM 55-U

Jing miniCAST
Soot Generator

FCE
GRIMM 5705

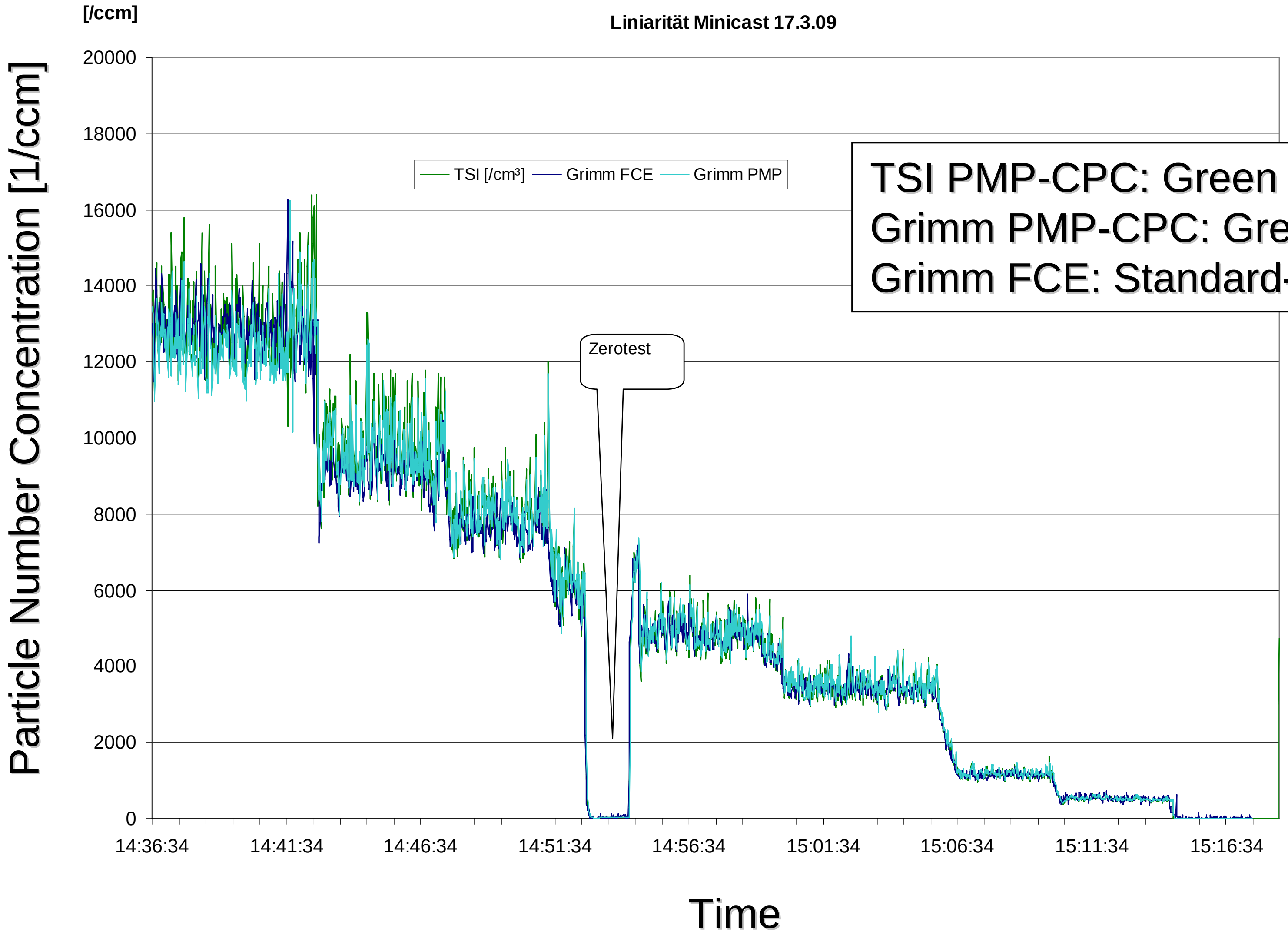
Setup at Volkswagen AG



Measurement of Accuracy and Linearity

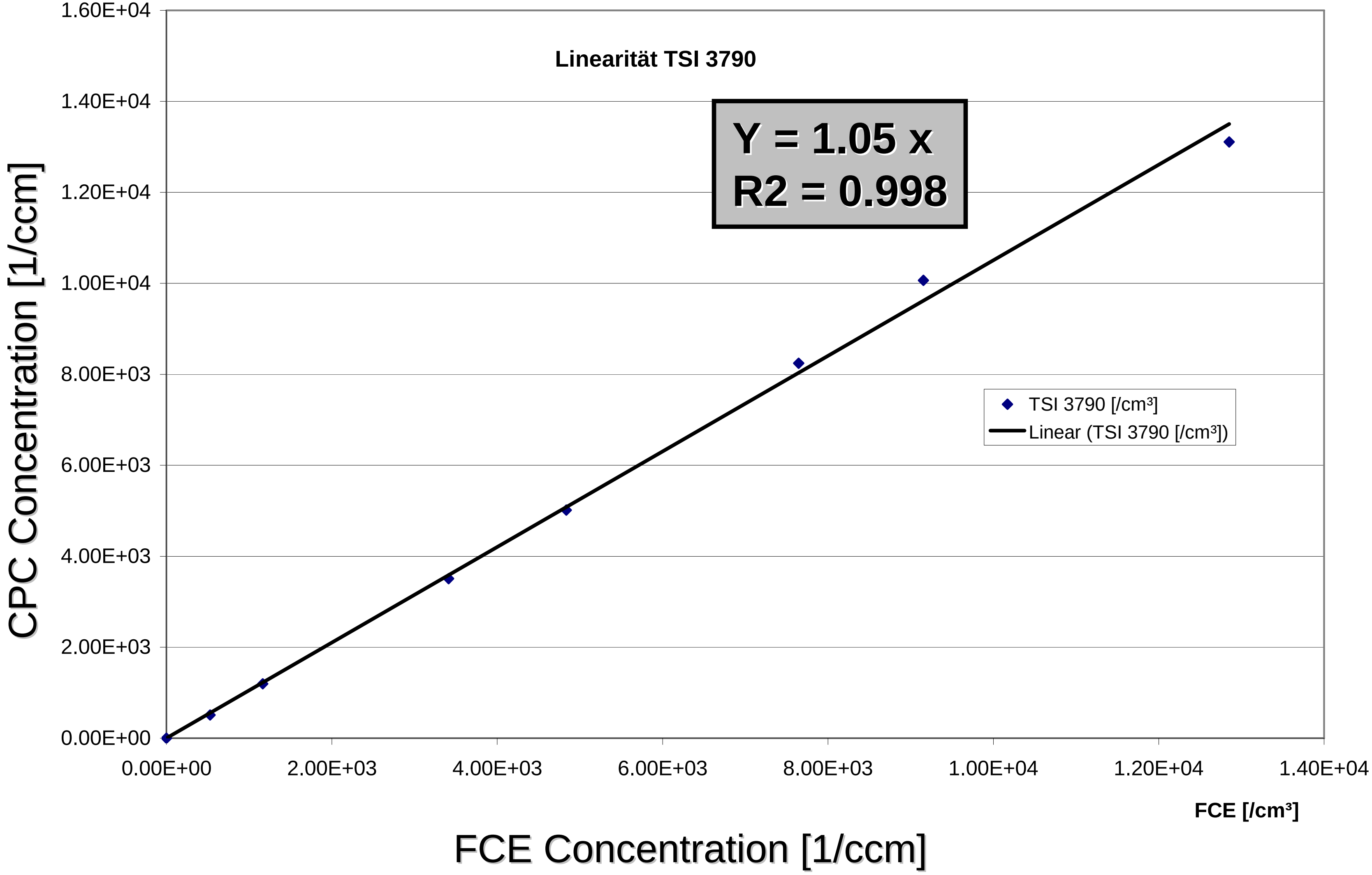
- Nominal particle diameter: 50 nm
- Eight concentrations (including zero) were measured
- CPC concentrations are compared with FCE conc.
- PMP regulations require $R^2 > 0.97$ and Slope 1 +- 10%

Raw Data for Accuracy and Linearity

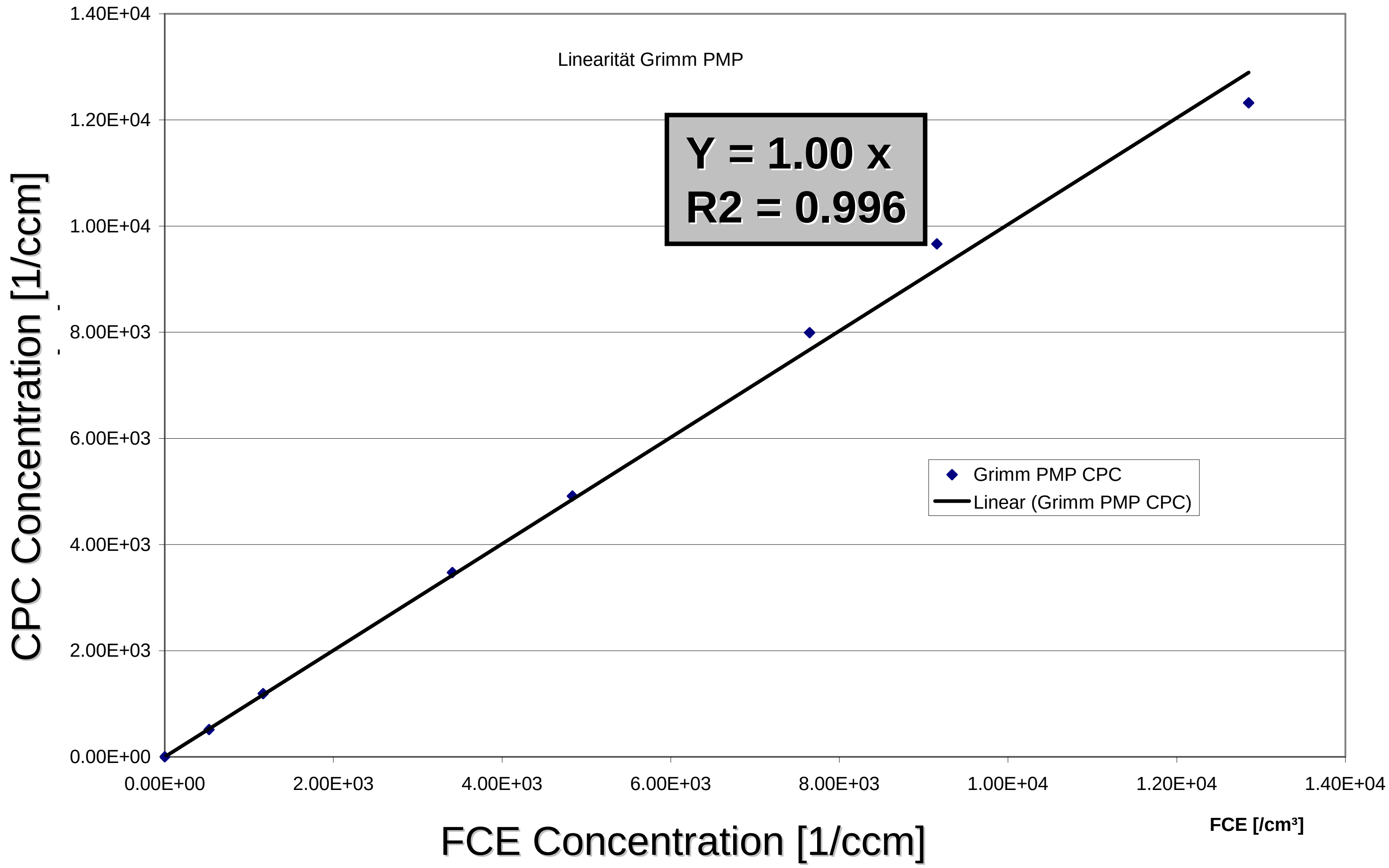


TSI PMP-CPC: Green
Grimm PMP-CPC: Grey-blue
Grimm FCE: Standard-blue

Accuracy and Linearity: TSI PMP-CPC



Accuracy and Linearity: Grimm PMP-CPC



Efficiency Measurements

- Required counting efficiency of PMP-CPC:

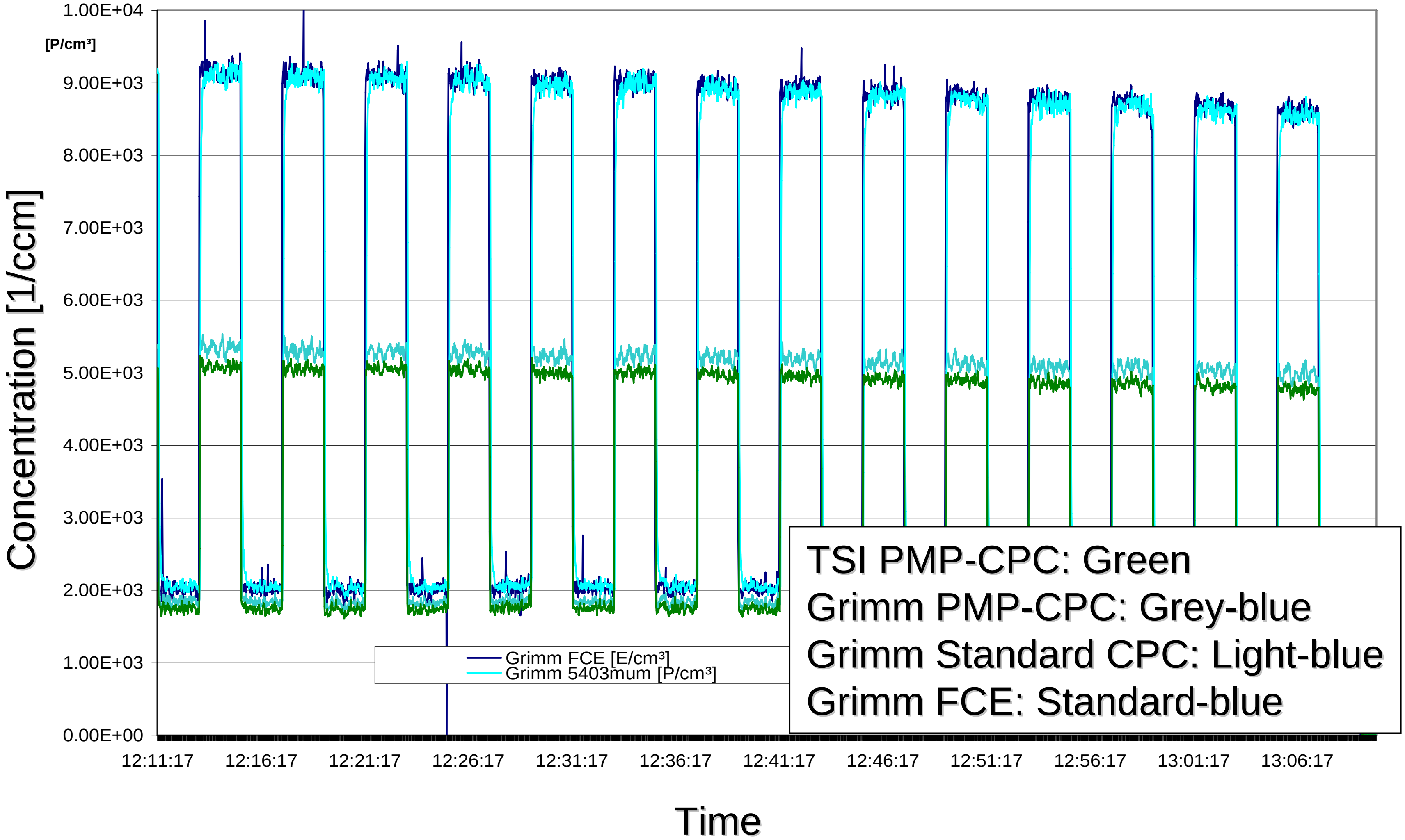
50%±12%	for 23 nm particles
> 90%	for 41 nm particles

- The efficiency is also measured with FCE as a reference.

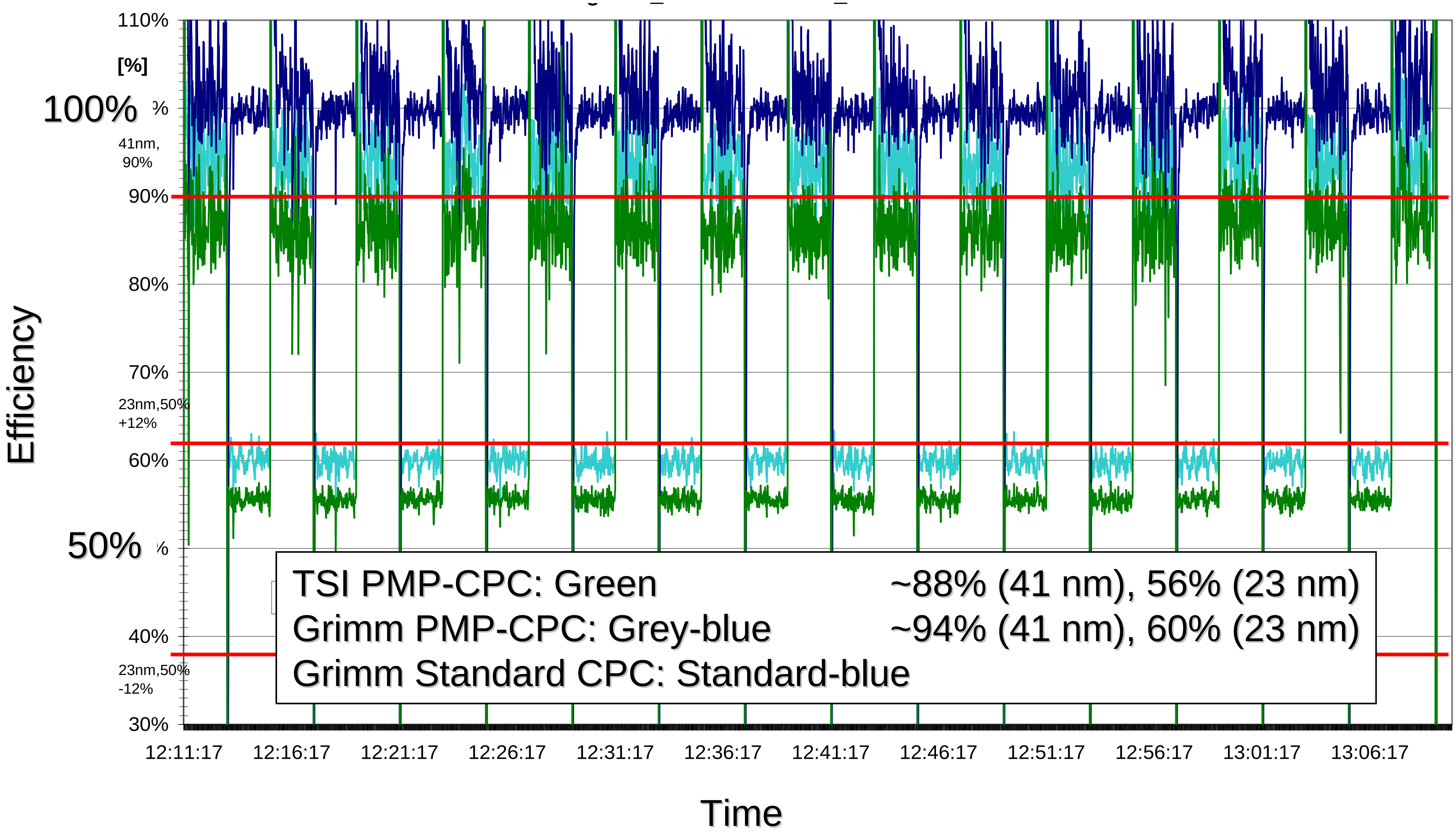
- In order to monitor double charged particles, a standard Grimm CPC was operated parallel to the FCE.

- Practically: DMA voltage was alternately set to select 23 and 41 nm particles, change of voltage after 2 minutes

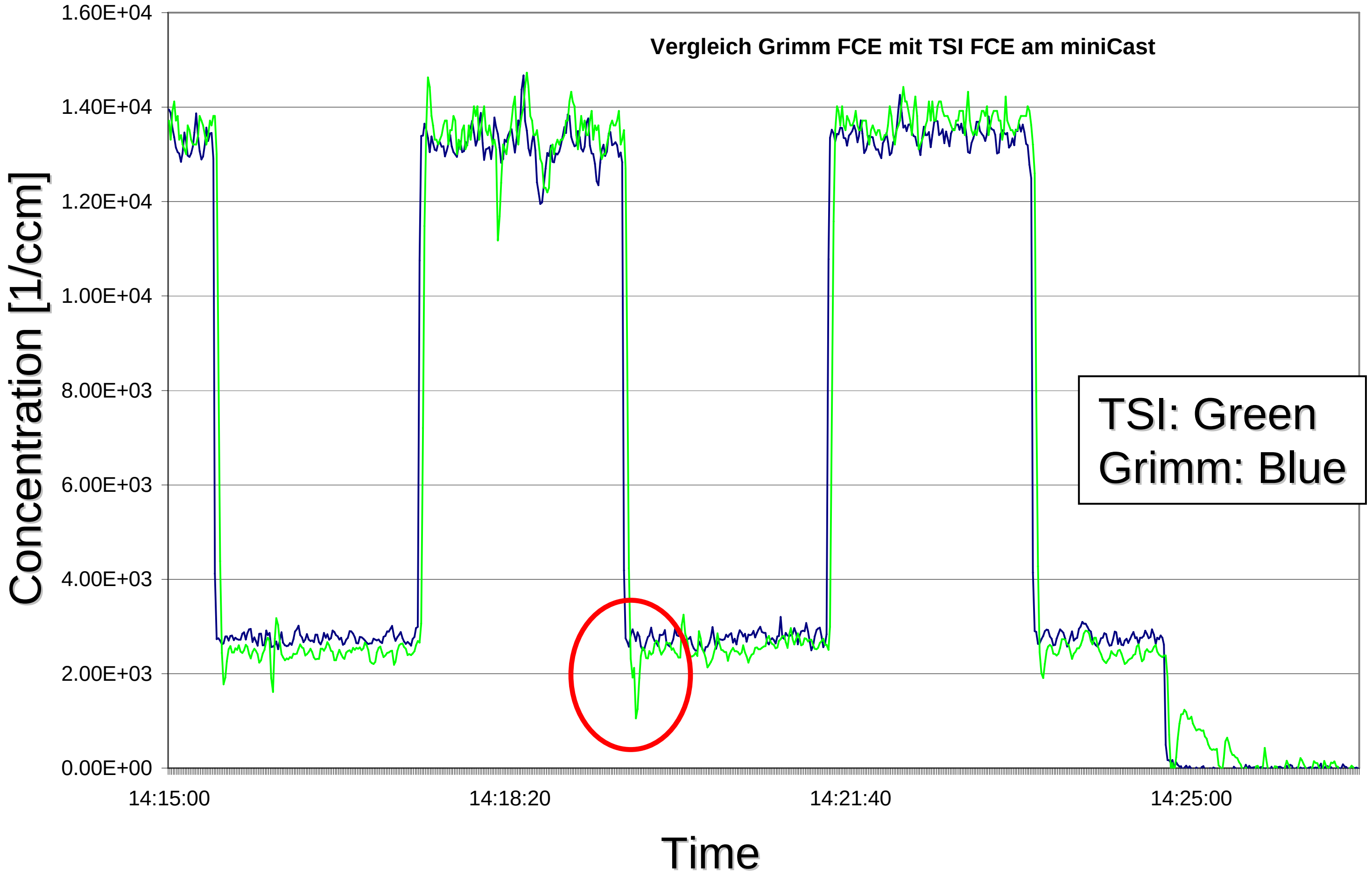
Raw data for efficiency measurements



Results: Efficiency



Comparison of TSI and GRIMM FCE



Concentrations of both FCEs agree well.
But we suspect that the TSI FCE overshoots at fast concentration changes

Summary

1. Both CPCs meet the accuracy and linearity requested by PMP regulations (slope 1+-10%, $R^2>0.97$):
   - ➢ $R^2 = 0.998$, Slope 1.05 for TSI CPC 3790
   - ➢ $R^2 = 0.996$, Slope 1.00 for Grimm PMP CPC

2. Both CPCs feature the required counting efficiency for 23 nm particles (50 +- 12%):
   - ➢ 56% for TSI CPC 3790
   - ➢ 60% for Grimm PMP CPC

3. The Grimm PMP features the requirement counting efficiency for 41 nm particles (> 90 %) without any correction factors.

4. Grimm FCE and TSI FCE measure essentially the same concentration

5. The GRIMM FCE measures fast concentration changes without overshooting.

Thank you for your attention