A portable instrument for PMP-like field measurements

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New type-approval regulations limiting the emissions of solid particle number from vehicles are emerging worldwide (e.g. Euro 6, Swiss regulation on off-road machines, proposed CARB LEV III standard). In Europe, the PMP protocol (UN ECE R83) will be adopted for these type approval measurements, and it is therefore natural to ask whether (or how) in-field compliance to the new Euro standards for solid particle number emissions can be verified. The PMP protocol is quite complex, requiring a CVS dilution tunnel, two diluters, an evaporation tube and a strictly specified particle number counter, which according to the specifications can only be a condensation particle counter (CPC). The complexity of the measurement protocol is reflected in the currently available PMP-compliant instruments available on the market - these typically have a weight of ~100kg, a power consumption of up to 1000W and a volume of ~100 l. These systems are probably too complex for use in a garage, and certainly too complex for true field use.

A field system should ideally be operated by a single person (the inspector), it should be truly portable (ideally handheld), and it should run on a battery for use in remote locations where mains power is not available. Its concentration range should be ± a factor of at least 10 around the PMP limit value, which is a bit hard to define, because the PMP limit value is given in terms of per km or per kWh emissions, while one can only measure a per-volume concentration in the field. By a rather straightforward stoichometric calculation of an ideal combustion process ($\lambda = 1$), one arrives at an approximate volumetric limit value of 10^5 pt/cm^3; i.e. the concentration range of the instrument should be at least from 10^4 - 10^6 pt/cm^3. The accuracy of the PMP number measurement is not defined very clearly in the protocol, but can be estimated to be around ±20-30%. A portable field-PMP system can probably not be expected to achieve the same level of accuracy, and therefore it would seem to us that an accuracy of ± a factor 1.5 - 2.0 would be sufficient.

Looking at the above requirements or wishes for a field-PMP system, it is obvious that this can only be achieved through a radical simplification of the process (at this point it is perhaps worth remembering that simplification is actually a very sound engineering principle). All possibly superfluous specifications in the PMP protocol have to be removed, and the other specifications have to be relaxed somewhat. Our approach is to remove nearly everything with the exception of the first dilution stage followed by an evaporation tube operating at only 200°C (instead of 300-400°C as specified in the PMP protocol). Such a system can be built in a number of ways, because there are both multiple possible dilution systems (rotating disc, ejector, porous tube, recirculating, etc.) and multiple possible number detection systems (handheld CPCs as well as new electrical particle counters, such as the Diffusion Size Classifier (DiSC), the NanoCheck and the NanoTracer) available that can be combined with the evaporation tube to construct a field-PMP system.

In our prototype instrument, we chose a recirculating 1:15 dilution system, where a small inlet flow is diluted by a circulating large flow of clean and dry air - the dilution flow is conditioned with a combination of dryer and filters which will have to be exchanged periodically. This dilution concept is simple, and can be made quite compact. There is a tradeoff involved in that it is easy to use in the field but requires some maintenance in the laboratory - however, our overruling design consideration was ease of use in the field, and therefore this tradeoff seemed justified. As a particle number detector, we chose the Diffusion Size Classifier which we developed previously. The final instrument weighs 6.5kg, fits easily into a backpack and runs for 4 hours on a battery. It is operated from a rugged PDA which connects to the instrument via bluetooth. Exhaust gas is sampled through a stainless steel probe where the dilution takes place at the tip of the probe.

To verify the performance of our system, the "diluting DiSC", we made both laboratory and field experiments. In the laboratory, we produced volatile Tetracontane particles at a concentration of ~$3*10^6$ pt/cm^3, and verified that they could be completely removed by the conditioning system. The PMP protocol specifies a 50% counting efficiency of the particle number counter at 23nm particle diameter, a behaviour which we could mimic (but not quite reproduce) with the ion trap of the particle charger in our instrument. We also compared our system with the SMPS for flame-generated soot particles of varying diameters and concentrations. Typically, our system agreed with the SMPS to within ±30%, but with a systematic deviation; our instrument typically reported lower particle diameters than the SMPS and higher particle numbers - this is probably a consequence of the calibration, which we performed with compact NaCl particles instead of fractal-like soot particles, and it is well-known that the charging properties of compact and fractal-like particles are slightly different. Moving to real applications, we compared our diluting DiSC with a standard DiSC running after a heated rotating disc dilution system on a pellet stove, and found an excellent agreement of the two systems, which proves that (for this application) the recirculating cold dilution followed by the evaporation tube is essentially equivalent to a 1:300 dilution at 120°C. Finally, we tested about a dozen construction machines on a construction site in the Swiss alps, under pretty harsh conditions (snow, mud), where the fieldworthiness of the instrument was very useful. We found that approximately 1/3 of the machines had a malfunctioning particle trap according to our measurements, which could be rather easily verified simply by visual inspection of the exhaust pipe. While such a visual inspection is a good indicator for malfunctioning particle traps, there are obviously also situations where this will not work, e.g. after a new retrofit, or for a quality control of the particle trap for new vehicles at the end of the assembly line. A last experiment where we wanted to compare our diluting DiSC to a PMP-conform system at the chassis dynamometer in Biel failed, because the vehicle under test was not equipped with a particle filter - the emission levels turned out to be higher than the detection limit of our instrument except when idling.

In conclusion, we have demonstrated a portable system capable of measuring solid particle number following the spirit of the PMP protocol, with an accuracy of approximately a factor of ± 1.5. We believe that the instrument could be further optimized in terms of size and weight to allow a simple in-field compliance verification for number-based emission standards.
However, following our general philosophy of achieving our goals with the simplest possible means it might be worth considering simpler means of particle detection: The goal is to detect defective particle filters so that they can be repaired, and this detection could also be performed with a diffusion charger (DC). This simplest of all electrical instruments gives a signal which is proportional to the total particle diameter (or d^1, d= particle diameter), and not the total particle number (or d^0) - however, this detection method is very sensitive and by far sufficient to decide whether a particle filter is working or not.

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Motivation

New type approval regulations limiting solid particle number are emerging – Euro 6 / PMP, proposed CARB LEV III

↓

Sooner or later someone will ask about field compliance

↓

Can I build a PMPometer to replace the opacimeter?

The PMP protocol

ECE/TRANS/WP.29/GRPE/2008/
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Appendix 5

Figure 14: Schematic of **Recommended** Particle Sampling System

Carbon and HEPA filters provide

La perfection est atteinte, non pas lorsqu'il n'y a plus rien à ajouter, mais lorsqu'il n'y a plus rien à retirer.

-- Antoine de Saint-Exupéry

Some PMP systems (without CVS)

Horiba SPCS

120 kg
~2.5 kW
43x84x60 cm

Dekati DEED

? kg
~2 kW
~60x60x60 cm

ME ViPR

60 kg
300 W
55x30x60 cm

Current PMP systems

- Are somewhere around 100kg, 1kW power consumption and 100 l Volume
- Additionally, PMP needs a CVS tunnel
- Obviously, this is not going to work in the field (more on this later)

Wishlist for a field-PMP-system

- Single person should be able to operate system
- ~~Trans~~Portable (handheld / backpack - <10kg)
- Operate on battery for 8h
- Concentration range 10^4 – 10^6 pt/ccm (because PMP limit value translates roughly to 10^5 pt/ccm)
- Accuracy? PMP has ~20% accuracy specified (10% from CPC, 10% from dilution/VPR)
-  „total reproducibility ±27%“ „good number for an aerosol measurement“
- I would settle for ± factor 1.5 - 2.0 (50-100%)

Adapt PMP to field-PMP

- ~~CVS dilution tunnel~~
- ~~sampling through a 2.5 μm cyclone~~
- Diluter 1, ~~heated to 150 - 400°C;~~ dilution 10x - **200x**
- Evaporation tube at ~~300 - 400°C~~
- ~~Diluter 2, unheated;~~
  ~~dilution 10-15x, to cool sample for PNC (CPC)~~
- PNC ~~(Condensation particle counter)~~ with well-~~defined 50% counting efficiency at 23nm.~~
- We are left with a cold dilution + evaporation

Field PMP construction kit

Dilution – Evaporation – Number Detection

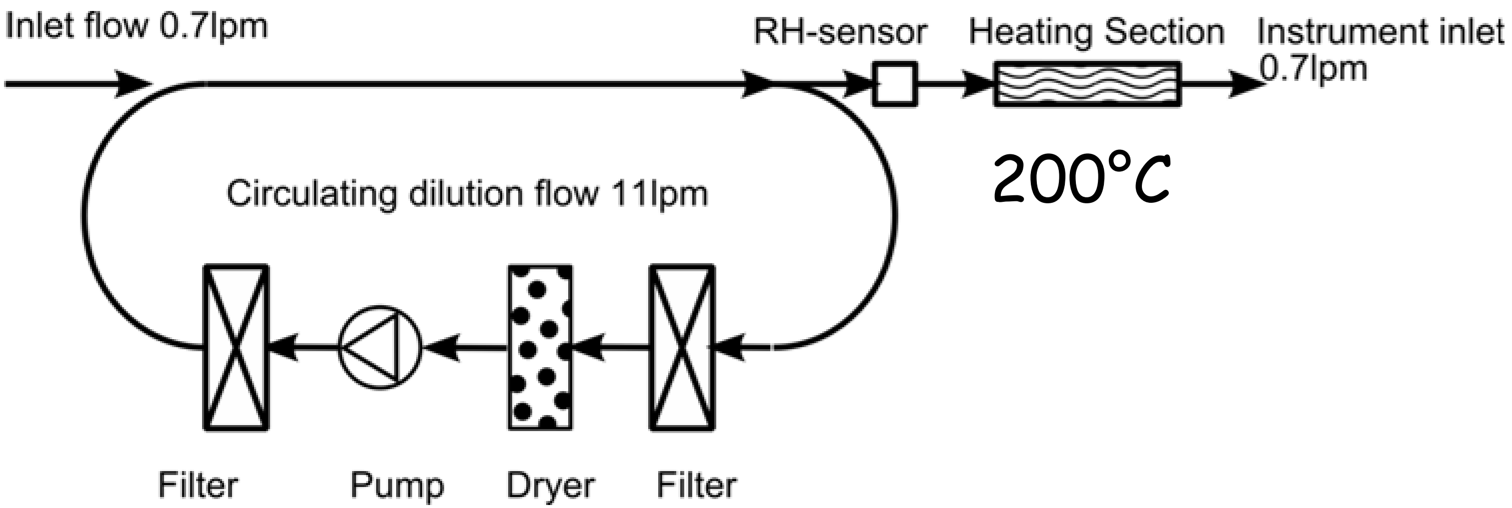
Dilution > ~16x to avoid H_2O condensation by...

- Rotating disc
- Ejector
- Porous tube
- Recirculating

Number detection by compact, fieldworthy instrument...

- Handheld CPC
- Electrical particle counter (DiSC, NanoCheck, Nanotracer)

Exhaust conditioning



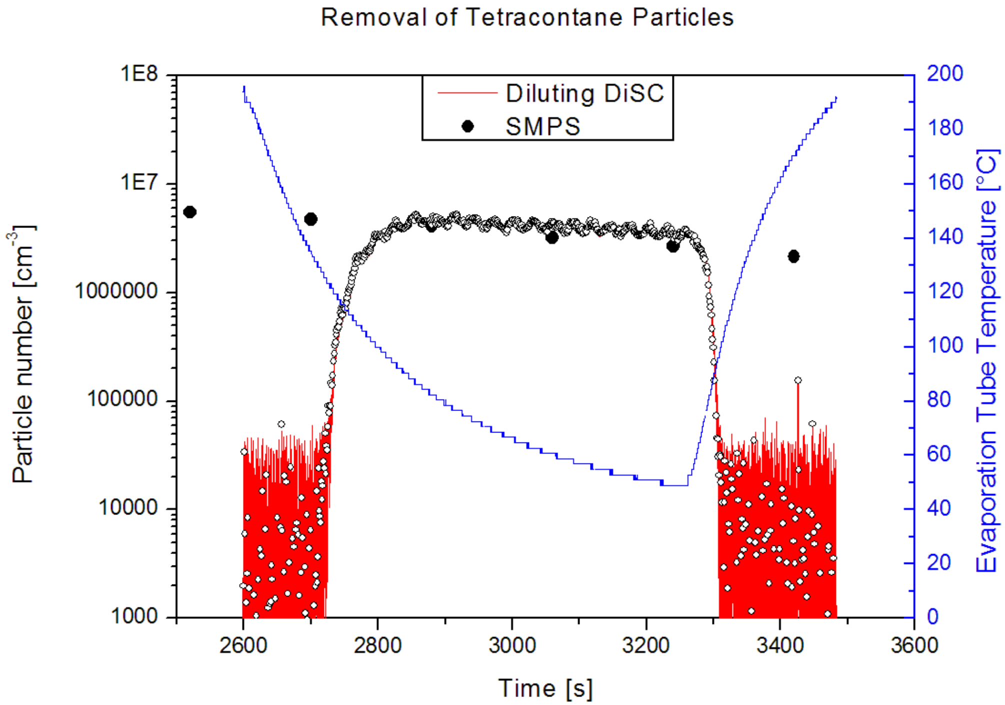
- Primitive/simple dilution system ~1:15
- Filters and dryer must be exchanged periodically
- Tradeoff: easy to use in the field, but needs attention „at home“
- Grimm „Emission Sampling System“ is very similar

Our instrument: „diluting DiSC"

- 19" housing but only 10cm high, 6.5kg -> backpack
- Operation / data acquisition on a field-PDA by bluetooth link to the instrument
- Stainless steel sampling probe to exhaust pipe with dilution in sampling tip
- 4 h battery lifetime

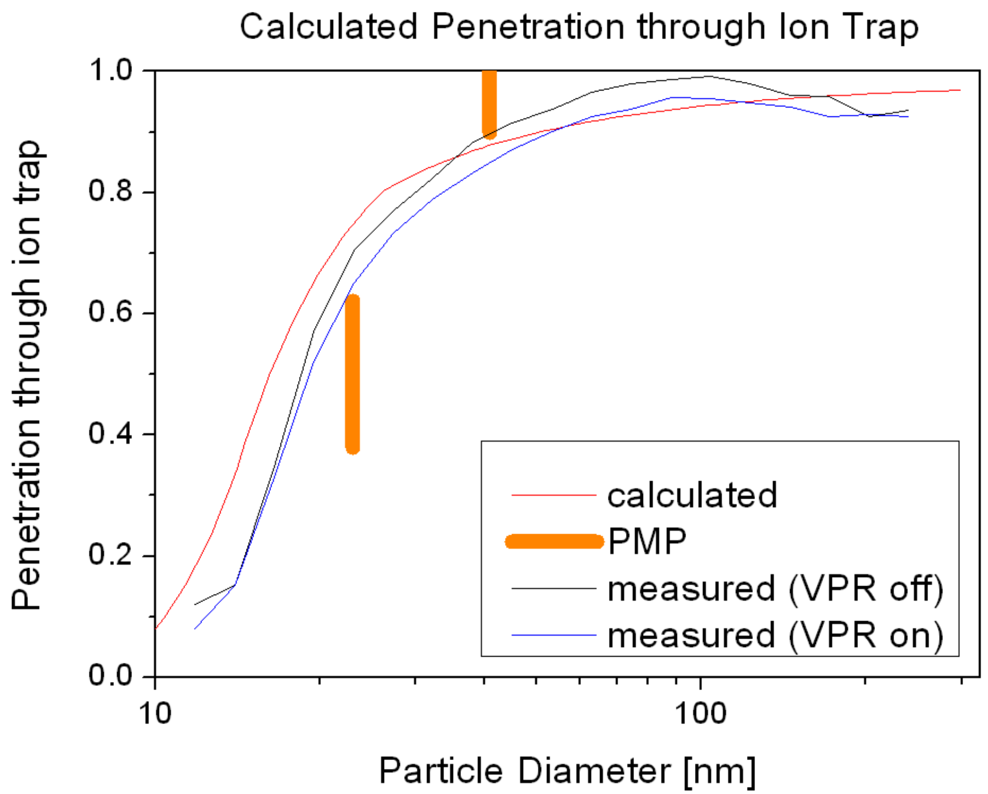
Tetracontane removal

- PMP protocol with strange spec (> 10^5 pt/ccm)
- Note noise floor of our instrument – these are 0.1s measurements – at 1s average noise is a few 1000 pt/ccn

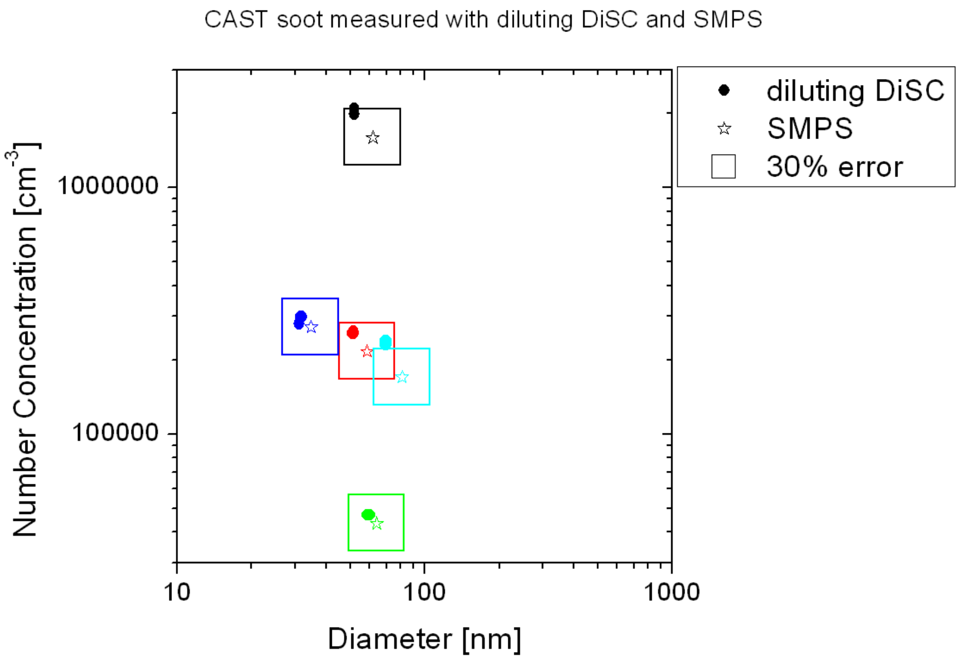


Ignoring the small particles

- Calculated and measured penetration through ion trap gives nearly PMP-conform penetration

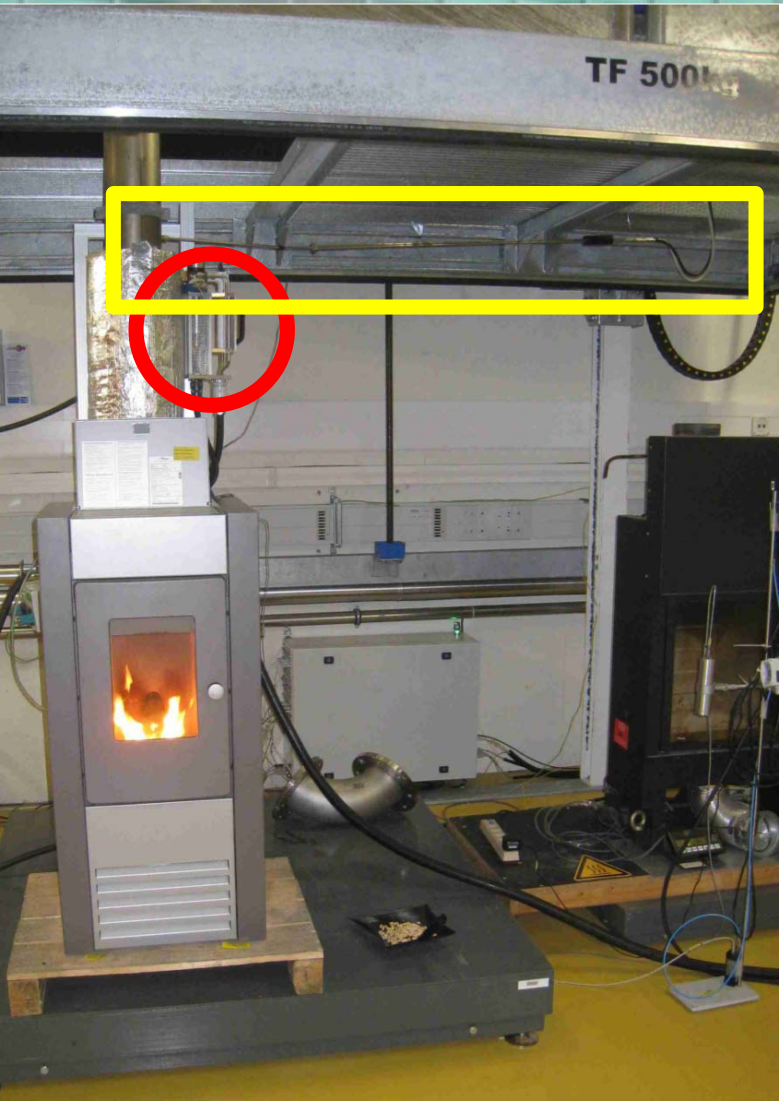


Laboratory: SMPS vs. diluting DiSC

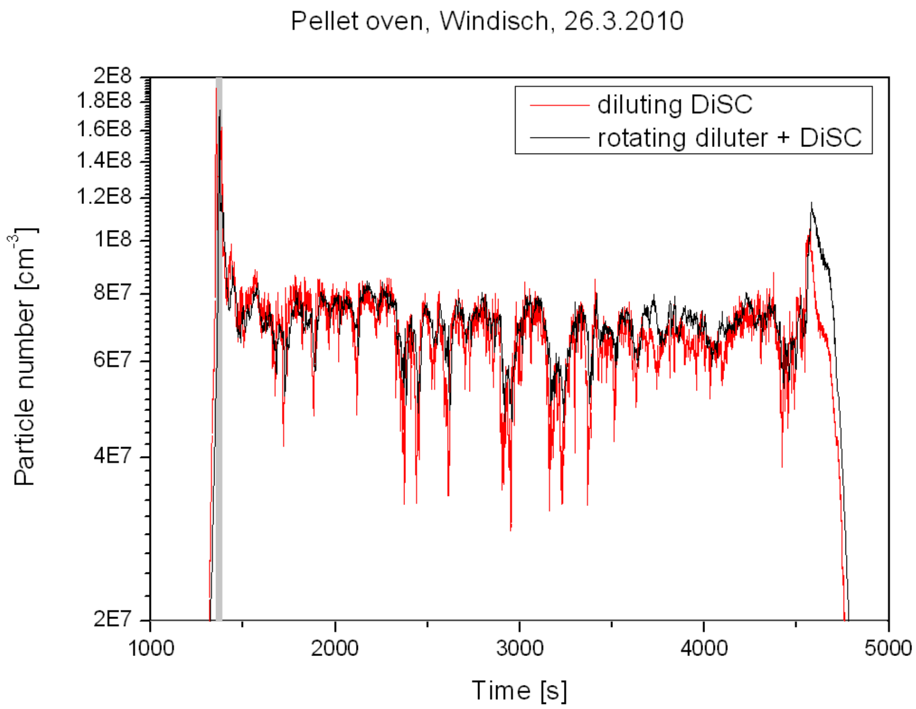


In general, slight overestimation of the particle number and underestimation of diameter
likely a calibration issue (calibrated with compact NaCl particles, measured fractal soot particles)

Laboratory: Wood combustion



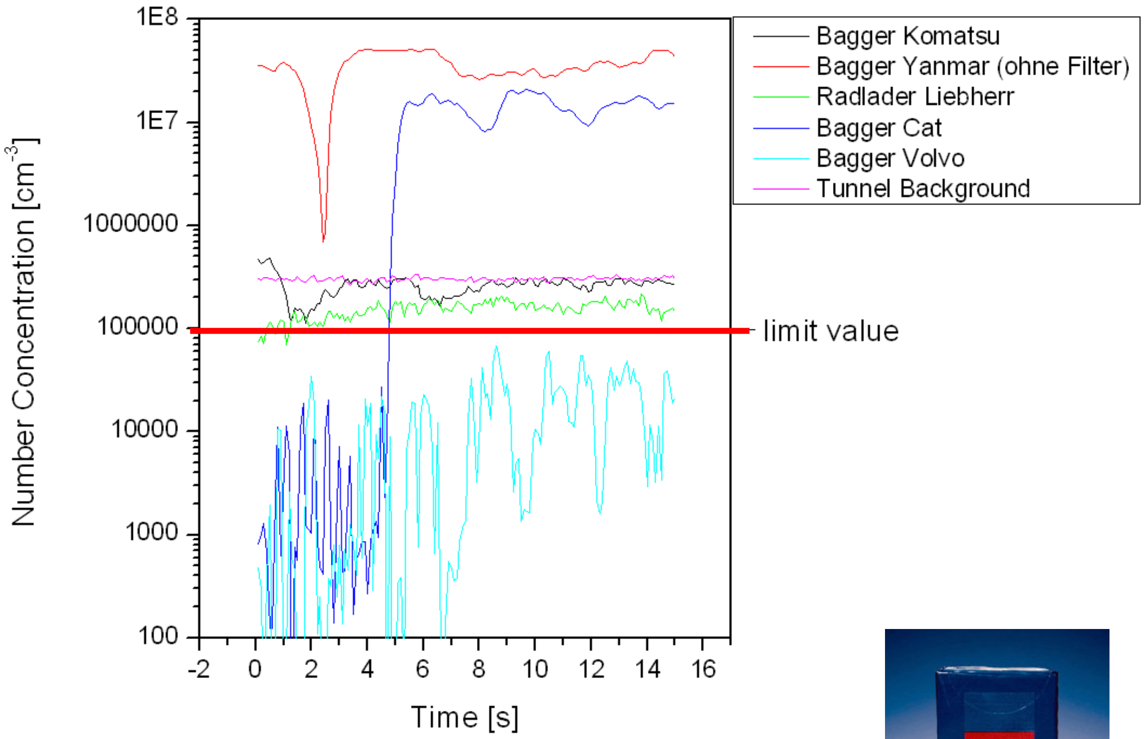
Diluting DiSC vs. Rotating Diluter + DiSC



Excellent agreement with exception of burnout

Field:Tunnel construction site

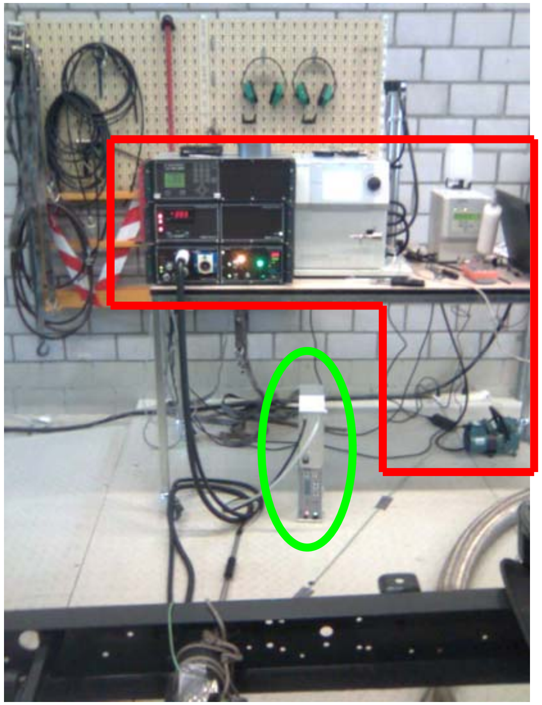
All machines idling (no free acceleration)

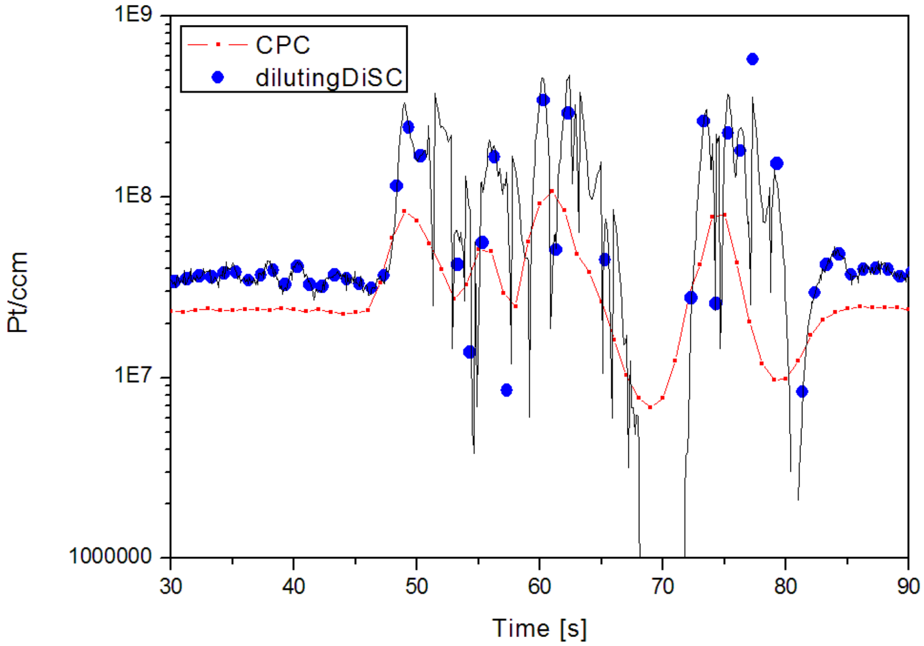


Comparison only with

Chassis Dyno

- Comparison with a not-quite-PMP (Matter Aerosol, direct dilution at tailpipe)
- and unfortunately, no DPF vehicle -> Overrange





Conclusions & Outlook

- Compact PMP-like field instrument prototype demonstrated (could be 25% smaller)
- PMP-like d_{50} by ion trap
- Tetracontane evaporation at 200°C seems ok
- Accuracy ~ ± 1.5x - need to calibrate with soot!
- Tradeoff: ease of use in the field <-> maintenance in the lab
- Compare with PMP-conform system somewhere (invite me!)

...final thoughts

- What kind of accuracy do we really need ?
- 1/km limit value -> 1/ccm field limit?
- PMP protocol was designed for type approval!
  Do we want to follow it blindly for field measurements?

- If all we want to know is whether a DPF is operating correctly or not, a simple DC charging signal is sufficient and from an engineering viewpoint IMO by far preferable!
  (think of very nice N-m-correlation shown by Vogt & Khalek yesterday, i.e. d^0-d^3, DC ~d^1),

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