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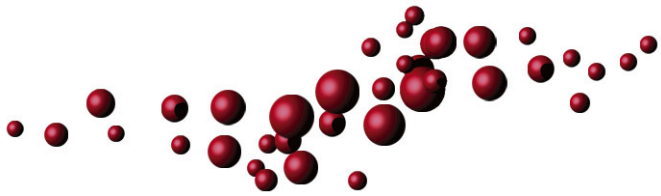

MMEA D4.5.1.5

Results of the feasibility studies for combustion and diesel exhaust gas measurements

V1 – March 2011

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12. Summary

A series of particle size, number, concentration and electrical charge measurements were performed at different locations in Finland to evaluate the feasibility and performance of the new ELPI+ instrument in difficult environments. Different sampling systems were combined with the instrument to allow hot combustion exhaust gas sampling.

Instrument performed almost flawlessly and the comparison against other instruments shows the usability and value of developed instrument in characterization of combustion gas particles.

13. Notes

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1 Introduction

Measurement, Monitoring and Environmental Assessment" (MMEA) is one of the research programs of the Cluster for Energy and Environment (CLEEN). A sub-project 4 of this research program is named "Development of on-line monitoring technologies".

Key part of the MMEA task 4.5.1 is instrument development for particle measurements in different environments. This report shows the progress of the task by describing and analyzing the measurements performed at diesel engine dynamometers and power plants during the 1st year of the MMEA programme.

2 Instrumentation

2.1 ELPI+

The ELPI+™ (Electrical Low Pressure Impactor) is a new real-time particle spectrometer for measuring airborne particle size distribution in real-time. The operating principle is based on well known ELPI™ technology. The particles are first charged to a known charge level in a corona charger. After charging, the particles are size classified in a low-pressure cascade impactor according to their aerodynamic diameter. The impactor stages are electrically insulated and sensitive electrometers are connected to each impactor stage. The charged particles collected in a specific impactor stage produce an electrical current, which is recorded by the respective electrometer channel. This current is proportional to the number concentration of particles on each stage.

The ELPI+™ measures particles in 14 size fractions in the range from 6 nm to 10 µm. The 13 impactor stages operating in the range of 17nm - 10 µm collect the sample in a way that the collected sample can be chemically analyzed. The final stage measuring in the range of 6-17nm is a back-up filter stage.

The ELPI+™ unit can be used either as a standalone instrument or with an external computer. Automatic zeroing function in the ELPI+™ unit enables long term standalone operation. Through the ELPI+VI software the unit can be controlled remotely with TCP/IP or serial connection. 6 analog inputs and 3 analog outputs from/to ELPI+™ unit can be used for transferring information between measurement systems. The ELPI+™ internal software ELPInux and the ELPI+VI software can both be used to save the measurement results.

2.2 Sampling and dilution system

An essential part of the combustion aerosol measurement is aerosol sampling and sample conditioning. This requires usually a controlled sample temperature decrease with controlled particle losses and without unwanted particle transformations and artifacts; especially it is important to avoid the volatile material condensation and / or adsorption or nucleation during sample cooling since that can cause unwanted variation to the data and make the comparisons to other methods more difficult. Various dilution systems were used in different

measurements while the common approach for the VOC control was a two-stage dilution and thermal treatment of the sample aerosol.

3 Overview of the measurements

Total of four combustion measurement campaigns were performed during the 1st 12 months of the programme: Two diesel measurements, one VTT Espoo and one at Proventia emission laboratory, Oulunsalo. Power plant measurements were performed at Piippola power plant and at HELEN power plants in Helsinki Hanasaari and Salmisaari.

Table 1: Field measurements

Location	Time	Plant / fuel	Sampling
VTT	8-10.6.2010	Diesel engine	Heated tailpipe dilution system
Piippola	24-25.8.2010	Wood firing power plant	Modified heated diluter system
Proventia	25.10-12.11.2010	Diesel engine	Heated Ejector diluters, Fine particle sampler
HELEN	17-31.1.2011	Oil and coal power plants	Fine Particle Sampler

3.1 Measurements at VTT

The first series of ELPI+ feasibility study was a measurement campaign at VTT, State research Centre in Espoo, Finland. The main purpose of the measurement was to evaluate the robustness of the ELPI+ system in real field conditions where the instrument must tolerate the heat, vibration and other interference caused by the engine and dynamometer. The first set of measurements were performed with a temporary instrument calibration, therefore the comparison to other instruments was limited to the classic ELPI model comparisons in current measurement mode; thus in arbitrary units only.

3.2 Measurements at Piippola power plant

Piippola power plant measurement was the first time the system was used in to real power plant conditions. Again the purpose of the measurements was to evaluate the feasibility of the system and installation possibilities in field use. Particle size distributions were measured at differerent locations of the plant, comparison measurements were performed against the classic ELPI model in terms of particle number and mass. Results have been presented in the International Aerosol Conference in Helsinki in August 2010.

3.3 Proventia measurements

Measurement campaign at Proventia was conducted in co-operation with MMEA task 4.5.2, and the purpose of the measurement was to collect a wide range of comparison data against other measurement equipment. The equipment included Classic ELPI, CPC (TSI inc.), SMPS (TSI inc.), PPS (Pegasor Ltd). The chemical composition of the particles was also analyzed using ACSM (Helsinki University). During the measurements the feasibility of the ELPI+ in engine exhaust measurements for both steady state and transient driving conditions. Also the maximum sampling frequency was tested against the PPS sensor, which is also capable to detect fast changes in the exhaust aerosol concentrations.

3.4 Helen measurements

The measurements were performed in January 2011 again in co-operation with MMEA task 4.5.2. Measurements took place at the Hanasaari power plant and at the Salmisaari B power plant. Besides the ELPI+ measurements there were many other instruments (SDI, MOUDI, Mini-AMS, MAAP,SMPS, EELPI etc.) installed to the same measurement location with the other participants of the research program (FMI, TUT, Metropolia).

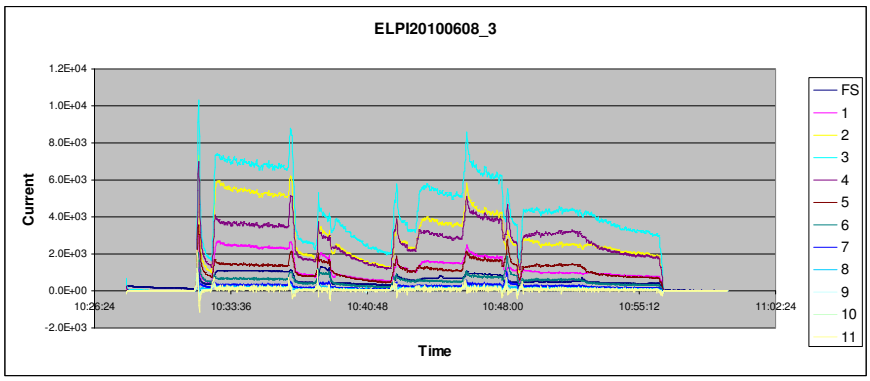
4 Feasibility and results

4.1 VTT engine laboratory

Although this was the first harsh field measurement campaign the measurement system performed well, except the dilution system mounted into the engine tailpipe broke down during the measurement. Also the sensitivity of the measurement system was not sufficient at low particle emission levels; however this was expected at that time since the system was still under the development phase.

4.1.1 Results

Figure 1 shows an example of the measurement data and comparison between the two systems. Classic ELPI on top, new ELPI+ instrument below.



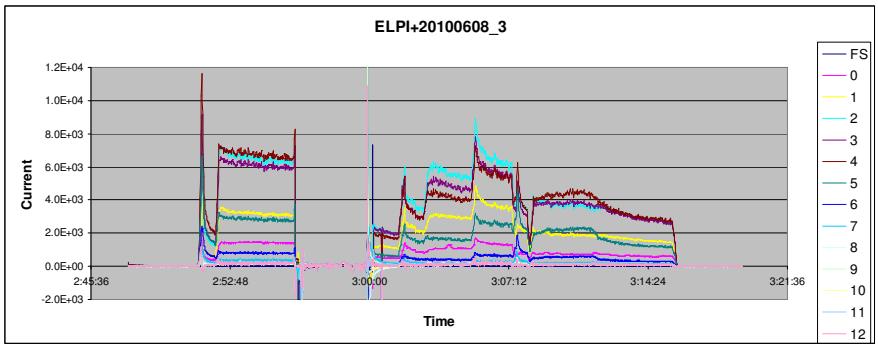


Figure 1: Instrument comparisons

ELPI+ had a problem after few minutes of measurement; after that break the current comparison was not the same than before. Figure 2 shows the current ratios between the instruments before and after the breakdown:

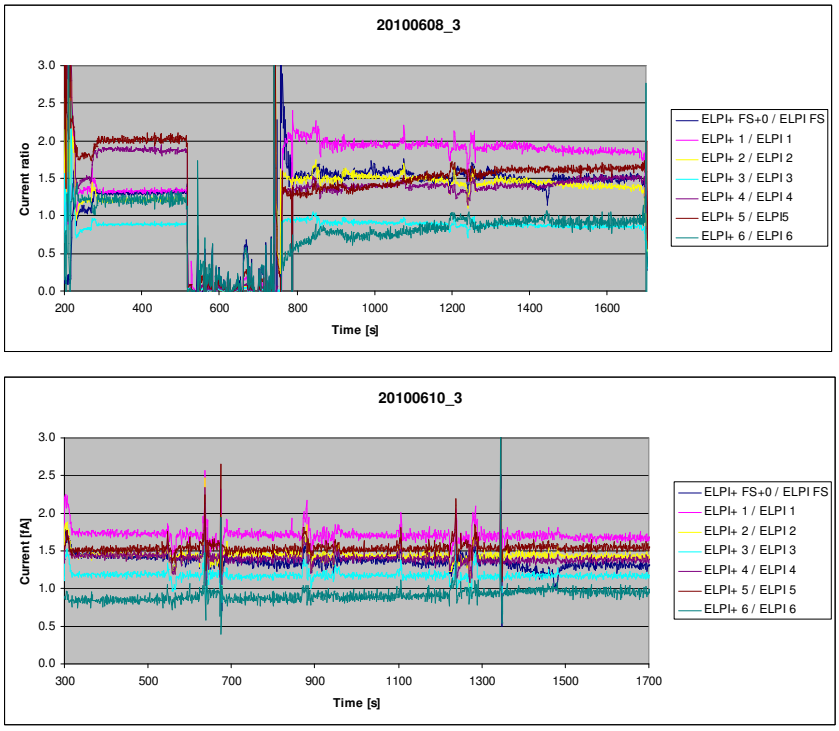


Figure 2: Relative difference at various impactor stages

Figure 3 shows the ratio between the total currents measured from the classic ELPI and new ELPI+. A general observation is that the total measured current from ELPI+ is about 30% higher than in the classic ELPI; this shows that the particle charging efficiency has improved about that much.

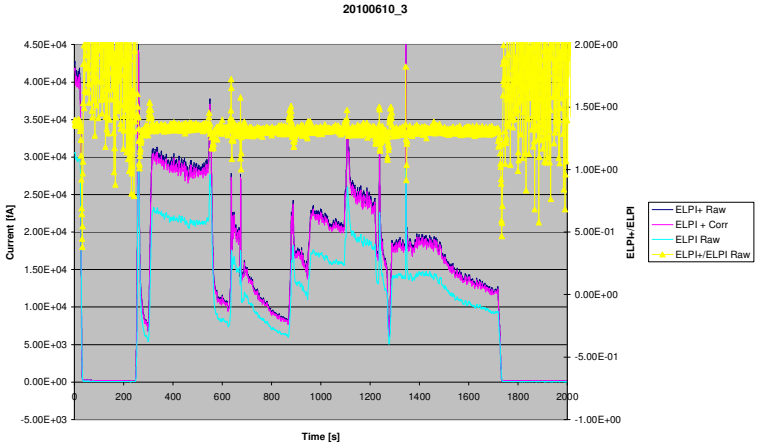


Figure 3: ratio of total currents

A 10Hz sampling option weas implemented to the ELPI+. However due to increased noise levels this is not yet feasible function as seen in figure 4:

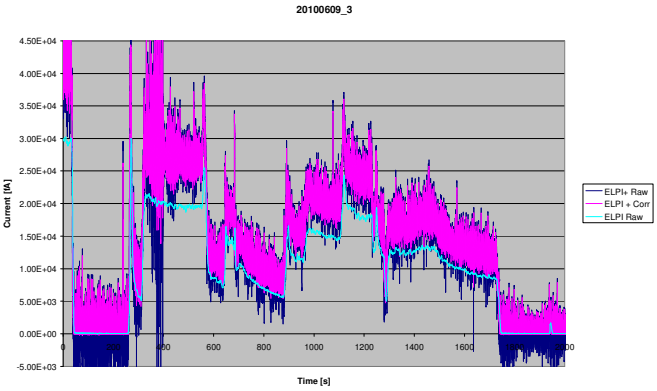


Figure 4: 10Hz sampling

4.1.2 Distributions

The main purpose of the measurements was to evaluate the ELPI+ capabilities for particle size distribution measurements. An example of the comparison is seen in figure 5:

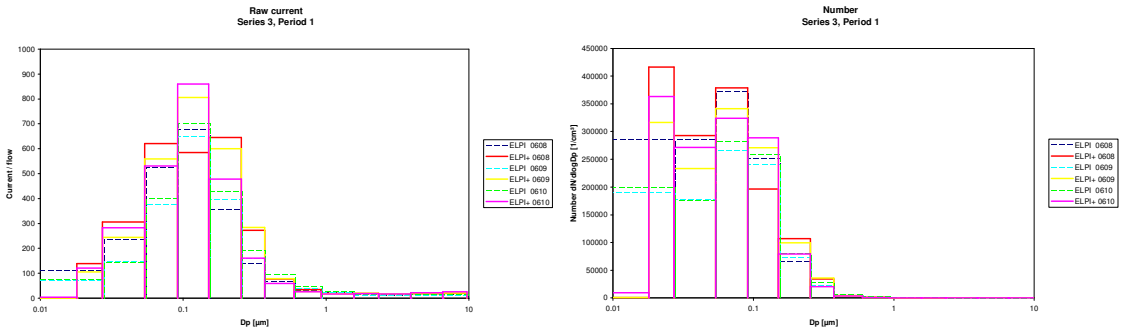


Figure 5: Size distribution comparisons; current in left, number right (preliminary calibration)

The following data shows both cumulative and stage-by-stage comparisons between the classic ELPI and ELPI+. the first one is calculated using equation

$$Err_{cum} = \frac{\sum_{i=0}^{n} I_{i\,ELPI+} - \sum_{i=0}^{n} I_{i\,ELPI}}{\sum_{i=0}^{n} I_{i\,ELPI}} \cdot 100\,\%$$

Where the ELPI+ calculation starts from stage 0 (filter stage not implemented here) and classic ELPI start from filter stage. n gets values from 0 to 11. Cumulative error is calculated for number, diameter and so on. Differences in flow rates have been compensated.

Stage-by-stage differencies have been calculated by equation

$$Err_{diff} = \frac{I_{i\,ELPI+} - I_{i\,ELPI}}{I_{i\,ELPI}} \cdot 100\%$$

where again stage width differences and different flow rates have been compensated. An example of the comparison is seen in figures 6 and 7:

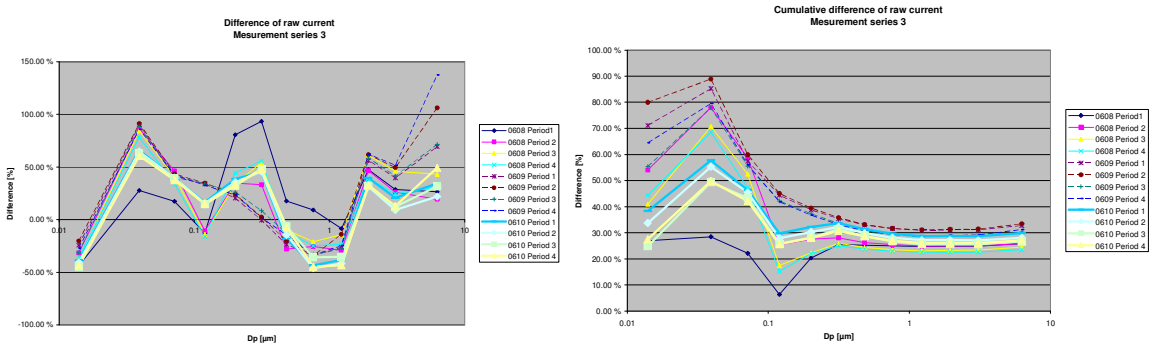


Figure 6: Differences in raw current; stage-by-stage left, cumulative right

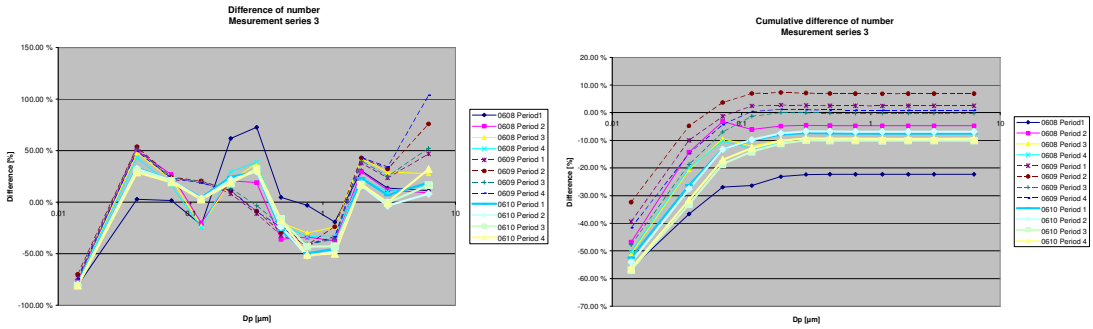


Figure 7: differences in number; stage-by-stage variations and cumulative distributions

4.1.3 Measurements after the diesel particulate filter

Some measurements were performed after a diesel particulate filter. Typically these nowadays mandatory cleaning systems have a very high PM filtration efficiency of more than 99,.9%. This was the case also in this data, there was no PM signal in the ELPI after the filters.

4.1.4 Summary

The measurements system performed well during most measurements. Some instrument breakdowns took place in harsh environment but in general the feasibility was good. Results show that in general the comparison data was good but some variance was observed between different days. The reason remains still unknown.

Instrument performance was improved as expected; by about 30%, even though the electronics noise levels were not yet at the level required for commercial product. .

4.2 Piippola measurements

The second set of measurements took place at Piippola wood-firing power plant. The plant is a 1.5MW power plant for district heating and uses gasified wood chips as fuel. The measurements were performed at three locations, in a gasification chamber, in combustion chamber and in flue gas channel.

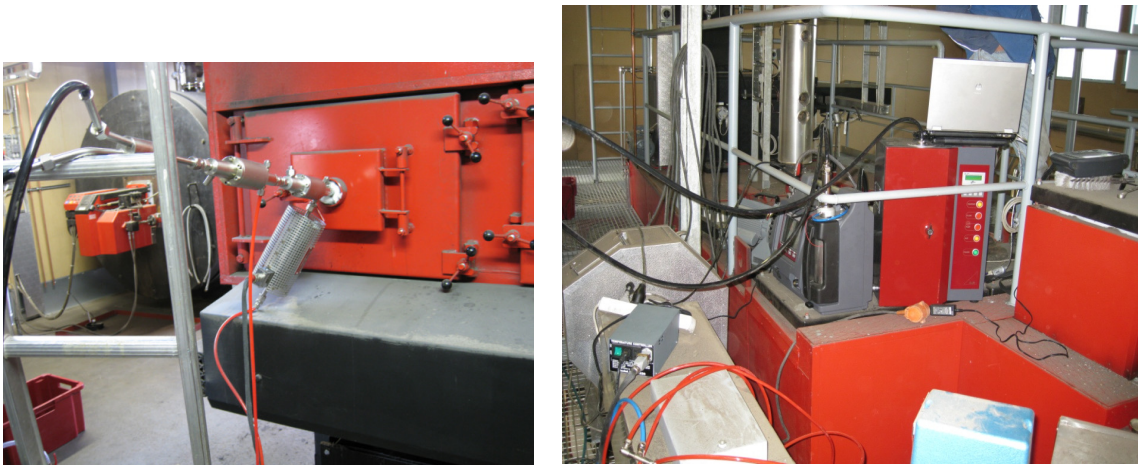


Figure 8: Measurement setup at Piippola plant. Sampling system at left, instruments right

Here the ELPI+ system was more close to the commercial version and the instrument comparison data was much better than before. An example of the ELPI/ELPI+ comparison data from gasification chamber is seen in figure 9:

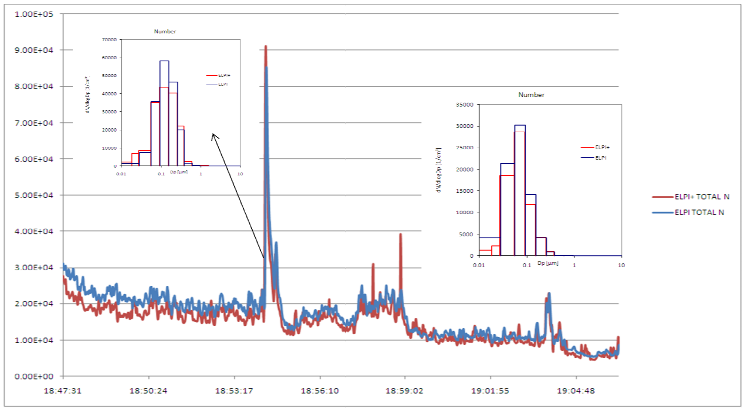


Figure 9: Comparison of ELPI and ELPI+ data; gasification chamber, particle number and size distributions

In combustion chamber the size distribution was totally different, due to higher temperature the particle size was smaller and there was a systematic difference between the ELPI and ELPI+ concentrations. However by looking at the size distributions it is obvious that the difference is caused by improved size resolution of the new instrument.

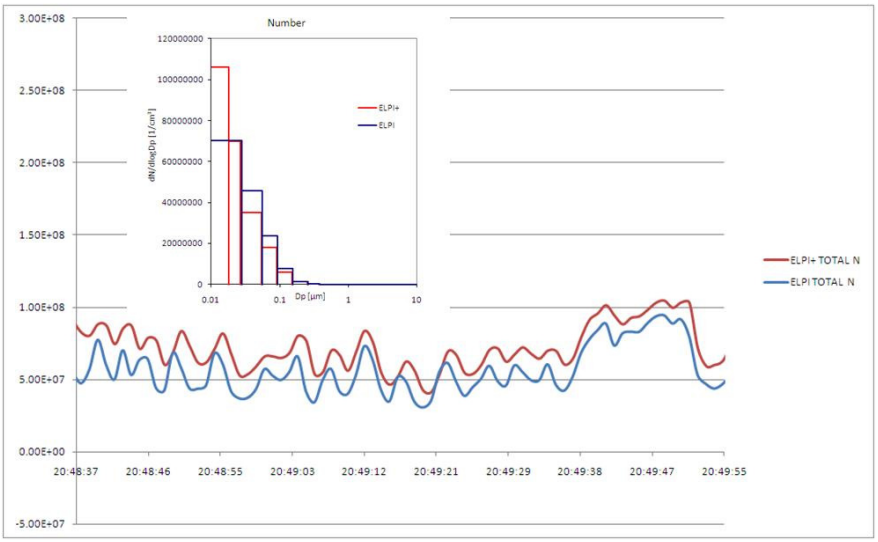


Figure 10: Concentration and size distributions in combustion chamber

In flue gas channel the particle size was again much bigger and the comparison data was excellent as seen in figures 11 and 12

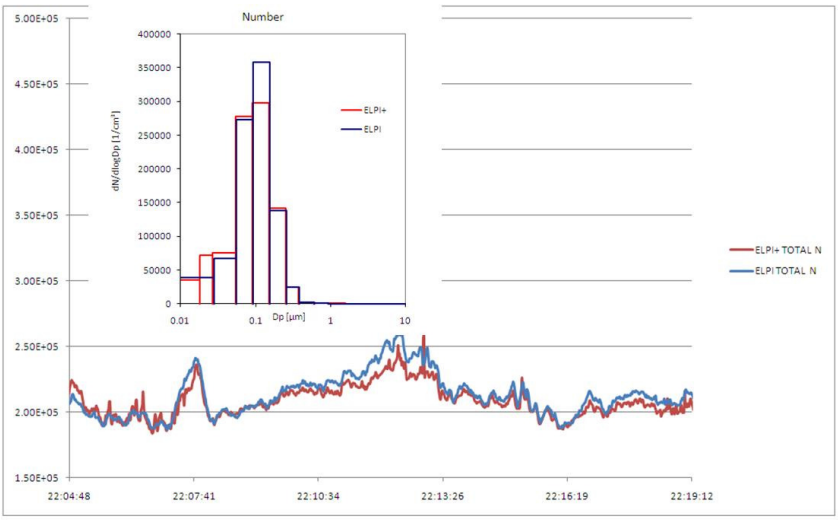


Figure 11: measurement from flue gas channel.

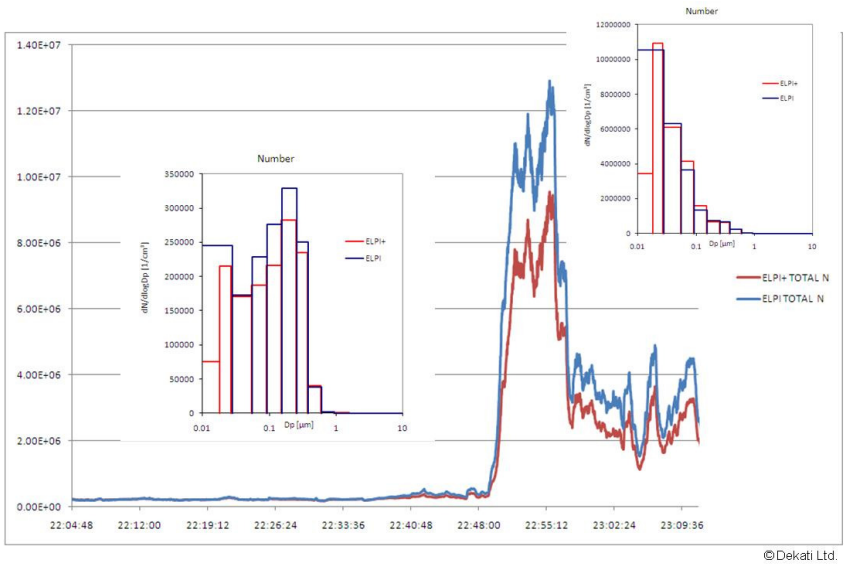


Figure 12: flue gas channel during load change.

4.2.1 Conclusions

In Piippola plant measurement the purpose was to evaluate the developed ELPI+ instrument capabilities for power plant measurements. Instrument and the sampling system performed well at all conditions and in different locations of the plant and the comparison data against other instrumentation shows excellent result.

The data shows how the particle size distribution and concentration changes in different parts of the power plant; in combustion chamber the particle number distribution dominated by freshly nucleated particles while in the flue gas channel and in the gasification chamber the size is much larger. Also it was observed that the low load operation of the plant causes significant increase to plant emitted PM.

The measurement results were presented in the International Aerosol Conference IAC2010 in Helsinki in August 2010.

4.3 Proventia measurements

4.3.1 Measurement setup

The ELPI+ system was tested in the engine dynamometer measurements at Proventia in October and November 2010. The tested engine was heavy duty off road engine manufactured by Sisu Finland. The engine was fitted with a prototype exhaust aftertreatment system consisting of a diesel oxidation catalyst (DOC) and a selective calatytic reduction (SCR). The measurements with the ELPI+ were made in only before the aftertreatment. The fuel used during the measurements was fulfilling the EN590 specifications.

In the measurements three different dilution systems were used. The first system consisted of a porous tube primary diluter (PTD) combined with a cold ejector diluter. This dilution system measures the exhaust aerosol with the volatile hydrocarbons, enabling nucleation and condensation of the volatile compounds.

The second system was the same as the first one, but with the addition of a thermodenuder to remove the volatile hydrocarbons from the aerosol. This setup measures the dry soot coming out of the tested engine. The third dilution system consisted of a hot ejector primary diluter and a cold ejector secondary diluter. The operation of this setup is similar to the second one.

The engine driving conditions used were off road NRSC, off road NRTC and modified off road NRTC test cycles. The modified NRTC cycle was based on the normal NRTC cycle so that engine loading was reduced by removing high load portions of the cycle.

4.3.2 Prelimimary results

In figure 13 the number size distributions measured during a NRSC test cycle are shown. The measurements were done without aftertreatment and the dilution system used was the PTD combined with the cold ejector diluter and without the thermodenuder. The NRSC cycle consisted of eight steady state engine loads; S1: 100% load at rated speed, S2: 75 % load at rated speed, S3: 50% load at rated speed, S4: 10% load at rated speed, S5: 100% load at intermediate speed, S6: 75% load at intermediate speed, S7: 50% load at intermediate speed and S8: low idle. In the Plots A and B size distributions measured with the ELPI+ and in the plots C and D size distributions measured with nano-SMPS are shown. Note the different size range in different instruments. The plots in figure 13 show comparable results between the instruments. Especially shown in plot A, the increased size resolution at small particles in the ELPI+ enables to distinguish the difference in the nucleation mode between the points S1 and S2

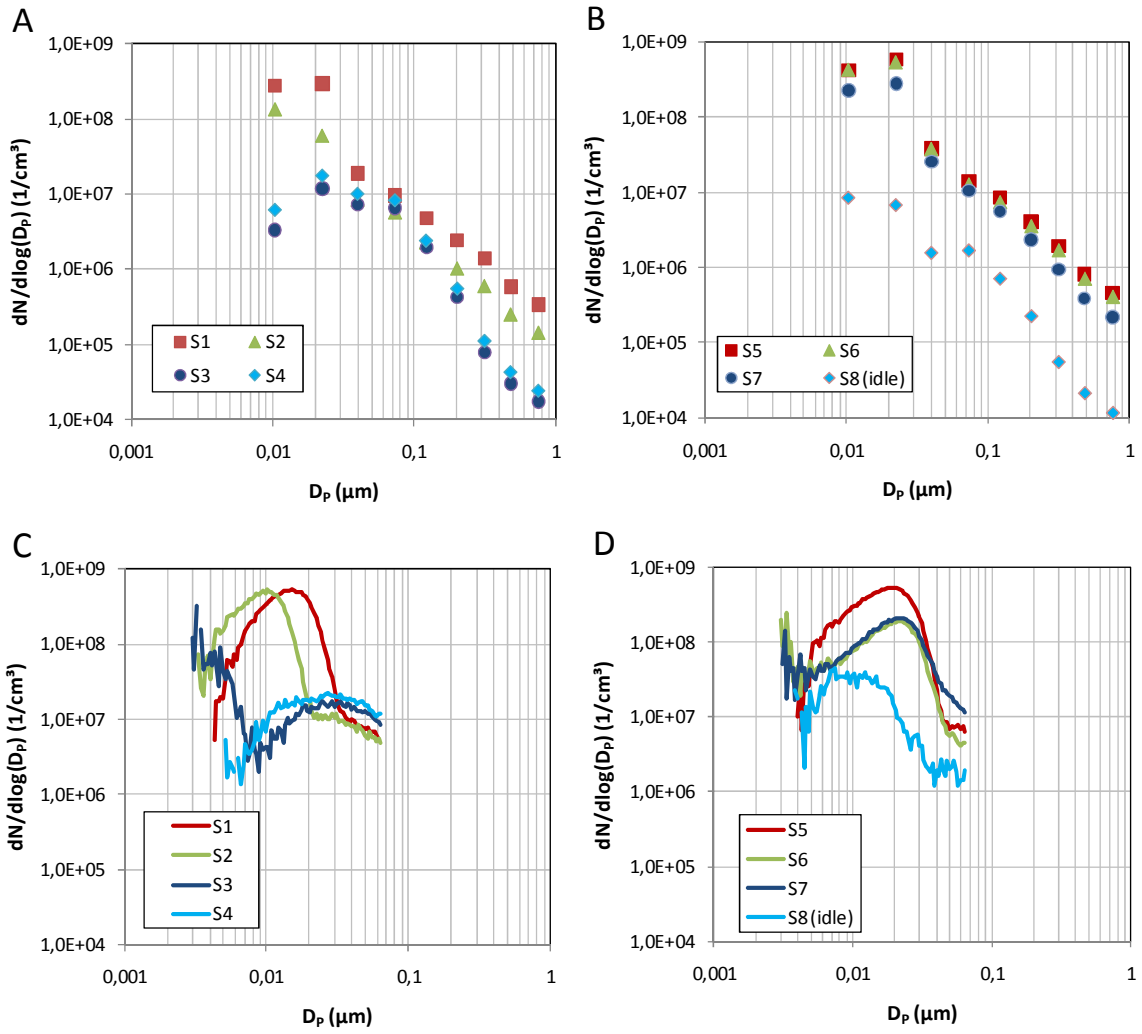


Figure 13: ELPI+ and nano-SMPS size distributions during a NRSC test cycle. Note the different size ranges in different instruments.

The figure 14 shows a temporal plot of the number concentration measured with the ELPI+ during standard NRTC test cycle. The measurements were made with the same dilution setup as above. The two runs shown in the figure shows the repeatability of the cycle. The Run 2 in the figure is measured with standard 1 Hz sampling and the Run 3 is measured with the increased 10 Hz sampling frequency. As seen in the figure, the difference between the two sampling frequencies is not significant. This is due the averaging effect of the dilution system used.

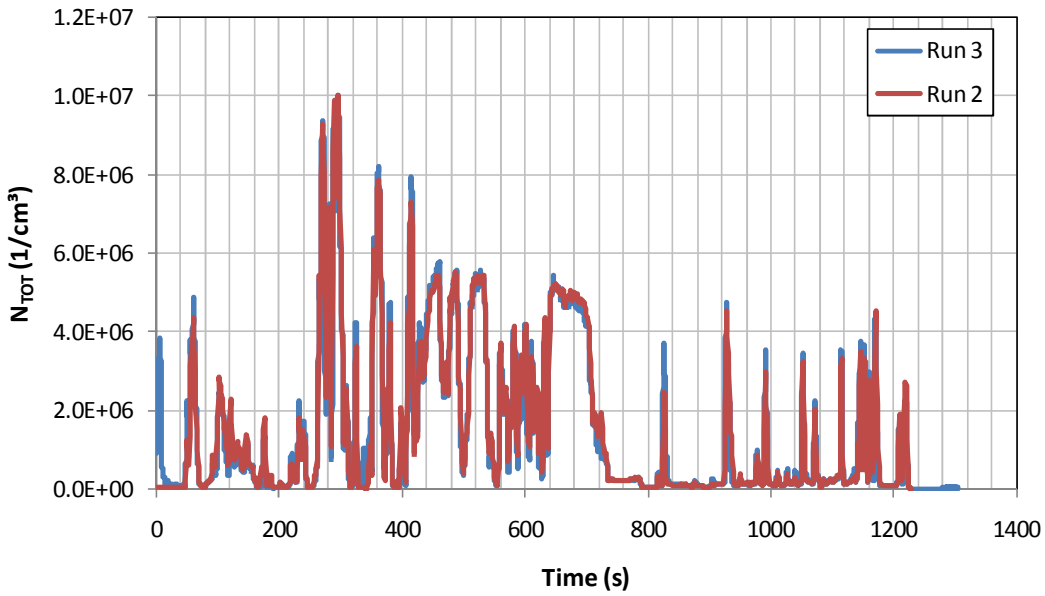


Figure 14: Total Number concentration during two NRTC test cycles measured with ELPI+ Dilution ratio is not corrected in the data.

The figure 15 shows the ELPI+ total current during a NRTC test cycle (Run 2 in figure 14) together with the PPS sensor output. As seen in the figure the two signals correspond well in the start of the cycle. During the rest of the cycle there are some differences. One reason for the differences could be the effect of volatile compounds in the exhaust gases. The PPS signal originates from the dry soot particles, whereas the ELPI+ signal contains also nucleation mode particles formed in the dilution. There are also some differences in the instrument responses against the particle size.

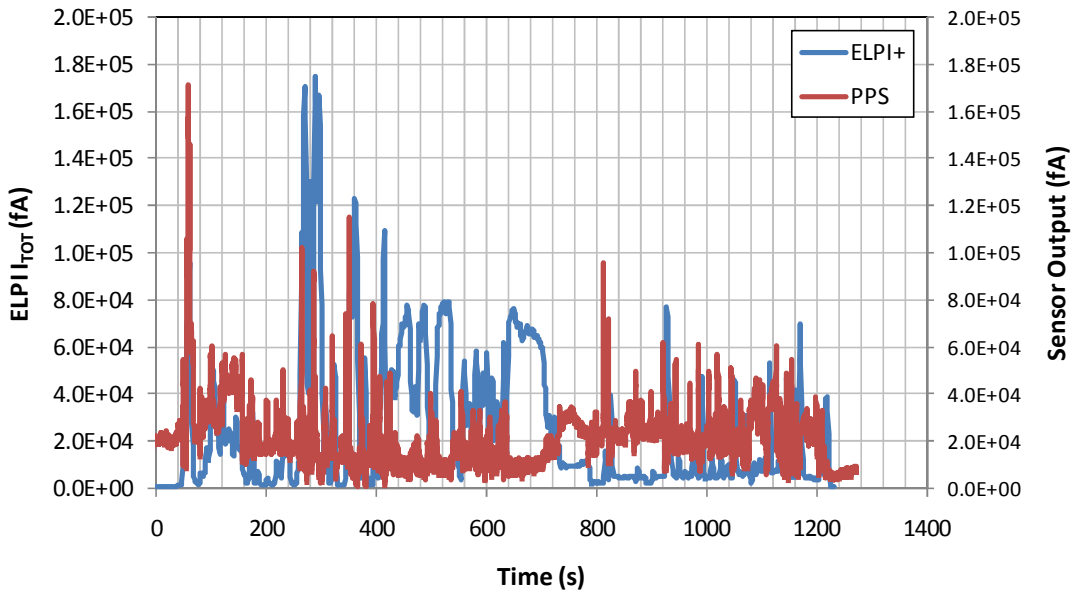


Figure 15: ELPI+ total current and PPS sensor signal during NRTC test cycle. ELPI+ data is the same as the Run 2 in figure 14.

4.3.3 Conclusion

The purpose of the measurement was to evaluate the feasibility of the ELPI+ system in the engine dynamometer measurements and to compare the ELPI+ data to reference instruments. The ELPI+ system performed well during the measurements and comparative data was measured using SMPS, CPC and PPS as reference instruments. The data validation is underway, and preliminary results are shown in the report. Preliminary results show a comparative results from the ELPI+ and reference instruments, but a further analysis is needed

4.4 HELEN Measurements

An ELPI+™ was tested at two power plants of Helsinki Energy, at the Hanasaari oil-fired peak-load heating plant and at the Salmisaari B coal-fired cogeneration plant in January 2011 in co-operation with MMEA task 4.5.2.

The measurement dates, power plants and positions are shown in the table below.

Table 2. Measurement schedule.

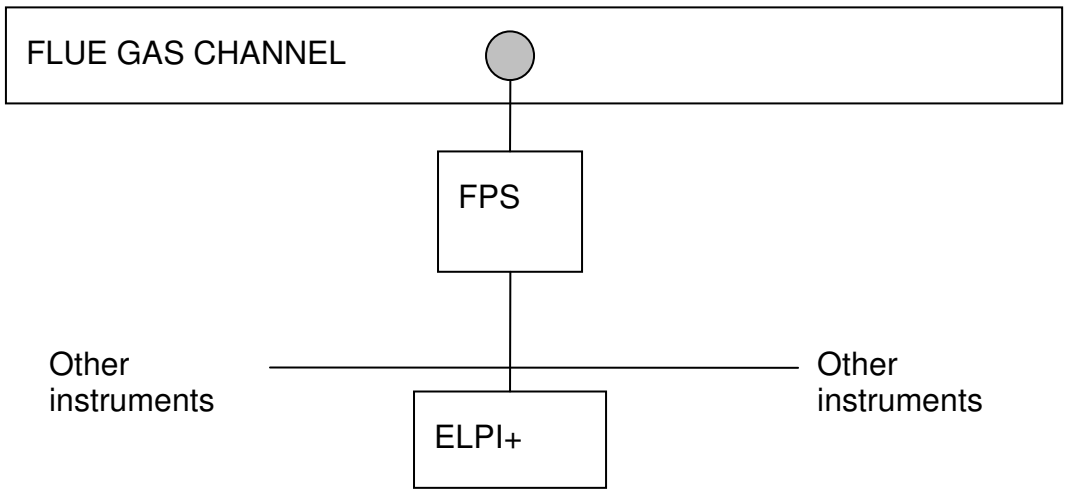
Date	Power plant	Measurement position	Process state	Diluter	Dilution
17.1.2011	Hanasaari	Flue gas channel	Startup and full power run	FPS	90
20.1.2011	Hanasaari	Flue gas channel	Full, half and 1/3 power run	FPS	90
25.1.2011	Salmisaari	Pipe	Normal?	FPS	30

26.1.2011	Salmisaari	Pipe	Normal?	FPS	30
27.1.2011	Salmisaari	Flue gas channel (after precipitator)	Normal?	Ejector	?
28.1.2011	Salmisaari	Flue gas channel (after precipitator)	Normal?	Ejector	?
31.1.2011	Salmisaari	Flue gas channel (after precipitator)	Normal?	Ejector	?

4.4.1 Measurement setup at the Hanasaari power plant

The Hanasaari peak-load power plant is oil-fired and it is used to generate district heat at times when the production of Helsingin Energia's own power plants is not sufficient. Therefore, the measurement dates were determined by the climate conditions.

The principle of the measurement setup is shown below.



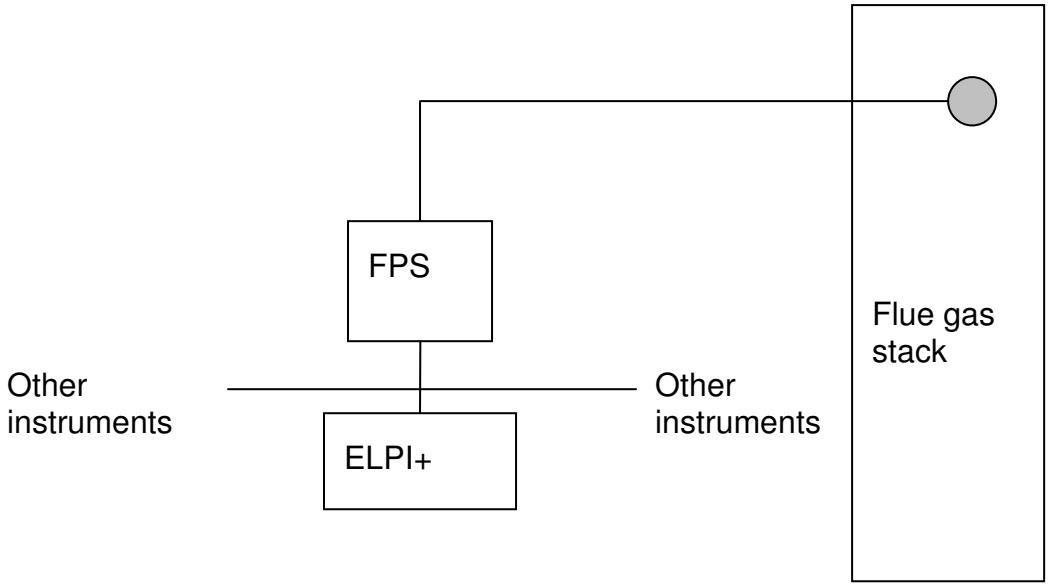
The diluted sample flow was conducted from the FPS to the ELPI+ and other measurement instruments through a 6 m long steel pipe with a diameter 25 mm. The FPS dilution ratio in all Hanasaari measurements was 1:90.

4.4.2 Measurement setup at the Salmisaari B power plant

The Salmisaari B power plant is coal-fired. It has one boiler and one steam turbine, capable of producing 160 MW of electricity and 300 MW of district heating.

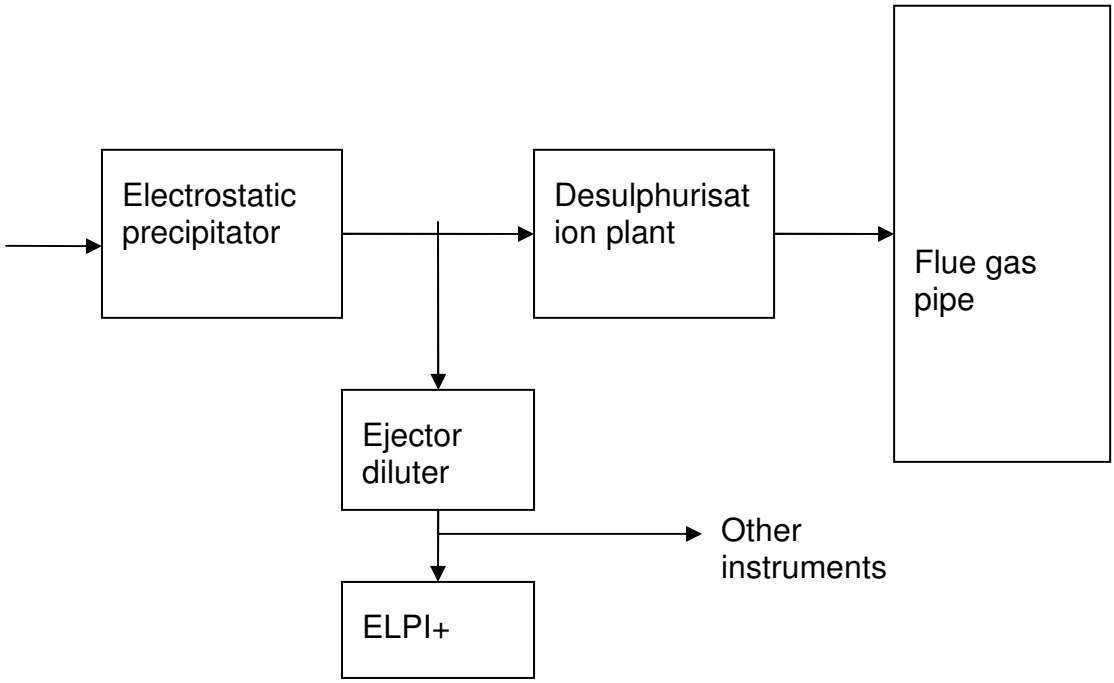
4.4.2.1 Stack measurements

The principle of the measurement setup is shown in the figure below.



4.4.2.2 Flue gas channel measurements after the electrostatic precipitator

The principle of the measurement setup is shown in the figure below.



4.4.3 Results

4.4.3.1 Hanasaari power plant 17.1.2011

The start-up of the power plant took place at about 11:50. An extra gas burner was used during the start-up. From about 13:00 on the plant has run with full power. The sample dilution ratio was 90.

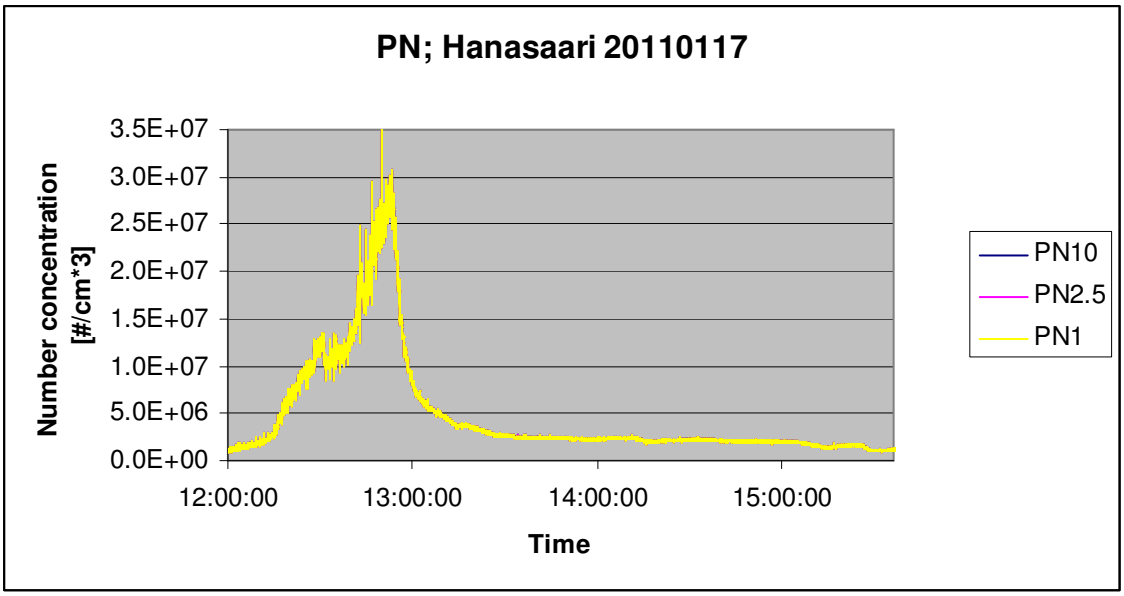


Figure 14. Number concentration measured with ELPI+ at Hanasaari 17.1.2011. The sample dilution ratio has been 90.

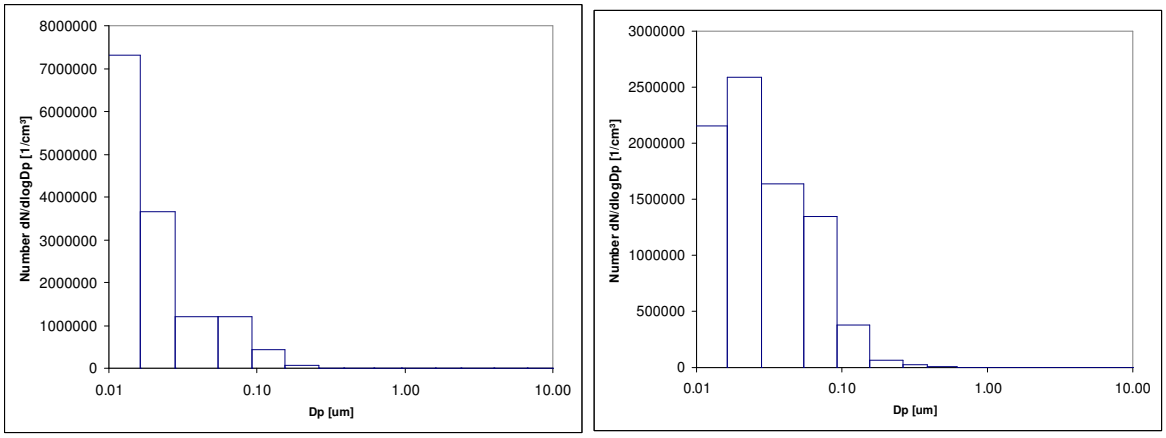


Figure 15. Averaged size distribution 17.1.2011 during the start-up from 12:00 to 12:30. and during the full power run from 13:20 to 14:20.

4.4.3.2 Hanasaari power plant 20.1.2011

After the start-up the plant has run with full power about three hours. From 13:30 it has run with half power and from 16:30 with 1/3 power.

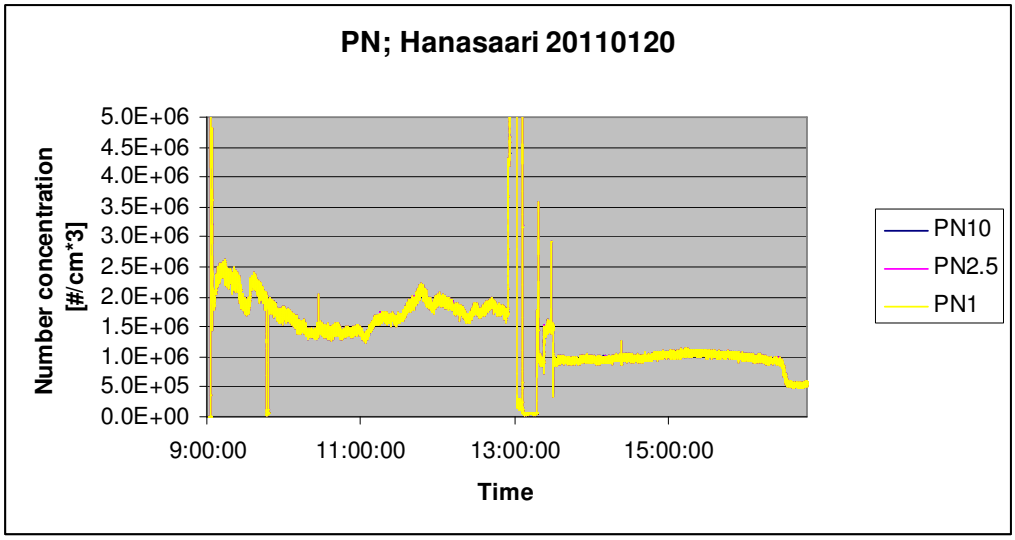


Figure 16. Number concentration measured with ELPI+ at Hanasaari 20.1.2011. The sample dilution ratio has been 90.

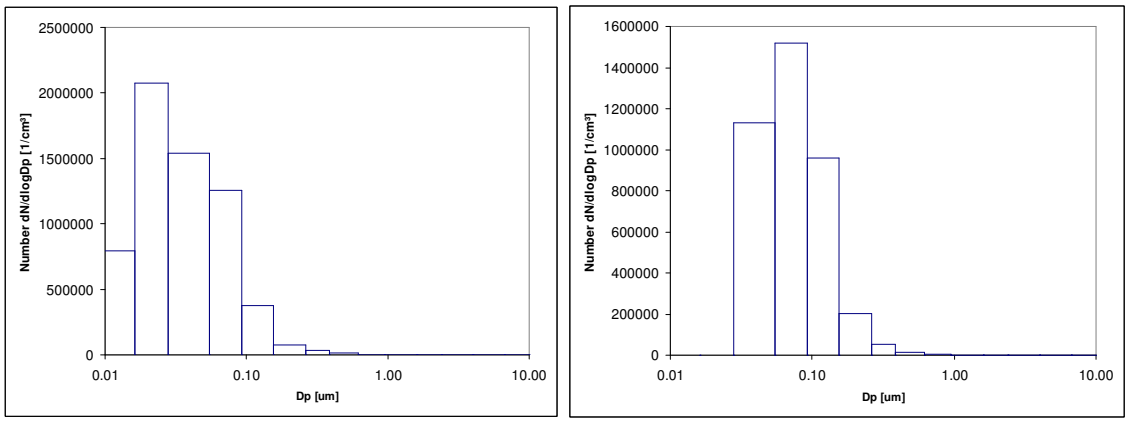


Figure 17. Averaged size distribution 20.1.2011 during the full power run from 9:30 to 10:30 (left) and during the half power run from 13:30 to 14:30 (right).

4.4.4 Salmisaari B power plant 25.1.2011

Measurements from the stack with a dilution ratio of 30. The concentration was very low. The dilution has kept as small as possible, which has caused condensation problems. The measurement data seems to be below the detection limit of the instrumentation.

4.4.4.1 Salmisaari B power plant 26.1.2011

Measurements from the stack with a dilution ratio of 30. The concentration was again very low.

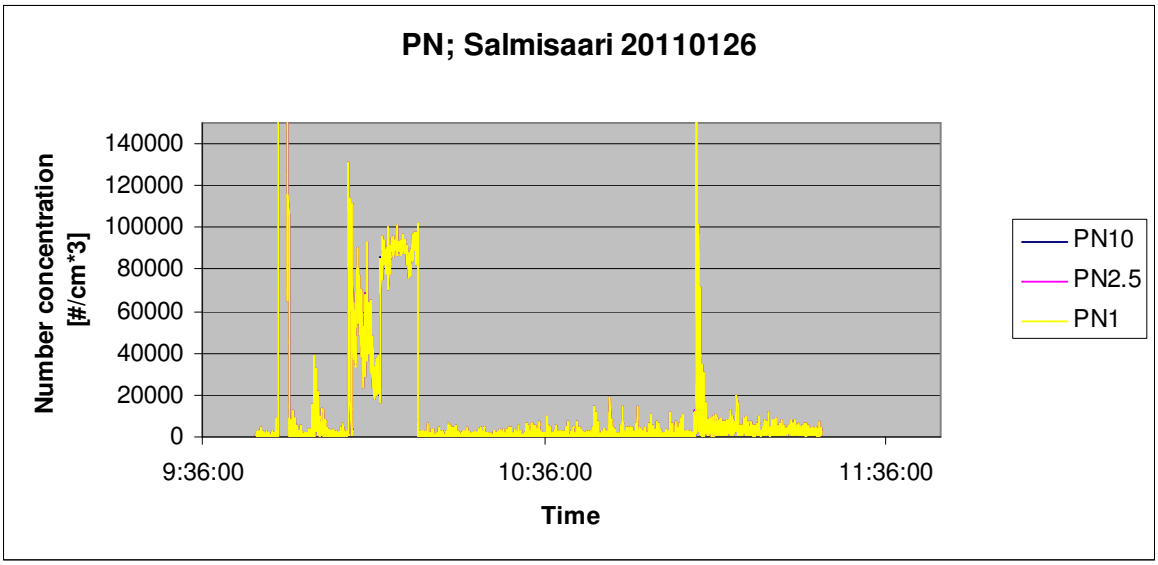


Figure 18. Number concentration measured with ELPI+ at Salmisaari 26.1.2011. The sample dilution ratio has been 30.

All in all the concentrations in the Salmisaari plant stack are in the order or even below the ambient PM concentration levels in Helsinki. In flue gas measurements the sample dilution is required in order to avoid water and other volatile material condensation, the typical minimum fur dilution ratio is about 1:20. Therefore the sensitivity of teh ELPI+ is not sufficient for these PM measurements especially with this dilution system. A better option for these low-concentration measurements ould be a sample dryer and some VOC stripper that would remove the water and VOCs without dilution; then the concentration would be high enough for the ELPI+

4.4.5 Salmisaari B 27.1.2011

Measurements from flue gas channel after the electrostatic precipitator. Dilution has been done with an ejector diluter.

These measurements contain experiments with the charge measurement feature of the ELPI+VI. Different averaging times have been tested.

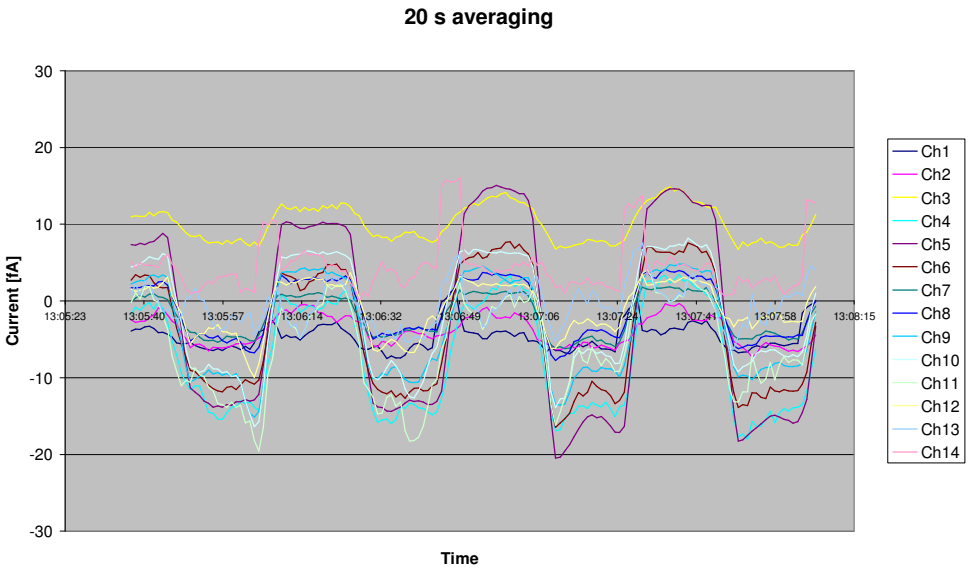


Figure 19. An example of the ELPI+VI charge measurement feature.

The charger is first turned on and the number concentration for every stage is measured as usual. Then the charger is turned off and the natural charge of the particles is measured. From these two measurements it is possible to calculate the net charge level of different particle sizes.

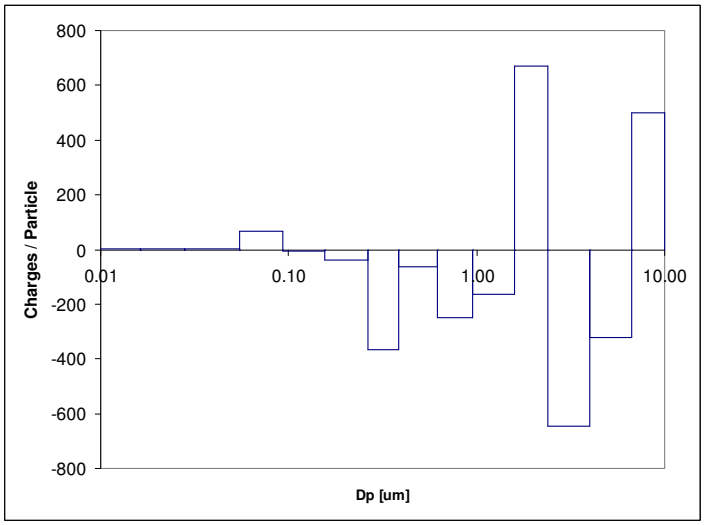


Figure 20. An example of the charge distribution.

A problem in these measurements was again the low concentration level of measured aerosol. Charge measurement requires enough concentration for reliable number and charge distribution measurements but the signals measured were just about the electrometer sensitivity levels. Therefore the result is not reliable enough.

The second part of the measurements of this day contained emission measurements over the night. The cleansing of the electrostatic precipitator can be seen from this measurement.

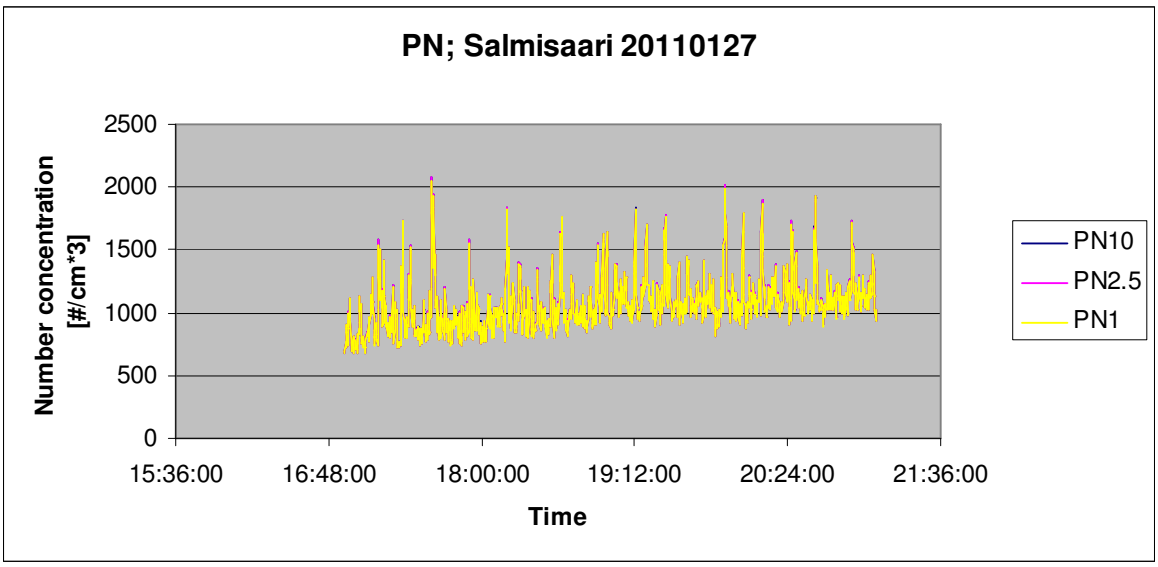


Figure 21. A short period of the number concentration measured with ELPI+ at Salmisaari 27.1.2011. The sample dilution ratio has been 30.

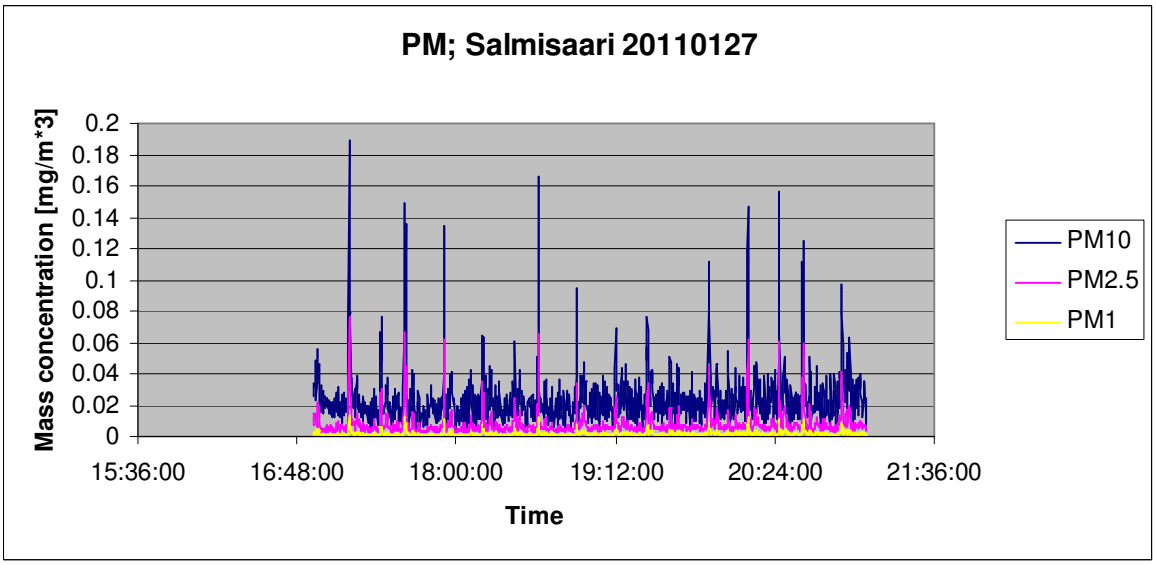


Figure 22. A short period of the mass concentration measured with ELPI+ at Salmisaari 27.1.2011. The sample dilution ratio has been 30.

This data shows nicely the low emission levels from Salmisaari plant. Concentration in the stack is below the typical urban PM concentration levels and in terms of mass approximately three orders of magnitude below the EU regulation of 50 mg/m^3.

4.5 Conclusions

The measurement system performed well during the measurements at two HELEN power plants in Helsinki. Hanasaari plant was an oil-operated power plant and thus the particle size distribution was very small; same size range than in diesel engine dynamometers. The concentrations during the startup of the plant are very high compared to the normal operation.

Salmisaari plant is a coal-firing plant with efficient flue gas cleaning systems. This measurement was the very first time where the ELPI+ sensitivity was not good enough for field measurement; a different sampling system is required for reliable PM size measurements that allows lower dilution rations.

5 Summary and conclusions

In MMEA task 4.5.1 the ELPI+ instrument has been used for field measurements at 5 different locations; two different diesel engine dynamometers and three different power plants.

In most measurements the instrument performed without any major problems; only in the first measurements the system was not in a condition required for reliable data. Also in the last measurements at Salmisaaari plant the instrument sensitivity was not sufficient for reliable data; this kind of plant requires some new kind of sampling system with lower dilution ratios. Same is required for diesel engine measurements after new and efficient particle removal devices.

The data gives valuable information about the instrument performance and its repeatability and comparability to other instrumentation. Several minor software and hardware modifications have been made to the system during the MMEA 1st year but the main finding is that the system is robust and reliable enough for field measurements in rough conditions and it produces a large amount of useful particle data from combustion sources.