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IN-LINE, REAL-TIME EXHAUST PM EMISSIONS SENSOR FOR USE IN EMISSION CONTROL AND OBD APPLICATION

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SUMMARY

Upcoming emission legislations, both within the US and Europe, will require implementation of On-Board-Measurement Diagnostics (OBD) systems for monitoring of the vehicle particle filter systems. Indeed, the US EPA Heavy-Duty OBD regulations already require monitoring of the diesel particulate filter (DPF) in 2010 for at least one engine series, with extension to all engines series by 2013. In Europe, not-to exceed limit values and OBD requirements for Euro VI will be decided in September 2010 with the regulation becoming effective by 2014. Currently, due to the absence of a reliable particulate matter (PM) sensor to monitor the DPF filtration efficiency, alternative methods based on pressure drop measurements and semi-empirical models are adopted. However, meeting the upcoming stringent OBD requirements will need the introduction of reliable sensors, capable of performing actual real-time PM concentration measurements on a continuous basis within the exhaust stream. Moreover, these sensors could also serve as integrated components in the aftertreatment control environment for monitoring DPF loading or as input parameter for DPF regeneration algorithms.

Further, PM sensors could be used off-line during the engine development phase to populate lookup tables for aftertreatment control strategies, aid in developing soot models aimed at DPF monitoring and regeneration or be used in combustion research as a replacement for the widely employed opacimeter.

A prototype sensor technology from Pegasor Oy (Finland) capable of performing continuous measurements directly in the exhaust stack providing a real-time signal with a resolution of 100 Hz, has been investigated for this study. Its operation is based on the escaping current principle. HEPA filtered dilution air is supplied at about 22psi and subsequently charged by a Tungsten corona wire (~2kV, 5µA) before drawing raw exhaust gas through an ejector-type diluter into a mixing chamber where the charge is carried over to the exhaust particles. The sample gas flow is controlled at 9.75 lpm by means of a critical flow orifice. An ion trap is employed to remove excess ions from the sample stream before the charge of the out flowing particles is measured using a built in electrometer. The sensor does not involve collection or contact with particles in the exhaust stream, which is especially advantageous for long-term stability and operation without frequent maintenance; hence, best suited for in-use application. The sensors output can be calibrated to measure the concentration of the mass, surface or number of the exhaust particles. In the remainder of the text, the soot sensor will be referred to as the *Pegasor Particulate Senor* (PPS).

The objective of this study was to test this newly developed sensor under laboratory conditions and compare it to other proven aerosol measurement instruments in order to understand its capabilities and limits with regard to future applications for OBD monitoring or control strategies of PM filter system. Testing was carried out on an engine test bench at WVU's Center for Alternative Fuel Engines and Emissions (CAFEE) using a Cummins ISM-370 (see Table 1), 11l heavy-duty Diesel engine (HDDE). The test matrix involved two transient test cycles, namely the FTP and ETC, as well as a four mode steady state cycle. In addition to engine-out exhaust emissions measurements, sampling was done after retrofitting the engine with three different aftertreatment systems, namely two new catalyzed DPF's, *DPF-A* and *DPF-B* (same substrate and coating, different volume) and one aged DPF (same type as *DPF-A*) which had been used for about 1000 hours in field. Two different test fuels were used, namely CARB certification fuel as well as commercially available ULSD.

Gaseous emissions (NO_x, NO, CO, HC and CO_2) and gravimetric PM (70mm T60A20 glass-fiber filter) sampling was carried out according to 40 CFR, subpart 86. Parallel to the PPS, a two stage dilution system was employed for PM sampling with a condensation particulate counter, CPC (TSI, Model 3025), and an engine exhaust particulate sizer (EEPS) spectrometer (TSI, Model 3090). The first stage used hot dilution (~130°C, DR = 6) followed by a subsequent cold dilution (~25°C, DR = 24) to prevent any nucleation (see Figure 1). For engine-out measurements, an additional third dilution stage (Cold, ~25°C, DR = 8) was needed for sampling with the CPC. Further, an aerosol electrometer, AEM (TSI, Model 3068B), was mounted in series to the PPS to measure the charge carried out by particulates from the soot sensor. Additional TEOM measurements were performed from diluted exhaust in the constant volume sampling (CVS) tunnel (see Figure 1).

First test results demonstrated a stable and repeatable response over consecutive FTP and ETC test cycles as well as over idle and constant load (steady state) operation, with coefficients of variation below 2.4%, which is a prerequisite for OBD algorithms to operate. Comparisons between the PPS and CPC, and between the PPS and EEPS showed similar and reproducible response patterns even during the highly transient portions of the FTP and ETC. Two new DPF's were tested during the degreening phase. Progressive reduction of PM (PPS signal) at DPF-out over consecutive FTP cycles was observed, which was in accordance with the build-up of the cake layer in a wall-flow filter; hence, the increase in filtration efficiency. The signal of the soot sensor (PPS) exhibited the same trend as measured with the CPC; thus, emphasizes the high sensitivity of the PPS.

Further measurements are currently under way, including multiple engine types and aftertreatment configurations, different fuels as well as on-road, in-use measurements to gain a more pronounced understanding of the soot sensor's capabilities, limitations and sensitivity towards different types of particulate matter.

Table 1: Engine Specifications

Engine Model	1999 Cummins ISM-370
Displacement	10.8 liter
Power Rating	370 bhp @ 2100 rpm
Torque Rating	1350 lb-ft @ 1200 rpm
Configuration	Inline 6-cylinder
Bore x Stroke	4.92 in x 5.79 in
Induction	Turbocharger with in-house aftercooler
Injection	Direct Injection, Electronic
Aftertreatment (Retrofit)	Catalyzed DPF 1 (new) Catalyzed DPF 2 (new) Catalyzed DPF 3 (aged ~ 1000h)

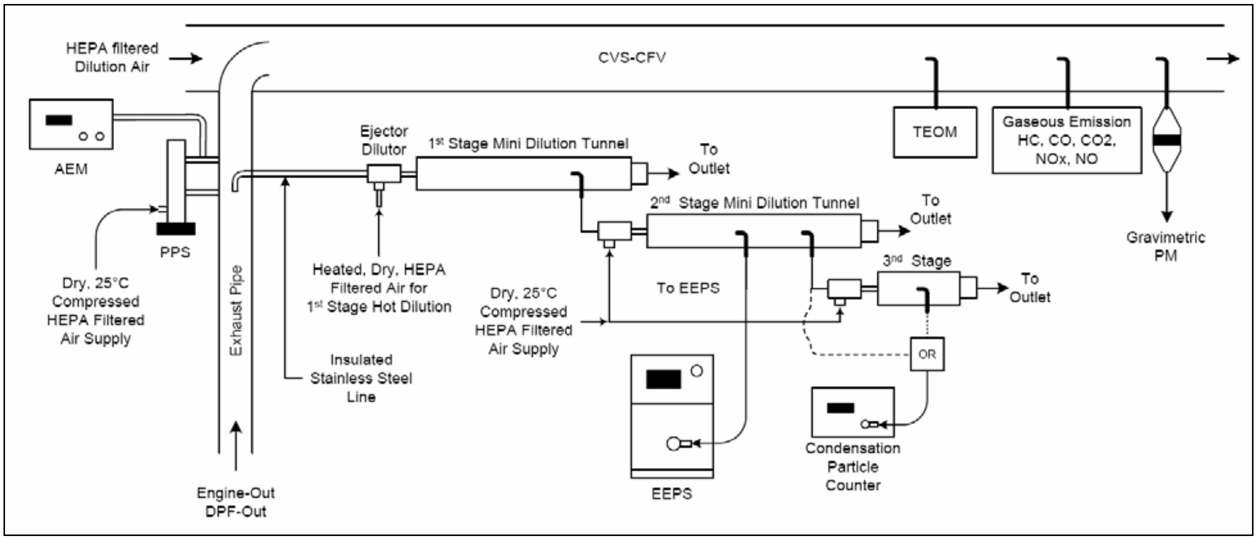

Figure 1: Measurement Setup

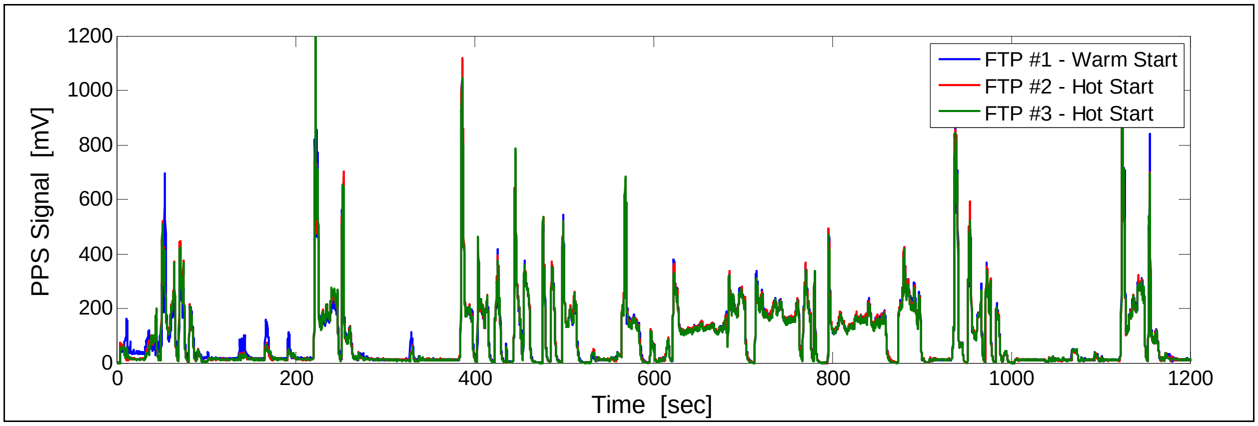

Figure 2: PPS Signal, Engine-Out Measurement

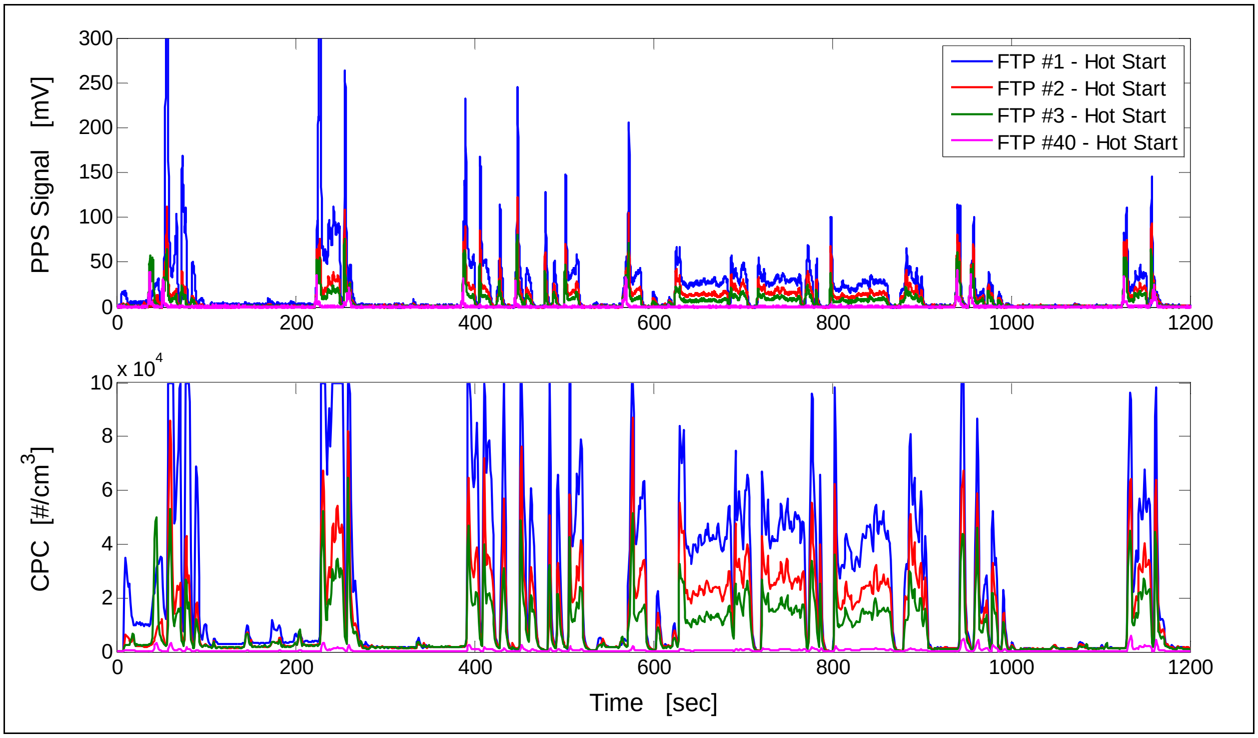

Figure 3: Comparison of PPS Signal vs. CPC, New DPF (Initial Degreening Phase), CPC Corrected for Dilution (DR = 145)

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Content

- Motivation for an in-line particle sensor
- Sensor technology and operational parameters
- Measurement Setup
- Results
  - PPS vs. EEPS / CPC / TEOM / Gravimetric PM
- Conclusions

Motivation for In-line PM Sensor

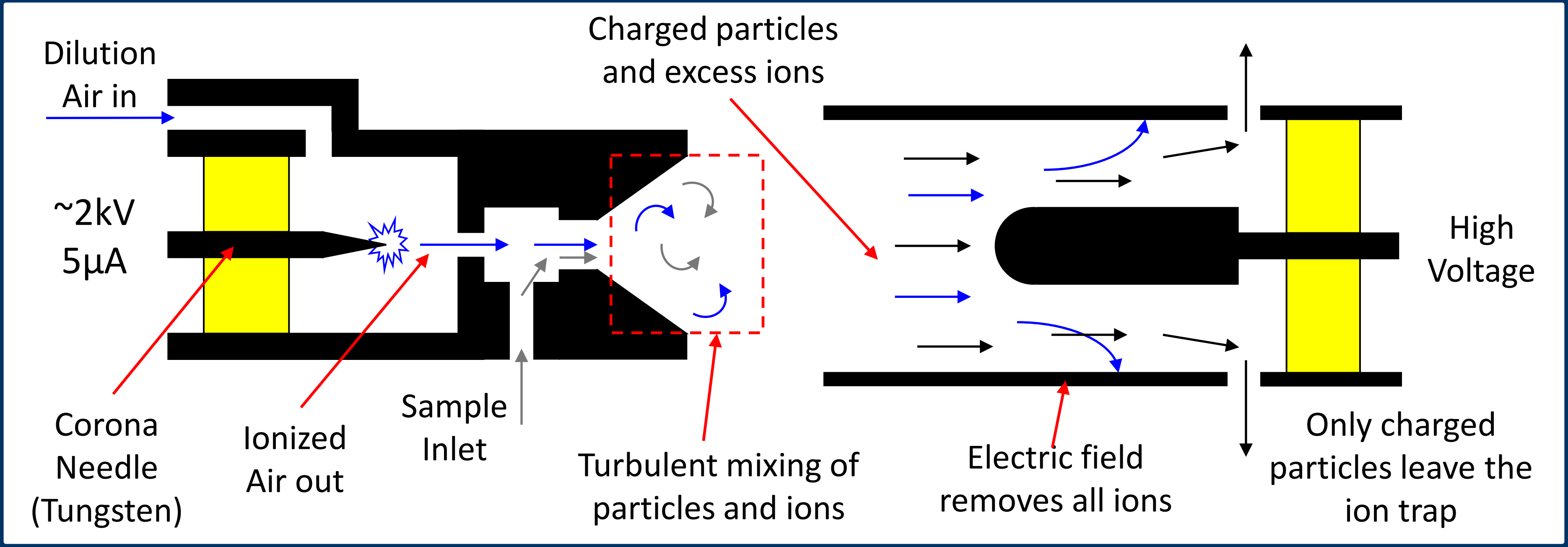
- Need for a PM sensor for development and implementation of DPF regeneration strategies:
  - Monitoring DPF loading
  - Control systems for DPF regeneration
  - Development of soot models aimed at DPF regeneration

- On-board Diagnostics applications:
  - US EPA Heavy-duty OBD requirements
    - 1 engine series in 2010
    - Extended to all engine series in 2013
  - EU regulations require OBD sensor for emissions
    - Euro VI limits to be set by September 2010
    - Regulation effective by 2014
  - Available OBD sensors currently are:
    - not real-time
    - not continuous in operation

- The long-term goal is to have a robust, continuously operating particle sensor that can be used for life-time on-board measurement of PM emissions

Sensor - Description of Technology

- Measurement based on escaping current principle

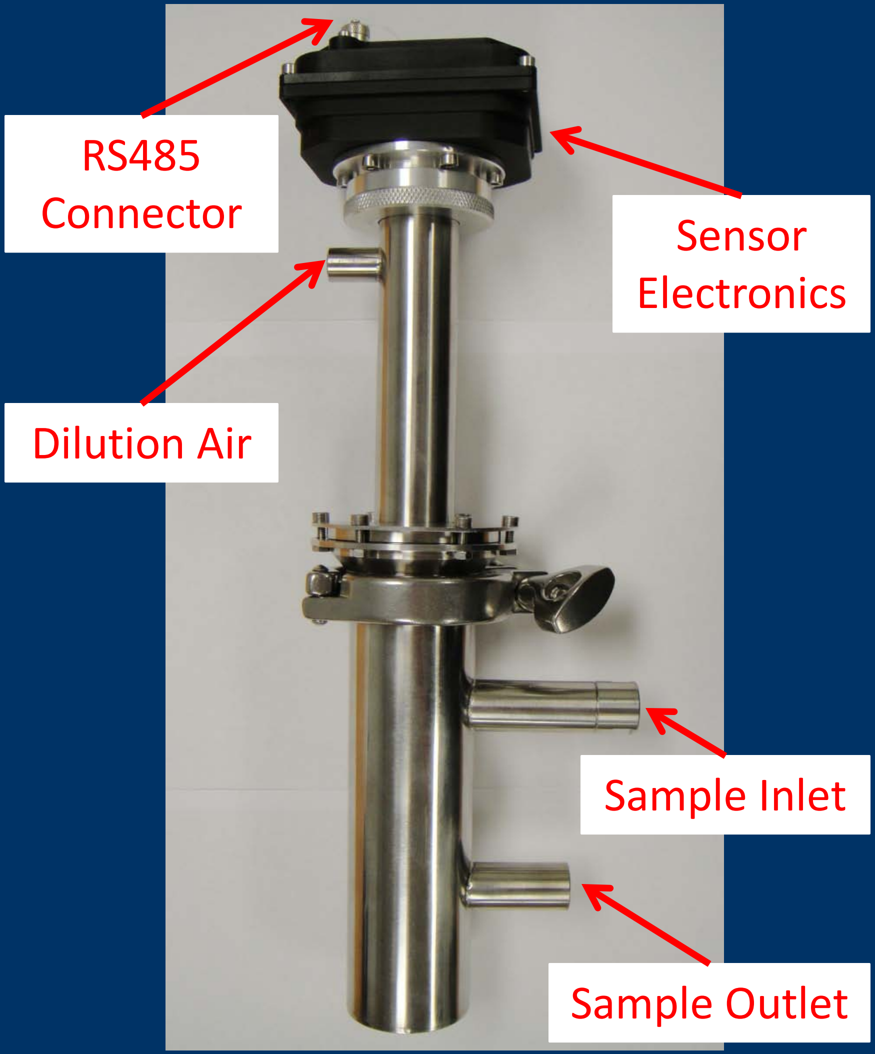


Picture provided by Pegasor Oy

Advantages:

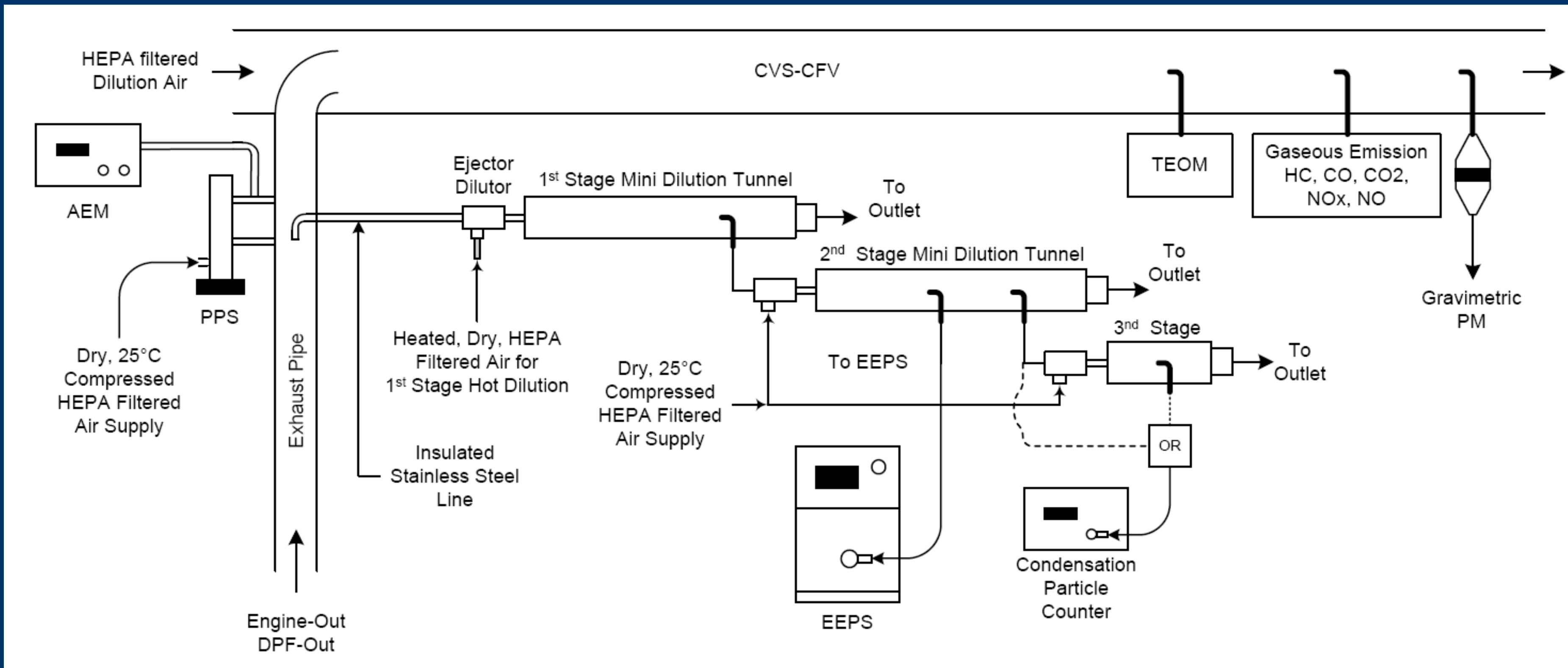
- Real-time
- Continuous operation
- No PM sample collection
- No external dilution of exhaust stream needed

Sensor - Operational Parameters



- Temperature range will stand DPF regeneration (High Temp. 850°C)
- Concentrations from about 0.01 mg/m^3 (outdoor air version 1µg/m^3) to 250 mg/m^3
- Sensor output can be calibrated to mg/m^3 or #-particles/m^3
- Response time 10 ms
- Analog input filtering 10Hz
- Sampling rate up to 100 Hz
- Operation parameters
  - Clean air flow ~1.75 LPM
  - Sample flow ~9.75 LPM (vacuum driven)
- High voltage ~3kV
- Power consumption 0.5 W, currently powered through USB port
- Data communication and power through USB
  - Total mass and total number reported (depending on calibration)
- Self diagnostics included
- Connector for additional device

Measurement Setup



- EEPS (TSI, Model 3090)
- CPC (TSI, Model 3025)
- AEM (TSI, Model 3068B)

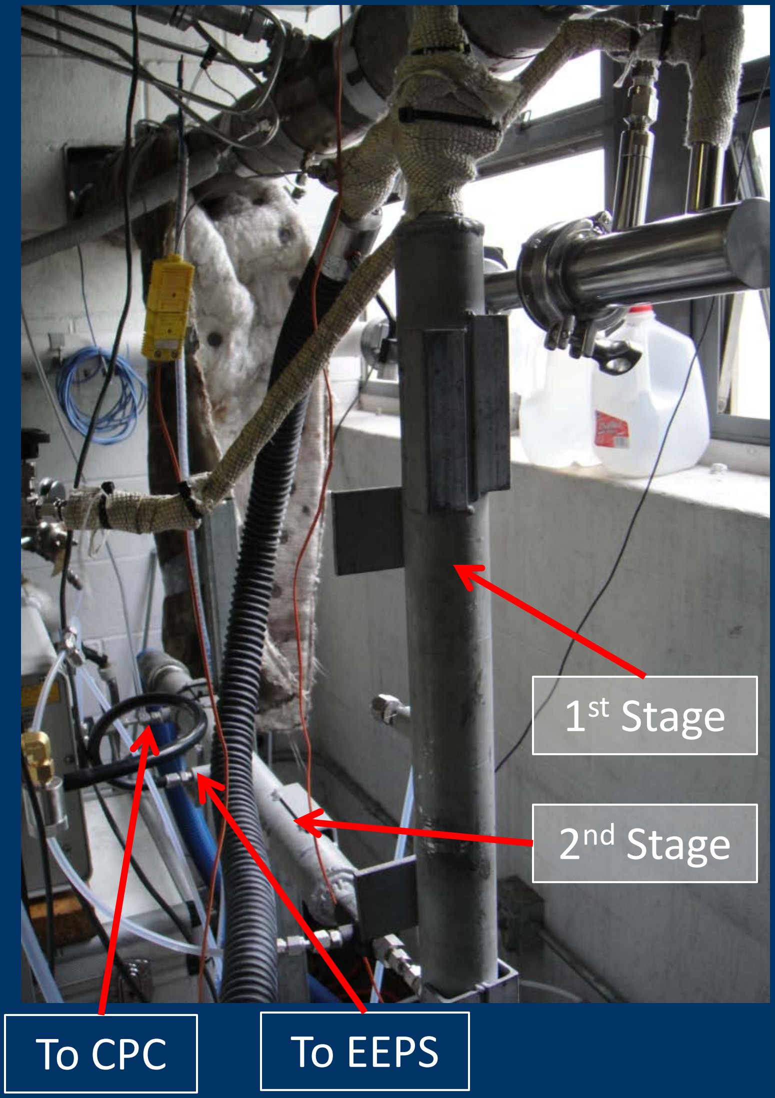
} From Exhaust Stack

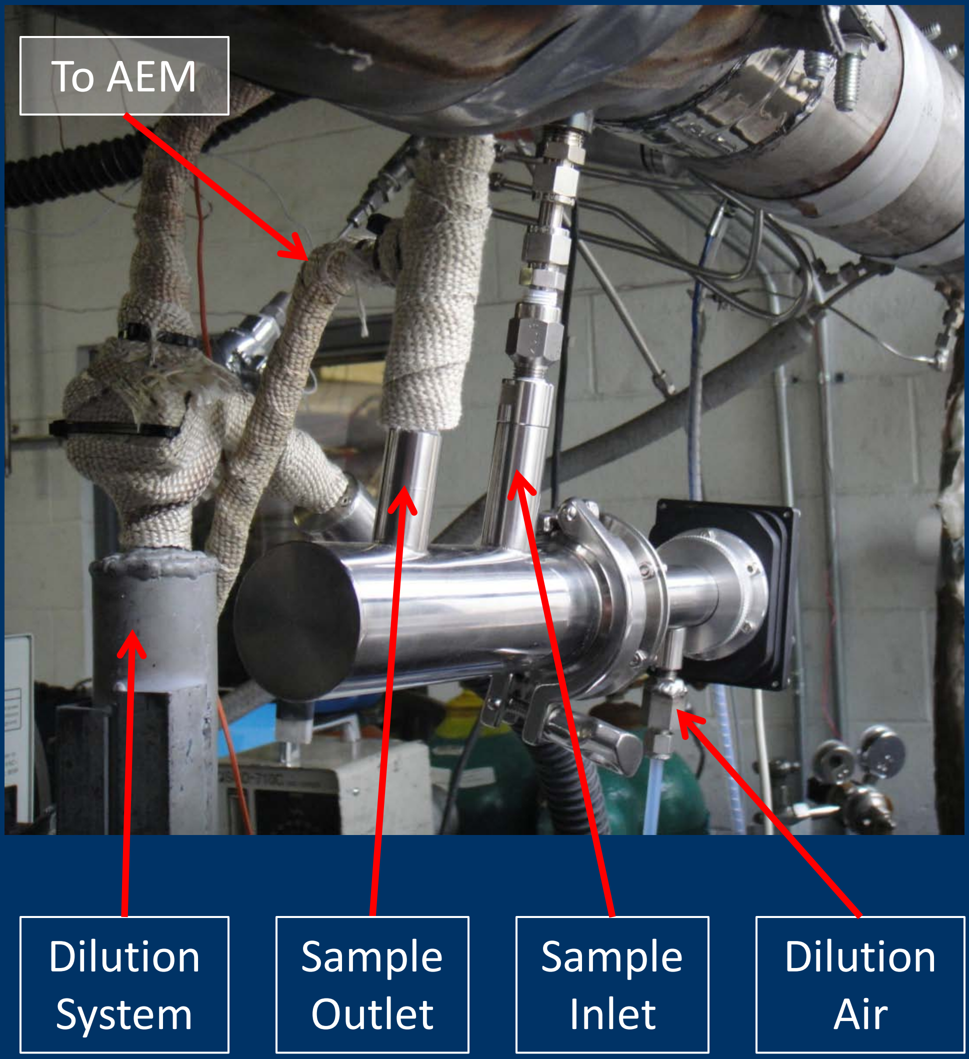
- TEOM
- Gravimetric PM

} From CVS Tunnel

- 1st Stage, Ejector Dilutor:
  - Hot Dilution ~130°C, Dry HEPA filtered Air
- 2nd Stage, Ejector Dilutor :
  - Ambient Temp. ~25°C, Dry HEPA filtered Air
- 3rd Stage, Ejector Dilutor :
  - Same as 2nd stage (different DR ratio)

Measurement Setup - Cont'd





Measurement Methodology

Test Engine:

Engine Model	1999 Cummins ISM-370
Displacement	10.8 liter
Power Rating	370 bhp @ 2100 rpm
Torque Rating	1350 lb-ft @ 1200 rpm
Configuration	Inline 6-cylinder
Bore x Stroke	4.92 in x 5.79 in
Induction	Turbocharger with in-house aftercooler
Injection	Direct Injection, Electronic
Aftertreatment (Retrofit)	Catalyzed DPF 1 (new) Catalyzed DPF 2 (new) Catalyzed DPF 3 (aged ~ 1000h)

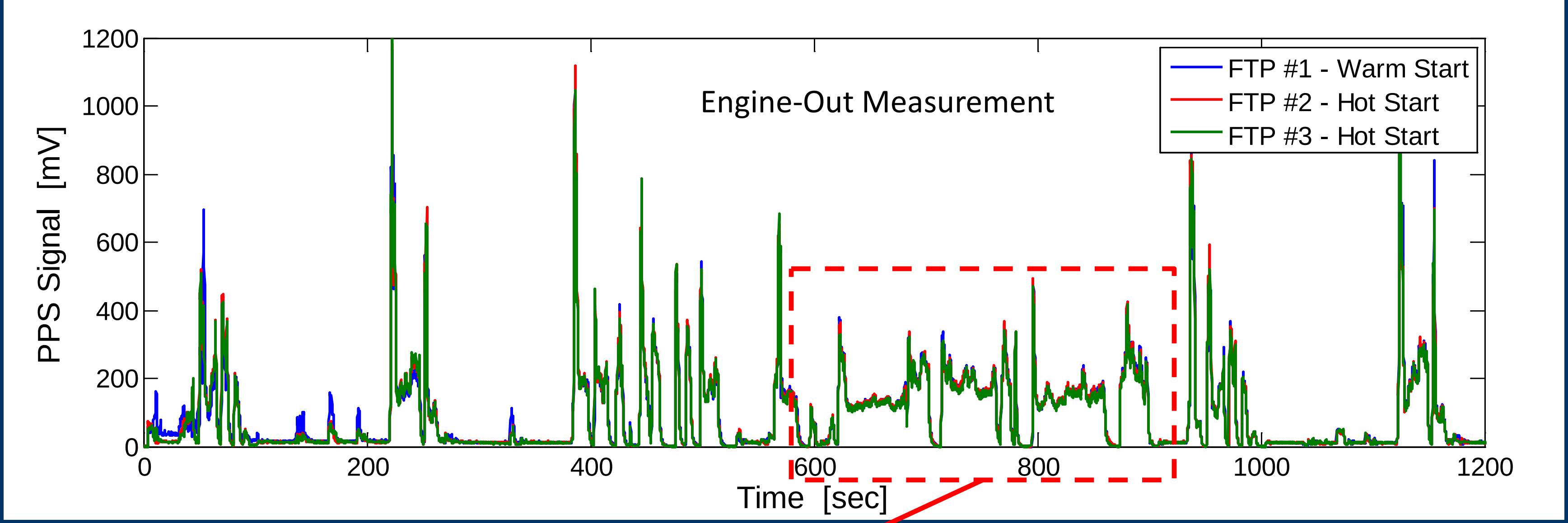
Dilution System Parameter:

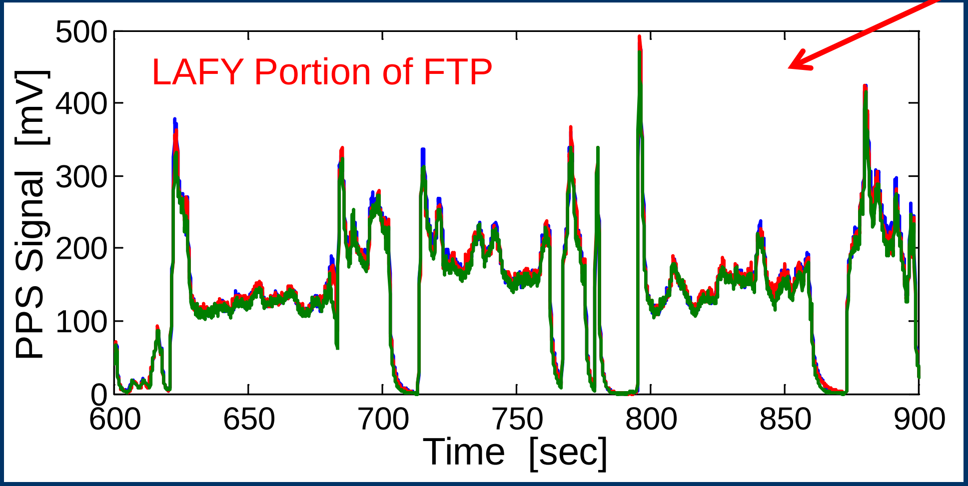
Pre DPF		
1st Stage	Hot, ~ 130C	DR = 6
2nd Stage	Cold, ~ 25C	DR = 24
3rd Stage **	Cold, ~ 25C	DR = 8
** *Only for CPC*		
Post DPF		
1st Stage	Hot, ~ 130C	DR = 6
2nd Stage	Cold, ~ 25C	DR = 24

Test Matrix:

Engine	Sampling Position	Aftertreatment	Test Cycle
Cummins	Pre DPF	Catalyzed DPF 2 (new)	FTP, ETC, 4-Mode-Cycle
	Post DPF	Catalyzed DPF 1 (new) Catalyzed DPF 2 (new) Catalyzed DPF 3 (aged ~ 1000h)	FTP, ETC, 4-Mode-Cycle

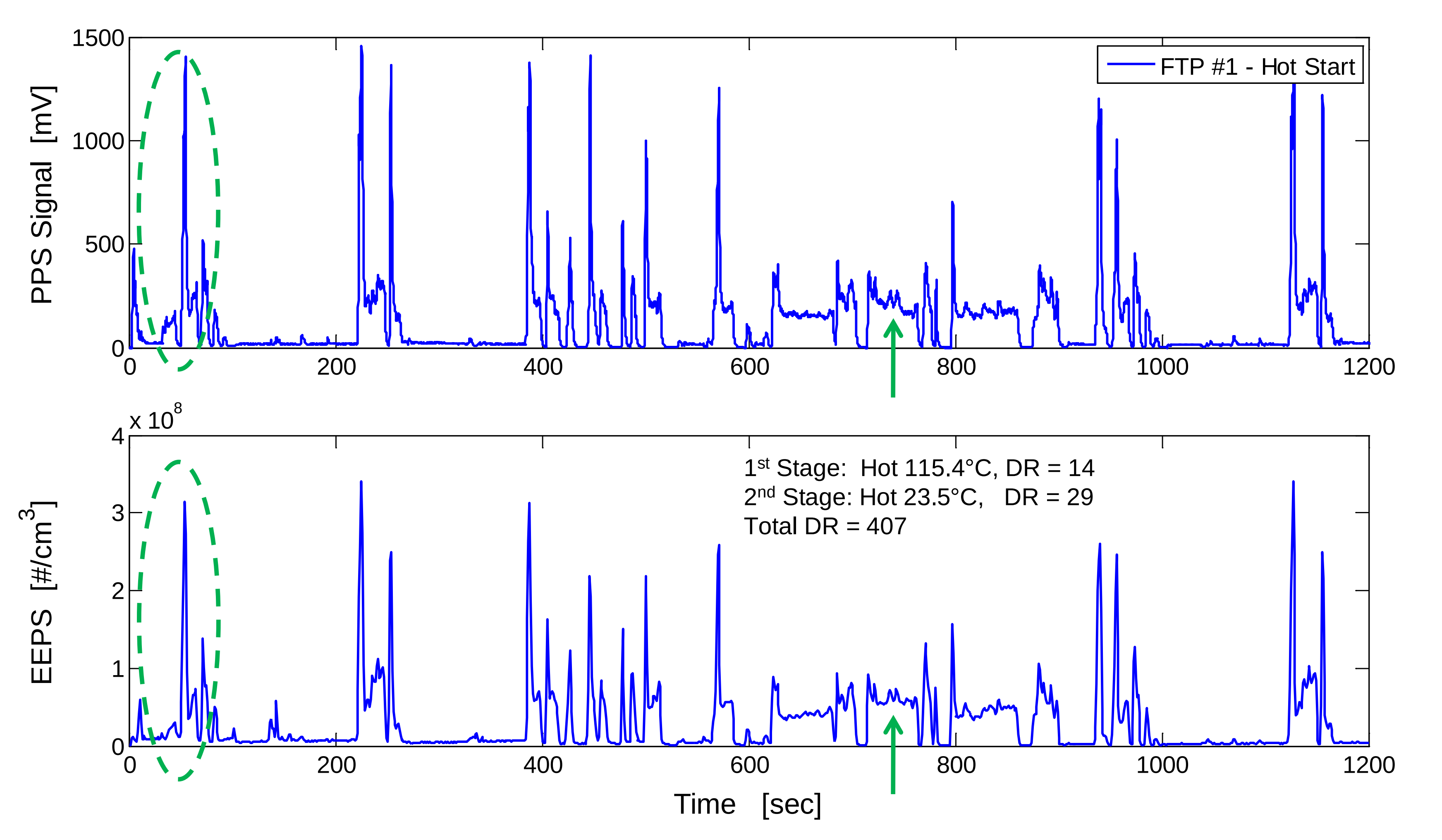
Results - PPS Repeatability over FTP



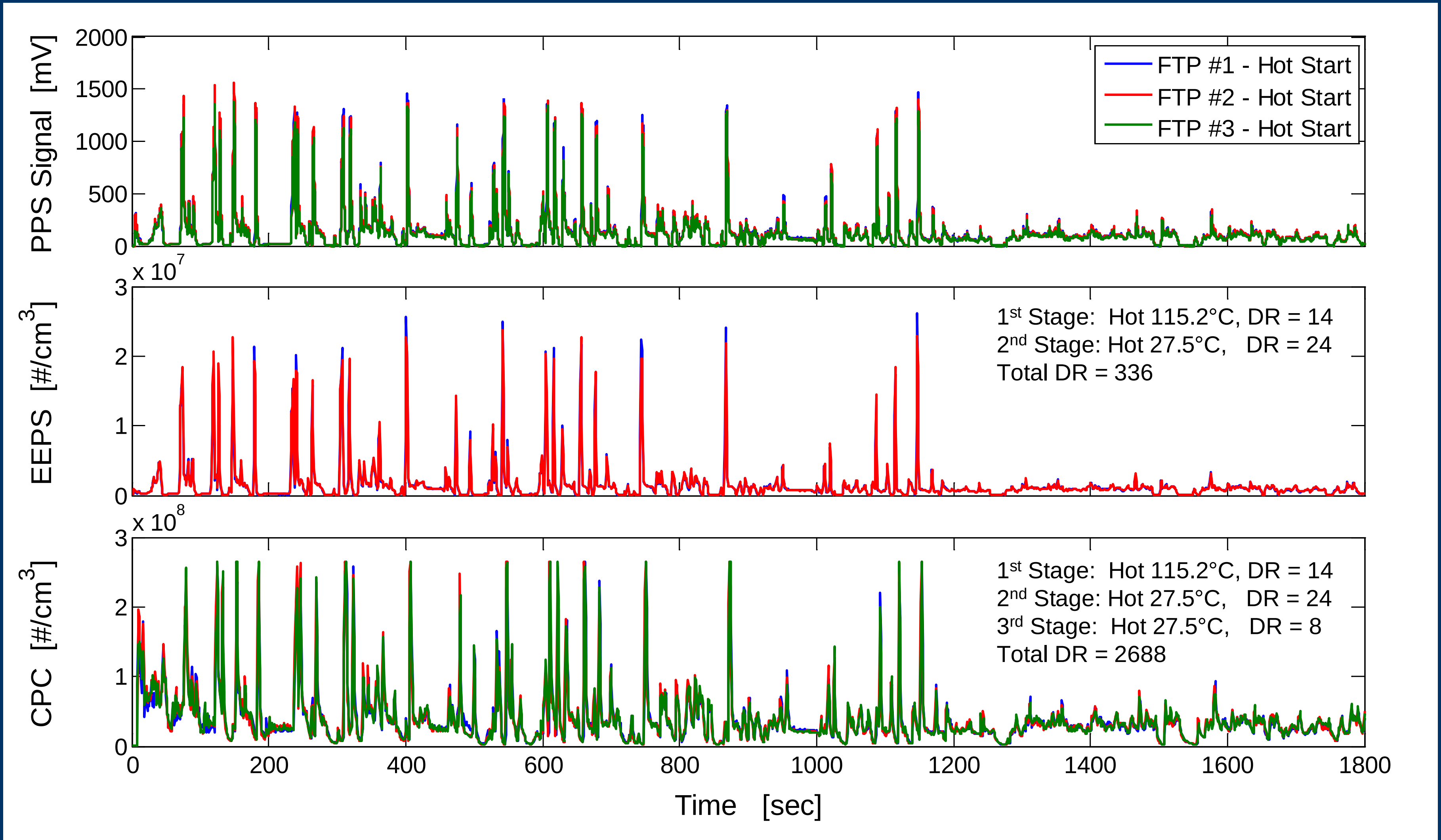


	PPS	Gravimetric PM	Multiplication Constant
	[mV]	[mg]	[-]
E02726-03	1.15E+06	1787.07	642.3
E02726-04	1.12E+06	1669.44	672.3
E02726-05	1.09E+06	1669.85	655.1
Average	1.12E+06	1708.79	656.6
STDEV	2.69E+04	67.80	15.1
COV	2.40%	4.0%	2.3%

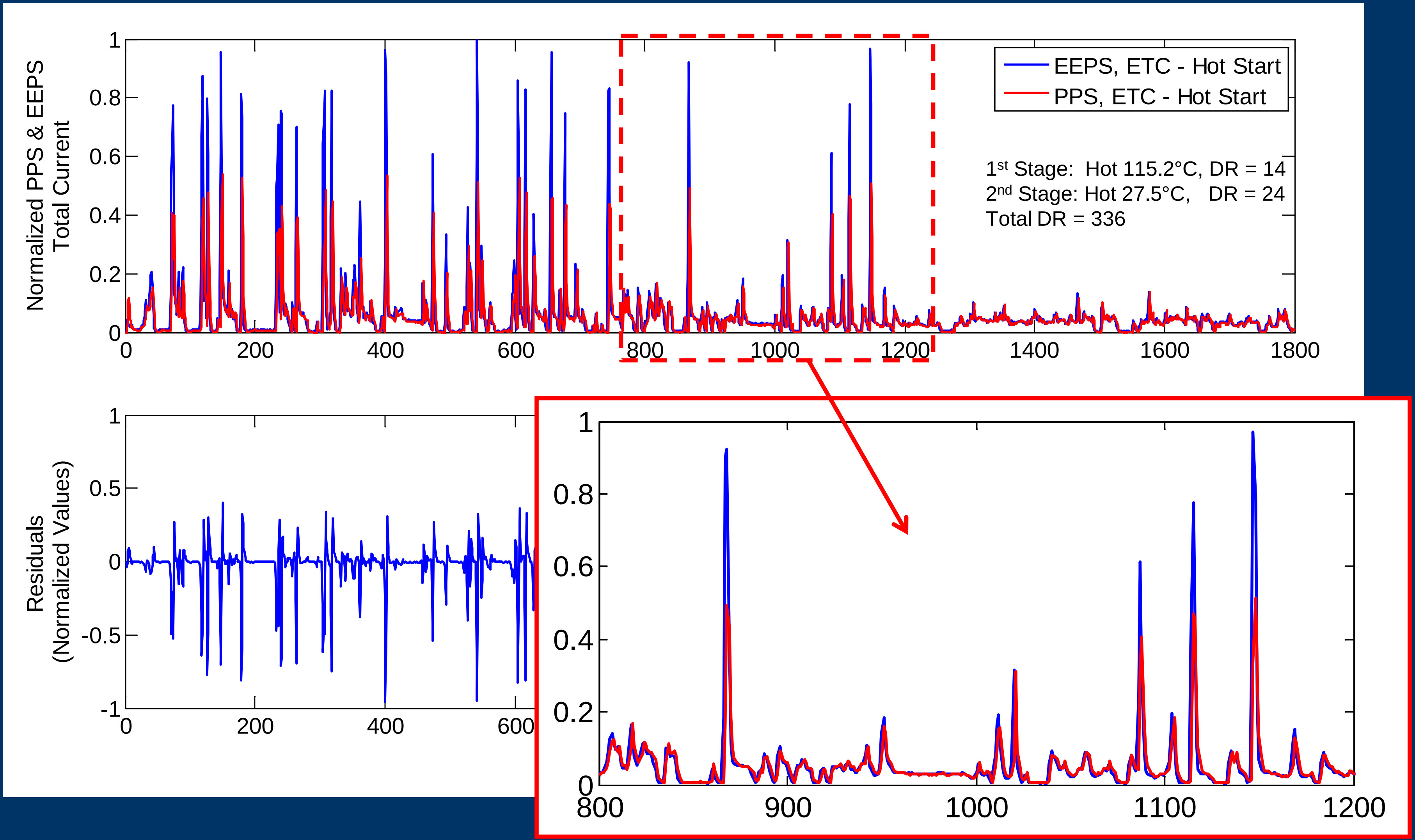
Results – PPS vs. EEPS, FTP, Pre-DPF



Results – PPS vs. EEPS & CPC, ETC, Pre-DPF

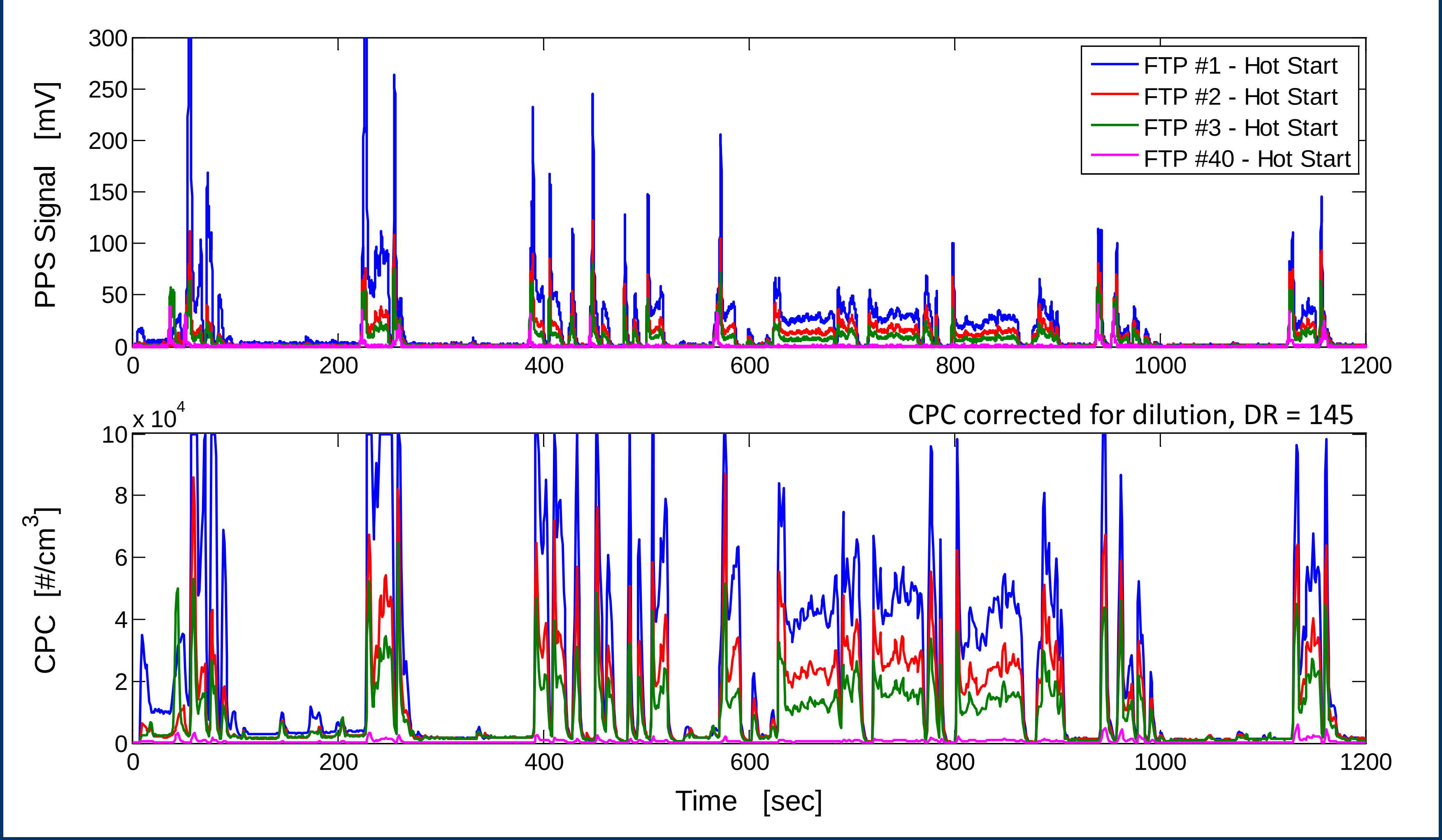


Results - Normalized PPS vs. EEPS, Pre-DPF

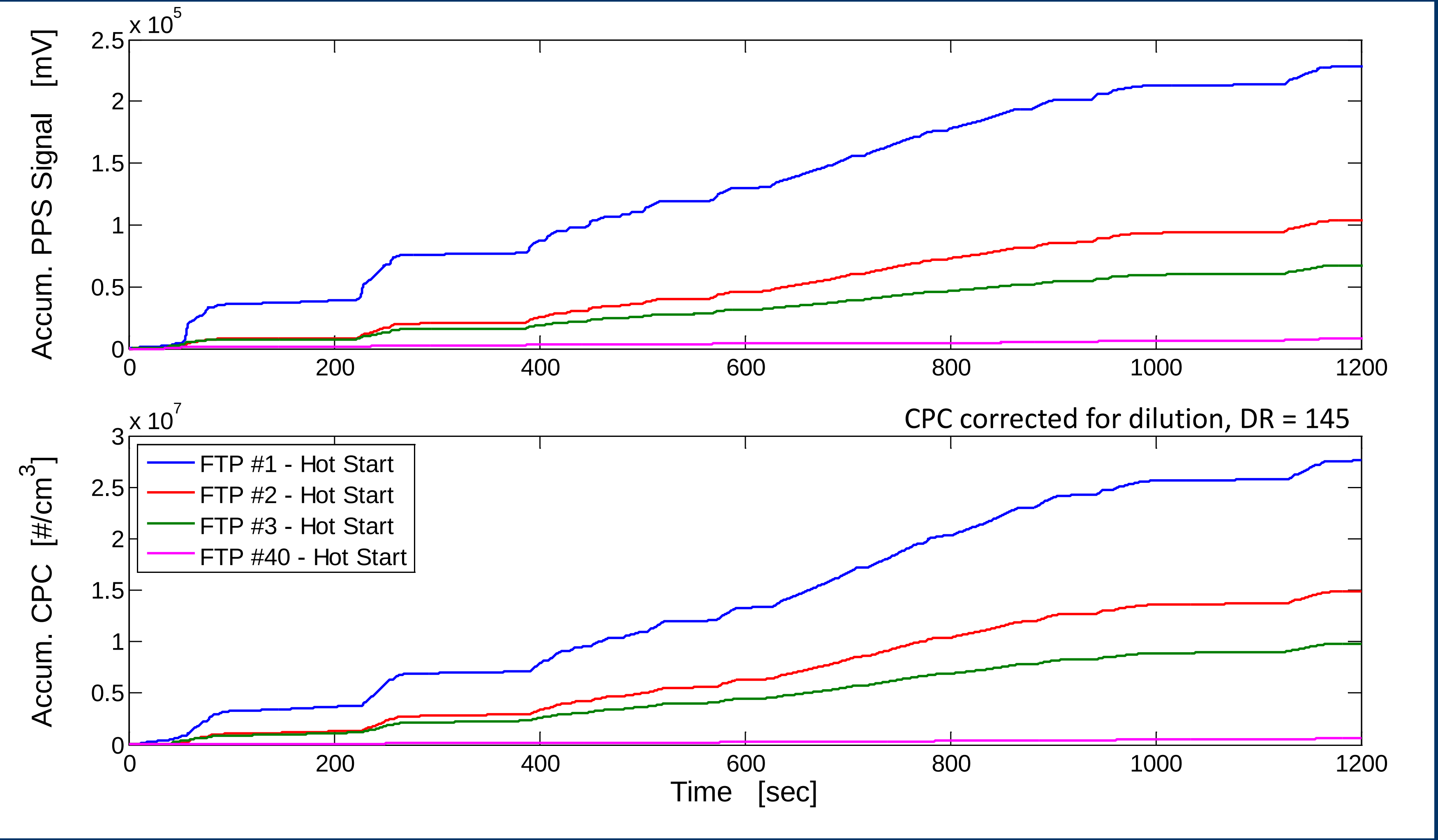


Results - PPS vs. CPC, New Filter

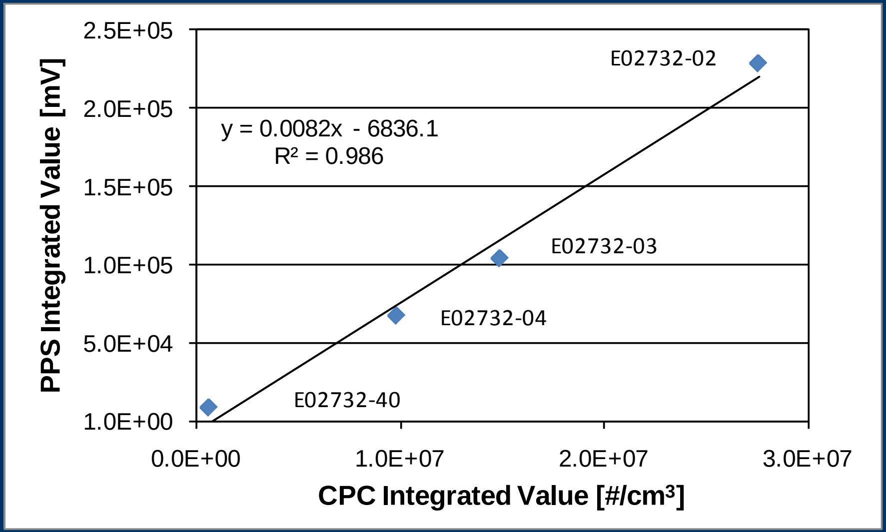
Cake layer built up of brand new DPF filter (pre degreening) during consecutive FTP cycles

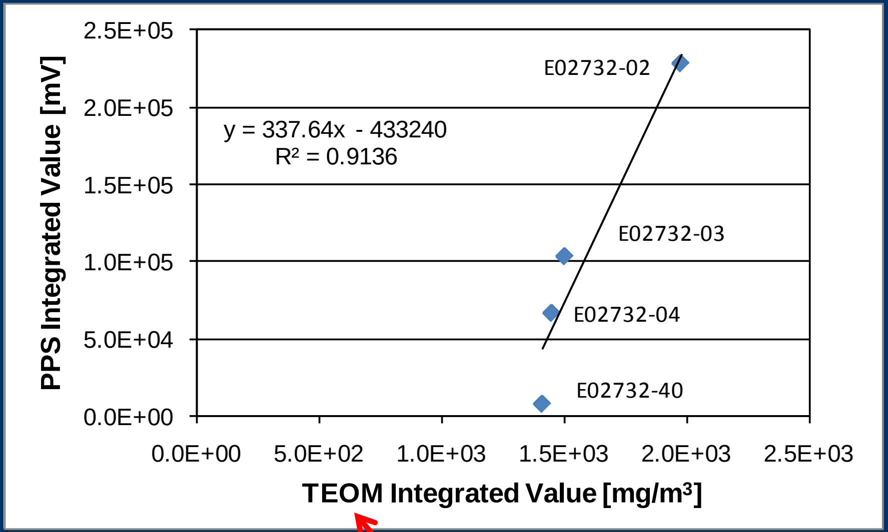


Results - PPS vs. CPC, New Filter, Cont'd

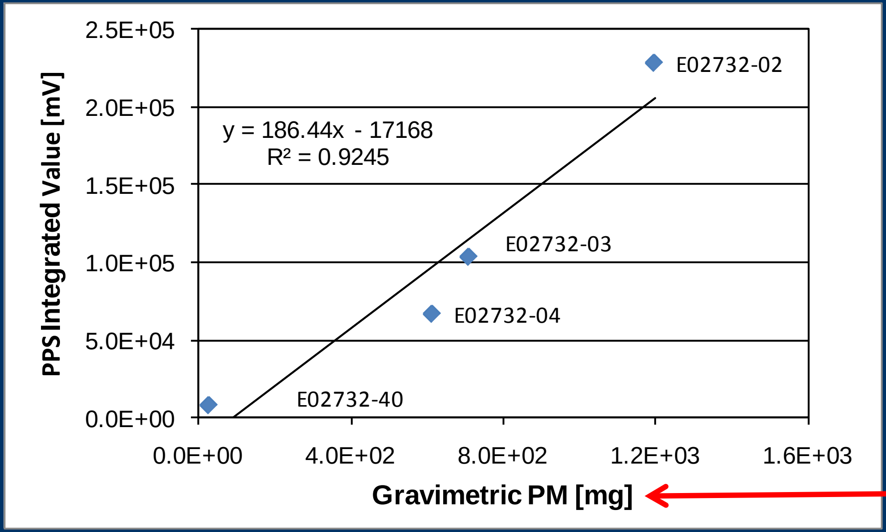


Results - PPS vs. CPC, New Filter, Cont'd





Measured from CVS tunnel, not corrected



- Correlation between PPS and CPC, TEOM, Gravimetric PM
  - Three consecutive FTP's with brand new DPF
  - One FTP after 13h degreening (E02732-40)

Measured from CVS tunnel, corrected to engine-out mass

Conclusion

- The new particle sensor shows good promise for OBD applications, and development of DPF regeneration controls and strategies.
- Plug and play operation opens a new era in engine emission PM monitoring and measurement
- Sensor shows repeatability over consecutive test cycles
- Response of PPS to PM emissions during the FTP and ETC transient test cycles was similar to that of EEPS.
- Evaluation of the PPS sensor is on-going
  - Pre- and post-DPF, steady state and transient cycles, on-highway and off-road engines, different fuels

Thank You for Your Attention

Sensor – Operational Parameters, cont’

- Low temperature version max 250 °C
- High temperature version max. 850 °C
- High concentration version 10 µg/m^3-250 mg/m^3
- High sensitivity version ~1µg/m^3
- Sensor dimensions 20-40 mm diameter, 100-200 mm long – to be decided together with customers
- Electronics; 80x40x20 mm^3
- Sensor output calibrated to mg/m^3 or #-particles/cm^3
- Sensor is installed outside the tailpipe with only inlet and outlet in the tailpipe
- Environmental conditions up to 85 degrees C, IP 45