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Marine Black Carbon emissions study at the University of Rostock, Germany

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ICCT's 3rd Workshop on Marine Black Carbon Emission: BC Control Strategies

A collaborative effort

Universität Rostock

Canada

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AVL

MARENA

CE Delft
Committed to the Environment

Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

Goals

Following IMO's PPR recommendation to Member Governments to initiate BC measurement studies, the German Government organized a measurement campaign with these goals:

- Black Carbon measurements
  - on a ship engine
  - with different bunker fuels
  - with different engine ratings
  - with alternative measurement methods
- Submission to PPR4 (by Germany and Canada)

Campaign Objectives

1. Use of miniCAST for instruments comparison
2. Instrument comparison on marine engine for test matrix of fuels and operating conditions
3. Evaluation of miniCAST results as a calibration adjustment factor
   – does it improve agreement?
4. Emission factors for test matrix
5. Study of the particle characteristics
   – TEM, Raman, EEPS, TOT-OC/EC, MS-OC/EC, effective density

Engine

1VDS18/15CR Elbe Werke Roßlau
(research engine)
technical specifications:

- medium speed 4 stroke engine
- style: 1 cylinder
- power: 76 kW
- bore: 150 mm
- stroke: 180 mm
- super-charging: externally supplied (4 bar)
- rated speed: 1,500 min-1
- heavy oil valid to 580 cSt
- injection pressure <1,300 bar
- common rail injection system (individual production)
- control of injection over the motor control unit
- emission standard IMO tier II / III

Fuels

Diesel Diesel Oil (according to DIN EN 590 upper limits):

- Very low sulphur content (0.00063%)
- Automotive Diesel
- Ash content <0.01%

DMA DMA fuel (ISO 8217):

- Low sulphur content (0.087%)
- 100% distillate oil
- Marine Gas Oil
- Ash content <0.001%

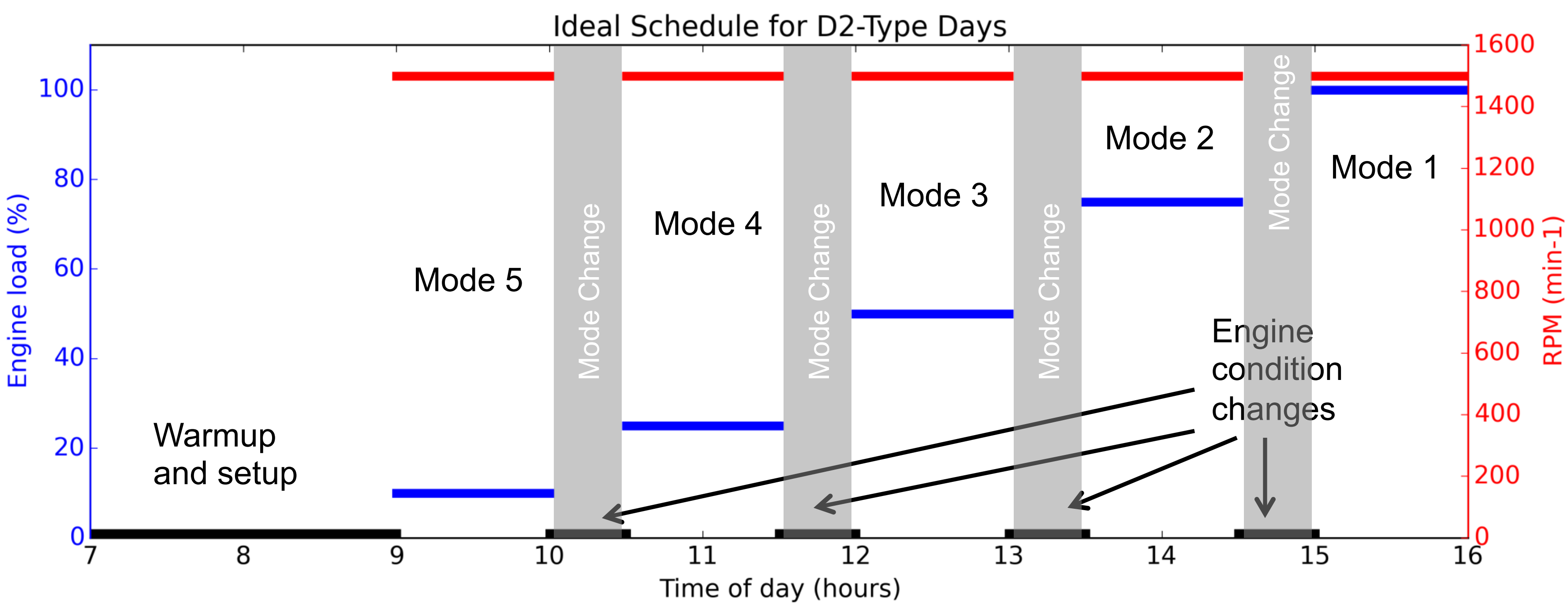
IFO Intermediate Fuel Oil IFO 380:

- High sulphur content (2.3%)
- Residual oil
- Marine fuel
- Ash content 0.055%

Engine test cycles – D2

Cycle #1: *reversed* **D2** (ISO 8178-4)

Mode #	5	4	3	2	1
RPM	1500	1500	1500	1500	1500
Load (%)	10	25	50	75	100



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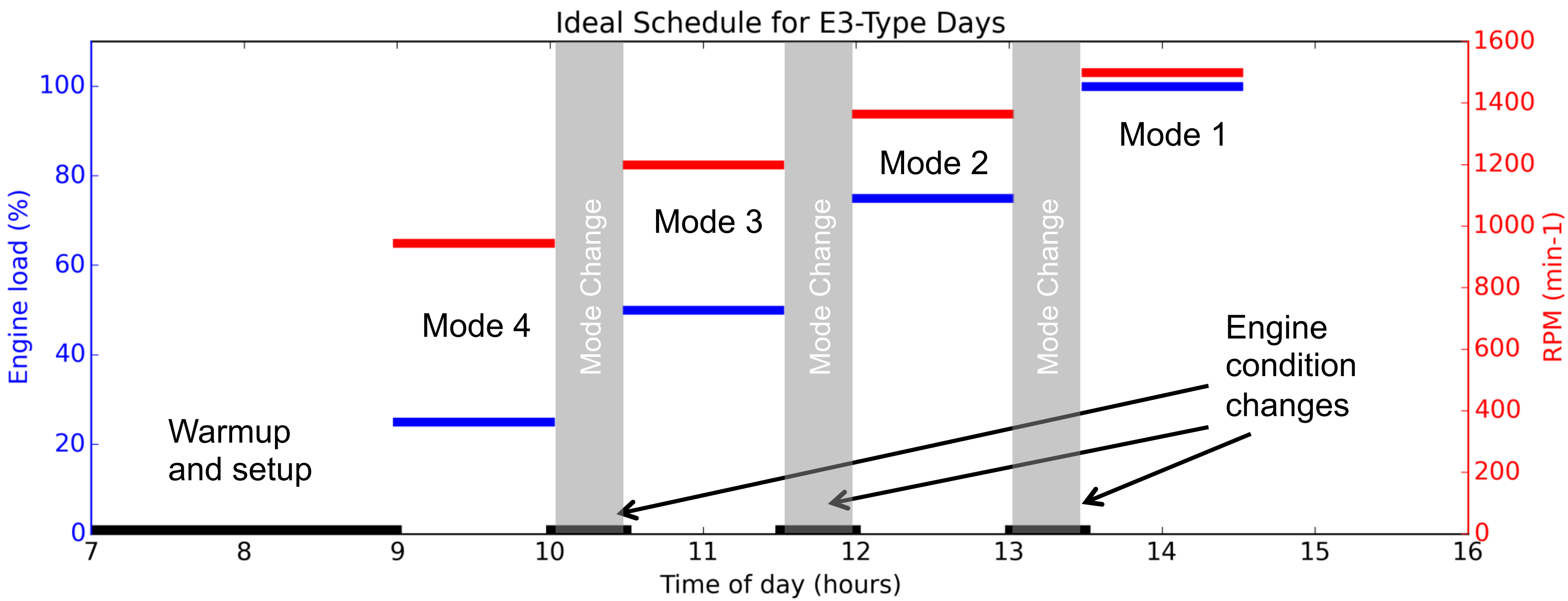
Engine test cycles – E3

Cycle #2: *reversed* E3 (ISO 8178-4)

Mode #	4	3	2	1
RPM	945	1200	1365	1500
Load (%)	25	50	75	100

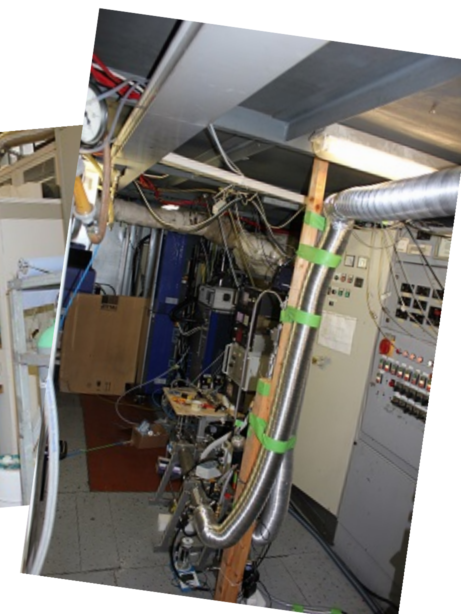


Campaign Schedule

Engine test cell was available for 2 weeks

	Monday	Tuesday	Wed.day	Thursday	Friday	Saturday	Sunday
1	Setup	Setup	Setup	Setup + MiniCAST	**D2**, **Diesel**	--	--
2	**E3**, **Diesel**	**D2**, **DMA**	**E3**, **DMA**	**D2** + part **E3**, **IFO**	Part **E3**, **IFO**	Tear down + packing	--



Engine test cycles

Not enough time to fully repeat all test points

Cycle #1: *reversed* **D2** (ISO 8178-4)

Mode #	5	4	3	2	1
RPM	1500	1500	1500	1500	1500
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Cycle #2: *reversed* **E3** (ISO 8178-4)

Mode #	4	3	2	1
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Load (%)	25	50	75	100

Participating Instrumentation

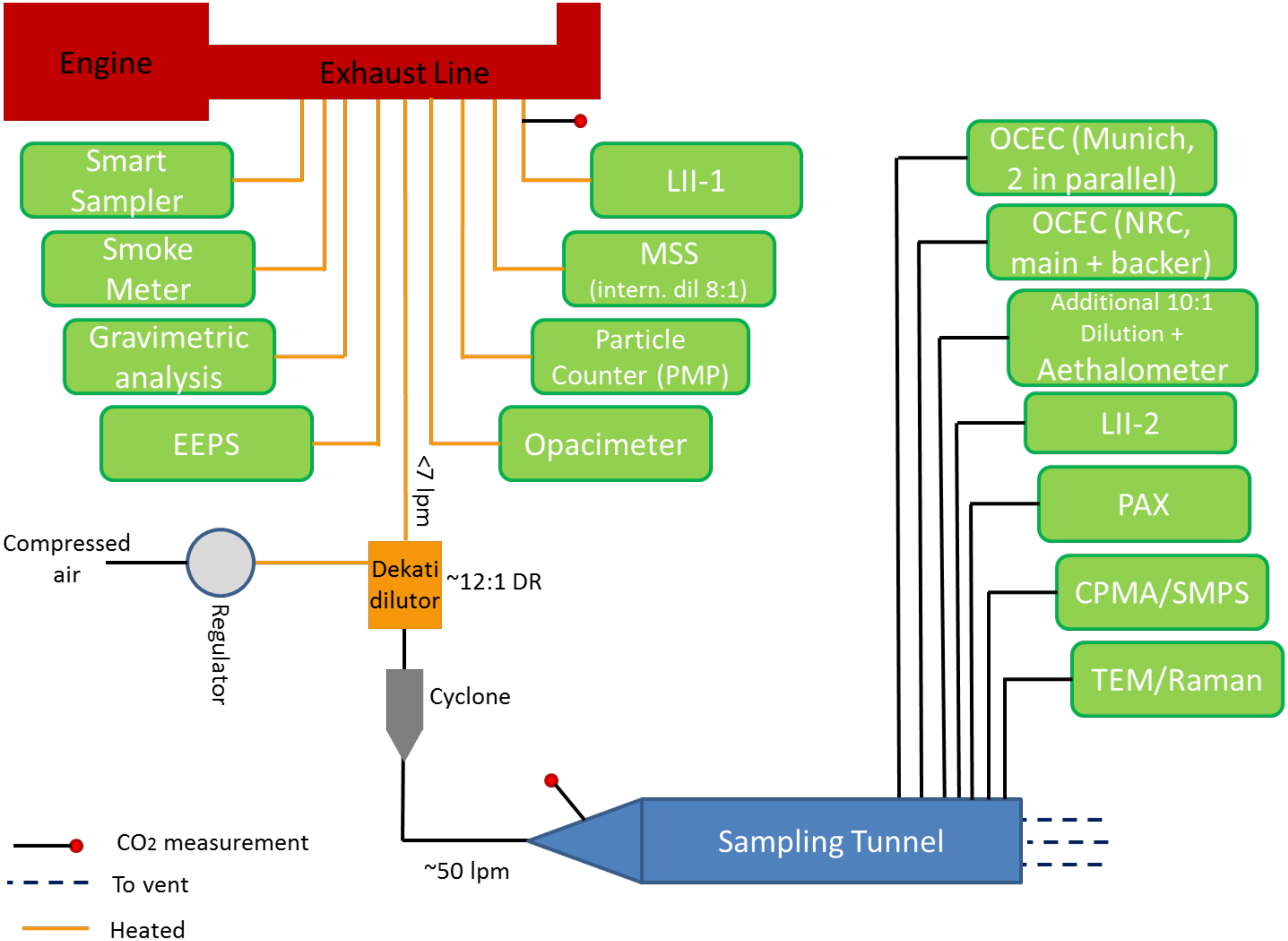
BC Diagnostics

- Laser-induced Incandescence
  - (LII 300, x 2)
- Micro Soot Sensor
  - (MSS+)
- Smoke Meter
  - (415SE)
- Photoacoustic Extinctiometer
  - (PAX λ=870nm)
- Thermal-Optical Analysis
  - (x 3)
- Aethalometer
  - (AE33-7λ)
- Gravimetric BC analysis

Other Diagnostics

- Transmission Electron Microscopy
  - (TEM)
- Raman analysis
- Effective Density
  - (CPMA/SMPS)
- Particle Counter
  - (PMP)
- Engine Exhaust Particle Sizer
  - (EEPS)
- Opacimeter
  - (439)

Experimental Setup – Engine Sampling

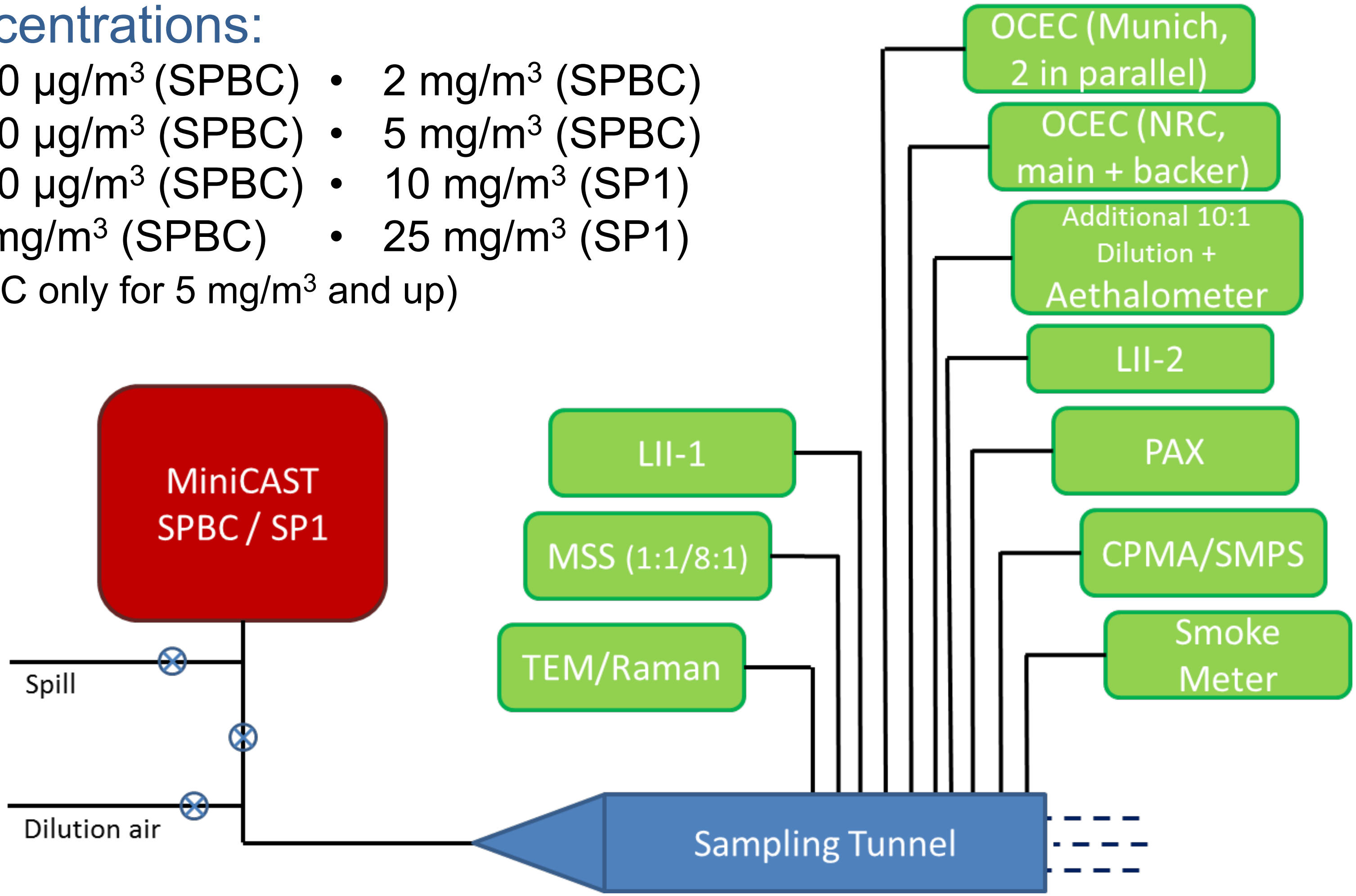


Experimental Setup – MiniCAST Sampling

Concentrations:

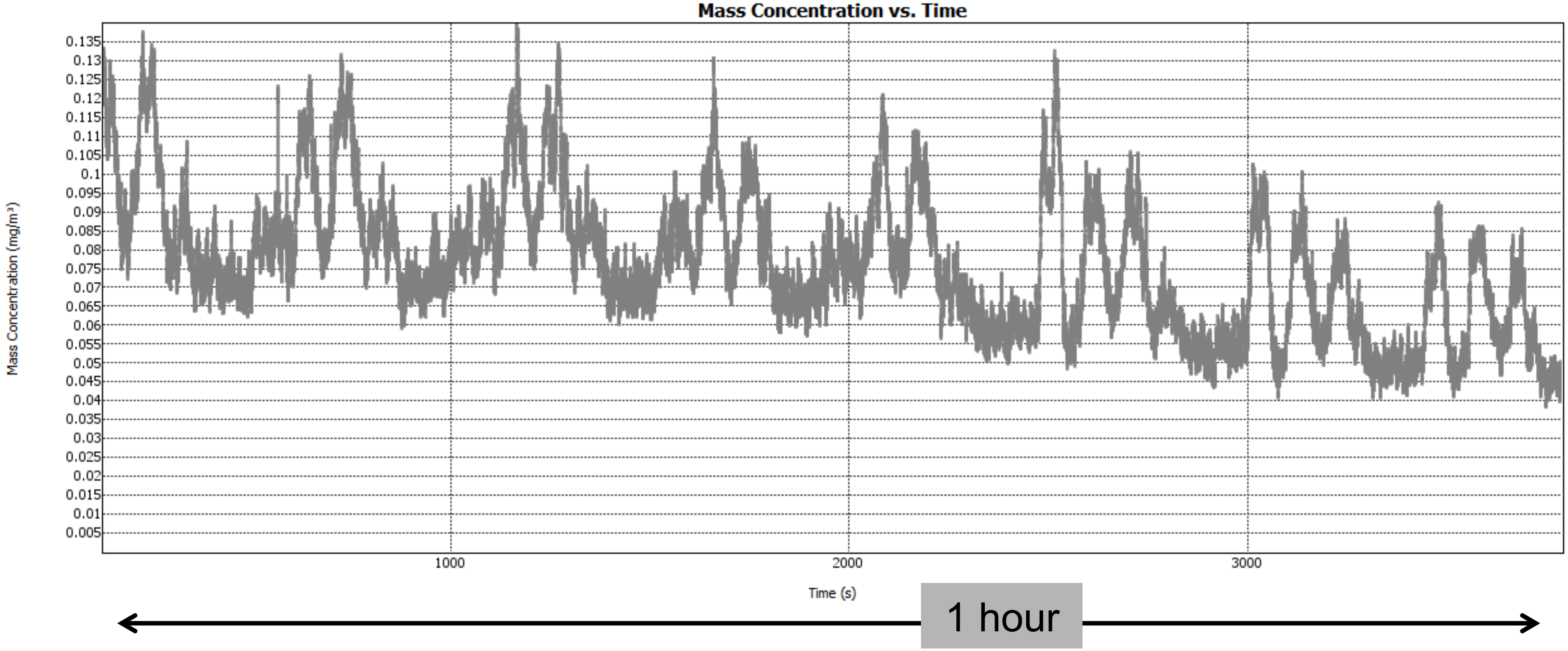
- 100 µg/m³ (SPBC)
- 250 µg/m³ (SPBC)
- 500 µg/m³ (SPBC)
- 1 mg/m³ (SPBC)
- 2 mg/m³ (SPBC)
- 5 mg/m³ (SPBC)
- 10 mg/m³ (SP1)
- 25 mg/m³ (SP1)

(OCEC only for 5 mg/m³ and up)



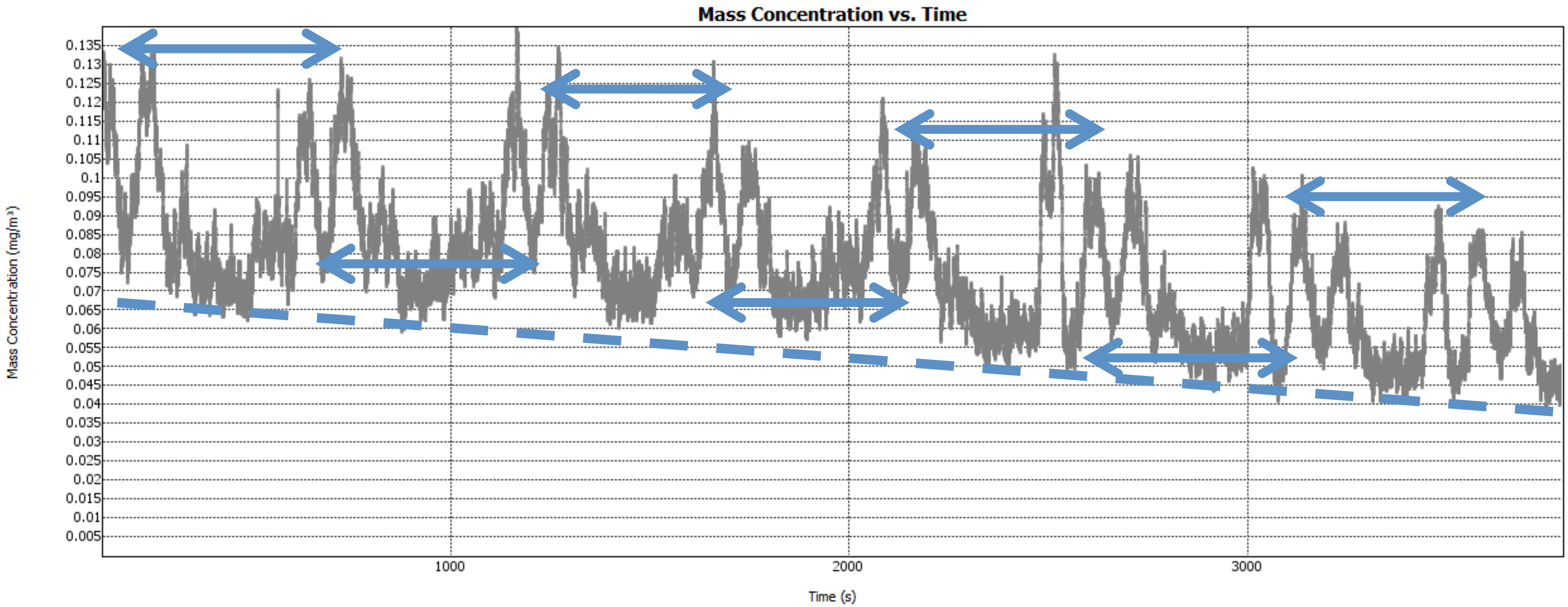
Preliminary impressions…

Concentration Variability



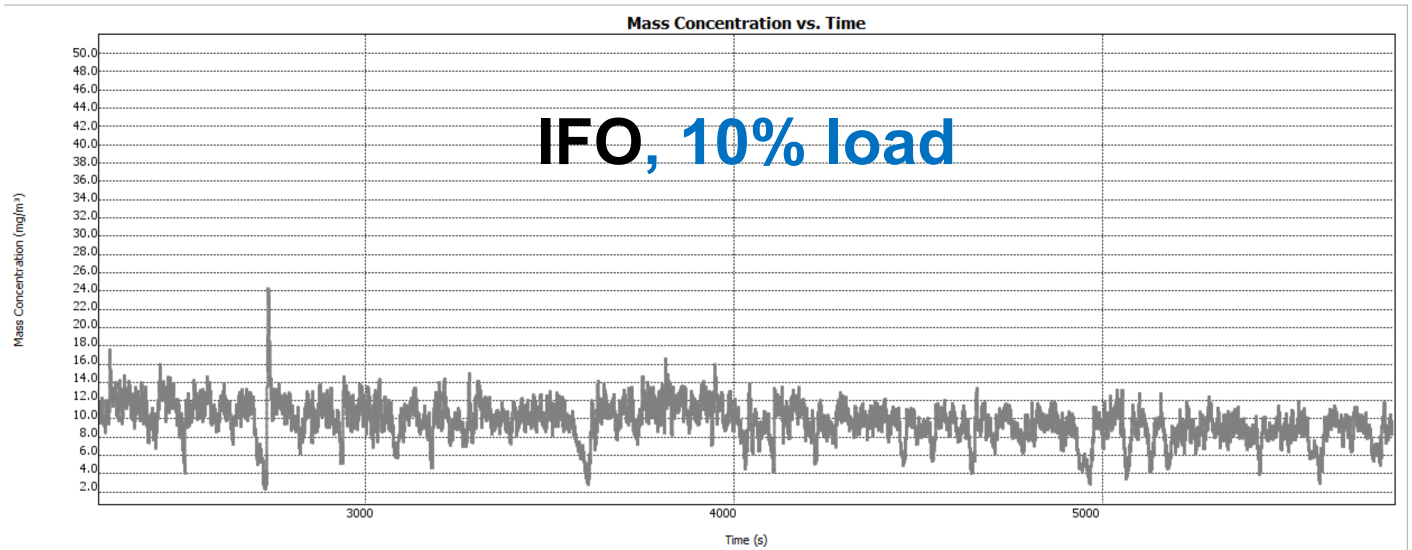
Concentration range through all test points: 0.05 – 40 mg/m^3

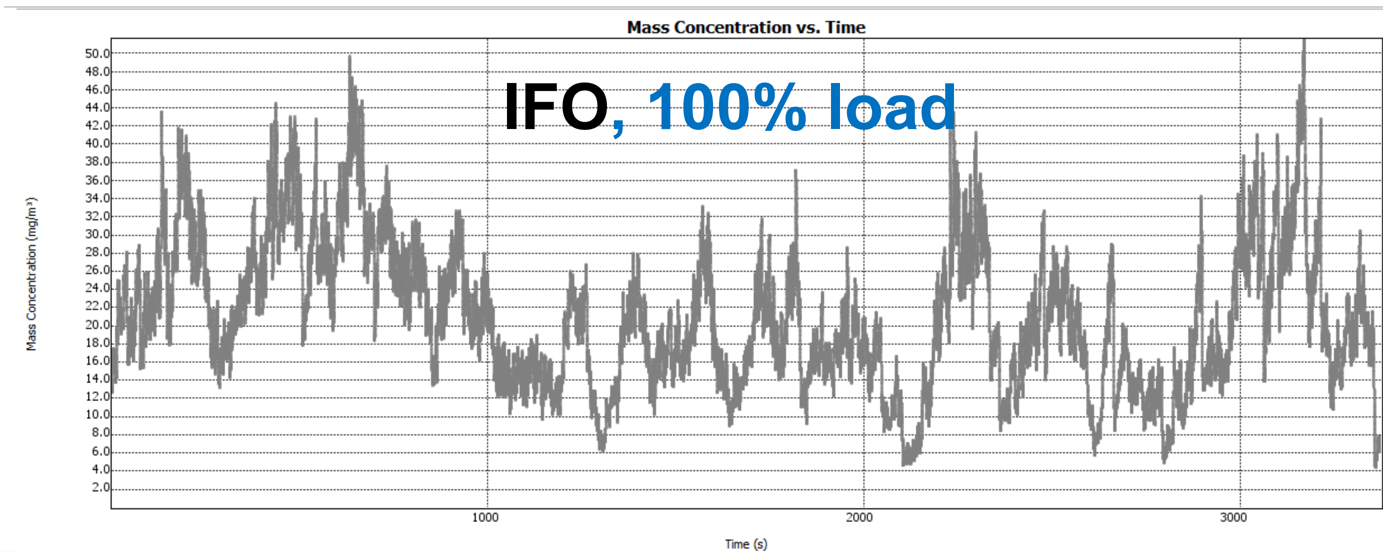
Concentration Variability



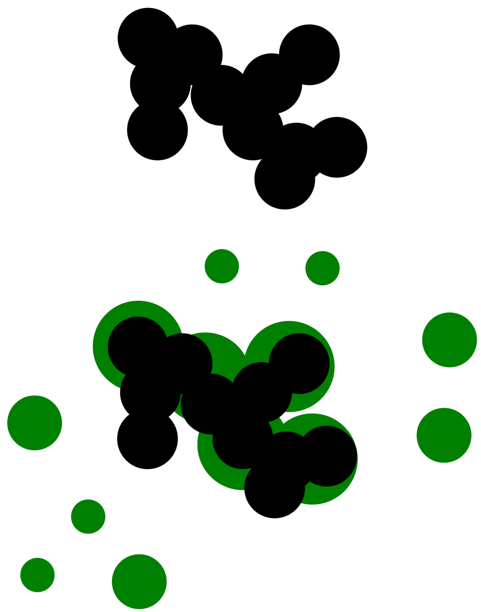
- Pattern in mass concentration emissions (~500 seconds)
- Concentration decreases over the hour

Concentration Variability… varied with load





Effective Density



Mass / Volume

→ Select particle size
→ Measure concentration for varying masses
→ Peak mass divided by mobility-equivalent volume

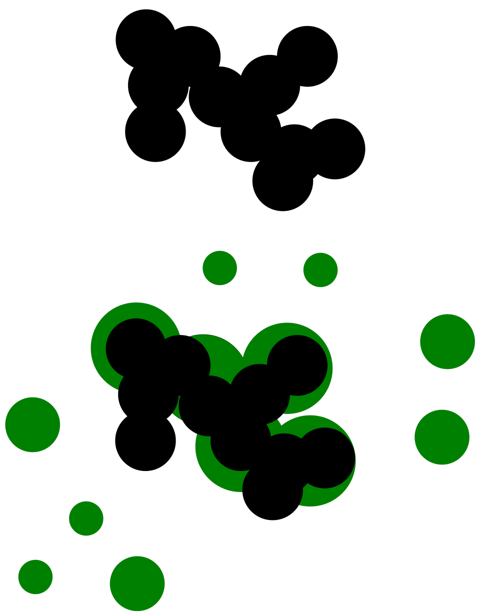
→ Use with or without thermodenuder / catalytic stripper to remove volatile coating

- Information about the particle's morphology
- Information about the extent of volatile coating

$$\rho_{eff} = \frac{m}{\frac{\pi}{6} d_m^3}$$

- Used for number concentration to mass concentration conversions
- Impacts particle transport and deposition properties in lungs

Effective Density



Mass / Volume

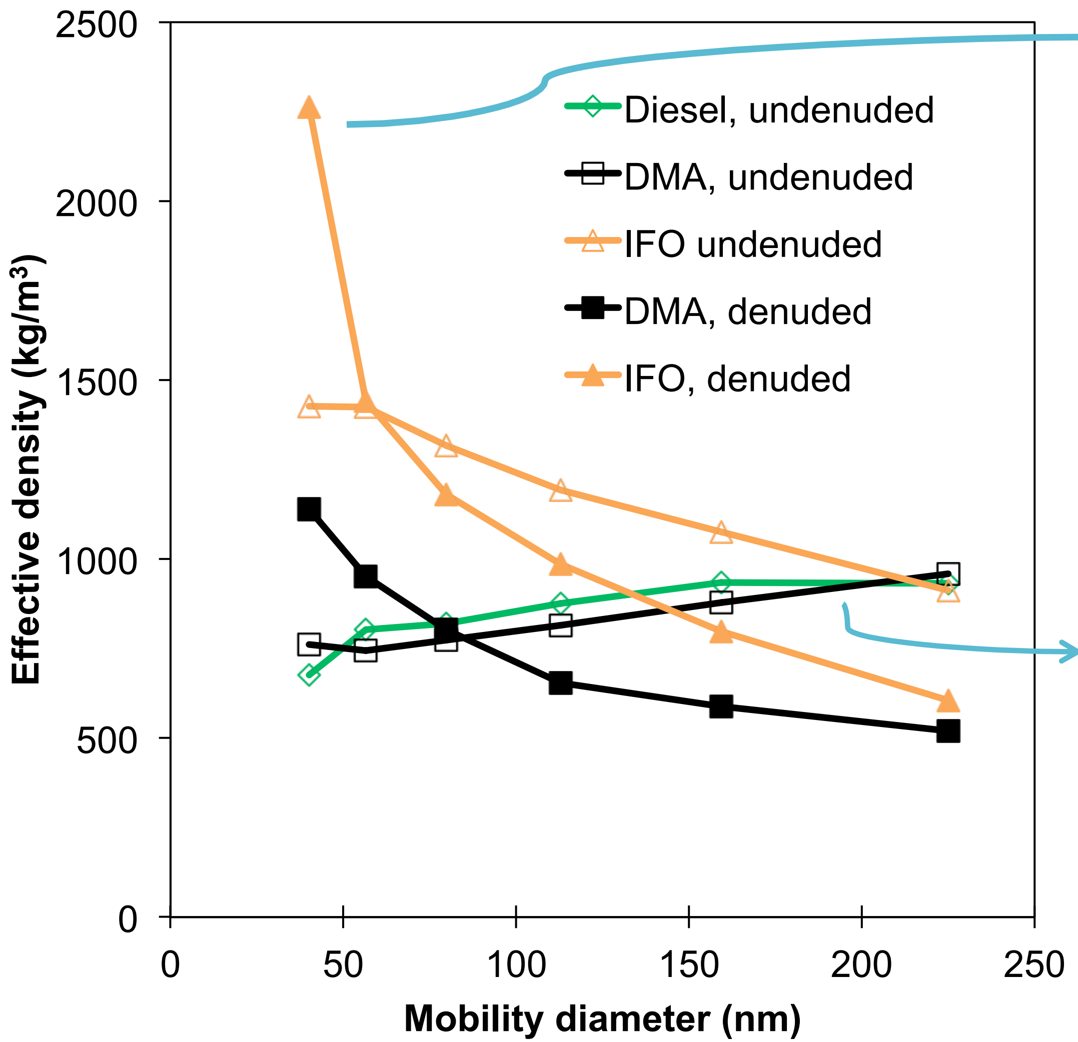
→ Select particle size
→ Measure concentration for varying masses
→ Peak mass divided by mobility-equivalent volume

→ Use with or without thermodenuder / catalytic stripper to remove volatile coating

$$\rho_{eff} = \frac{m}{\frac{\pi}{6} d_m^3}$$

- black carbon material density: 1900 kg/m^3
- Diesel fuel material density: 800 kg/m^3
- 250 nm d_m BC aggregate effective density: 400-500 kg/m^3

Effective Density



IFO denuded 40nm effective density > BC eff dens (1900 kg/m^3) ➔ other material e.g. perhaps metals

Undenuded **Diesel** & **DMA**: corresponds to effective density of semi-volatile material ➔ particles are largely semi-volatile material

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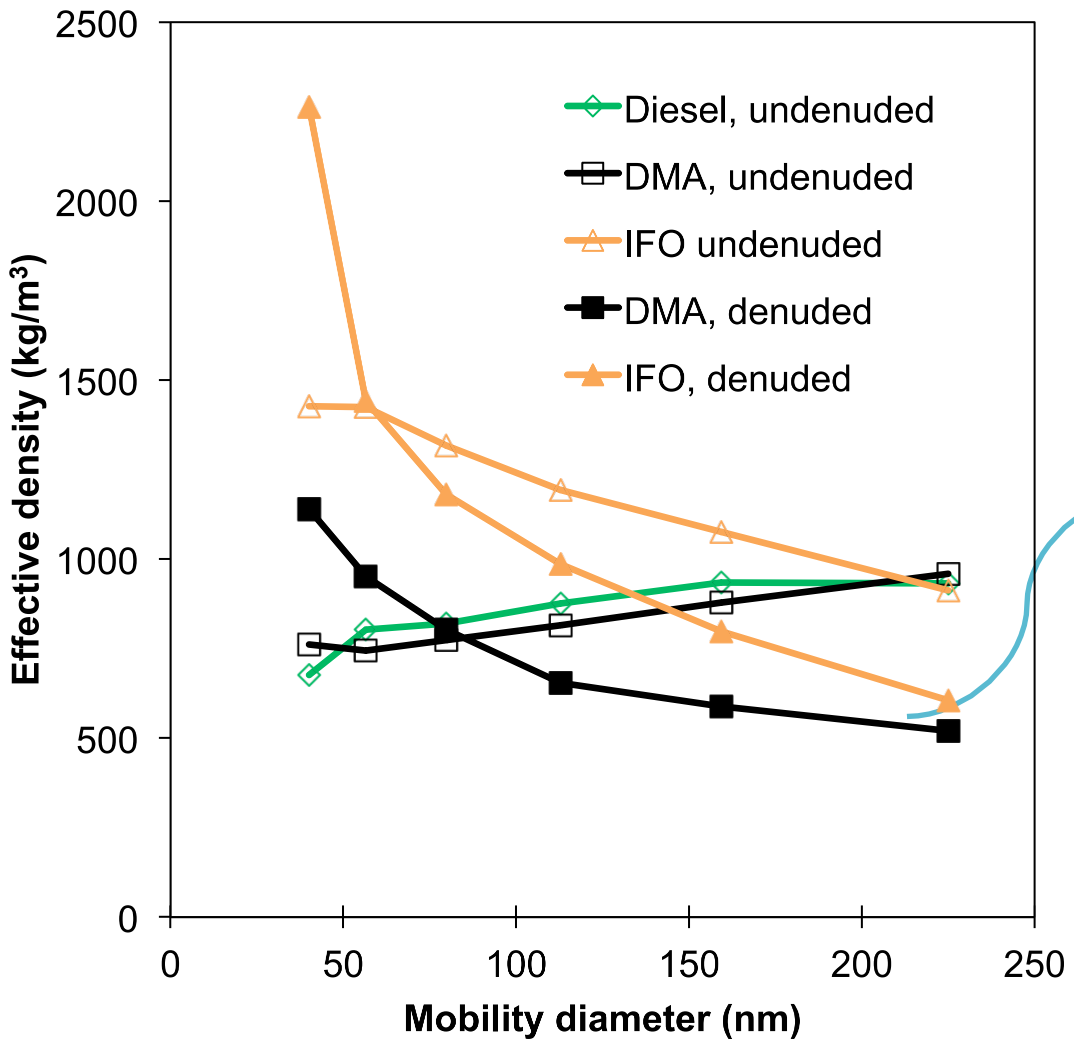
Effective Density



Effective density for denuded particles decreases with increasing particle size ➔ supports the idea that particles from marine engines are fractal-like aggregates

Challenges arising from emission variability

Emissions were not stable through a 1h test point

- What is the best approach to averaging in order to compare instruments?
- Some continuous instruments had breaks during some test points. How best to process the data?
- Some instruments were not continuous. How to compare adequately?
- Particularly challenging for Effective Density measurements, where size/mass is scanned as a function of time with an assumption of a constant source concentration
  - introduced a mixing chamber into CPMA sampling line to damp oscillations

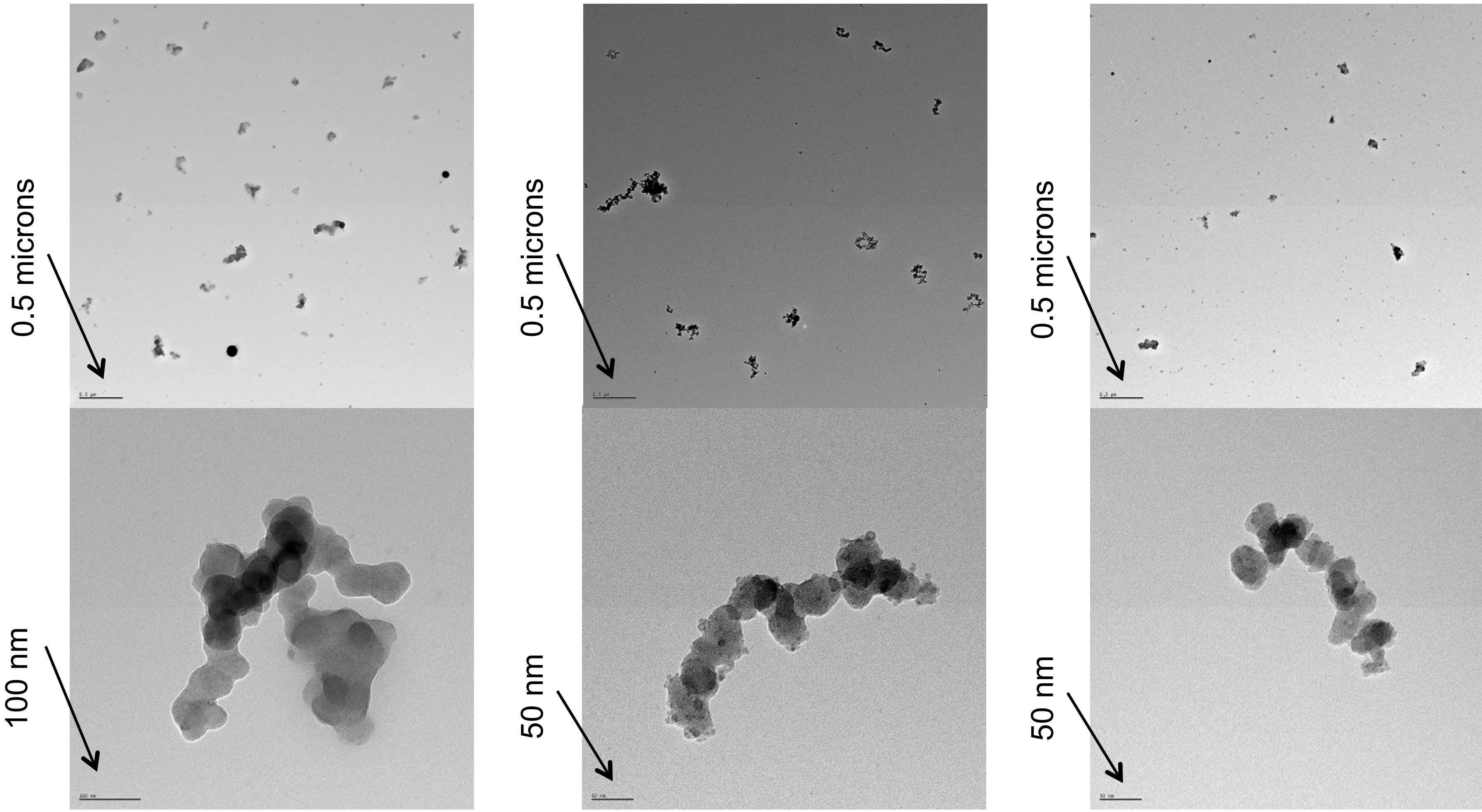
General issues during the campaign

Issues that will affect validation of some measurement data:

- Shipping damage to one instrument was not fully fixed until day 2 of engine testing
- One instrument displayed overheating error message
  - Some missing minutes during some DMA tests points
  - Resolved before tests with IFO
- One instrument reported some internal leak errors at times (although there were no actual leaks)
- Dilution ratio to the sampling tunnel varied widely due to particle buildup in the dilutor
  - Can be corrected with real time CO_2 monitoring of dilution

TEM images

Diesel (100%, 1500 RPM) | **DMA** (100%, 1500 RPM) | **IFO** (100%, 1500 RPM)



Summary

Test matrix was successfully completed with data acquired at all test points

Some general issues resulted in missed data for some instruments at a few test points

Need to develop strategies for appropriate data averaging for each instrument at each test point

Full data processing underway with objectives:

- comparison measurements of different instruments using a miniCAST
- instrument comparison on engine
- engine emission factors
- chemical/physical particulate emission characterization

Aiming to submit results as a paper to PPR4

Acknowledgements / Funding

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Umwelt Bundesamt

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Transport Canada Transports Canada

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Thank you

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Engine test cycles

Two hour warmup with diesel used for engine start and shutdown

Hold each test point for 1 hour

Stabilization period > 30 min for each test point

Cycle #1: *reversed* **D2** (ISO 8178-4)

Mode #	**5**	**4**	**3**	**2**	**1**
RPM	1500	1500	1500	1500	1500
Load (%)	10	25	50	75	100

Cycle #2: *reversed* **E3** (ISO 8178-4)

Mode #	**4**	**3**	**2**	**1**
RPM	945	1200	1365	1500
Load (%)	25	50	75	100

Engine test cycles

>2 hours warmup/setup with diesel used for engine warmup
Each test point held for 1 hour
Stabilization period > 30 min for each test point
➔ **9-10 hour days when everything goes well**

Cycle #1: *reversed* **D2** (ISO 8178-4)

Mode #	1	2	3	4	5
RPM	1500	1500	1500	1500	1500
Load (%)	10	25	50	75	100

Cycle #2: *reversed* **E3** (ISO 8178-4)

Mode #	1	2	3	4
RPM	945	1200	1365	1500
Load (%)	25	50	75	100