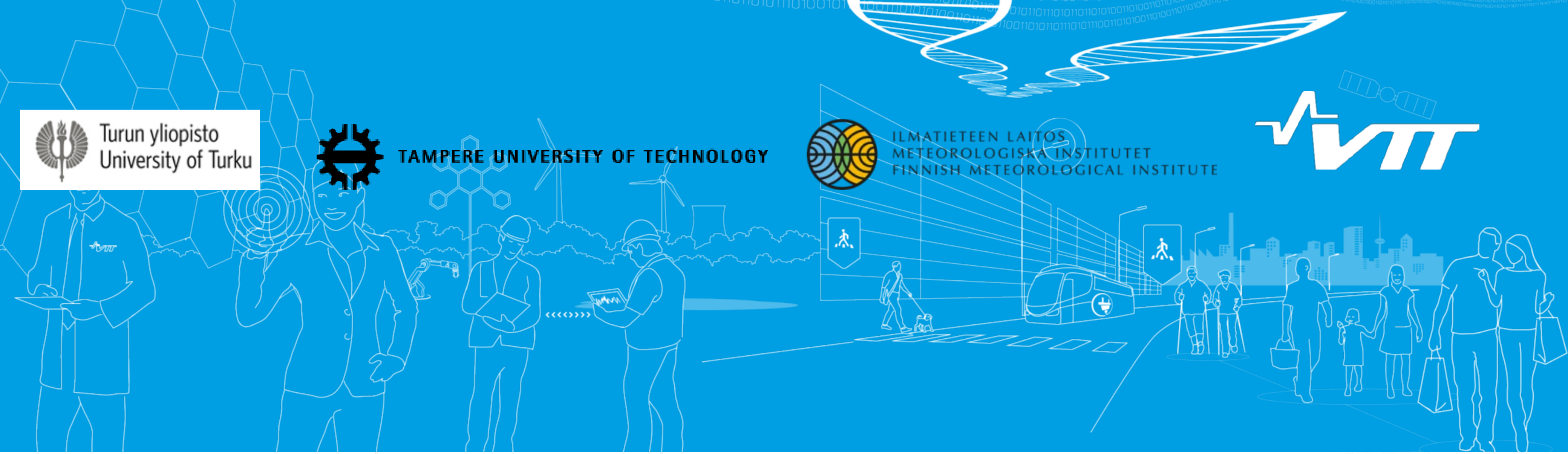

SEA-EFFECTS BC 2015-2016

Tekes Arctic seas program

CIMAC

Black carbon measurements in different conditions

8th CIMAC CASCADES

May 5, 2017, Helsinki, Finland

List of authors in the next slide.

SEA-EFFECTS BC project, Finland, 2015-2016

Research organisations, authors

- VTT Technical Research Centre of Finland Ltd. P. Aakko-Saksa, T. Murtonen, H. Vesala, P. Koponen, S. Nyyssönen, K. Lehtoranta, T. Pellikka, J. Lehtomäki
- Finnish Meteorological Institute, FMI H. Timonen, K. Teinilä, M. Bloss, S. Saarikoski, R. Hillamo
- Tampere University of Technology,TUT P. Karjalainen, N. Kuittinen, P. Simonen, T. Rönkkö, J. Keskinen
- University of Turku, UTU O-P. Brunila, E. Hämäläinen

Industrial partners

- Funding from Wärtsilä Finland Oy, HaminaKotka Satama Oy, VG-Shipping Oy, Pegasor Oy, Spectral Engines Oy, Gasmet Technologies Oy, Vopak Oy and Kine Robot Solutions Oy
- Contribution in the experiments: Wärtsilä Finland Oy, VG-Shipping Oy, Pegasor Oy, Spectral Engines Oy and Gasmet Oy

External contributions

- AVL (Austria), Metropolia, UEF, Gasera Oy in the BC measurements, Neste (one fuel)

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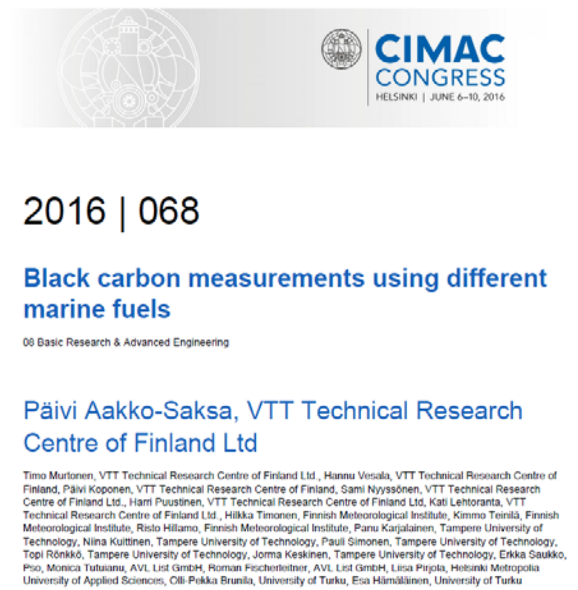
Content

1. Why black carbon (BC)?
2. BC results from the **laboratory** * and **preliminarily from the ship measurements****
   - Different BC measuring principles
   - Different engines, engine loads and fuels
3. The effect of conditions on the results
4. Summary



*) CIMAC Paper no. 068, 6-10 June 2016, Helsinki, Finland. (CIMAC database http://www.cimac. com/ publication-press/technical-database/index.html and www.researchgate.net)

**) Reporting of the ship measurements ongoing.

Results have been reported to IMO PPR 4

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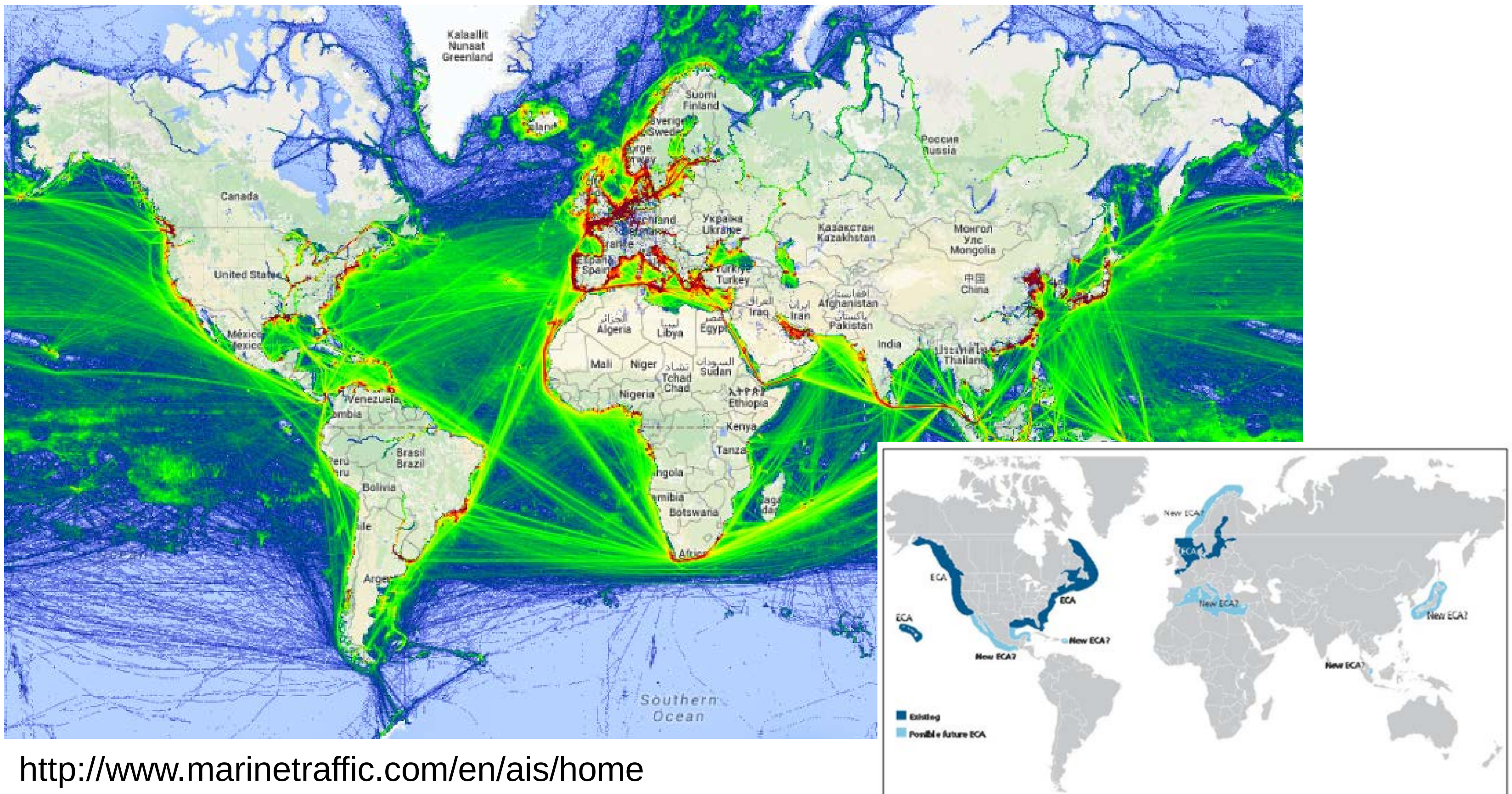
ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

Turun yliopisto
University of Turku

VTT

Ships travel close to coast where dense population lives

Globally, from shipping appr. **9% of SO_x**, **18-30% of NO_x** and **8-13% of diesel BC** (*Winther 2014, Azzara 2015*).



http://www.marinetraffic.com/en/ais/home

Existing and possible ECAs

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BC from increasing shipping in Arctic would threaten climate

BC is a major contributor to Arctic warming. Extending ship BC to the Arctic region would be detrimental to the climate. BC on snow and ice accelerate melting by reducing the reflectivity.

IMO limit for BC from ships is anticipated. Controls on BC are on a high priority.

SEA-EFFECTS BC project aims at more reliable BC emission measurements from ships in different conditions.

BC RESULTS

Test matrix in laboratory

Wärtsilä Vasa 4R32 LN 1.6 MW medium-speed engine at VTT's engine laboratory.

Two engine loads:

- 75% corresponding to the open sea engine loading conditions.
- 25% corresponding to the near-harbor engine loading conditions.

Test fuels:

- Marine Diesel Oil with 0.1% sulphur content: "0.1%S"
- Fuel with 0.5% sulphur content: "0.5%S" (not a distillate)
- Heavy fuel oil: "2.5%S"
- A blend of "biofuel" and distillate in ratio of 30:70: "Bio30"

Engine oil: Shell Argina XL 40 engine oil.

Ref. CIMAC Paper no. 068, 6-10 June 2016.

From the IMO's candidate BC methods, FSN, PAS and MAAP were included

BC: Smoke Meters. BC based on Filter Smoke Number (FSN). The relative change in optical reflectance of visible light from a filter.	AVL 415S *(VTT)* AVL 415SE *(AVL)*
BC: AVL Micro Soot Sensor, photo acoustic method (PAS).	AVL MSS (AVL)
BC: Multiangle Absorption Photometer (MAAP). Relative change in optical transmission as particles are collected and measurement of reflectance of scattered light with multiple detectors.	MAAP 5012 *(FMI)*
BC: Aethalometers. Change in absorption of transmitted light due to continuous collection of aerosol deposit on filter.	MAGEE AE42 *(FMI)* MAGEE AE33 *(Metropolia)*
EC/OC thermal-optical analysis. Organic and elemental carbon, partial flow dilution (ISO 8178) samples (in-stack EN 13284-1 in lab)	Sunset 4L *(VTT)*
The Soot Particle Aerosol Mass Spectrometer, SP-AMS. Chemical composition (ions, organics, BC, metals) of submicron PM	SP-AMS (FMI)
Pegasor Particle Sensor (PPS). Electrical charge of carried by particles.	Pegasor
Sample pre-treatment with catalytic strippers (CS), thermodenuder (TD)	Pegasor, TUT
PM and its composition incl. anions, metals and PAHs **In-depth analysis**, e.g. PAM, SMPS, CPC, ELPI+, TUT-HTDMA	VTT, TUT, FMI

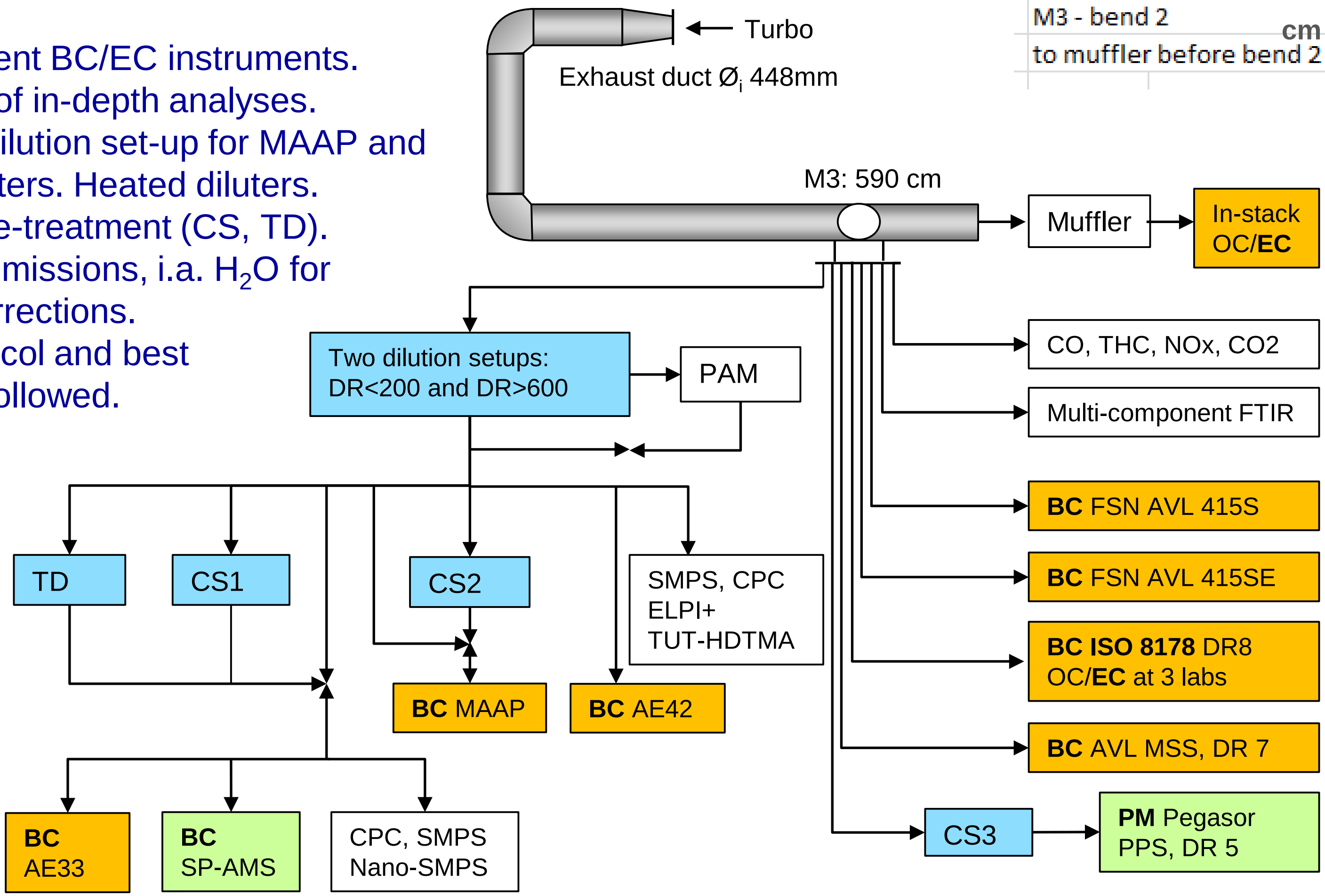
Ref. CIMAC Paper no. 068, 6-10 June 2016.

Test set-up in laboratory

	d	d/id
M3 - bend 1	167	3,8
M3 - bend 2	508	11,4
to muffler before bend 2	78	1,8

cm

- Nine different BC/EC instruments.
- A number of in-depth analyses.
- Complex dilution set-up for MAAP and aethalometers. Heated diluters.
- Sample pre-treatment (CS, TD).
- Gaseous emissions, i.a. H_2O for dry/wet corrections.
- Daily protocol and best practices followed.



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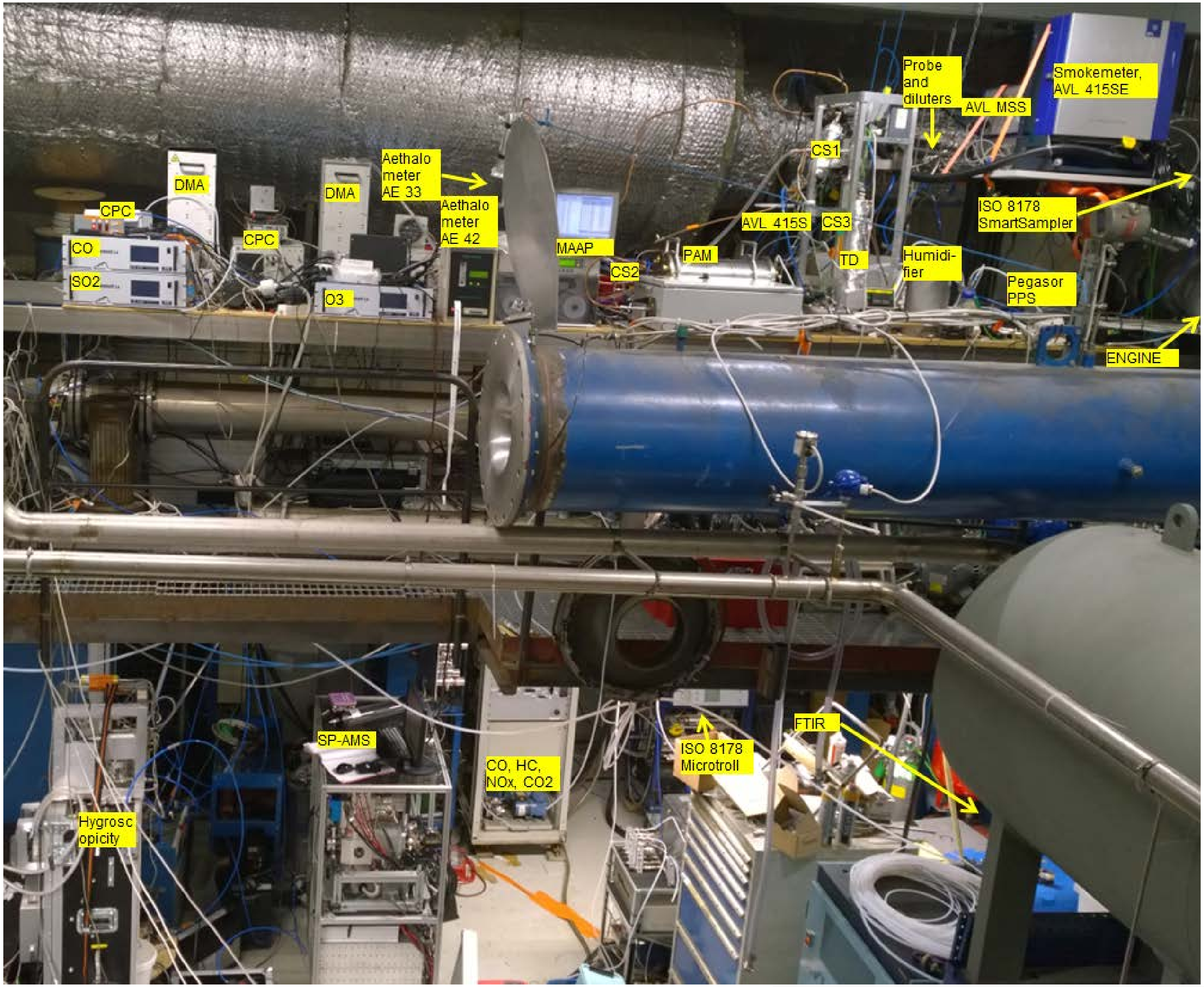


Ref. CIMAC Paper no. 068, 6-10 June 2016.

The best practises for emission tests followed

Before/after test campaign

- **Engine and test set-up stabilisation**
- **Lube oil running hours** checked
- **Fuel and lube samples** analysed
- **One fuel tested before and after campaign** (stability of the set-up)

During the test campaign

- **Warm-up and load change protocol**
- On-line measurements (e.g. NO with FTIR) to **follow engine stability**
- **Fuel temperature** adjusted according to engine manufacturer's requirements
- Systematic **daily protocol and "dummy"** tests before actual sampling

Periodical recordings

- Engine speed, alternator power, rack position, bearing temp, HC of blow-by
- Test cell T&RH, intake air T, pressure diff, under pressure in meas pipe, T and P before/after TC, TC speed, air gauge P before cooler/ in receiver, air T in receiver, exhaust T, cyl. T
- Water T from different locations
- Fuel mass flow rate in/out/booster, fuel T/P after feed pump, fuel P before/after engine (booster), fuel volume flow rate in/out, fuel T before/after engine, fuel viscosity before engine, fuel P on engine (in/out)
- Lube T from different locations, lube P

Ref. CIMAC Paper no. 068, 6-10 June 2016.

Test matrix on-board a modern cruising ship

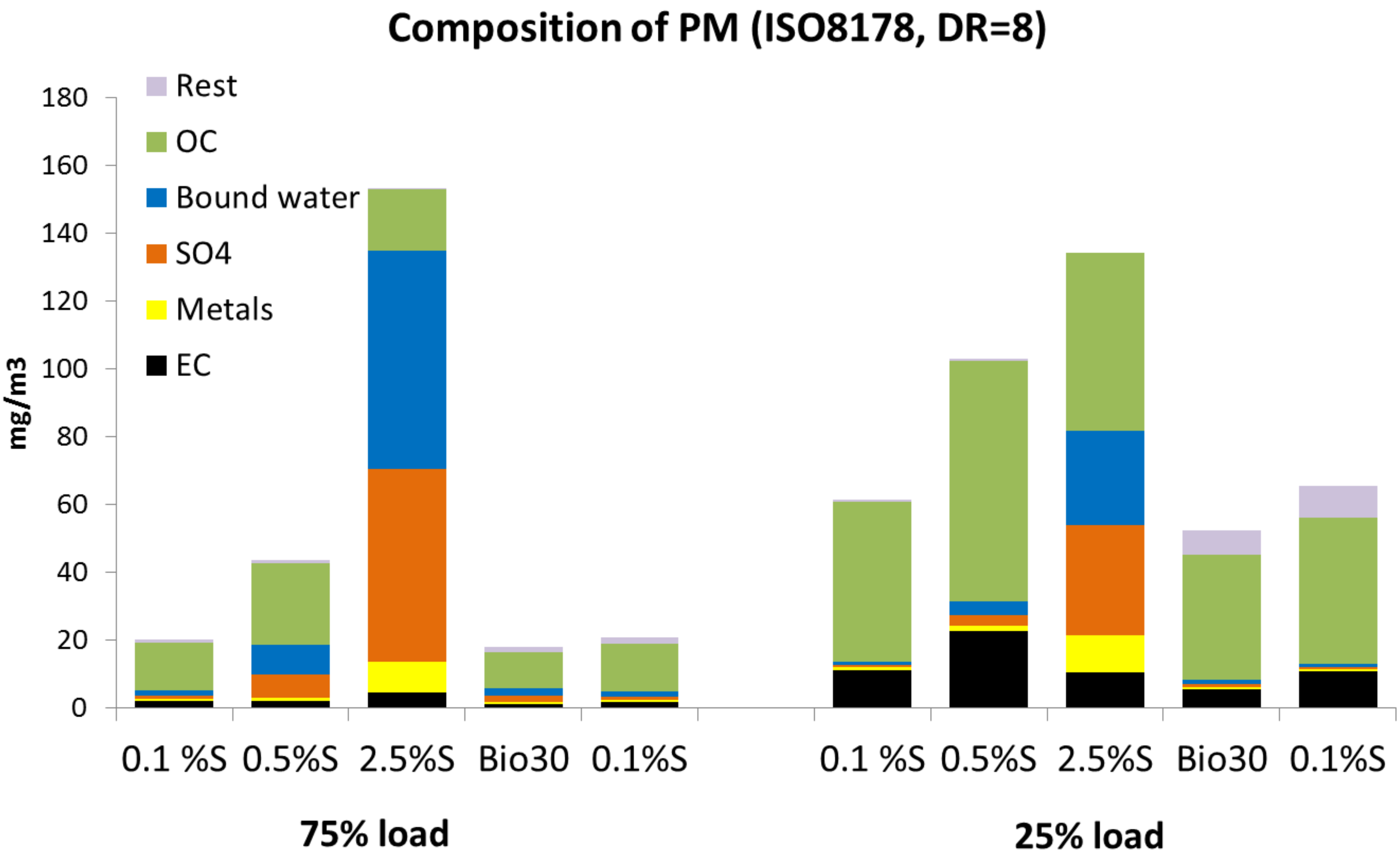
- Two different engine sizes
- 40% and 75% engine loads

- Two different fuels:
  - HFO fuel
  - MGO fuel (only one engine at 40% load)

- Measurements after and before scrubber

Measurement set-up on-board resembled that of the laboratory measurements

These ship results not been published before.



Share of EC in PM low for all fuels. Heavy PAHs lowest for 0.1%S and Bio30.

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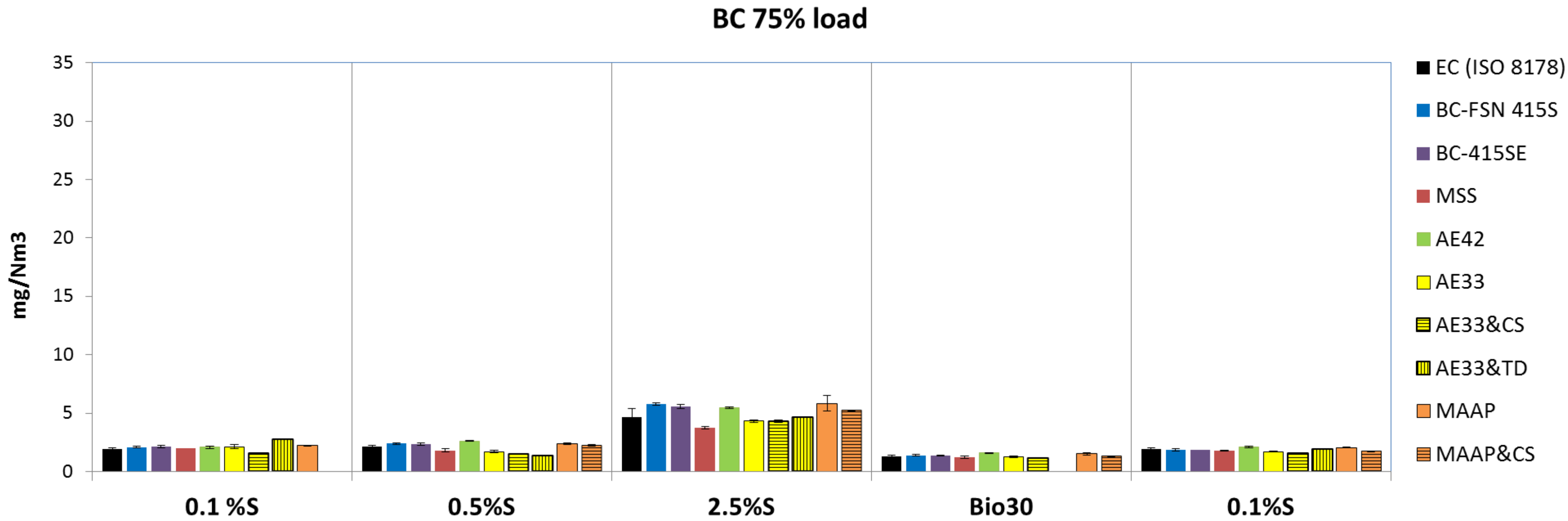
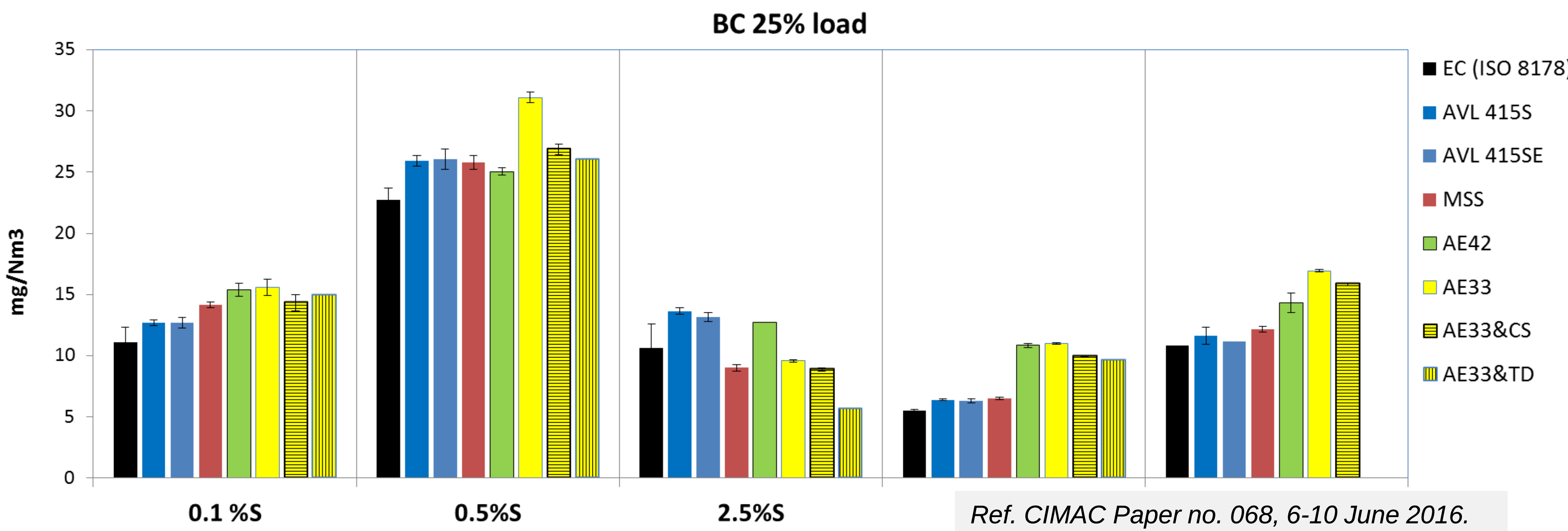
Ref. CIMAC Paper no. 068, 6-10 June 2016.





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Turun yliopisto
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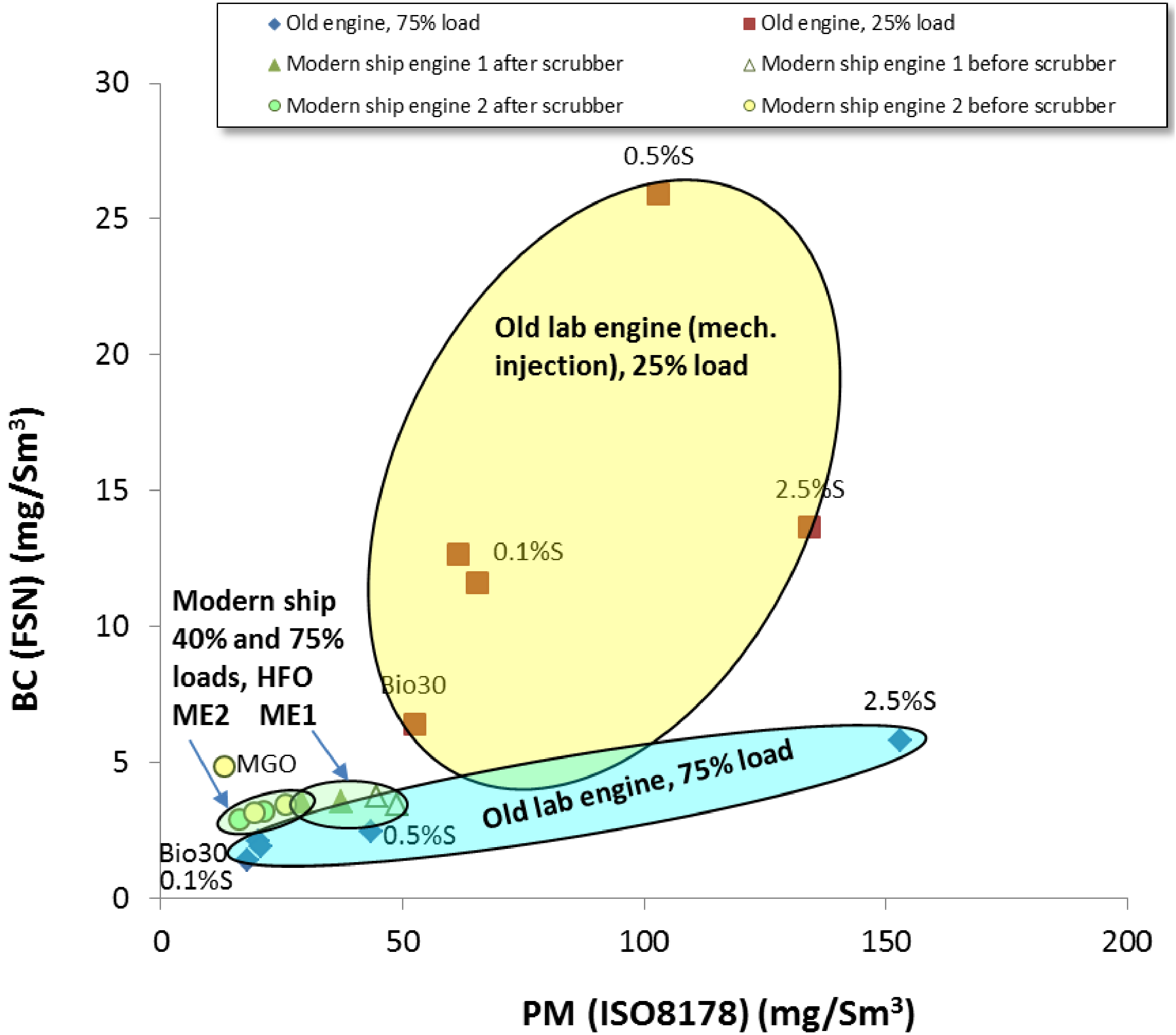
PM and BC from an old engine in lab and from a modern ship



The ship results not been published before.

Lab engine in CIMAC Paper no. 068, 2016.

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CHALLENGING CONDITIONS IN BC MEASUREMENTS

Raw exhaust? Mild or high dilution ratio?

Equipment designed for ambient measurements need high dilution ratios at high BC concentrations

ENGINE

Exhaust duct

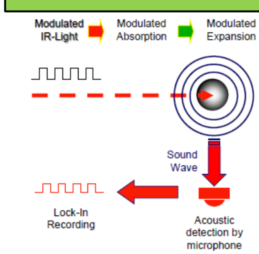
EC from PM filters
ISO 8178 modest DR

RAW EXHAUST

BC (FSN)
"Smoke meters"

Modest dilution e.g. DR 7-20

BC (PAS)
Own diluter



Several diluters

BC MAAP

$$DR = \frac{CO2_{raw} - CO2_{bg}}{CO2_{dil} - CO2_{bg}}$$

DR>400
at BC~10 mg/Nm^3
for MAAP (16.7 lpm).

How to measure DR 400? E.g. raw CO_2 50 000 ppm, diluted CO_2 500 ppm, background CO_2 380 ppm.
Prone to CO_2 contamination in engine environment.

High dilution ratios are challenging

- **Multi-stage dilution set-up is complex**
- **Extensive instrumentation, procedures and experienced personnel needed for reliable results.**
  - CO_2 measurements at different locations of the sampling system
  - CO_2 measurements on-line from dilution air.
  - CO_2 contamination risk in the engine environment.
  - T, RH, impurities (PN) of dilution air to be monitored.
  - Ultra-pure dilution air without CO_2 recommended.

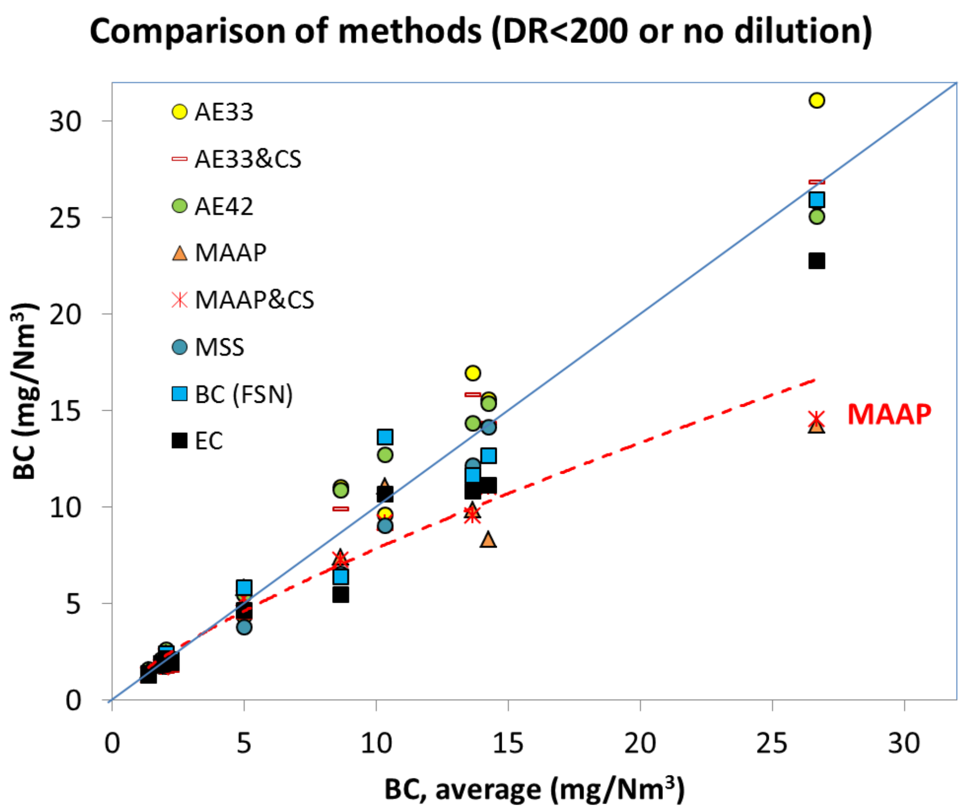
- High DRs are **challenging in laboratory and not practical on board**.

Dilution ratio is a multiplier in the calculation of the BC results → bias in DR is directly reflected in the BC results.

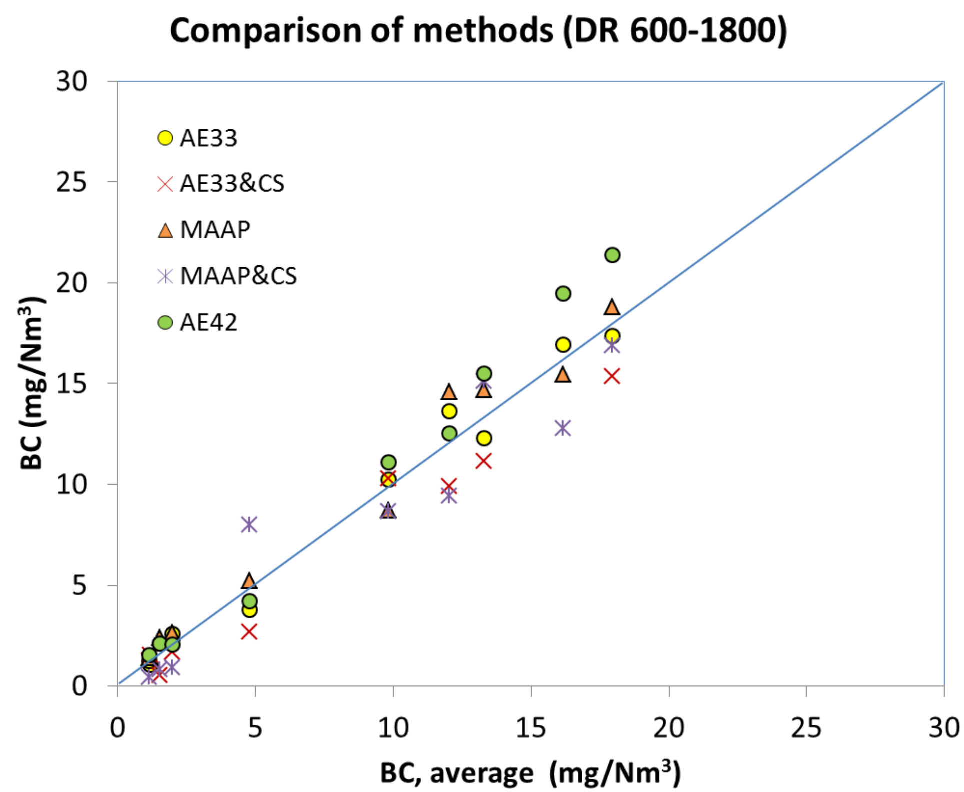
Exceedance of the measurement range of MAAP is not easily recognized.

How exceedances of MAAP range were found?

Lower BC with MAAP than with the other instruments at DR<200.



Similar BC in the same dilution line at DR>600 (not quantitative).



	Pros	Cons
Raw exhaust measurements (FSN)	• No need for pressurised air and filteration or drying (typically) • Simple installation • No need to consider the uncertainty of dilution ratio	Condensation of sample gas to be avoided
Instrument's own dilution, low dilution ratio (AVL MSS, Pegasor PPS)	• Low risk of condensation of the sample gas • Simple system • Manufacturer's procedures for calibrations and quality assurance	• Pressurized air needed from ship (or small compressor) • Filteration and drying of the dilution air • More complex installation and more devices compared to a raw measurement • Increases uncertainties to some extent
High dilution ratios DR>>100 (MAAP, aethalometers)	Good for research (qualitative) purposes	• Not for regular ship BC measurements • Complicated test set-up • Experienced operators needed • High uncertainties due to DR

Observations of the BC methods

BC meas. instruments using raw exhaust or low DR performed well (FSN, PAS)

Comparability of BC was good for two smoke meters (FSN), AVL MSS (PAS), MAAP and aethalometers when all requirements for test conditions were met.

Instruments designed for ambient measurements are challenging

- High uncertainties in the results as DR is a multiplier in the calculation.
- Measurement range of MAAP exceeded.
- EC method designed for ambient PM needed development for ship PM.

Pretreatment (CS, TD) alleviated bias between BC instruments, but at the cost of increased complexity of the test set-up.

Size-dependent corrections for **soot particle losses are need** for the calculation of the results when using high DR and/or pre-treatment (CS, TD).

Heated diluters are needed for high-sulphur fuels (clogging and corrosion are threats).

On-board a ship, heavy and large instruments are not desired.

Ref. CIMAC Paper no. 068, 6-10 June 2016.

Summary

- In the laboratory for an old engine, the results unveiled dependences between BC, fuel types and engine loads. **BC was not directly dependent**, while PM was dependent on the fuel sulphur content.

- On-board measurements on **a modern cruising ship showed low BC** from two different size engines at two loads and two different fuel types (HFO, MGO).

- Conditions in ship measurements are challenging. Not all IMO candidate methods are recommendable to be used in practise.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