DOWN TO 10

HORIZON 2020

Call: H2020-GV-2016-2017
Technologies for low emission light duty powertrains

Action:

"Measuring automotive exhaust particles down to 10 nanometres – DownToTen"

Jon Andersson, Ricardo

Outline

- Introduction
- The path to the DTT sampling system (WP2)
  - Technologies developed DTT dilutor, Counter Flow Denuder, Helios Sicrit MS
- Lab-based DTT sampling system (WP3)
- DTT on the road (WP4)
- October 2018 perspectives

Consortium

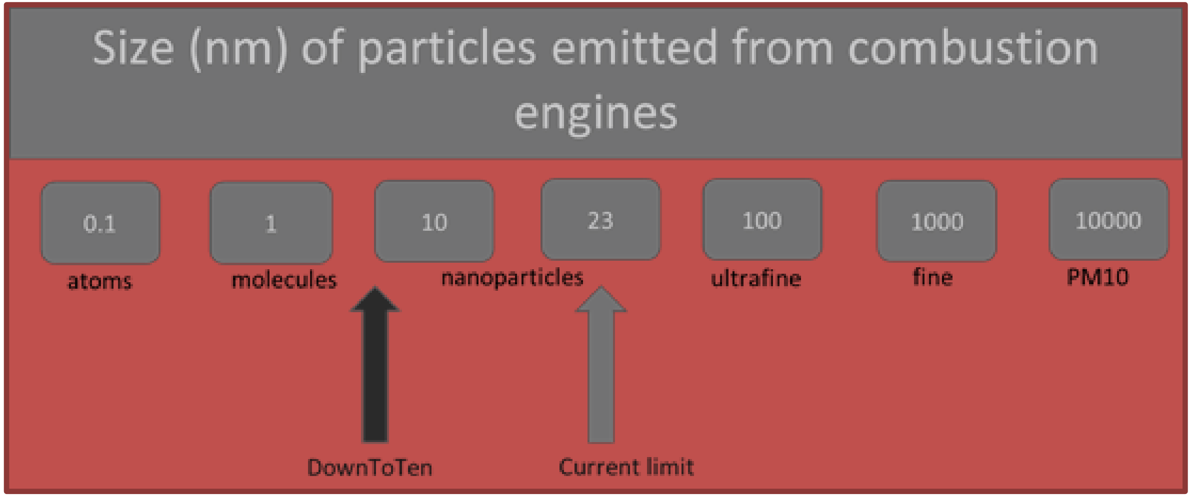
In collaboration with:

The University of California at Riverside,

Tokyo Denki University(Japan) and
National Metrology Institute (Japan)

Project Objectives

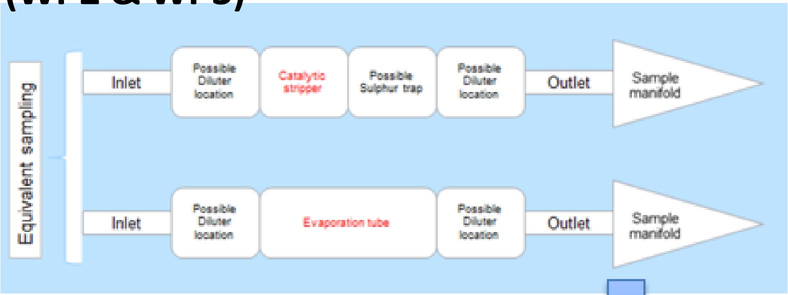
To propose a robust approach for the measurement of particles from about 10 nm both for PMP and RDE, complementing and building upon regulation development activities and addressing topics not tackled so far



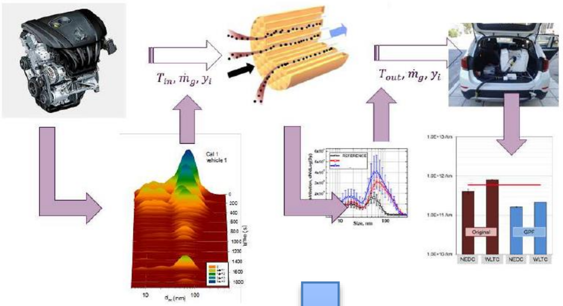
The objective is a PN-Portable Emission Measurement System (PEMS) demonstrator with high efficiency in determining PN emissions of current and future engine technologies in the real world

Overall concept and approach

Measurement equipment and sampling set-up **(WP2 & WP3)**



Modelling particle transformation (tailpipe-out to the inlet of the measurement equipment) (**WP3**)



Testing (emphasis on technologies that will be developed in the parallel projects (**WP4**)

GDI Technology Project: **PaREGEn**
Ricardo, Bosch

GDI Technology Project: **uPGrAdE**
LAT/AUTh, CRF, AVL

Diesel Technology Project: **DiePeR**
AVL, Ricardo, CRF

Hybrid Technology Project

DownToTen: Particle Measurement Project

Synthesis and evaluation of testing results, incl. metrology (WP5)

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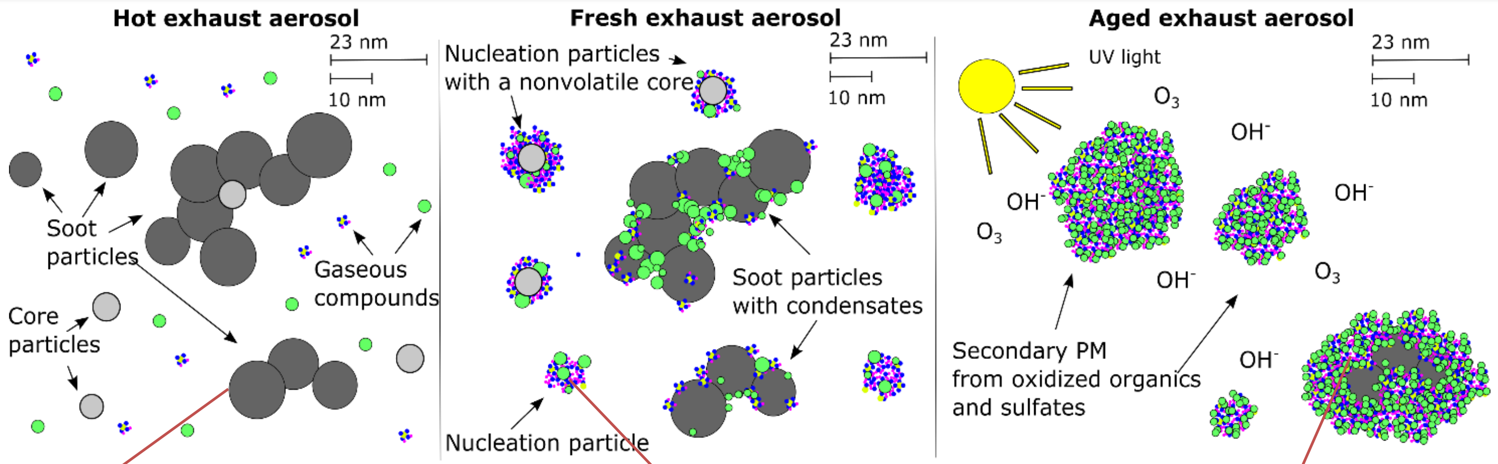
Types of exhaust originated aerosol particles

Tailpipe (ms to s) … Roadside (s to min) … Urban Environment (h)



These are regulated

This mode tends to dominate roadside particle number

This part is not regulated, but affects AQ more than the PN limited

The path to the DTT sampling system (WP2)

Steps taken on measurement methodology

- Literature review of exhaust particles from vehicles
- Technology screening for available instrumentation
  - Diffusion charging instruments and CPC's available, decision not to delve into this
  - Accept instruments operating close to room temperature
  - Cut diameter provisionally 10 nm; CPC capability to go to 2.5 nm, 1.2 nm
- Technology screening for sampling/dilution techniques
  - On-board readiness
- Decision for sampling technologies to study further / implement in the DTT sampling system
- Aerosol laboratory tests of the DTT sampling system
  - Particle losses
  - Artefact tendency
  - Secondary aerosol measurement capability
- Measurement technology development
  - Counter flow denuder
  - Composition analysis

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DTT sampling system: development and performance

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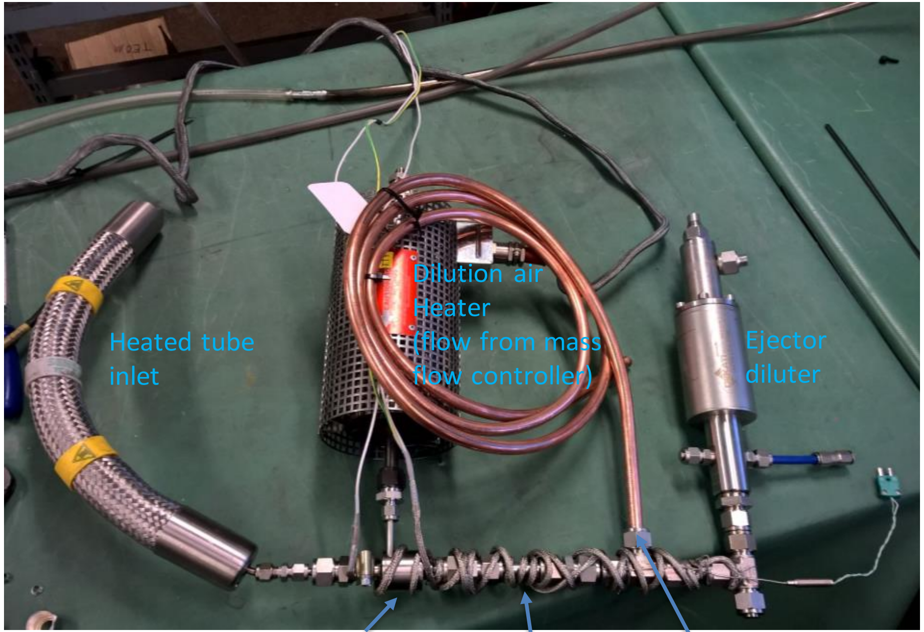
First generation of the DTT sampling set-up



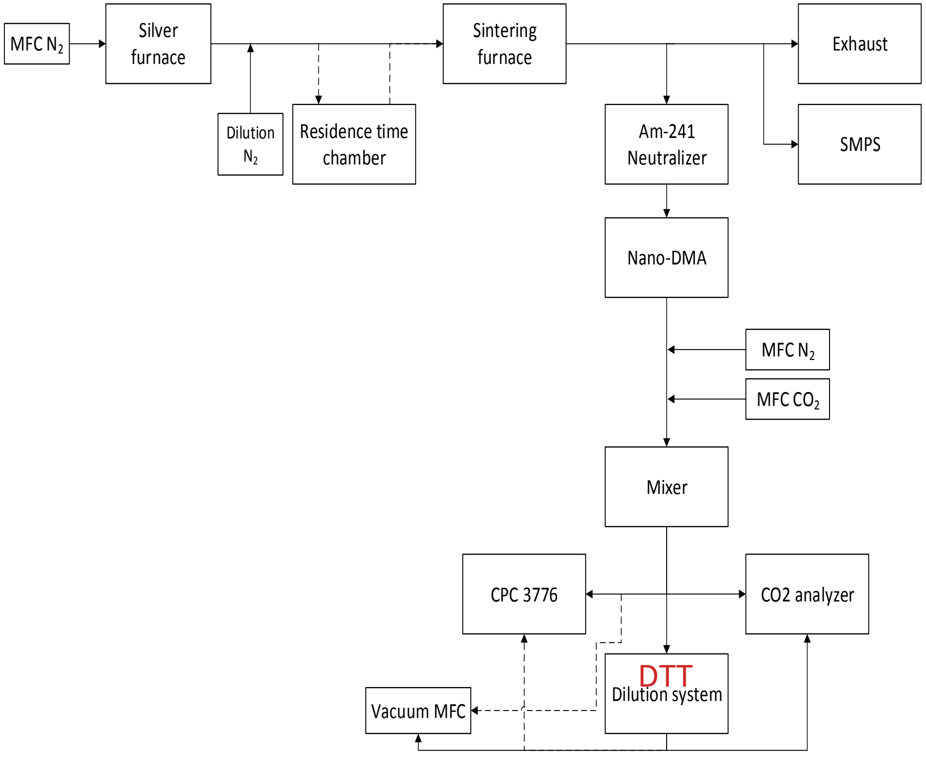
Porous tube diluter

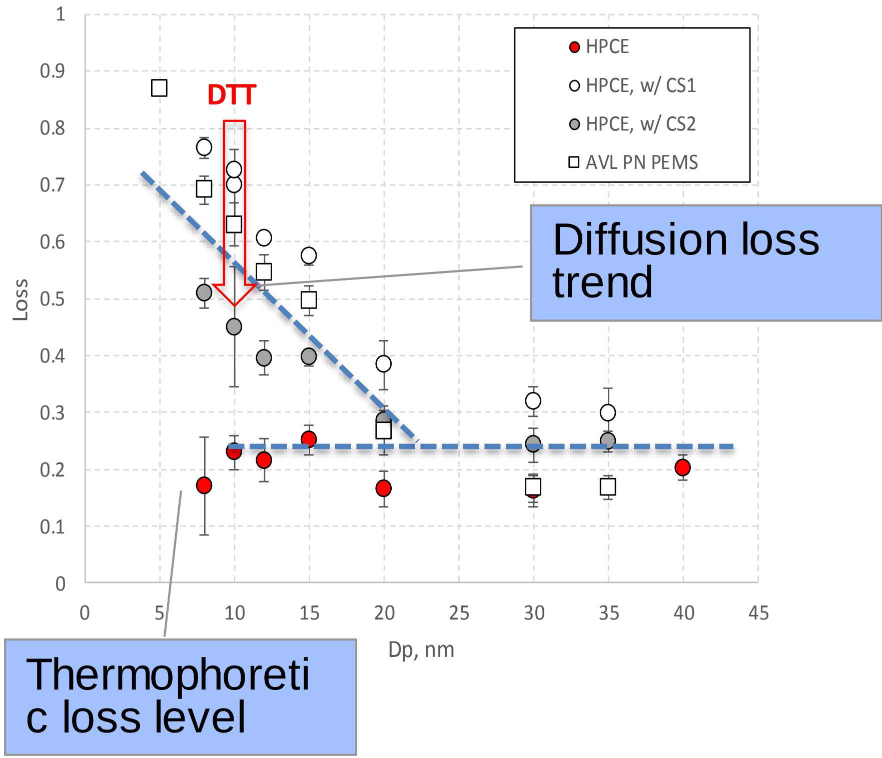
Static mixer

Excess flow to mass flow controller

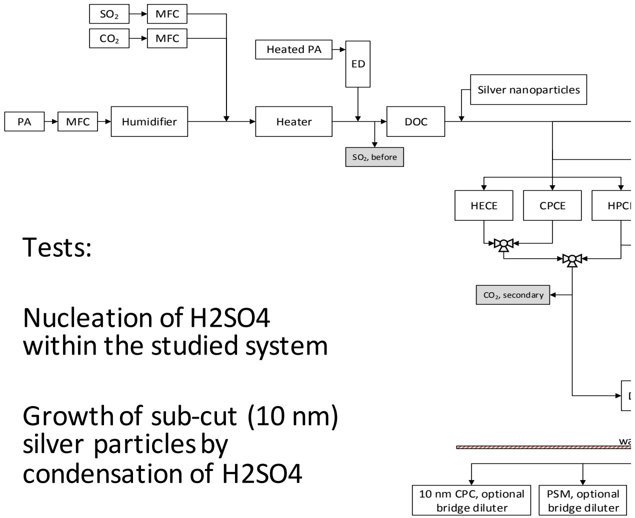
- Hot Porous tube diluter (PTD) followed by a Cold Ejector diluter (ED)
- Heated tube between the diluters/optional catalytic stripper
- Static mixer after the PTD to ensure complete mixing of the sample and dilution air
- ED for stationary tests to accommodate various research instruments
  - Possibly to be removed/replaced for RDE

Particle losses





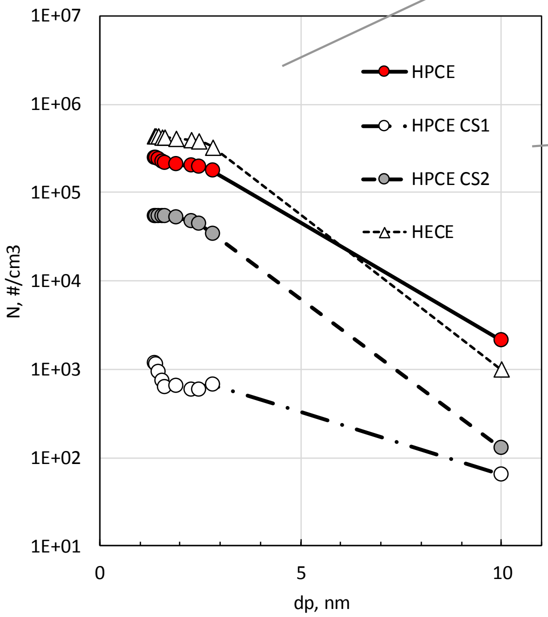
Robustness against artefact particle count



Tests:

Nucleation of H2SO4 within the studied system

Growth of sub-cut (10 nm) silver particles by condensation of H2SO4



Nano cluster formation (< 3nm) but 10 nm count close to background (concentrations before dilution)

GSA mole fraction $5.5\text{-}5.7 \cdot 10^{-6}$

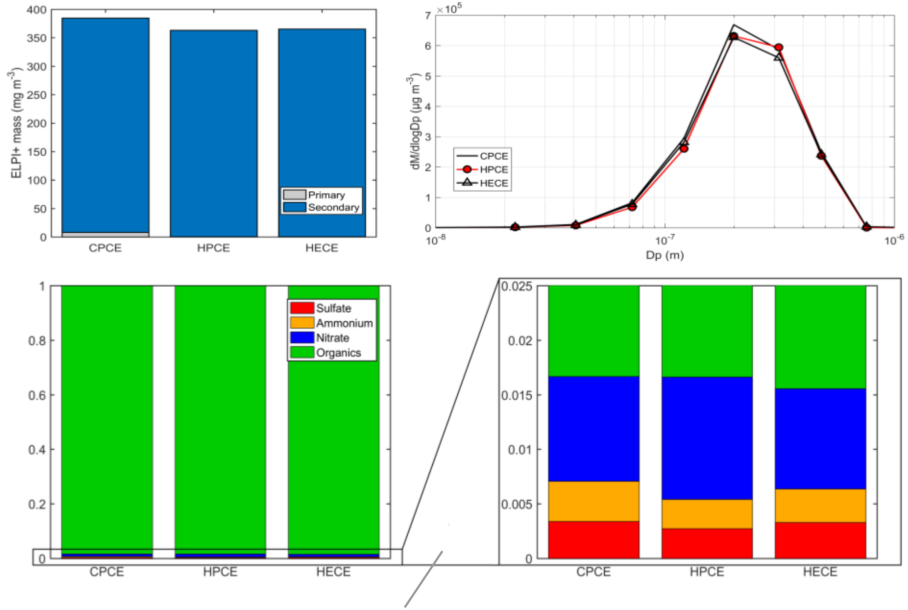
Sampling system	Concentration, $1/cm^3$	Fraction counted	Growth, nm
Primary	NA	8.3E-04	0
HECE	990	2.5E-02	1.4
HPCE	2200	5.4E-02	1.7
HPCE CS1	65	1.6E-03	0.3
HPCE CS2	130	3.3E-03	0.5

DTT system (HPCE) artefact free with CS

Suitability for secondary aerosol measurement

Suitability of DTT sampling system for secondary aerosol measurement w/o CS

- Secondary aerosol formation potential typically much higher than primary emission
- Continuous flow oxidation reactors enable semi-real-time measurement
- No established sampling systems, TUT has used a PARTICULATES derivative
- Laboratory test on the suitability of the DTT sampling system (w/o CS)

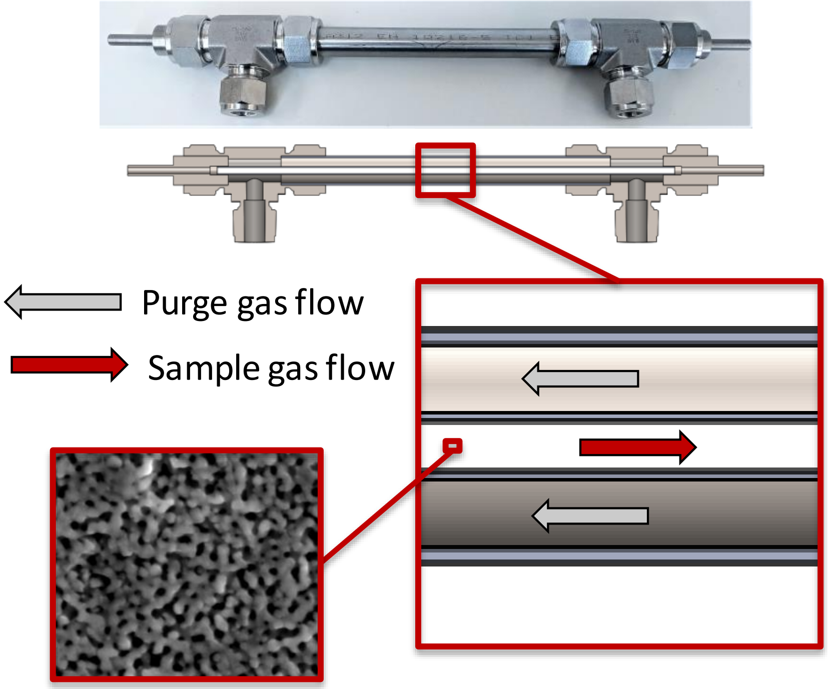


DTT system w/o CS works as well as the benchmarks

Counter flow denuder

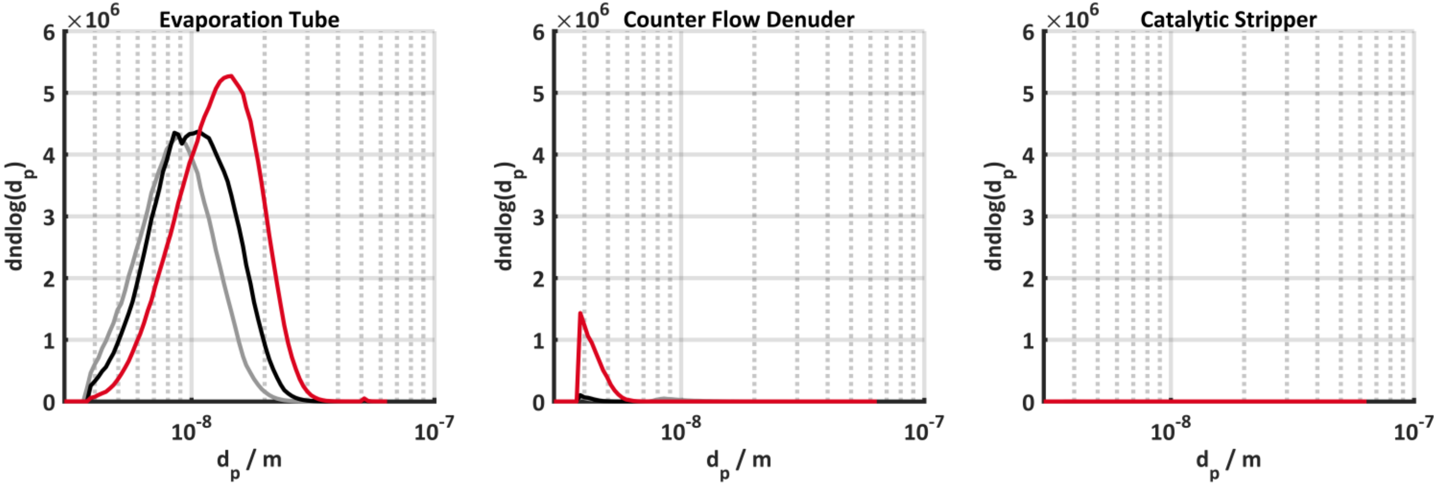
Gas phase component removal: Counter Flow Denuder

- Cylindrical porous glass membrane (sample flow)
- Surrounded by concentric stainless steel tube (purge gas flow)
- Gas exchange between flows by diffusion
- No storage involved
- Can be scaled to diffusion limit to minimize particle losses
- Can be operated at elevated temperatures
- Sensitive to pressure transients



Hagino, H., 2017. Laboratory evaluation of nanoparticle penetration efficiency in a cylindrical counter flow denuder for non-specific removal of trace gases. *Aerosol Science and Technology*, *51*(4), pp.443-450.

Demonstration: Nucleation mode artefact prevention test



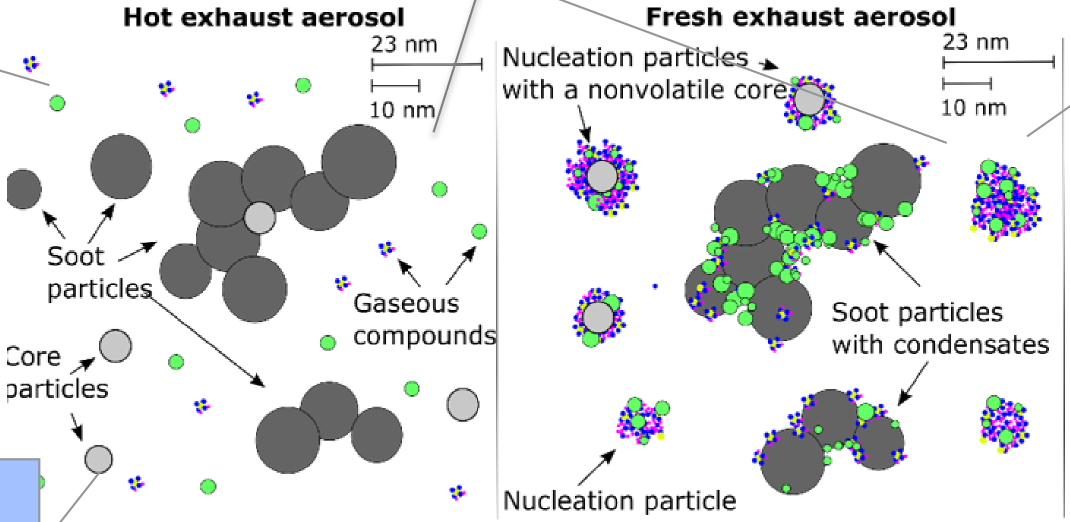
On-line composition analysis

On-line composition analysis: mass spectrometric techniques

Atmospheric research tools: CI-Api-TOF

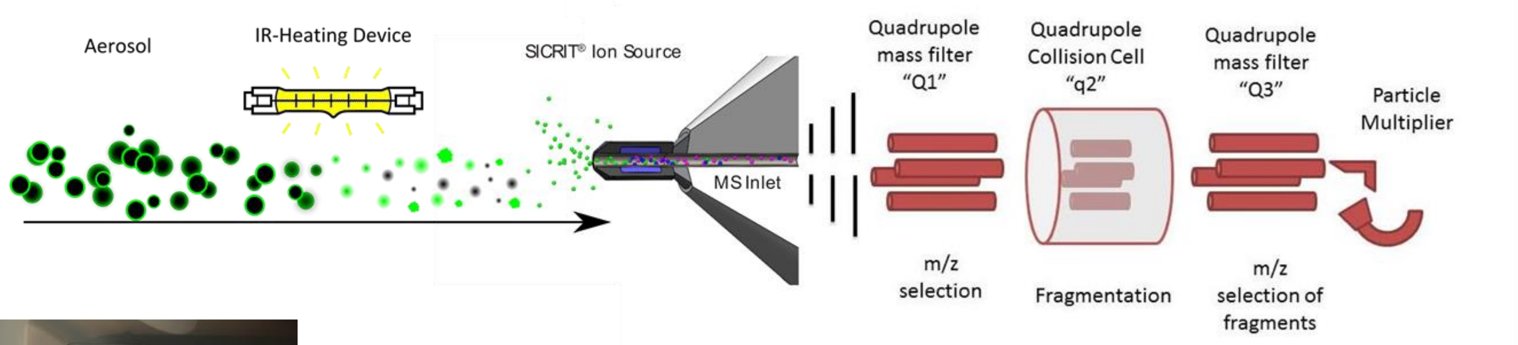
SP-AMS for all particle material, but only down to 50 nm

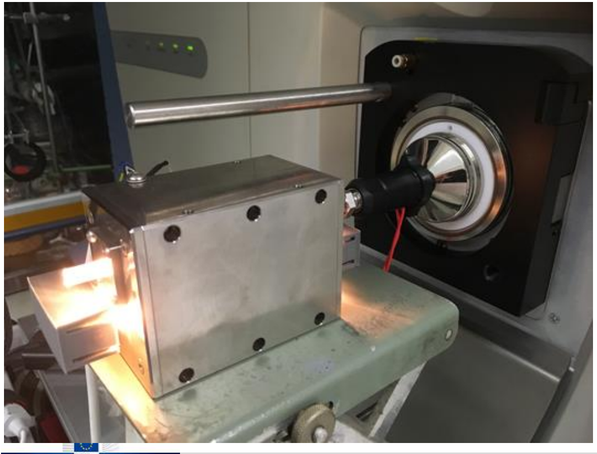
New instrument for semi-volatile particle material



Sub 50 nm particles into SP-AMS: Agglo-inlet

On-line composition analysis: HELIOS-SICRIT-MS

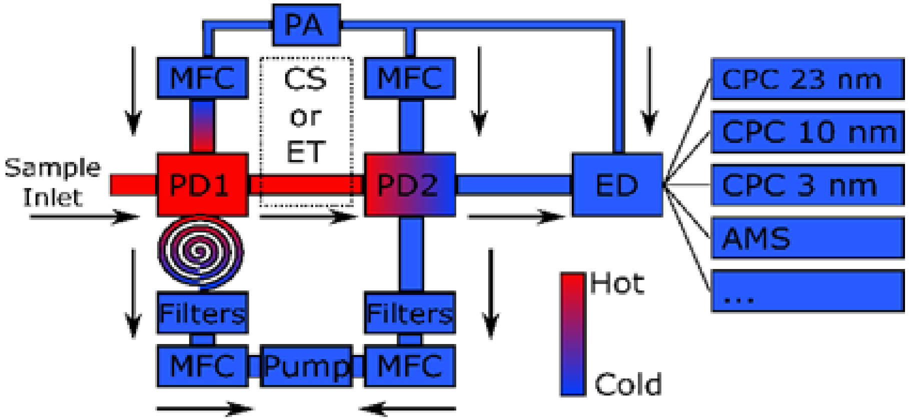


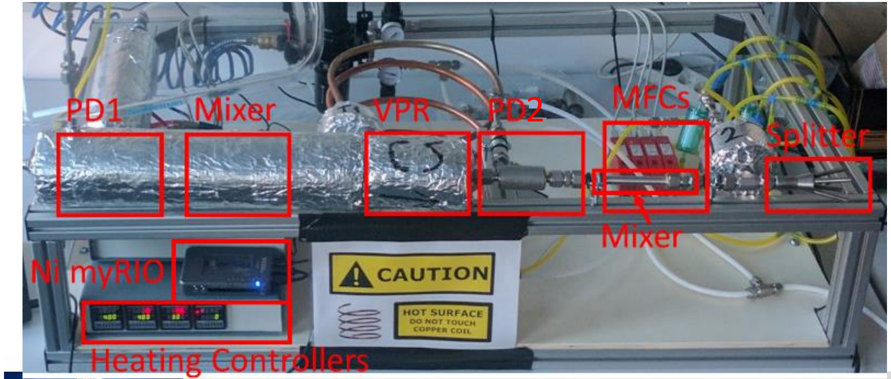


- Direct photo-heating of particles
- Unselective soft ionization
- Robust at high concentrations
- Ongoing work on sensitivity vs substance

Lab-based DTT sampling system: what do we learn when we use it? (WP3)

DownToTen 2nd prototype sampling system: Lab-based

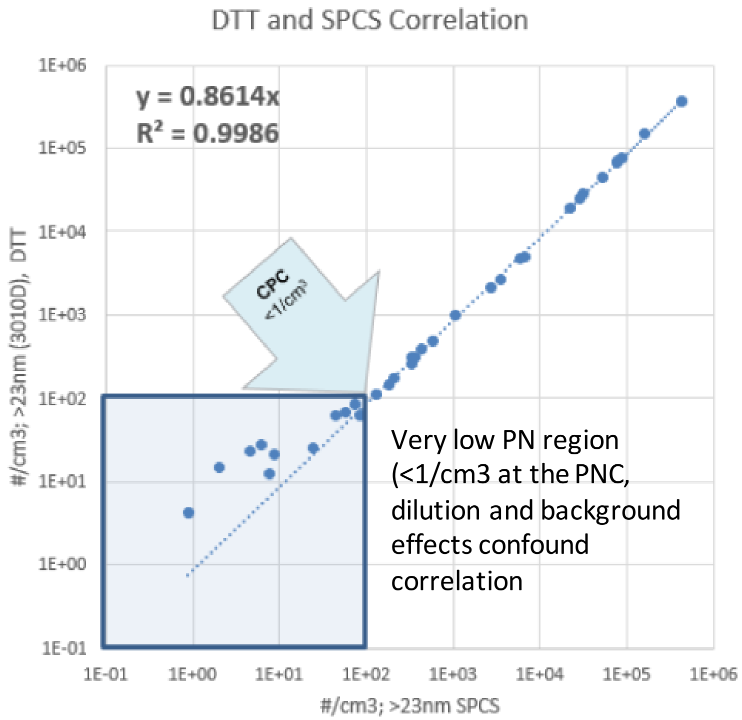




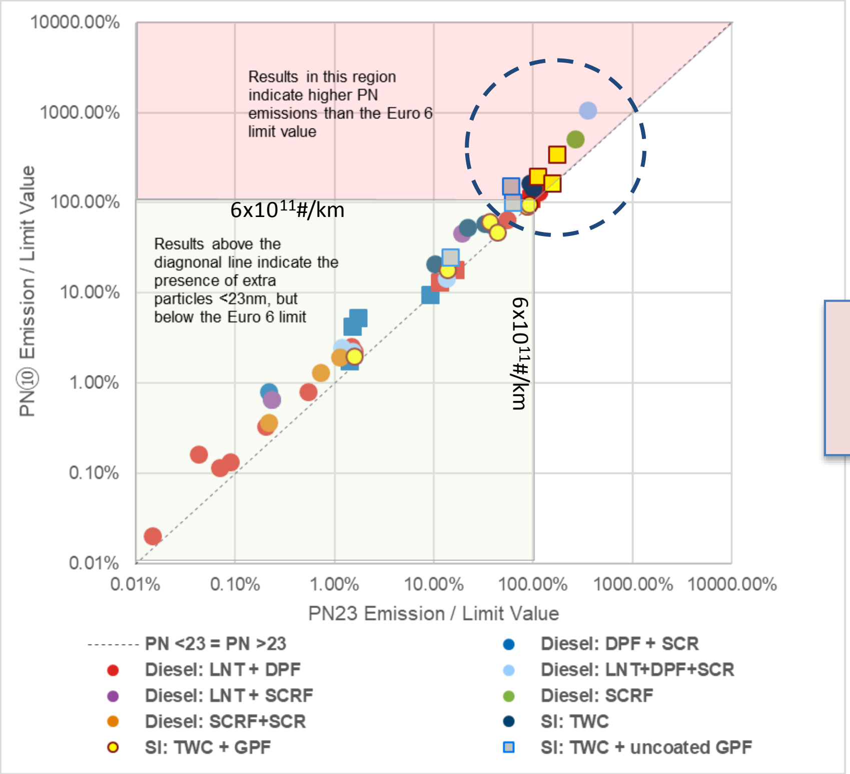
- Lab-based system used in DownTo10 WP3 for measurements
  - Growing understanding of particle production by SI, CI, drive cycles, fuels and artefacts
- For evolution to a PN-PEMS system, parallel studies:
  - of pressure impacts on dilution ratio
  - considering the need for ET or catalytic stripper
  - Considering more efficient packaging
  - simulation of particle evolution from tailpipe to measurement via CVS and impact on CF

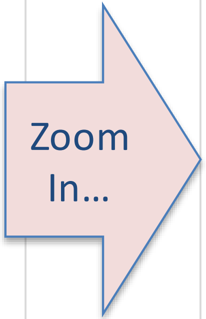
DTT lab-based prototype compliant with current PMP specifications – when used with 23nm d50 particle counter

- DTT prototype can be considered compliant with current PMP requirements, d_{50} ~ 23nm
- Excellent linear agreement between the DTT system and Horiba 2000SPCS above 1#/cm^3 across a wide concentration range (four orders of magnitude)
- Additional <23nm capability with alternative / additional particle counter
- Parallel use of <23nm **"PN⑩"** and ~23nm d50 particle counters **"PN23"** from the DTT prototype enabled <23nm PN production to be studied

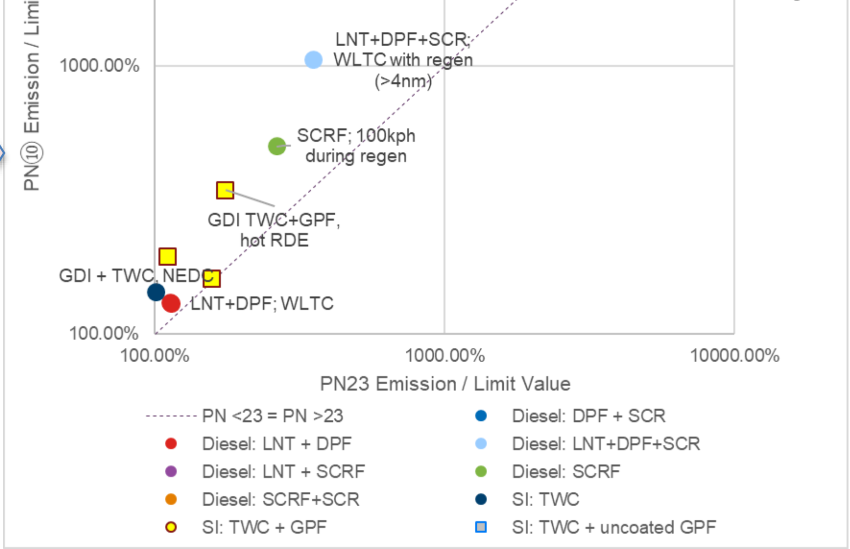


Global regulatory drive cycles: Majority of Tests below $6x10^{11}$#/km for PN⑩ and PN23. But…

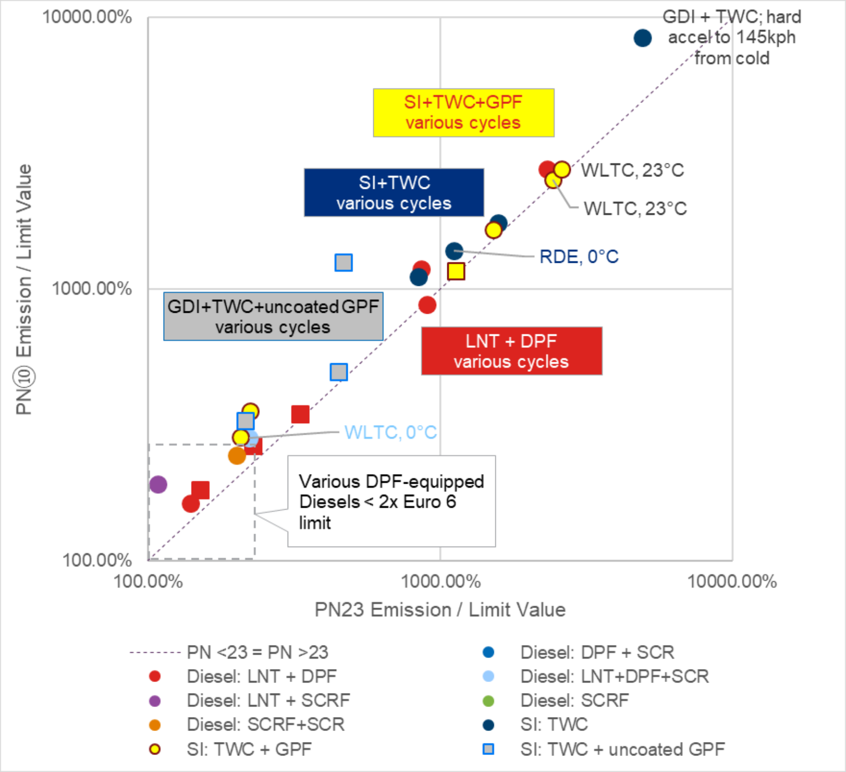




A few results demonstrate emissions levels of PN⑩ up to ~10x the current limit value, with these tests also exceeding the limit value for the PN23 range

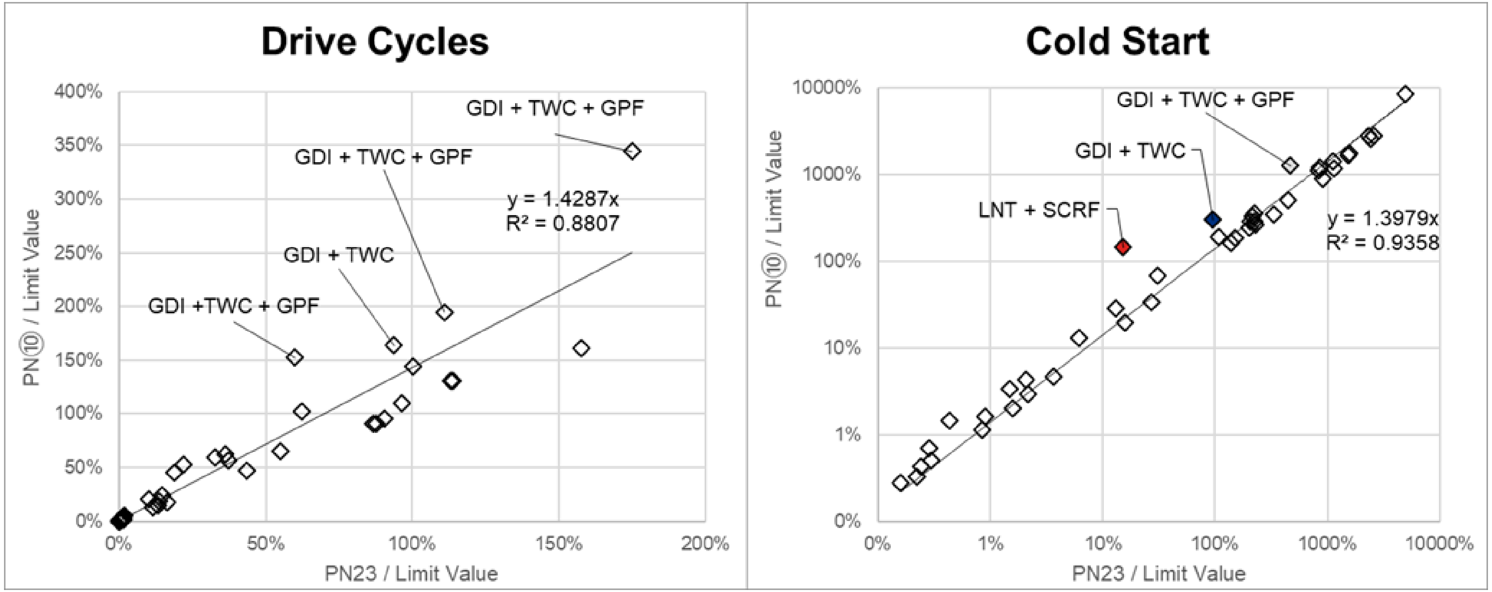


Discrete discontinuous events, in this case cold start, indicate instantaneous high emissions



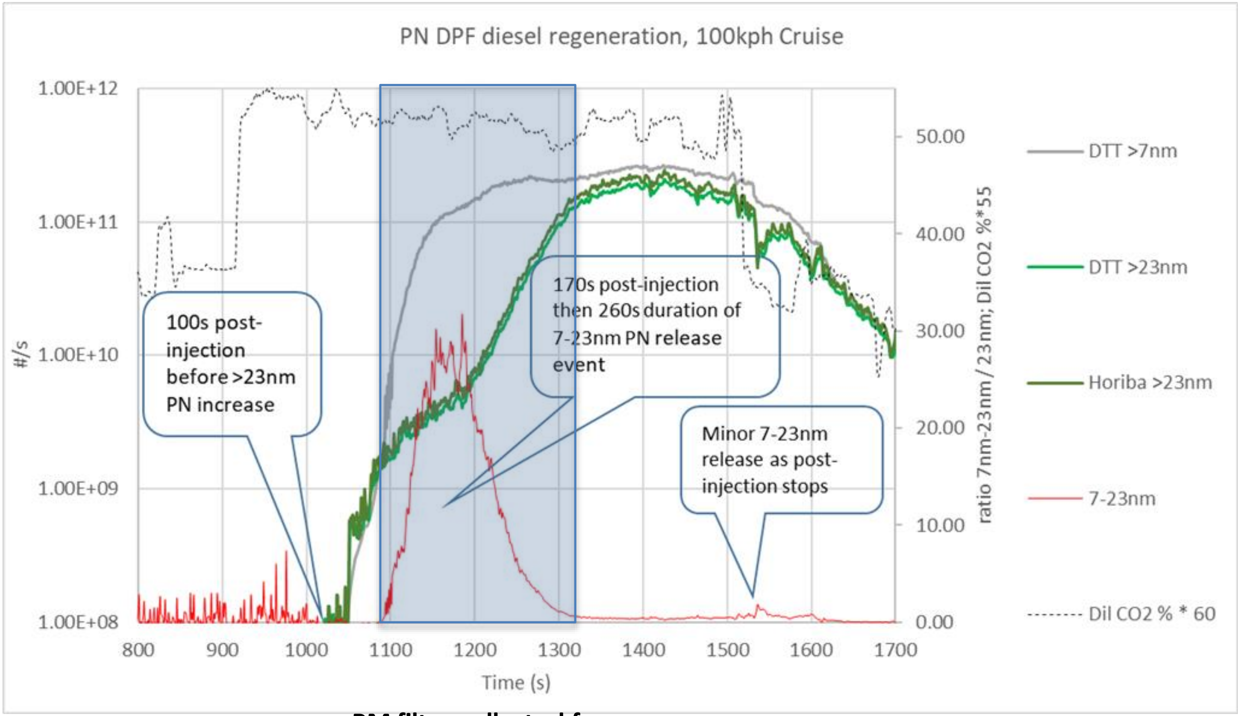
- Short-term events (~100s) compared to Euro 6 limit value
  - Cold start would not be regulated in isolation!
- Applications with highest emissions tend to be SI, even with GPF
  - Indicative of cold-start PN challenge with SI applications
- Some diesels are marginally over the "limit"

Ratio of PN⑩ to PN23, Drive Cycles and Cold Start Period



- The average increment between PN23 and PN⑩ is ~40%
- However, there are tests, primarily on GDI, where the increment is greater, and the PN emissions of PN23 and/or PN⑩ are above the limit value
- But, the ratio of PN⑩/PN23 did not exceed 4, and in the majority of cases, this was below 2

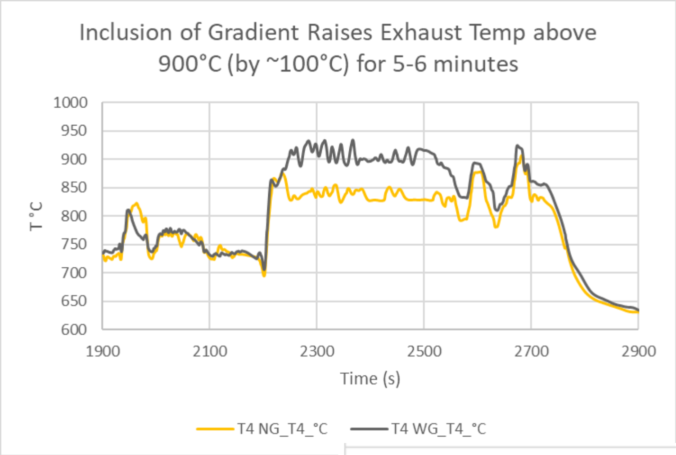
You can find <23nm PN from DPF Diesels, these birthed by the fires of regeneration…

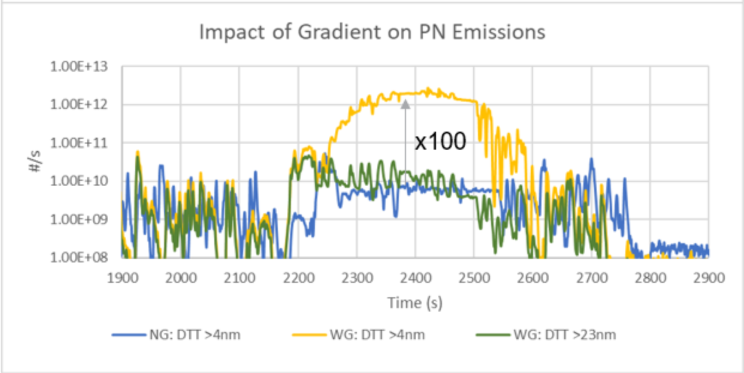


PM filter collected for chemical analysis of <23nm PN [TUM]

- There is a <23nm particle production event that takes place a few minutes after post-injection starts. This leads to emissions of <23nm particles at levels 10 to 100x times those seen in the >23nm range for a period of 2-3 minutes
- **These particles are not numerous enough to influence a pass or fail result at the Euro 6c PN limit once the Ki factor is included**

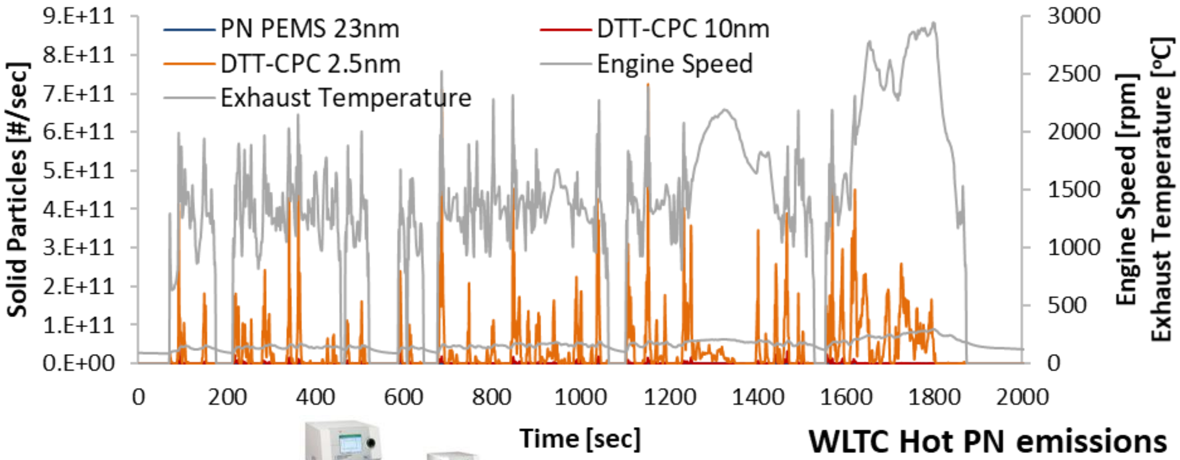
Non-volatile "artefact" <23nm particles can be produced by a test facility under extreme conditions

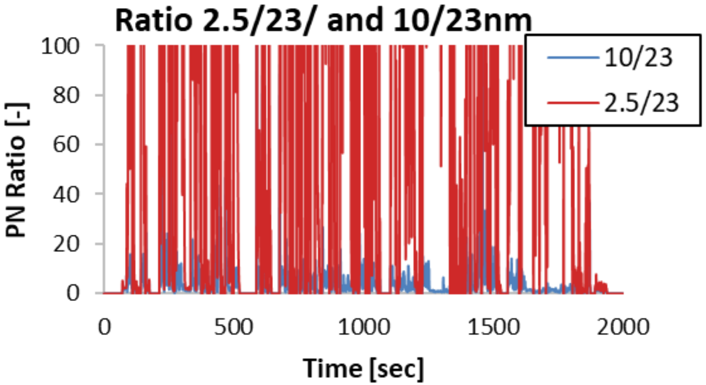


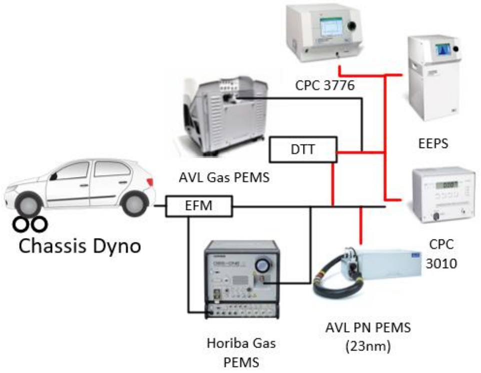


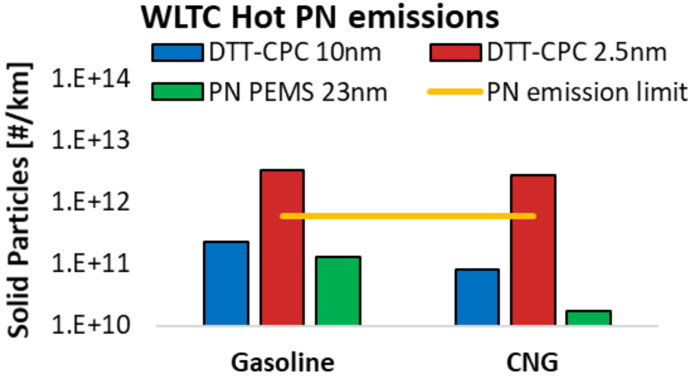
- ARTEFACT
  - High temperature artefact identified while using GDI engine at extreme conditions: exhaust temperature post-4WC at ~950°C
  - 100x increase in >4nm PN
  - Substantially greater impact than on >10nm, and limited impact on >23nm range
  - Believed to be transfer line artefact
  - **Outside the range of any regulatory cycle and close to the maximum RDE**
  - **RAW lab measurements would avoid this possibility**

High-load light-duty CNG (no GPF) operation shows PN2.5 >10^{12}#/km – but PN23/PN10 < 6×10^{11}#/km









Average ratios

- 10/23 ratio 3.7
- 2.5/23 ratio 133.7

Significant particle emissions for 2.5nm cut-off size-range under high loads

What have we learnt so far about the origins and numbers of <23nm PN, and how to measure them?

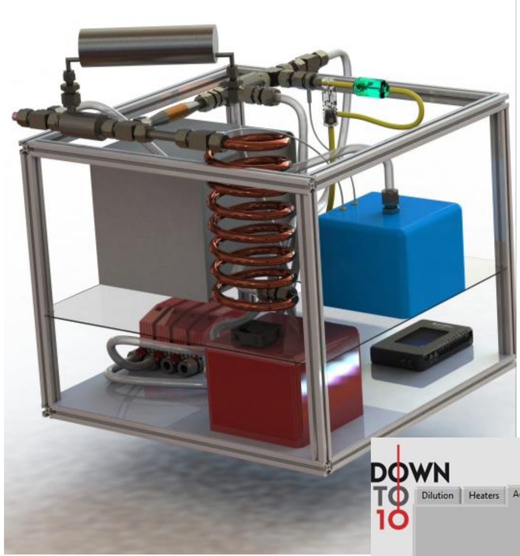
Solid particle relevant conclusions / What we've learned

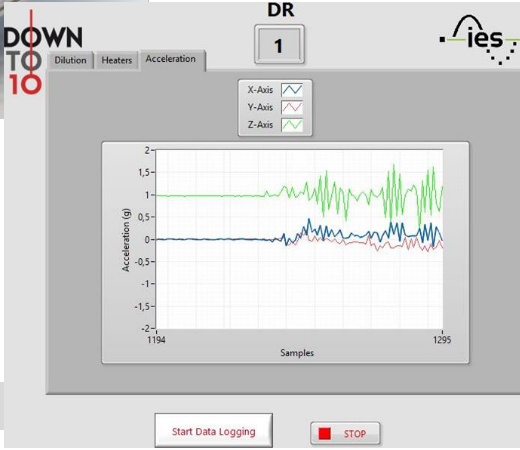
- With a PCRF calibration the CVS-based DTT prototype is fully compliant with current requirements for 23nm d50 measurements. Elevated measurement uncertainty arises below 30nm and will need to be a primary aspect of calibration activities.
- Indications from globally-relevant drive cycles, on both SI and CI applications, are that PN >10nm increases relative to PN >23 by ~40% on average, but most results are sub $6x10^{11}$#/km
- There are discontinuous events that lead to short-term increases in particles 10-23nm. These increases (>10x) have moderate drive cycle impacts; highest cycle emissions observed were ~4x the limit
- Highest >10nm PN emissions were observed from SI vehicles, with and without GPF, and from diesels with DPF/SCR/LNT.
- Trends in >10nm PN increases were also reflected in >23nm PN.
- From the current data there is no obvious indication that changing the lower regulatory size boundary to ~10nm is necessary, but initial indications suggest particle traps would be beneficial for CNG
- Potential measurement artefacts, primarily impacting the <23nm size range, indicate that it may be advisable to compare <23nm PN-PEMS with a raw exhaust lab-based <23nm measurement system, rather than a CVS-based one

DTT on the road (WP4)

The DTT PN PEMS

- Dimensions: 50x50x50 cm
- 2 CPCs: 10 nm, 23 nm
- ~ 100 W required heating power
- Optimized Catalytic Stripper
- Battery pack for energy supply
- Dedicated software





Test matrix

Overview on the tests planned inDTT WP 4									
	....fits in test progam proposed in Grant Agreement								
	....does not fit in test progam proposed in Grant Agreement								
red fonts	missng info and missing vehicle categories								
Category	**Vehicle**	**EURO class**	**Fuels**	**Technology variations**	**Lab**	**veh DTT No.**	**Timeline**	**Link Sheet "Vehicle Details"**	**Comment**
Pass cars diesel	Serial	EU6d-temp	D7, Biofuel blends on demand	none	TUG	1	09/2018	Diesel EU6 engine with various fuels and DPF regen strategies	
Pass cars diesel	engine dyno	EU6d	D7 with Blends of HVO, OME, Kerose	Variations in applications on demand	TUG	2	12/2018	Diesel EU6 engine with various fuels and DPF regen strategies	
Pass cars diesel	Serial	EU6a	D7	different DPFs	LAT	3		Diesel EU6a passenger car (1.6l)	
Pass cars diesel	Serial	EU5	D7	none (basic = DOC+DPF)	LAT	4		Diesel EU5 passenger car (2.0l)	tbd how many EU5 shall be tested (depends on available reso
Pass cars diesel	Serial	EU5	D7	none (basic = DOC+DPF+LNT)	LAT	5		Diesel EU5 passenger car 2.0l	needed?
Pass cars diesel	Serial	EU4	D7+HVO+FAME blends	none (basic = DOC)	LAT	6		Diesel EU4 passenger car (2.2l)	needed?
Pass cars diesel	from Dieper	EU6	D7	(DOC or PNA or LNT)+SCRF+u/f SCR PC (DIEPER)	AVL	7	01/03/2019	Euro 6 (DOC or PNA or LNT)+SCRF+u/f SCR PC (DIEPER)	
LDV diesel engine 1,4l	engine dyno	EU6	D7	aftertreatment customizable according to our needs	LAT	8		Diesel EU6 LD engine (1.4l) (dyno)	tbd if veh 8 and 9 shall be tested (if capacity needed for HEVs)
LDV diesel engine 2.0l	engine dyno	EU6	D7	aftertreatment customizable, can be operated as GDI and/or PFI	LAT	9		GDI EU6 LD engine (2.0l) (dyno)	
LDV diesel engine 2.2l	engine dyno	EU5	Market fuel + HVO (100%) + FAME bl	aftertreatment customizable according to our needs	LAT	10	<11/2018	Diesel EU5 LD engine (2.2l) (dyno)	tbd if vEU5 engine shall be tested (if capacity needed for HEV:
Pass car gasoline	1.8 GDI	EU6b	Reference gasoline	?	CRF	11	01/2019	1,8 GDI - EU6b with GPF	
Pass car gasoline	Serial GDI	EU6d-temp	Reference gasoline, Biofuel blends o	none	TUG	12	11/2018	EU6d-temp serial otto car	
Pass car gasoline	1.0 3cyl from GasOne p	EU6	Reference gasoline	?	CRF	13	>06/2019	from uPGrade project: E6d-Jeep Renegade 1.0l 3 cyl engine TC VVA GDI	
Pass car gasoline	GDI + 4WC (from upgra	EU6	reference fuel (D7) + china fuel	none	AVL	14	ongoing<06/	Euro 6 GDI+4WC (UPGRADE)	
Pass car CNG	1.0 3cyl from GasOne p	EU6	NG	?	CRF	15	>10/2018	from GasOne project : EU6 -500L 1.0 l 3 cyl engine TC VVA with methane DI	ok, oone CNG promised in GA
Pass car HEV	missing	EU6	Reference gasoline		??	16			
Pass car HEV	missing	EU6	D7		??	17			
HDV diesel	Serial	EU VI	D7	variation NH3 dosing, DPF cell density, crankcase ventilation me	TUG	18	10/2018	HDV (EU VI tractor)	
HD diesel engine 3.0l		EU VI	D7	aftertreatment customizable according to our needs	LAT	19	>11/2018		
HDV CNG	missing		NG		??	20			
2-Wheeler gasoline	missing <50ccm	EU3			??	21			
2-Wheeler gasoline	missing > 50ccm	EU4			??	22			
	missing > 50ccm	EU3			??	23			do we need EU3 + EU4 to check development?

- WP4 testing focuses on:
  - Testing conditions previously shown to release high <23nm PN, H2020 engines and vehicles and other new technologies
  - PN-PEMS development and robustness

October 2018 Perspectives

October 2018 Perspectives 1/2

Primary (solid) particles

- Is it necessary to drive the regulation to sizes below 23 nm, i.e. are we really missing an important part of the PN?
- Do losses and artefacts prevent us going lower than 23 nm?
- Can we robustly measure sub23 nm particles in the real world?
- Do we obtain the “same” results on the CVS and with PEMS?
- Can solid PN regulation provide effective control of vehicle contribution to air quality PM?

October 2018 Perspectives 2/2

Delayed primary (volatile) and secondary particles

- Is it enough to measure solid particles only?
  What are we going to do with the total PN (i.e. incl. volatile particles)
- Do we need to understand the chemical composition of particles? Size resolved? Do we need that?
- Why does regulation ignore the secondary aerosol?
  - We need to further work for the development of representative measurement methodology

DOWN TO 10

WE ARE EXPLORING
THE **DOWN TO TEN**
WORLD OF EMISSIONS
AND WE WILL WORK
TOGETHER TO BRING IT
TO SUPER LOW LEVELS.

HORIZON 2020