EVALUATING THE PERFORMANCE OF A PARTICLE COUNTING SENSOR BASED ON CONTINUOUS WAVE LII

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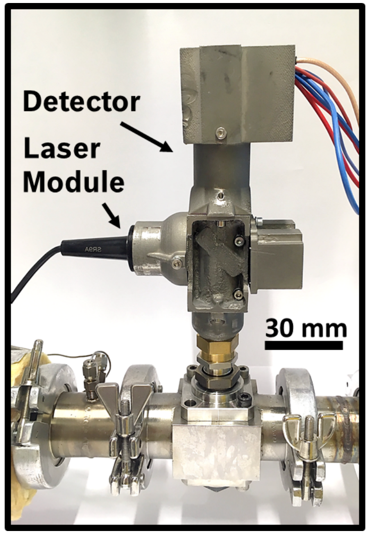
Performance of a Particle Counting LII Sensor
Motivation

Goal: Development of an optical sensor to determine the (soot) particle number

- ▶ Monitoring of particle number concentrations also for the sub-100 nm range
- ▶ Creating a compact & low-cost sensor for measurements close to the particle source



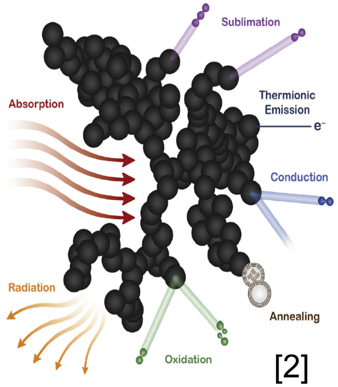
[1]

State of the art of optical particle sensors:

- ▶ Scattering-based optical sensors: limited to particle diameters >100 nm
- ▶ Condensation particle counters & LII systems: too bulky for universal, mobile use

Performance of a Particle Counting LII Sensor
Laser-Induced Incandescence

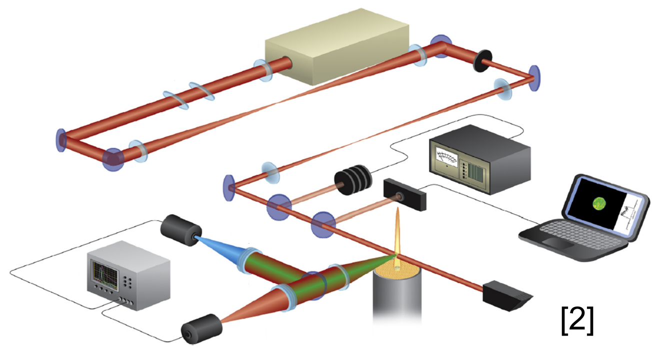
- Heating of nanoparticles to temperatures above 3000 K through **absorption of optical energy** emitted by a laser
- Heated particles emit broadband **incandescence light**, which can be captured by a photodetector



[2]

Available LII methods:

- Most LII systems rely on bulky (nanosecond) **pulsed**, high-power Nd:YAG lasers
- Pulsed LII setups cannot count <u>individual</u> soot particles
- Commercially available CW-LII device SP2(-XR)[1] provides this counting capability


[2]

➡ **Continuous wave** LII as a possible solution with the potential for a compact realization

[1] Droplet Measurement Technologies

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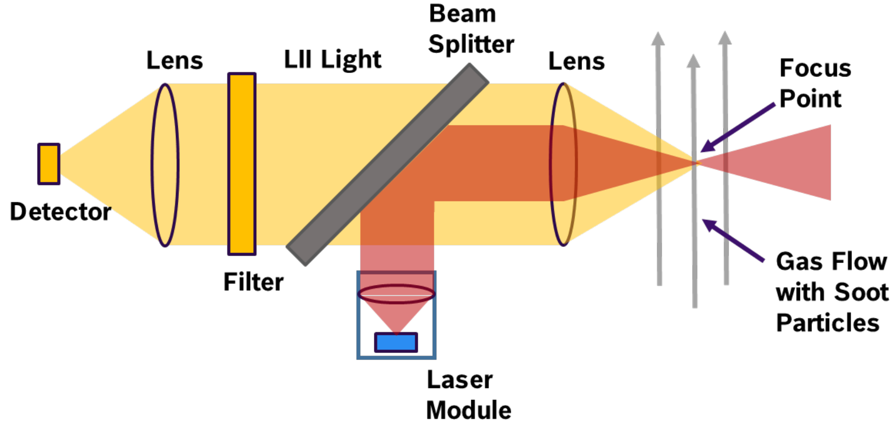
Performance of a Particle Counting LII Sensor
Sensor Demonstrator Design & Setup

- **Laser source: NIR laser diode** (currently: λ=830 nm, P=650 mW)
  - Beam shaping to focus the laser beam to a µm-sized spot to create a particle detection area with high power densities (up to $10\uparrow6\ \mathrm{W}/\mathrm{cm}^2$)
- **Compact optics design**
  - Collinear guidance of excitation & detection light
  - Intensity difference (laser & LII) requires highly efficient filter systems
- **Detector: Silicon photomultiplier array - SiPM**
  - Highly sensitive for light intensities ranging from several pW to nW
  - Several hundred (parallely connected) pixels operated in Geiger mode

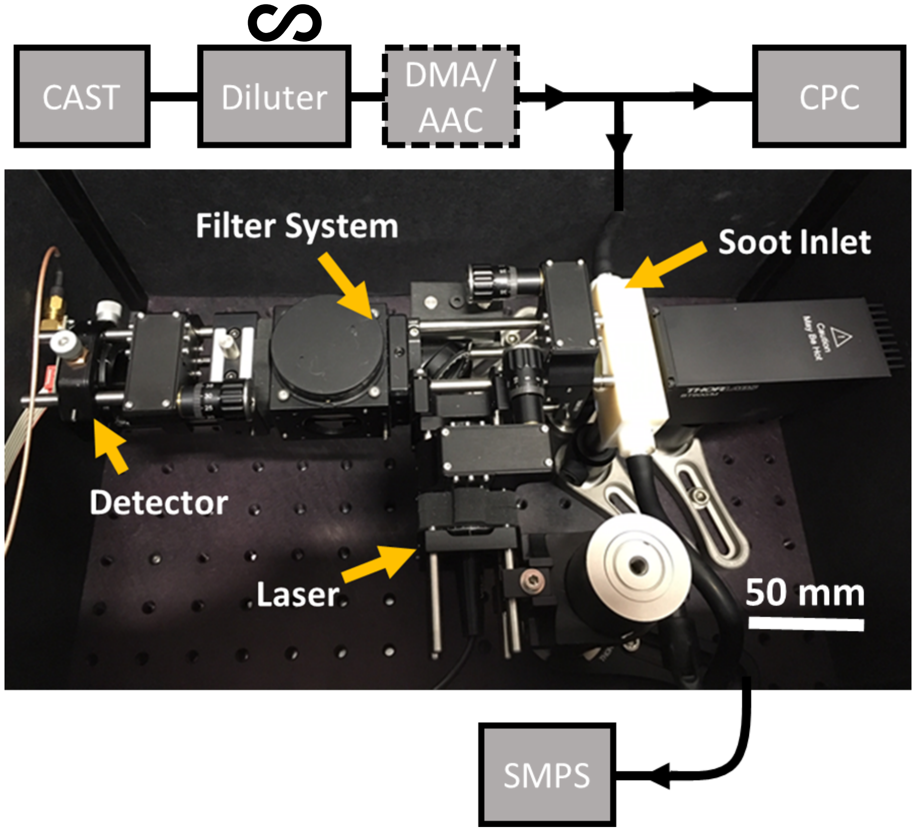


Performance of a Particle Counting LII Sensor
Sensor Characterisation Setup

- **Soot source**: miniCAST 5203C
- **Diluter**:
  - Dekati eDiluter with variable dilution ratios
  - Dekati DI-1000
- **Particle size selection:** DMA or AAC

- **LII laboratory demonstrator:**
  - Easy to align, change & test components
  - Potential for compact setup

- **Reference devices**:
  CPC (Airmodus), SMPS (TSI)



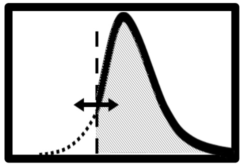
[3]

Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Methods

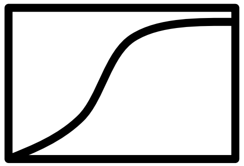
- **Detection limit** as a key performance indicator
  → measurement capability for soot particles w/ diameters below 100 nm as a goal
- Difficulty of a direct determination due to sensor characteristics & soot properties

Evaluation of the sensor performance

1. **Indirect procedure for a quick estimation and simple check of cause-effect relationships and parameter variations**



2. **Measurement of "quasi-monodisperse" particle distributions for a calculation of the sensor's size-dependent detection efficiency**



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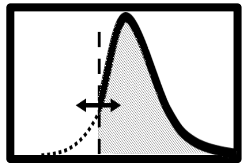
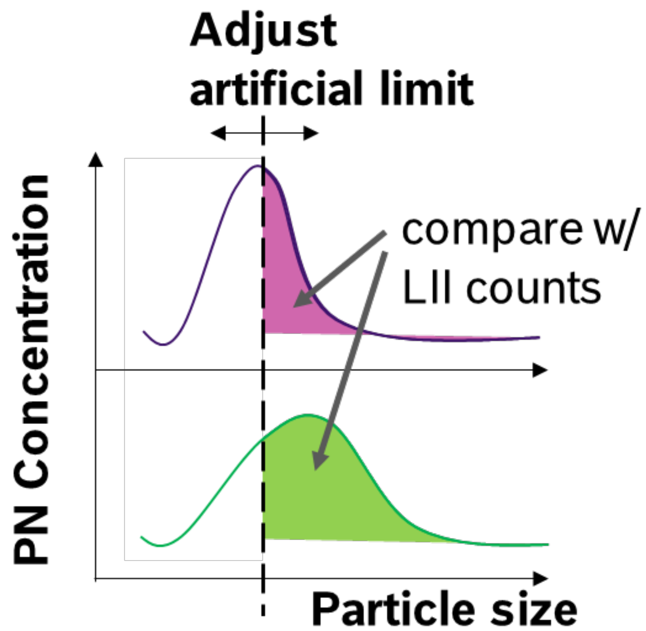
Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Pt. 1



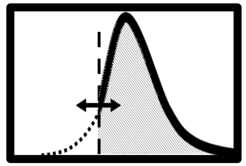
Approach: Indirect ratiometrical measurement procedure for detection limit

- Measurement of particle size distribution with reference equipment (e.g. SMPS)
- Simultaneously measure LII events (#/min) with sensor demonstrator
- Cut of reference data by introducing an artificial detection limit
- Adjust artificial detection limit, until comparison between LII & reference particle concentration data match for several measurements with different CAST particle size distributions

- Assumption of size-independent detection efficiencies gives a rough approximation of sensor performance

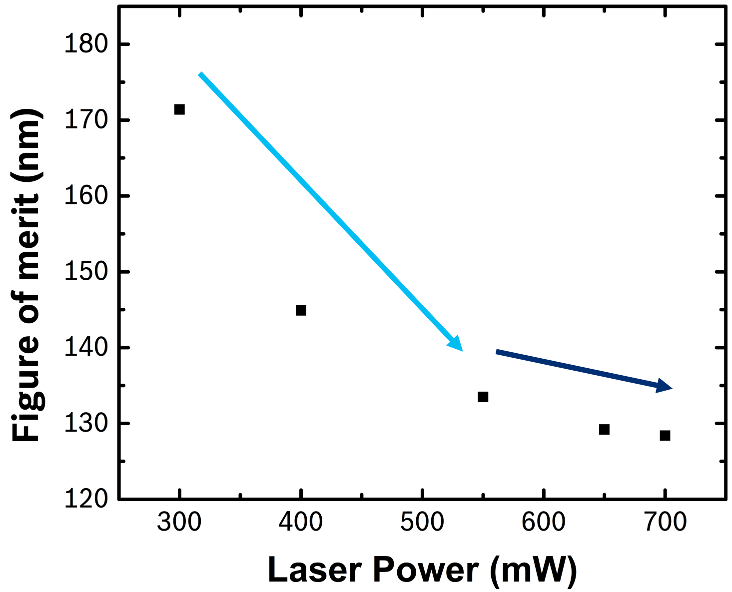


Performance of a Particle Counting LII Sensor
Dependencies of the Sensor Performance



- Gain sensor knowledge by evaluating influences of varying parameters:
  - **Laser power (power density within focus area)**
  - Lens combinations
  - Particle velocity
  - Flow orientation compared to laser beam orientation

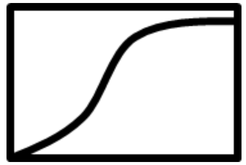
Figure of merit:
Adjusted artifical detection limit



Example: Change of laser power from 300 to 700 mW

- Initially strong decrease of the calculated figure of merit **(300 to 550 mW)**
- Saturation for a further increase of the laser power (density)

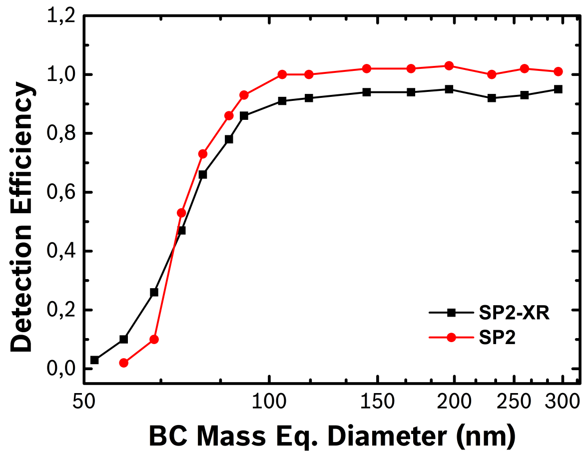
Performance of a Particle Counting LII Sensor
Determination of the size-dependent detection efficiency



Sharp cut-off limit does not reflect the sensor’s real behaviour:

- Typically, a transition area with size-dependent detection efficiencies can be observed
- Geometry of the focused laser beam is reason for a size-dependent detection area

Efficiencies of the SP2(-XR)



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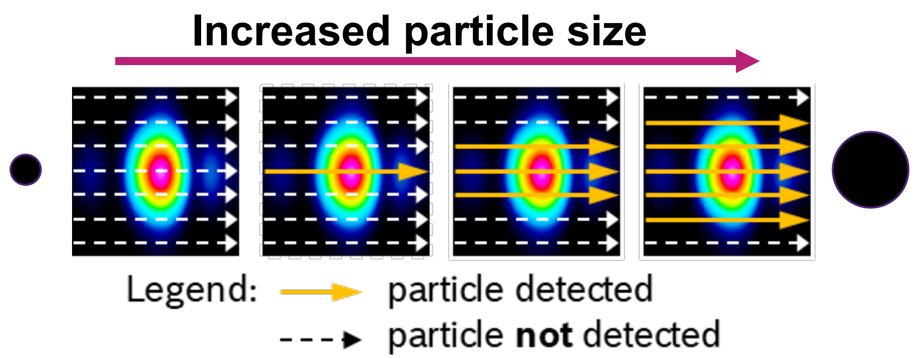
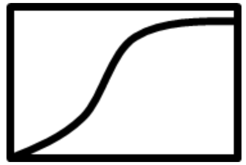
Detection area of LII sensor

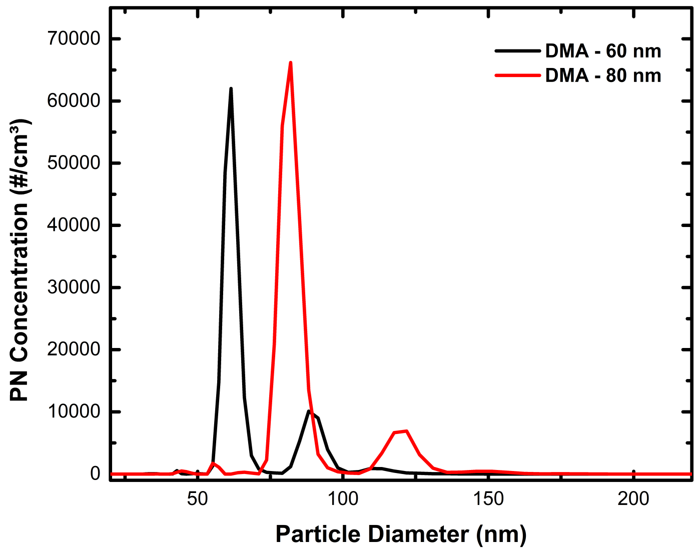


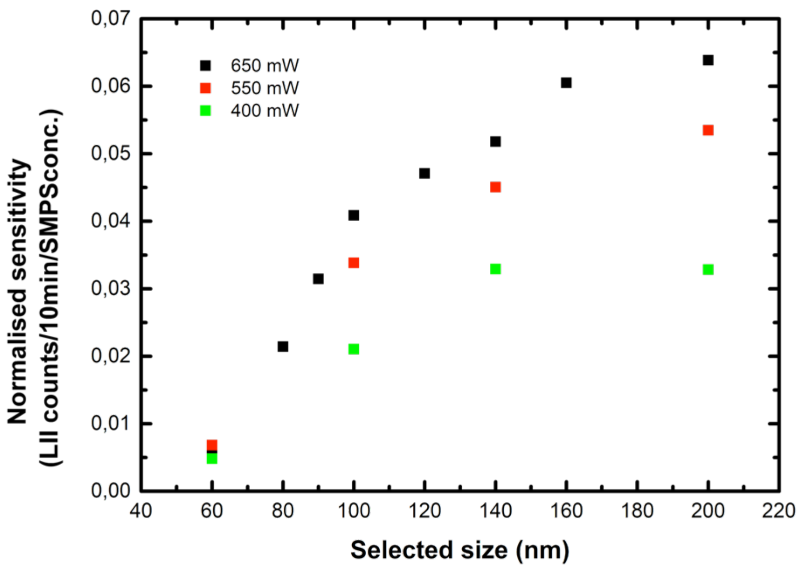
Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Pt. 2



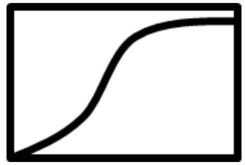
- Detection limit not as a sharp edge, but as a **size-dependent detection efficiency curve**
  - Cut-off diameter as the smallest detectable particle size

- Use of a classifier (DMA or AAC) to select a quasi-monodisperse particle size distribution





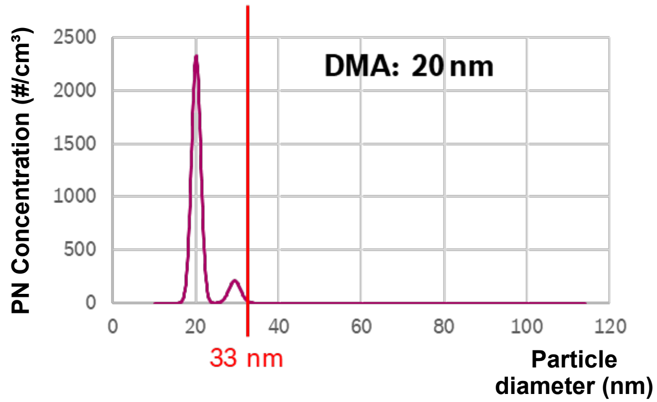
Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Pt. 2

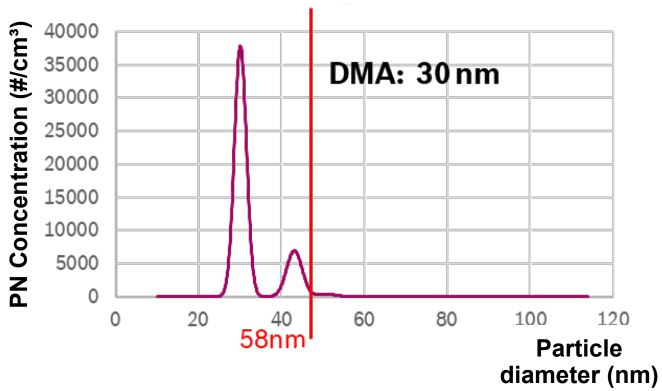


Estimation of the cut-off diameter

- Selected size: 20 nm – no LII counts
  - Largest particle diameter of this distribution (33 nm) not detectable

- Selected size: 30 nm – **LII counts registered**
  - Largest particle diameter of this distribution (58 nm) **detectable**





Cut-off diameter between 33 nm and 58 nm

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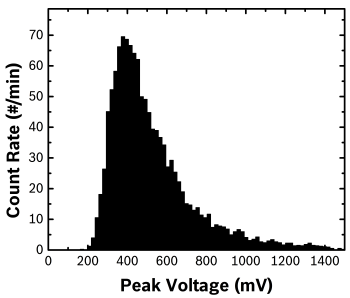
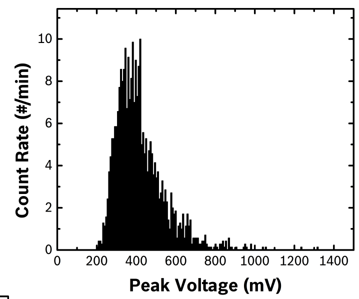
Performance of a Particle Counting LII Sensor
Determination of the Particle Size

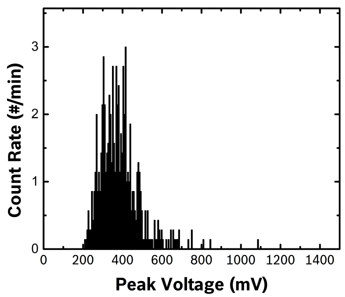
Goal:

Gain size information directly from registered LII signal shapes w/o additional device (e.g. SMPS)

- ▶ Dependency of the emitted LII signal to the soot particle diameter ($Q_{rad} \propto d_P^3$)
- ▶ Calculation of the distribution‘s mean diameter through fitting of mean data to calibration values







Distribution	Mean Peak Voltage (mV)	Mean Diameter (nm)
1	383.9	90
2	311.8	70
3	286.8	60

$$d_{mean} = \left(V_{max,\,mean} / X\right)^{Y} \cdot Z$$

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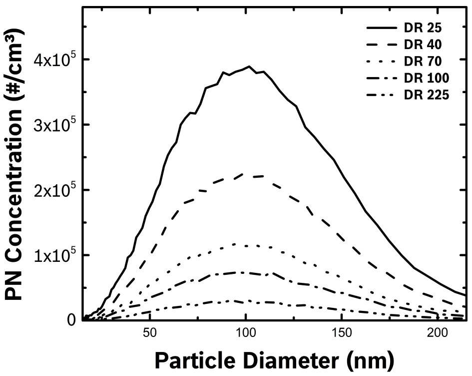
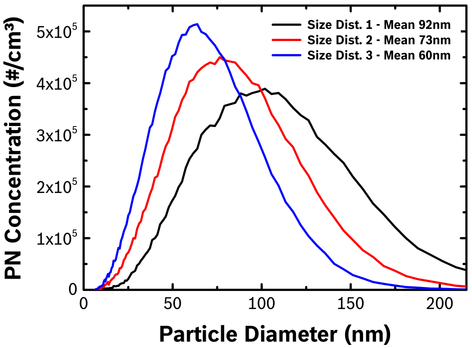
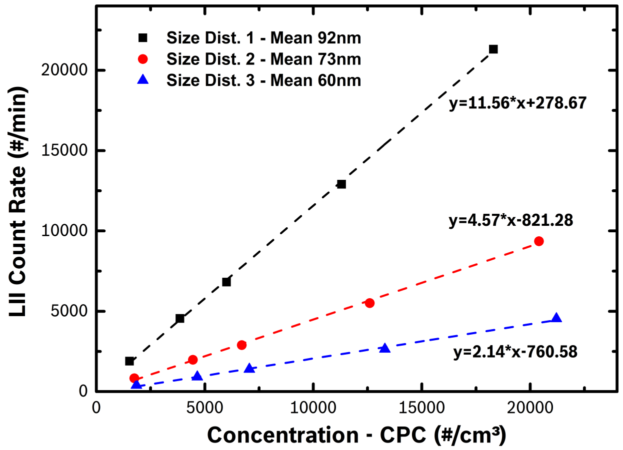
Performance of a Particle Counting LII Sensor
Particle Counting Capability

Alternation of PN concentrations



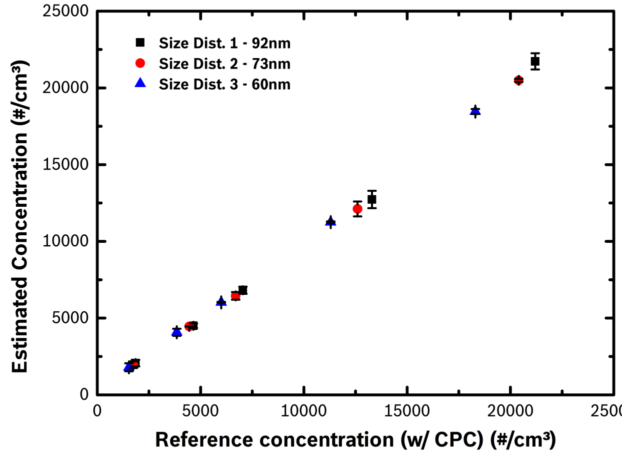


Linear relationship between LII count rates and PN concentration



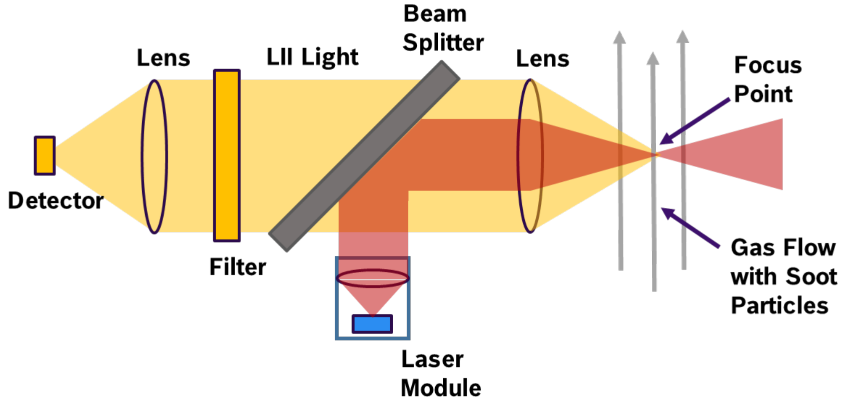
LII Counts $\times f(d_{\text{Particle,mean}})$ = Estimated Concentration

Size-independency w/ correction function based on mean diameters



Performance of a Particle Counting LII Sensor
Conclusion & Outlook

- Functional sensor demonstrator for measurement of CW-LII signals of soot particles
- Influences on sensor performance investigated
- Detection efficiency curve successfully determined
- Calculation of particle mean diameters



Next steps:

- Transfer gained knowledge to a compact sensor demonstrator
- Online determination of particle size distributions

Performance of a Particle Counting LII Sensor
Literature

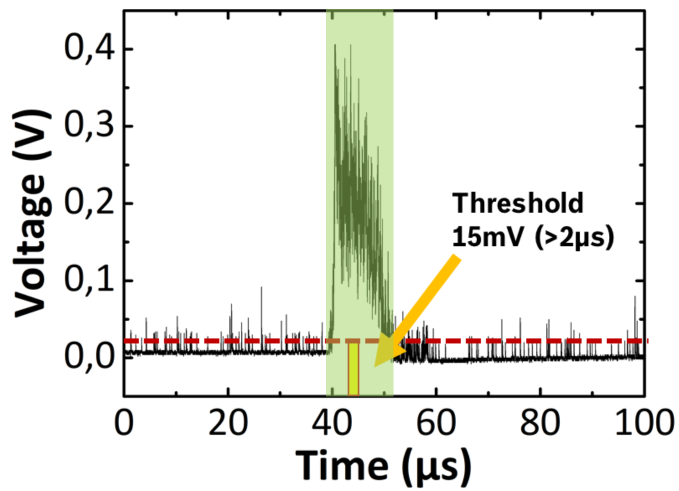
- **[1] Kammerer, M., Purkl, F. (2019).** Poster presented at the 23rd ETH-Conference on Combustion Generated Nanoparticles, Zurich, CH.
- **[2] Michelsen H.A. *et al.*.** Laser-induced incandescence: Particulate diagnostics for combustion, atmospheric, and industrial applications. *Progress in Energy and Combustion Science 51 (2015) 2–48.*
- **[3] Kammerer M., Purkl F., Geigle K.P. (2020).** Presented at the European Aerosol Conference, Aachen (online)
- **[4] Bertò M. *et al.*. (2019).** Presented at the 23rd ETH-Conference on Combustion Generated Nanoparticles, Zurich, CH.

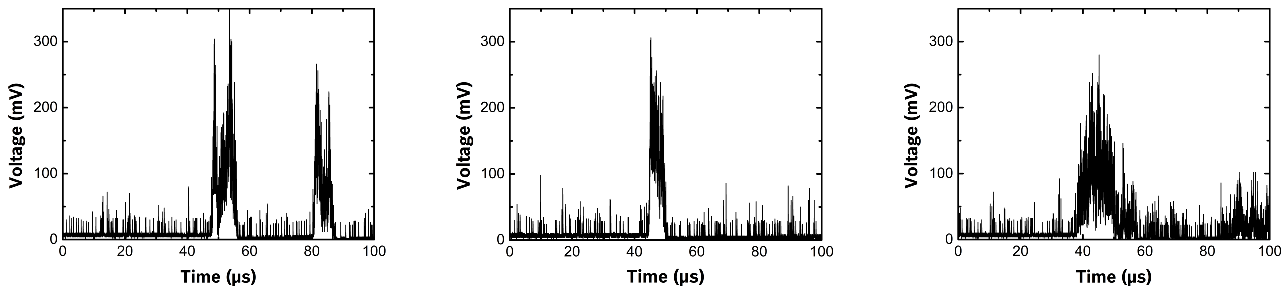
BACKUP

Performance of a Particle Counting LII Sensor
Experimental Evaluation of LII Events

- LII events are registered and counted when surpassing a set threshold (voltage **+** duration)
  - Settings depend on the demonstrator electronics' noise level

- Typical detector events show a duration of **several µs** and pulse heights ranging from 15 mV to >1 V
  - Signal duration depends on the heat-up time and duration of particles propagating through laser focus (and focus geometry)
  - Intensity relates to individual particle size





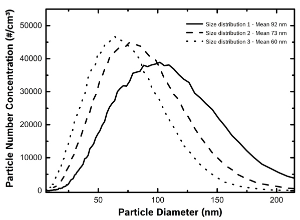
Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Pt. 1

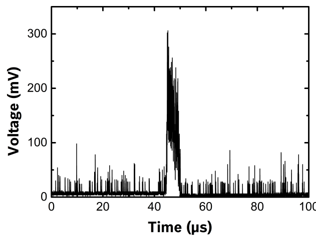
▶ Ratiometrical method to ensure a fast assessment of the sensor performance

Measurement of particle size distributions w/ SMPS

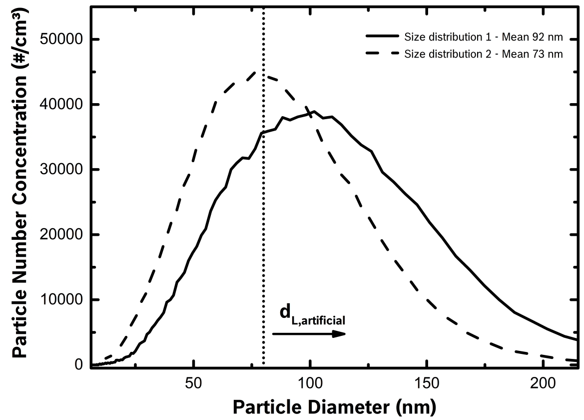
&

Record LII events per time

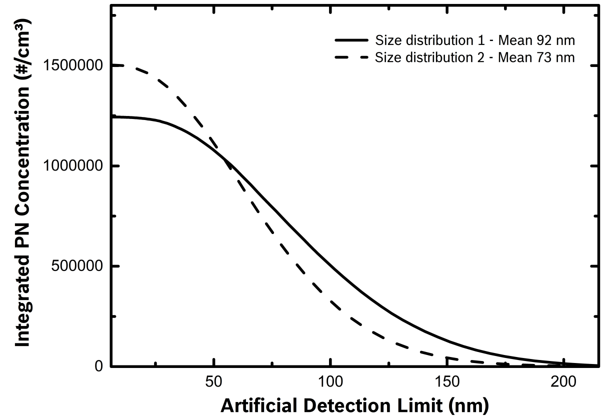




Introduction of an artificial lower limit $d_{L,\text{artificial}}$ for SMPS measurements



Sum of PN concentrations starting at $d_{L,\text{artificial}}$

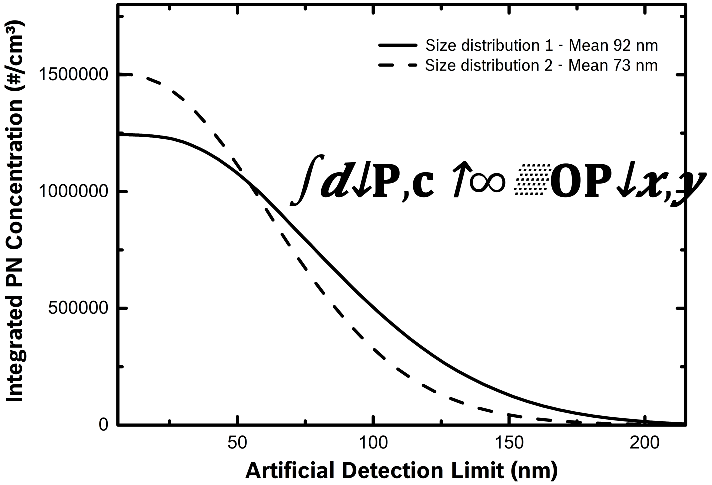


Performance of a Particle Counting LII Sensor
Determination of the Sensor Performance – Pt. 1

- Ratiometrical method to ensure a fast assessment of the sensor performance

Sum of PN concentrations starting at $d_{L,\ artificial}$

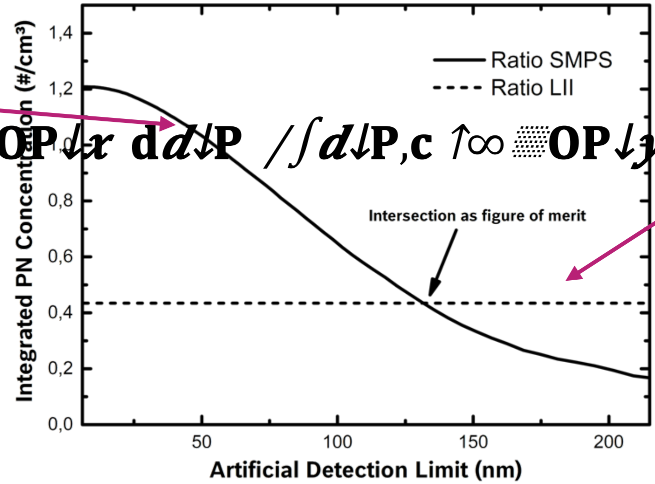
$$\int_{d_{P,c}}^{\infty} OP_{x,y}\, dd_P$$



Compare LII count ratio for corresponding measurements to SMPS ratio

$$\int_{d_{P,c}}^{\infty} OP_x\, dd_P \Big/ \int_{d_{P,c}}^{\infty} OP_y\, dd_P$$

$$\sum \#_{LII}\ ($$



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