Determination of soot size and concentration in optically dense sprays by optical methods

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Introduction

The understanding of the formation and oxidation of soot is of interest to become able to reduce the emission of soot particles to the atmosphere from direct injection engines. A possible path to study the formation of soot in diesel sprays is by laser-based optical methods, having the potential for high temporal and spatial resolution; moreover they can be combined to obtain information of soot at any given instant from the start of combustion. Laser Induced Incandescence (LII), Elastic Light Scattering (ELS) and Light Extinction (LE) have been widely used for soot studies [1]. Soot particle size and concentration can be measured simultaneously combining LII, ELS and LE, the combination of these three techniques has proven to be functional when used to measure soot in optically thin flames in atmospheric conditions [2] and exhaust gases [3]. Optically dense systems such as diesel spray combustion, and the diagnostic of soot in them, require special attention to the LII signal because of its strong non-linear dependence on the laser fluence. Moreover particular concern must be given to the enhanced conductive heat transfer term in the LII interpretation due to the high pressure inside the combustion chamber at which diesel engines are usually operated [4].

This paper presents a method to measure particle size and particle concentration in optically dense sprays in conditions similar to those prevailing in real direct injection engines. For this purpose a non-linear compensation method to approximate the laser intensity across optically dense sprays was developed together with a new non-continuum heat transfer model for the LII signal.

Experimental set up

Soot formation and evolution were investigated with simultaneous planar LII, ELS (Rayleigh scattering) and LE. Due to the relation between the size of the spray and the height of the laser sheet, the spray was divided into four different regions, vertically translating the combustion chamber to study each of them. The laser sheet had a height of 24 mm, a wavelength of 532 nm and a Gaussian temporal profile with a FWHM of 12 ns. The laser pulse was divided into two overlapping pulses delayed by 24 ns, the first one with an energy of 5 mJ for elastic scattering and a second one with an energy of 40 mJ for LII. The elastic scattering and the LII signals were acquired by two intensified CCD cameras. Before each camera there was an optical filter; the elastic scattering camera had an interference filter centred at 532 nm with a FWHM of 10 nm and the LII camera a long-pass filter whose transmittance starts at 570 nm. Extinction was measured with the aid of two beam samplers and two cuvettes, one beam sampler before the combustion chamber and one after, impinging the sampled laser light to the cuvettes containing Rodamine 6G solved in ethanol.

These studies were carried out in the Chalmers High Pressure, High Temperature (HP/HT) Spray Rig. The Chalmers HP/HT spray rig is an optically accessed combustion chamber with a volume of one litre. The conditions inside the combustion chamber were controlled to achieve operational conditions similar to those in an internal combustion engine, 50 bar and 520 °C. Pressurised and preheated air flowed at a constant velocity (0.1 m/s) through the combustion chamber. The conditions before each injection can be considered quiescent. Fuel was injected into the combustion chamber using a common rail system equipped with a solenoid injector and a vertically aligned single-hole nozzle. Two different injection pressures were studied using Swedish environmental class I diesel fuel. The measurements were made at two intervals after the start of combustion in order to obtain information on soot evolution.

Evaluation model

One of the major challenges doing LII resides in the correct evaluation of the heat transfer from the laser heated soot particles to the surroundings. At high pressures the conductive term becomes dominant; therefore special attention must be paid to it. For this purpose LII was evaluated using a new non-continuum heat transfer model developed for this work [4]. The model accounts for heat conduction based on the collisions between soot particles and pyrolysed diesel fuel molecules. The vaporisation term considers that the molecular weight of soot vapour is a function of temperature and the radiation term uses the Mie-Planck correction for black-body radiators.

Although LII is commonly believed to be proportional to the soot volume fraction, even in diesel spray combustion, this is not always true. Because of the strong dependence between LII and the laser fluence, the LII signal should not be considered to be proportional to the soot volume fraction in optically dense systems. To treat this problem it is possible to calculate the laser fluence across the combusting spray with the aid of the extinction measurements, and based on the approximated fluence to correlate the LII signal to the correspondent soot volume fraction. Another important aspect to be considered in optically dense systems is the light extinction in the direction towards the detectors, which can be compensated supposing that light is attenuated similarly along and perpendicularly to the laser plane.

The laser fluence across the spray is calculated based on the extinction measurements, thus enabling the calculation of particle size based on the ratio between the LII and the ELS signals. The ELS signal is then compensated for extinction along and perpendicularly to the laser plane. Particle concentration across the spray is calculated from the compensated ELS signal, the evaluated particle size, and the LE data. Each spray is analysed and processed individually, statistically values of 50 different and consecutive sprays were processed for each operational condition.

Results and conclusions

Measurements of the size and concentration of soot across the sagittal plane of the spray are presented for each operational condition. It is possible to observe that particles far away from the injection nozzle are bigger than the particles closer to the nozzle, and also that the particles found in the spray just after the start of combustion are smaller than particles found at later times. Furthermore it was noticed that increased fuel injection pressure leads to smaller particles although the number of particles remains without dramatic changes. This work shows that it is possible to calculate particle size and concentration even in optically dense systems with high light extinction i.e. up to ninety percent. This procedure enables studies in diesel flames using commercial fuels under engine like conditions.

Acknowledgements

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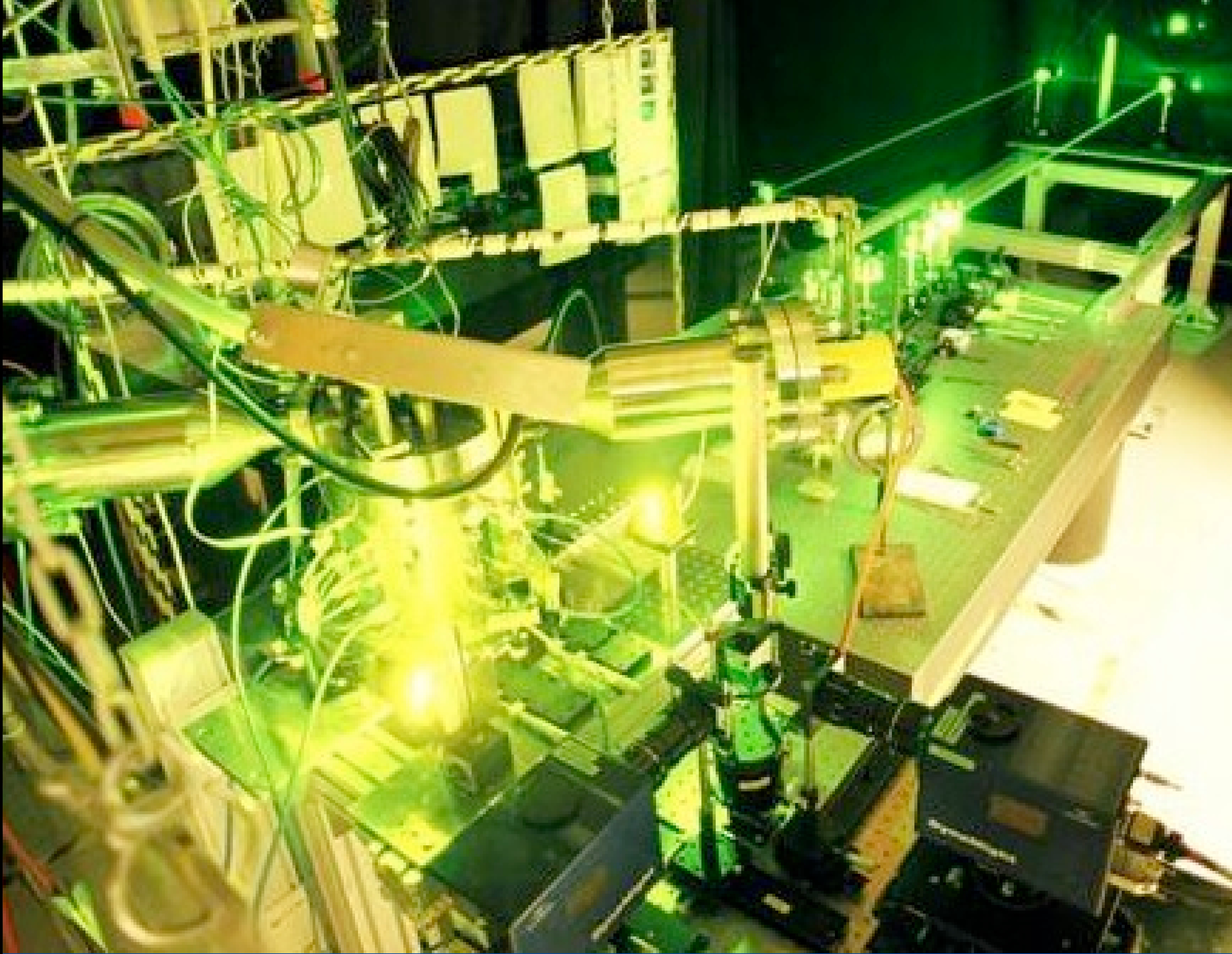
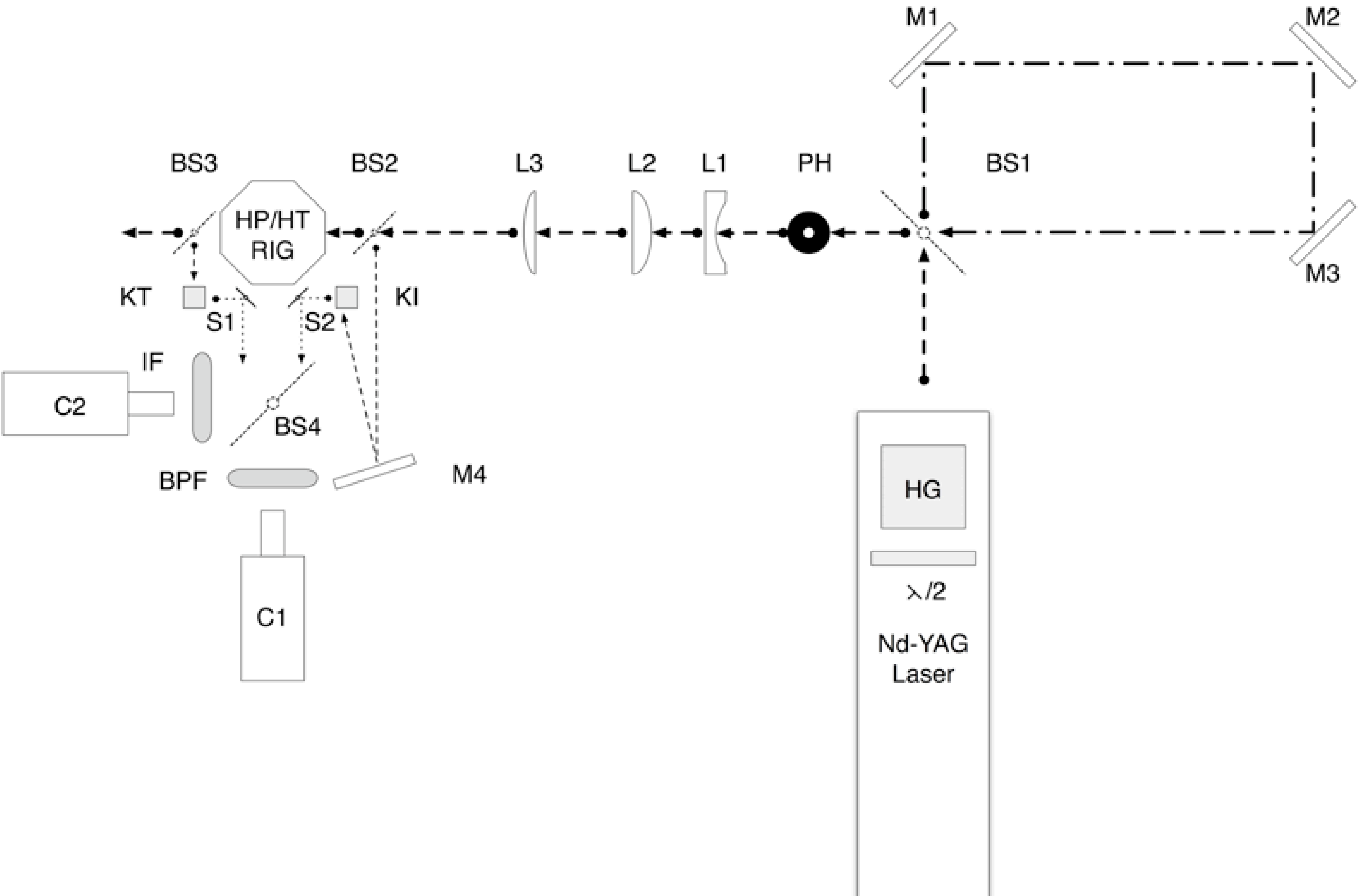


Chalmers HP/HT spray rig

- Optically accessed combustion chamber (<2 litre volume)
- Preheated and pressurised air flows through it ("quiescent conditions")
- Controlled gas temperature (500-630˚C)
- Controlled gas pressure (30-100 Bar)
- Common rail injection system with a single-hole vertically aligned nozzle


M1
M2
BS3
BS2
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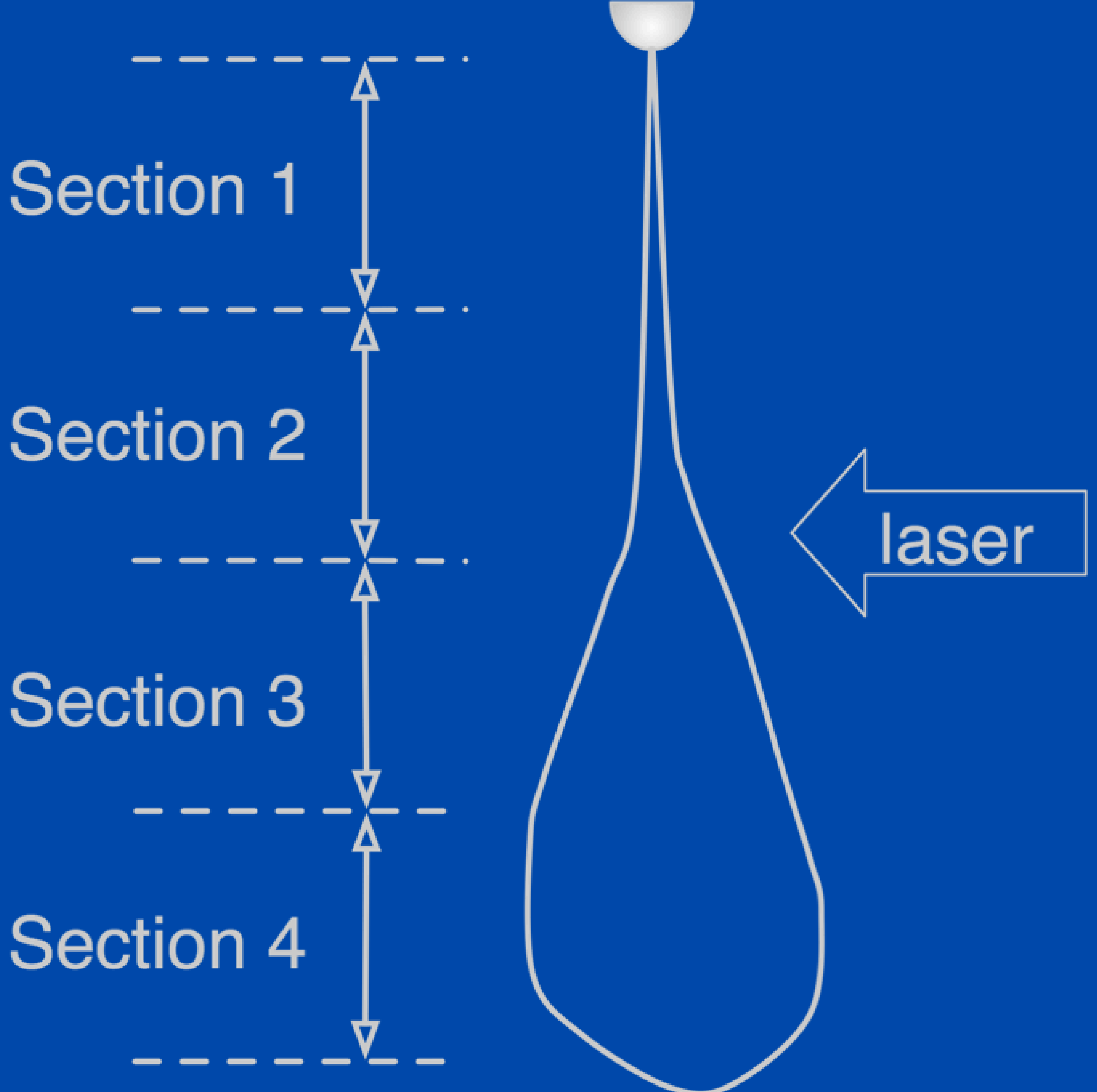
L2
L1
PH
BS1
HP/HT RIG
M3
KT
S1
S2
KI
IF
C2
BS4
BPF
M4
HG
C1
λ/2
Nd-YAG Laser

Complex laser diagnostics

- Simultaneous laser measurements in optically dense sprays (size and concentration)
  - Laser induced incandescence (LII)
  - Elastic scattering (Rayleigh scattering)
  - Light extinction


Section 1
Section 2
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Section 4
laser

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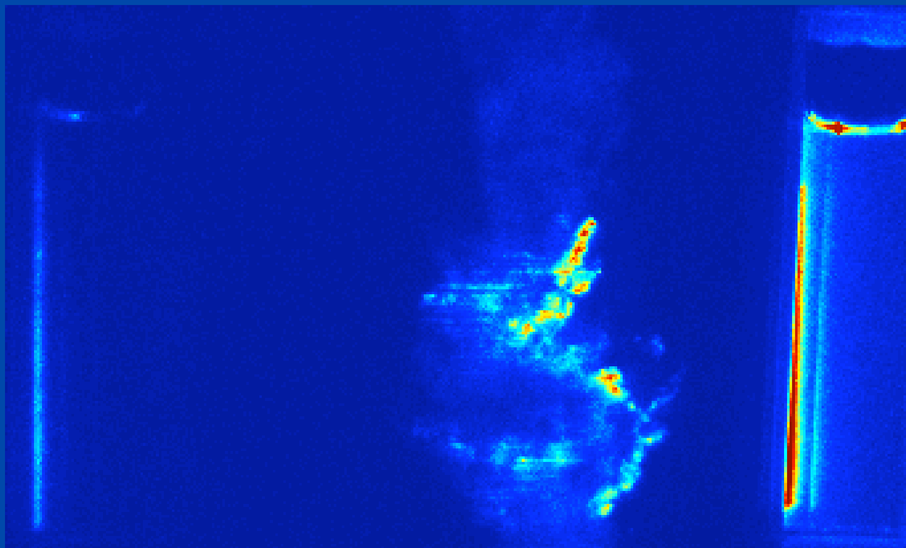
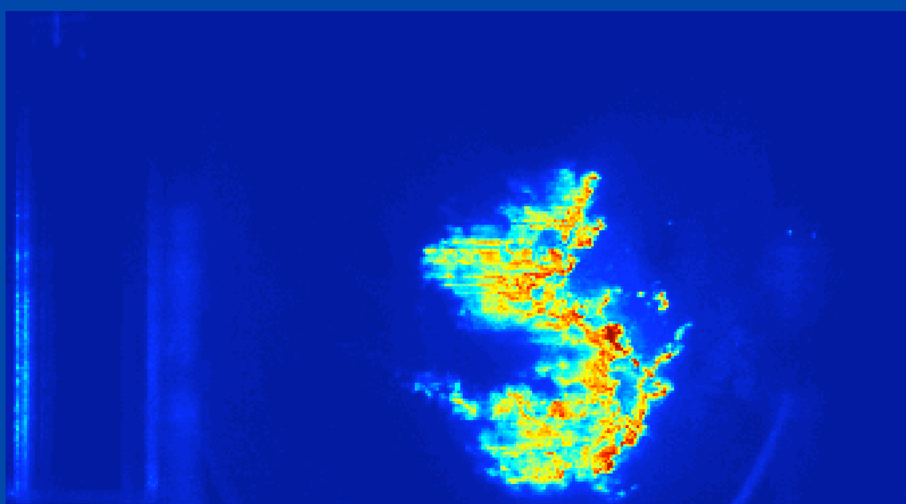


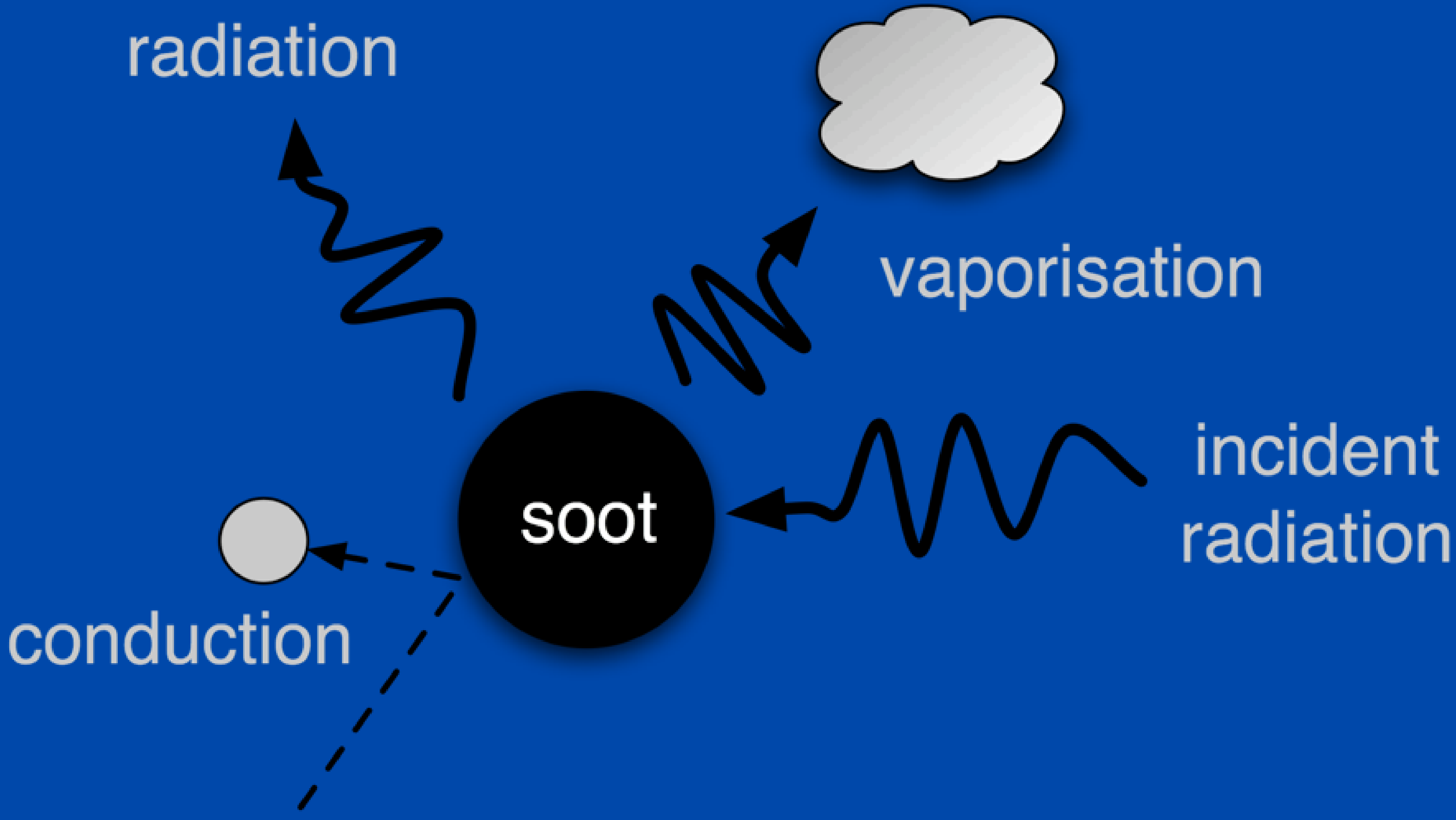
LII signal (non linear)

$f(N, V, I_i, E(m), \dots)$



Rayleigh signal

$f(N, V^2, I_i, \dots)$


radiation
vaporisation
incident radiation
soot
conduction

Evaluation models

- New non-continuum heat transfer model for superheated soot particles developed and implemented
- Non linear compensation method for particle size and concentration measurements

NCHTM (1)

- Based on collisions between soot particles and gas molecules (Non-continuum)
- Gas pressure and gas temperatures differences are considered (Not done in published LII models)
- Soot molecular weight, $C_{v(p)}$ and $C_{v(g)}$ vary with temperature

NCHTM (2)

- Soot vapour pressure, vaporisation enthalpy and molecular weight vary with temperature
- Radiation is calculated using a nanoparticles approach with a constant complex refractive index by means of the Mie-Planck correction (used in astrophysics)

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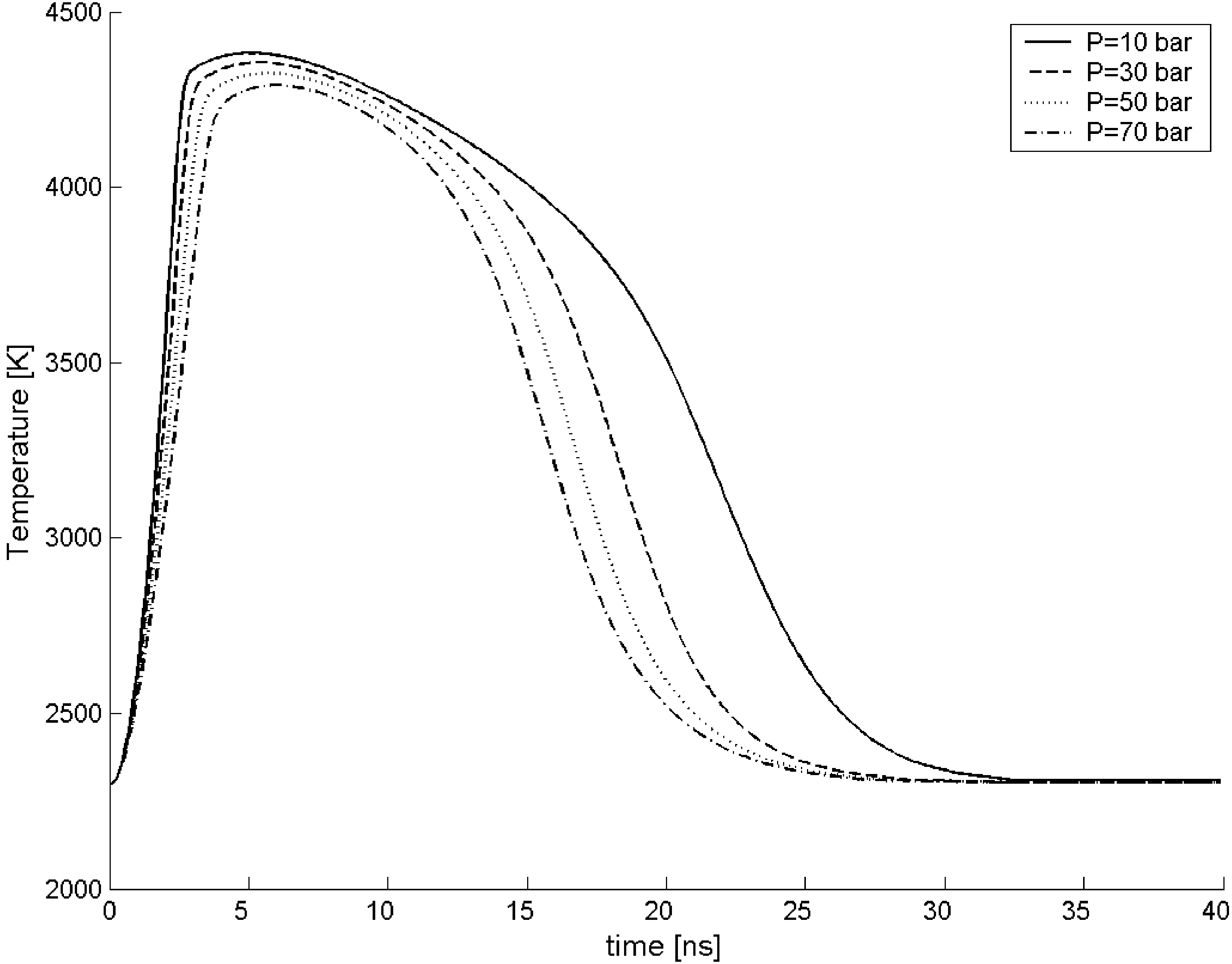
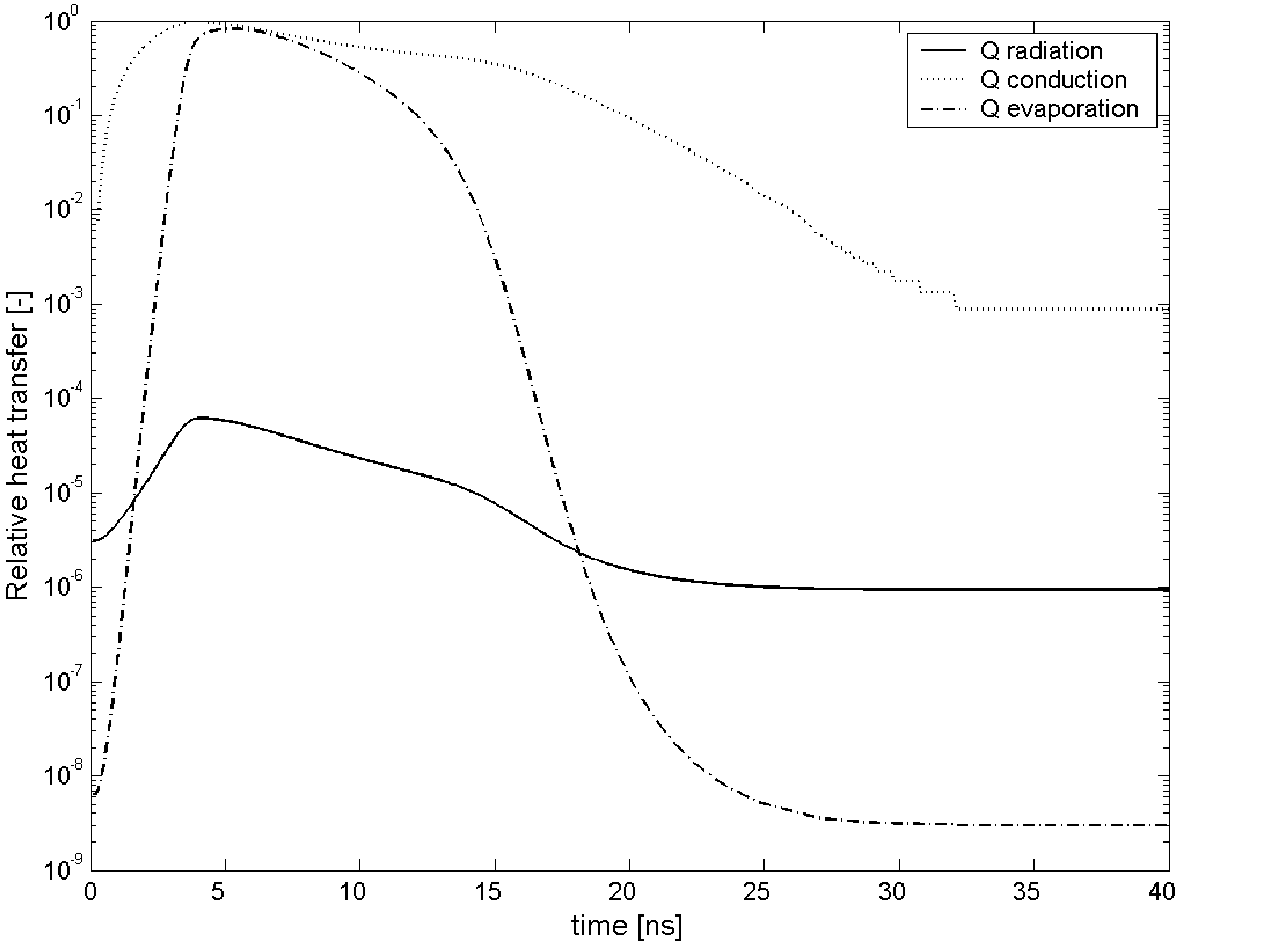
Temperature evolution as function of time and pressure



Heat transfer contribution by every term



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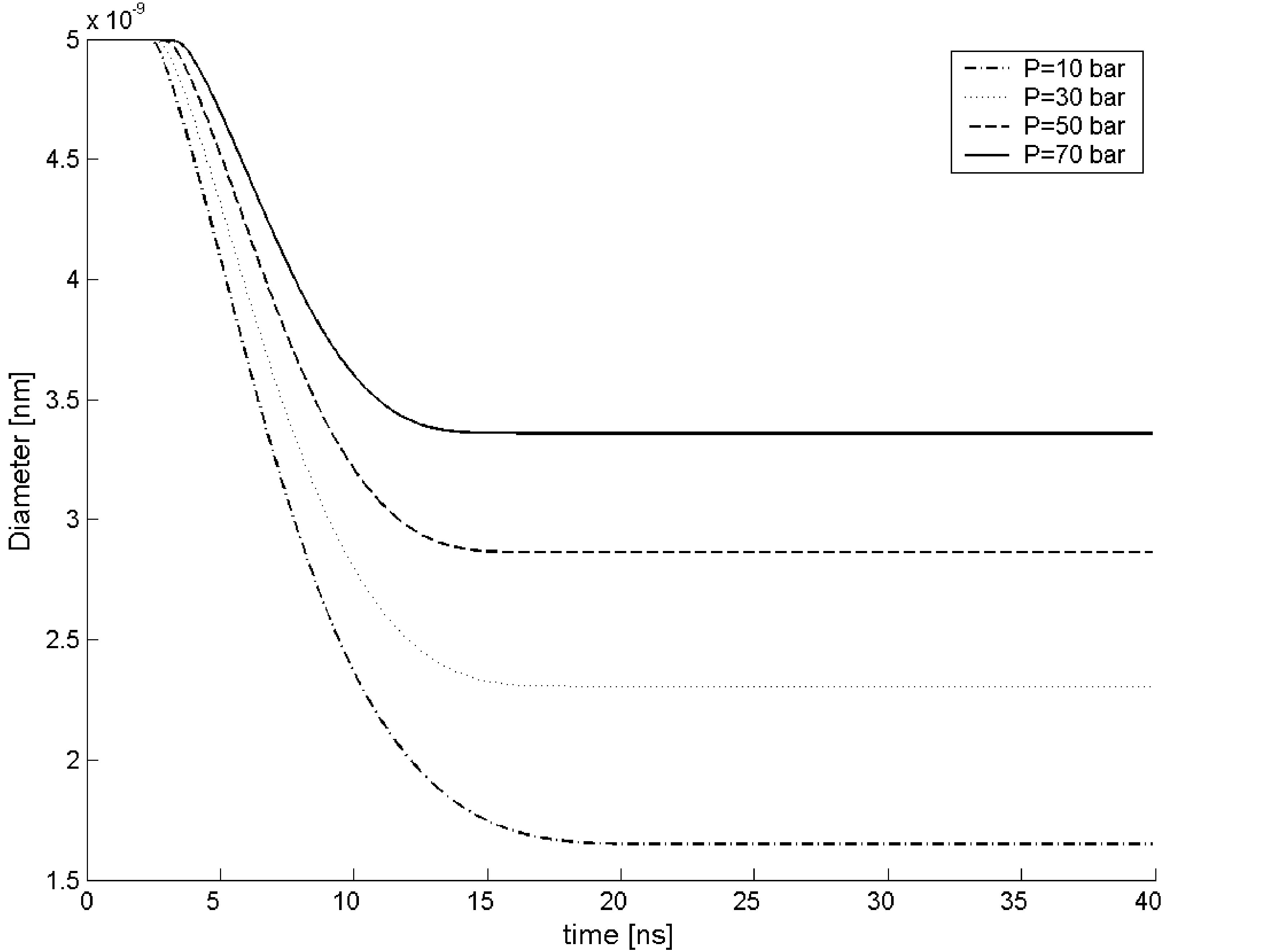
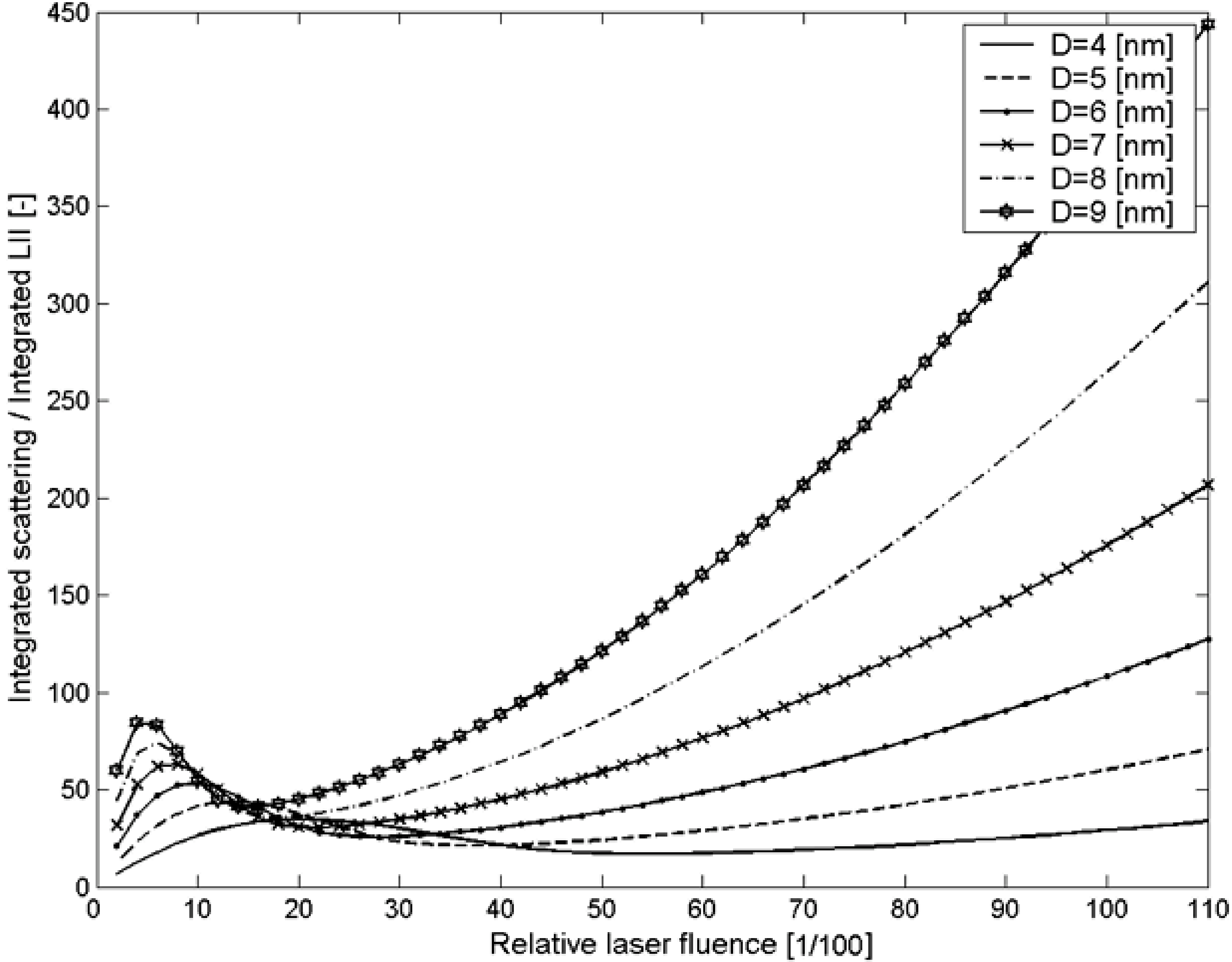


Integrated elastic scattering over integrated LII



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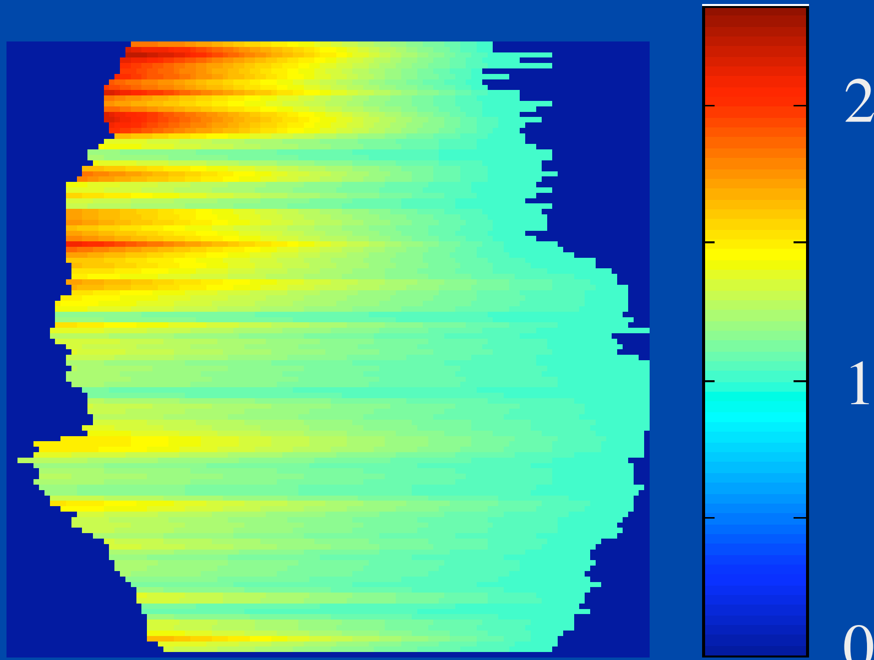
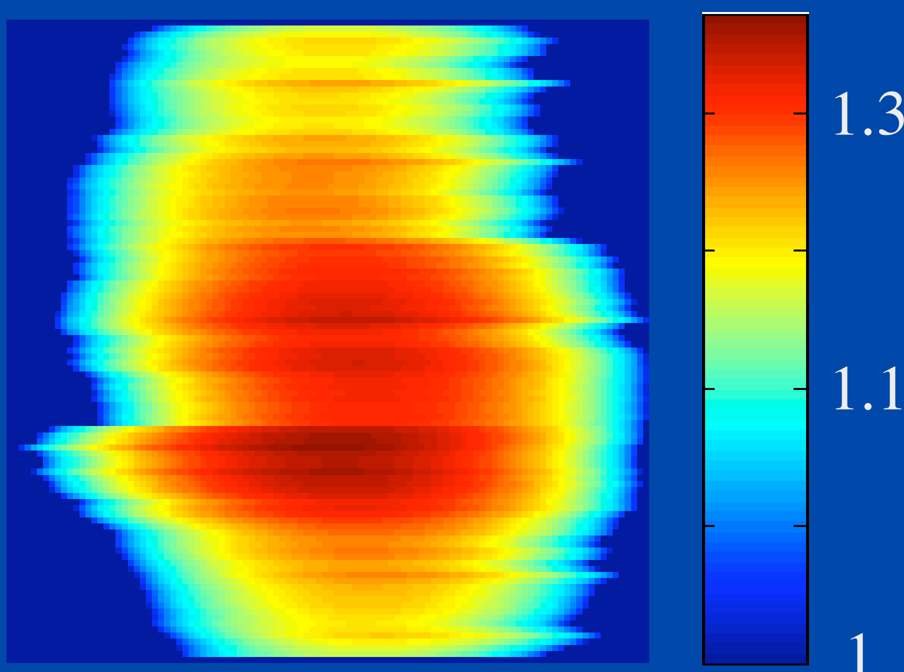


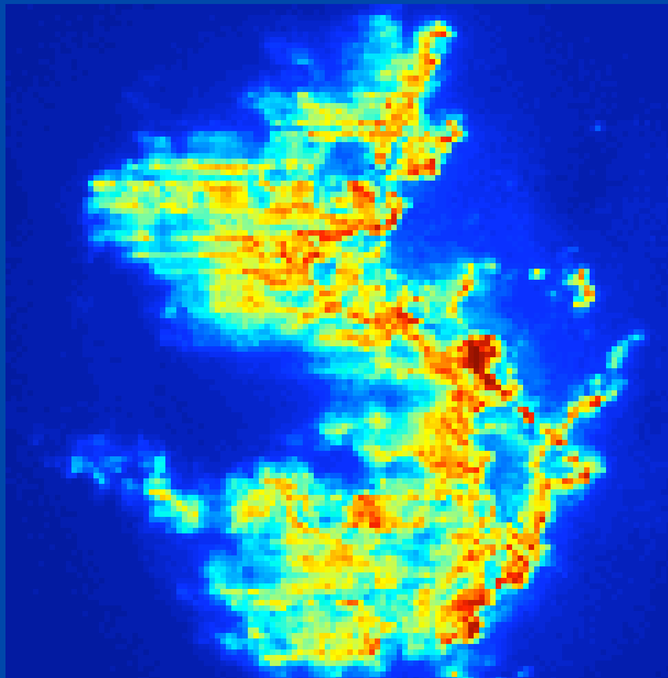
Fluence calculation

&

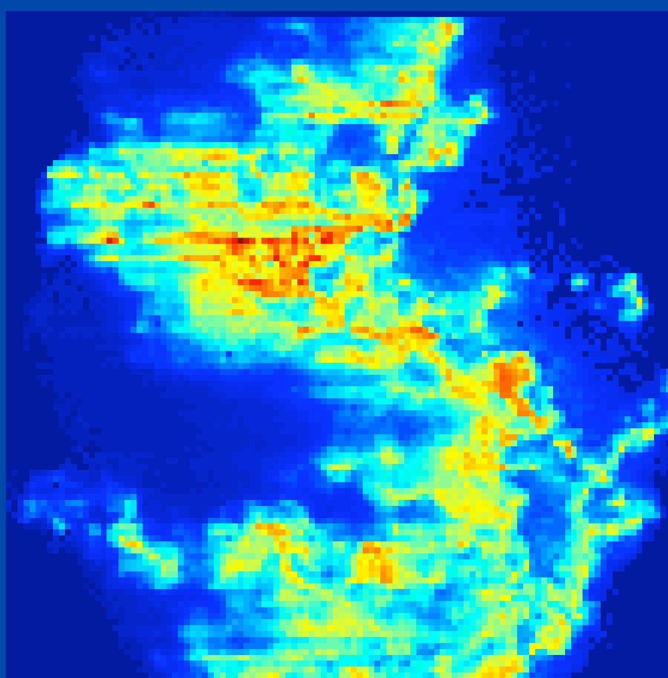
along laser compensation



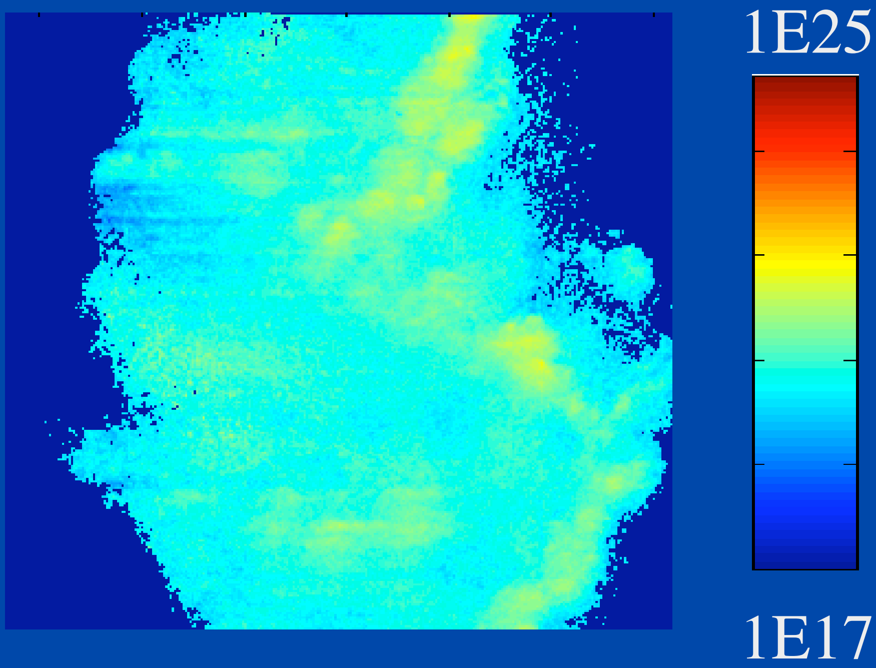
perpendicular compensation



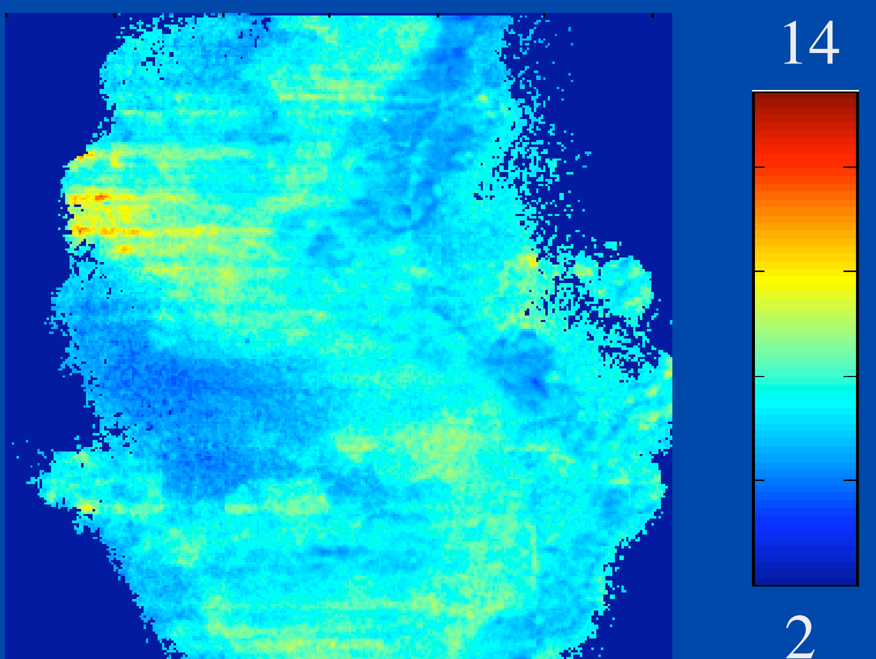
Original Rayleigh signal



Compensated Rayleigh signal

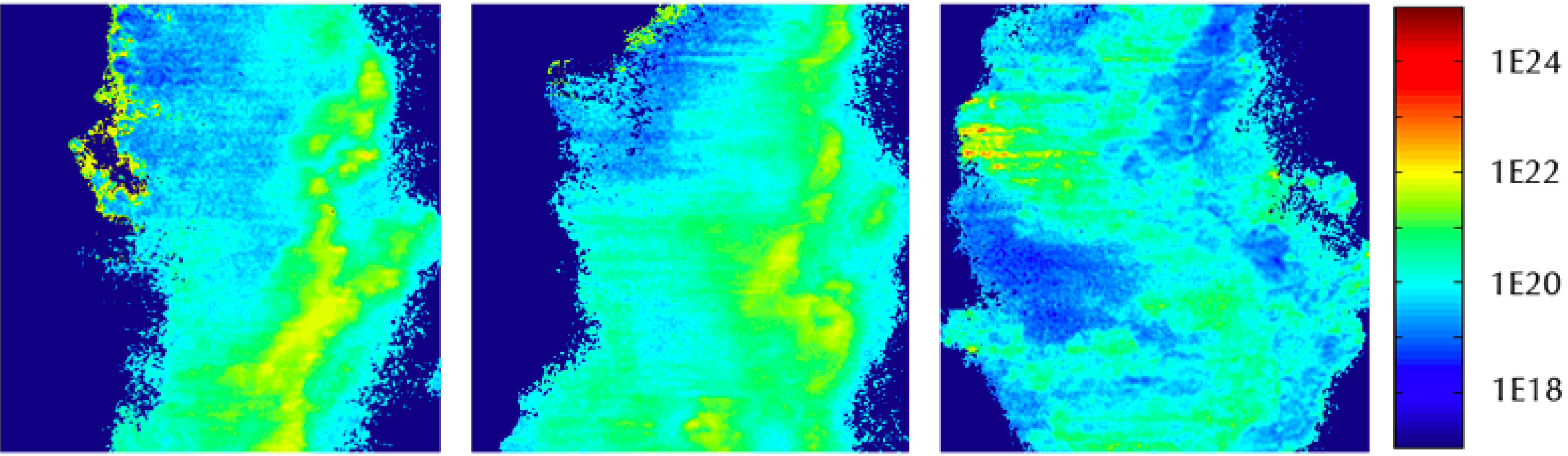


Particle concentration
[1/m^3]

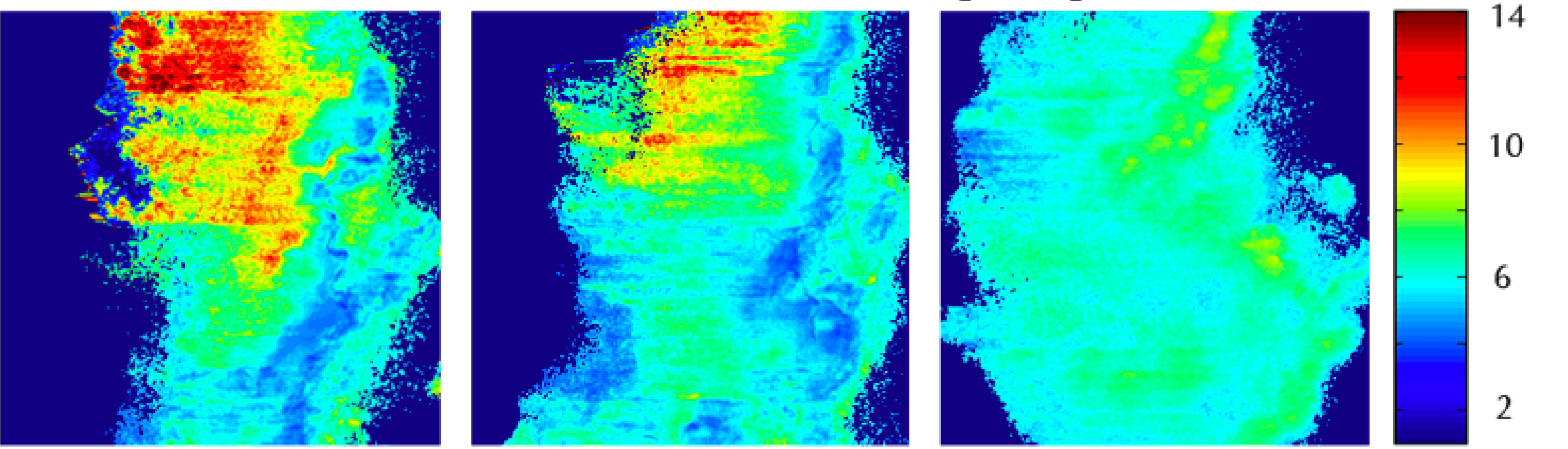


Particle diameter
[nm]

Particle concentration [1/m³]



Particle diameter [nm]



Conditions “A”

- Gas temperature 520 Celsius
- Gas pressure 50 Bar
- Injection pressure 800 Bar
- 0.25 ms asoc (mode) and 2.0 ms asoc (mode).

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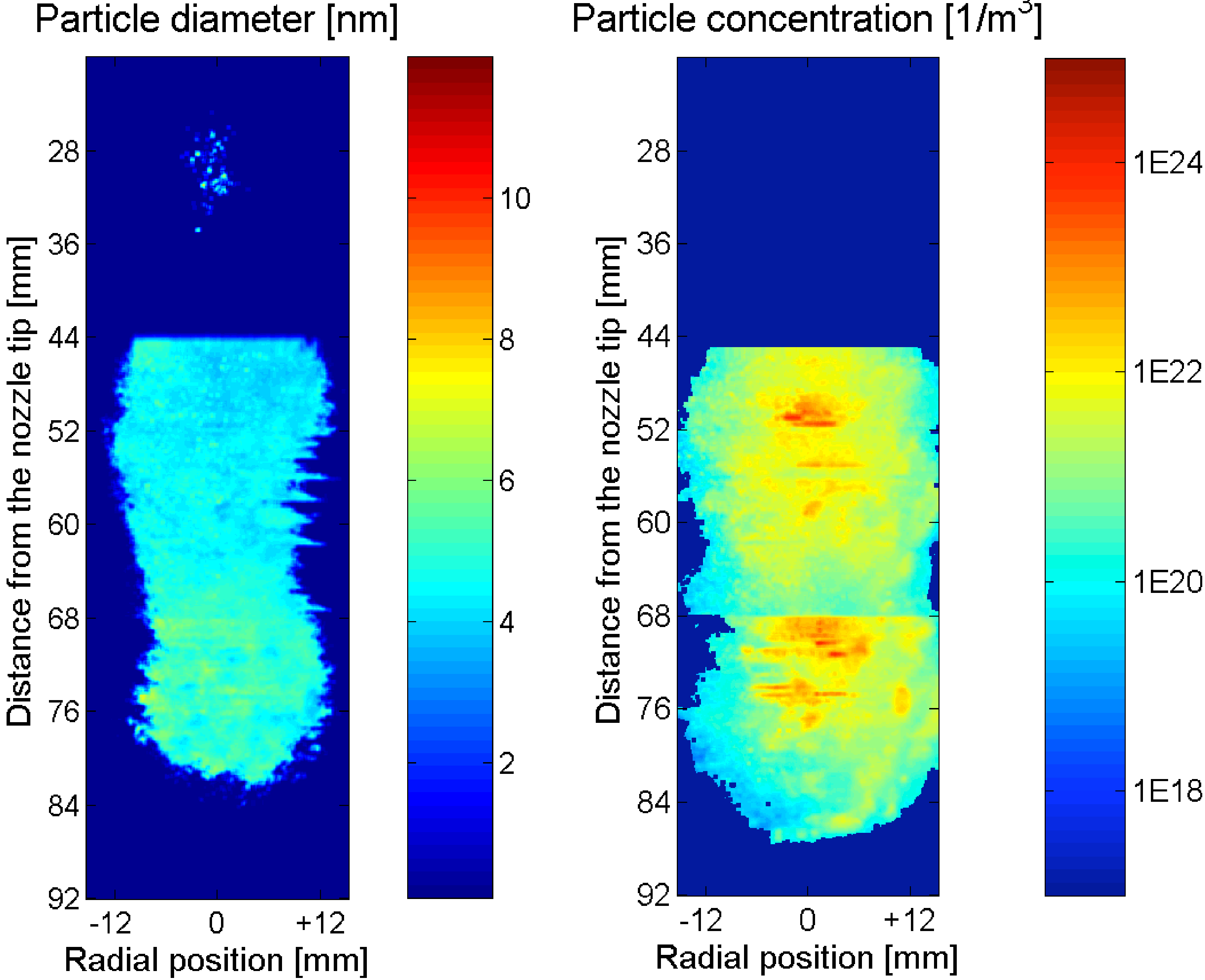

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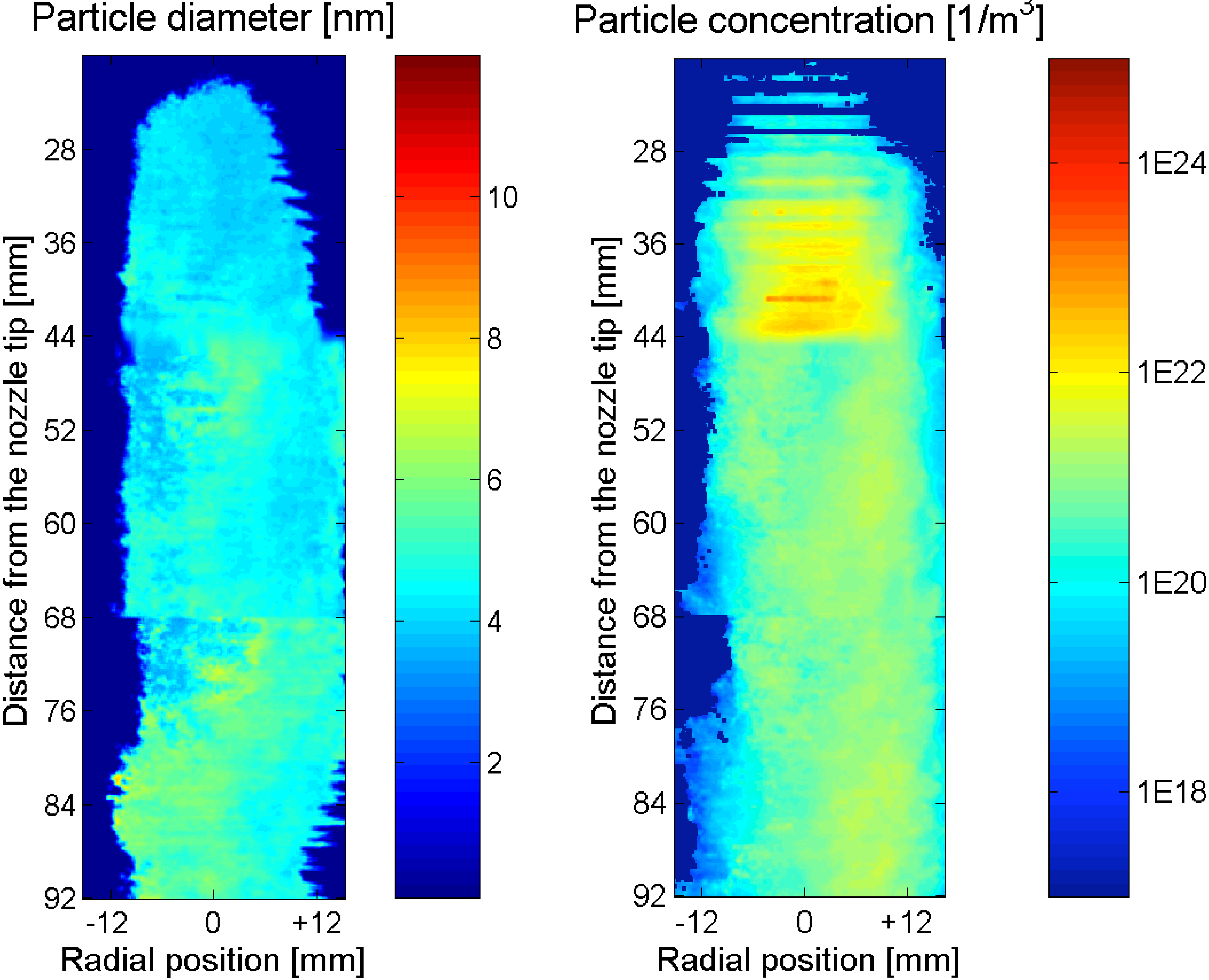

Conclusions (1)

- Particles are bigger downstream the spray.
- Particles are smaller using high injection pressures than particles found in sprays injected at “low” pressures (in average).
- If particles are big there are fewer.
- Extreme high extinction is a problem.

Conclusions (2)

- A new non-linear method for laser compensation in optically dense sprays was successfully developed (extinction>80%).
- Spray is compensated perpendicular and parallel to the detectors.
- Measurements were done with real fuel (a real challenge).

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In case of questions...