Laboratory PolyCO Based X-ray Imaging of High-Pressure Fuel Sprays

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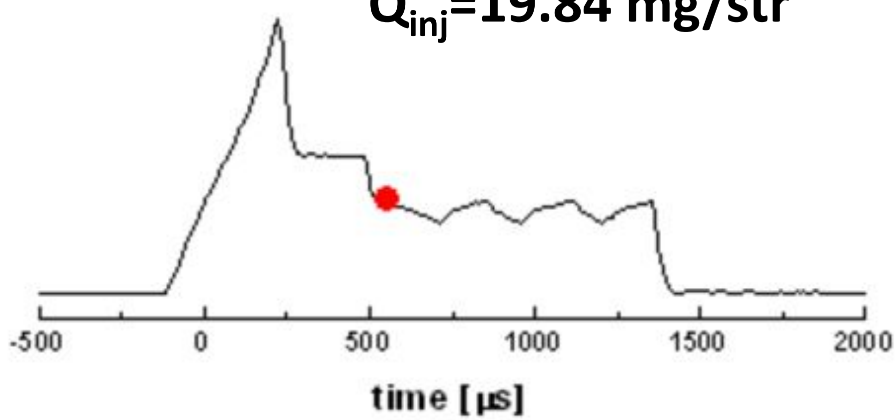
Introduction

Development and optimization of internal combustion engine is strictly related to the efficiency of the combustion process

In the last decade, conventional engines have based the rupture and atomization of the injected fuel mainly on high-pressure high-speed supplying technology

P_{inj}=10 MPa – t_{inj}=1.45 ms
Q_{inj}=19.84 mg/str



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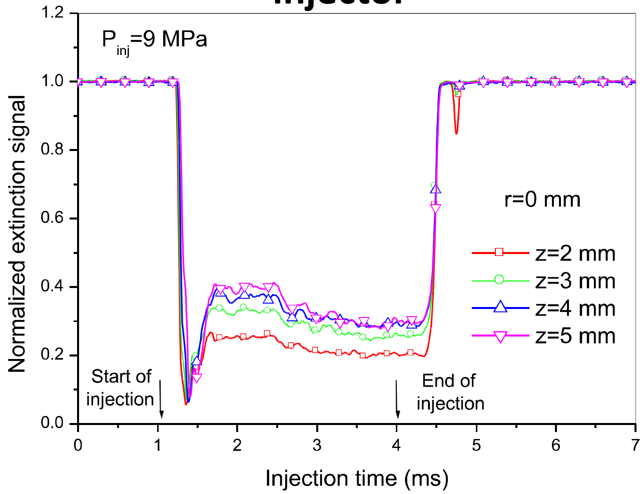
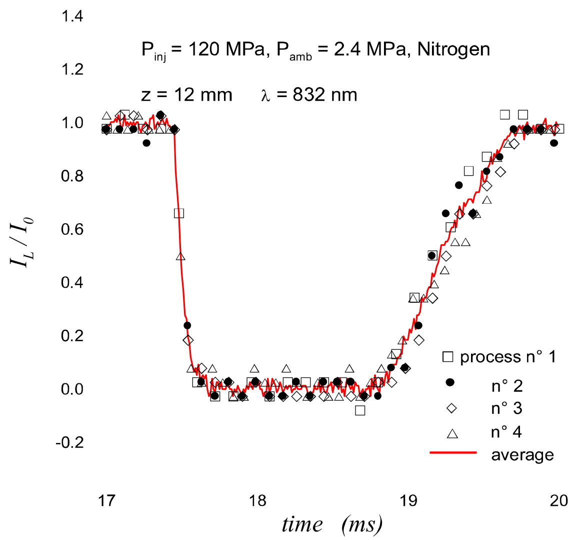
The knowledge of spatial and temporal distribution of fuel density and droplet diameter distribution is fundamental for the air/fuel mixture formation and control. Both for experimental and numerical approach

The liquids are optically dense and frequently the light, used to investigate, scatters so strongly that the detailed structure of the spray can not be resolved by conventional optical techniques

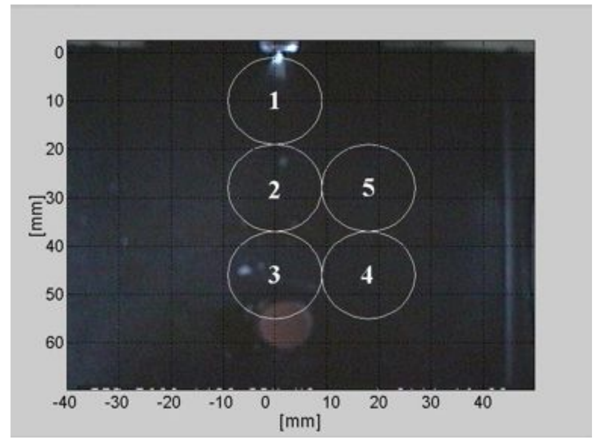
Extinction along the axis of a hollow-cone GDI injector

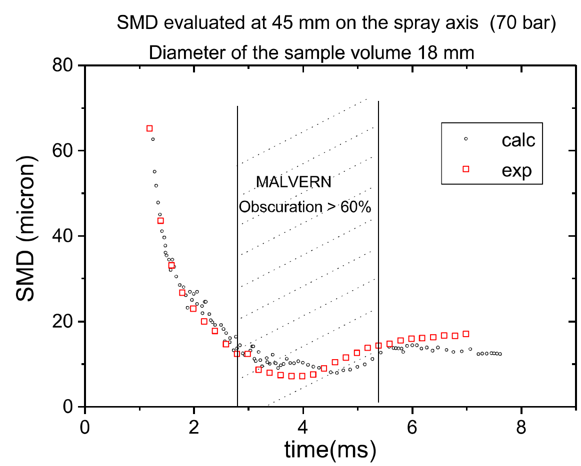


Extinction along the axis of a diesel spray



Diffractometric measurements of a hollow-cone GDI injector (Malvern app.)





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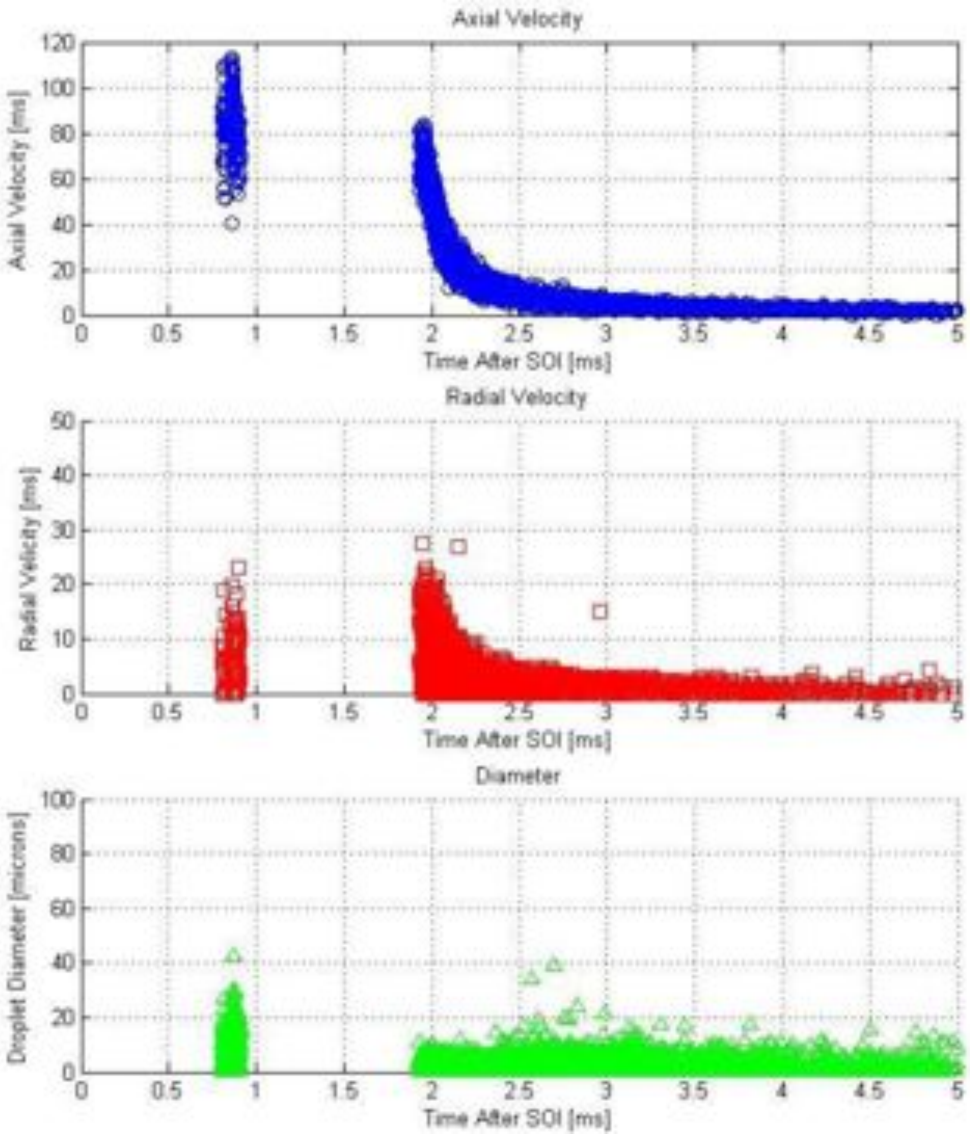
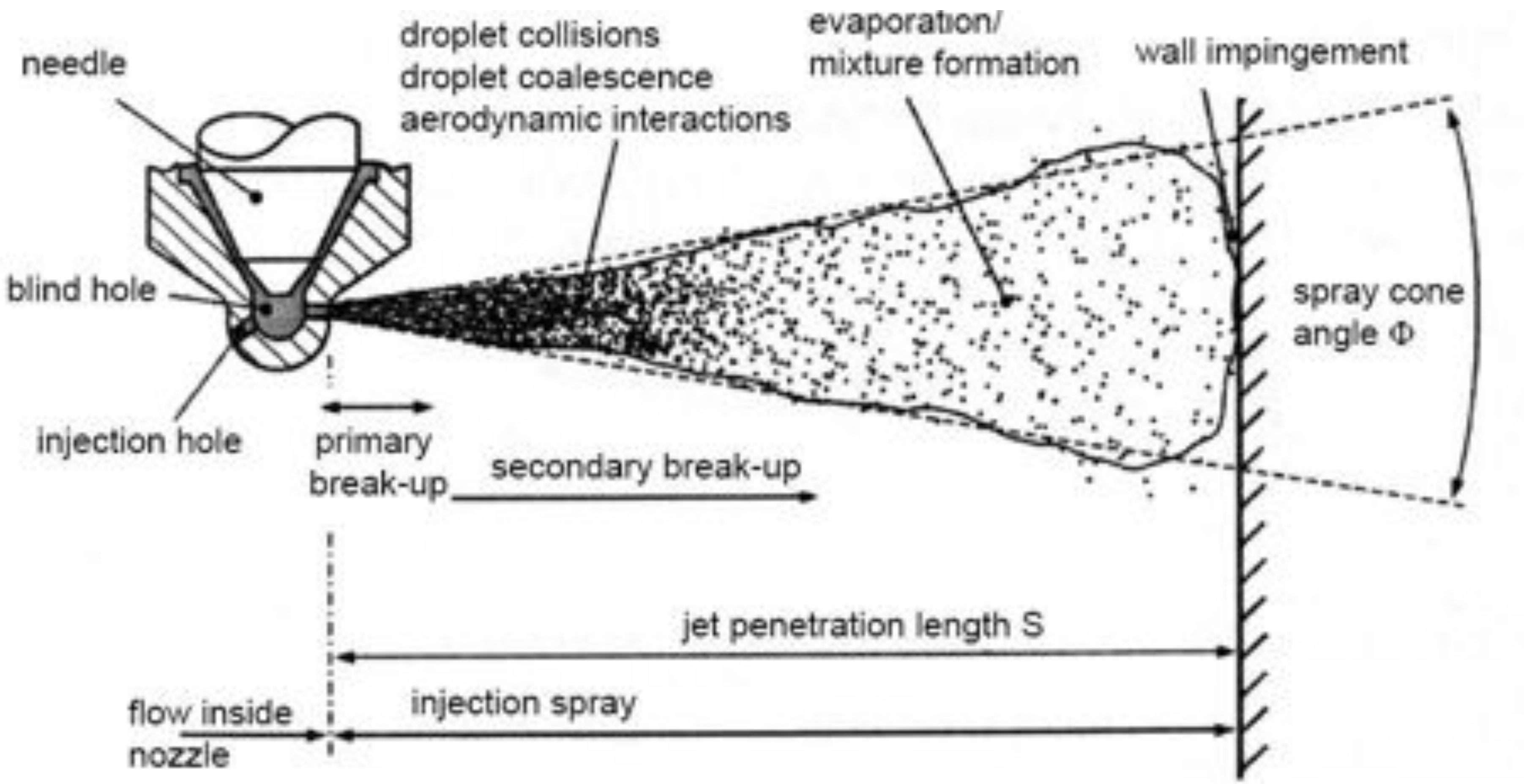
Significant progresses have been achieved using advanced optical diagnostic techniques, laser-based, such LDA/PDPA, PIV, LIF, Shadowgraph /Schrielen … but frequently they can not penetrate the high-dense regions

PDPA Raw data at 10 mm downstream the injector nozzle




needle
droplet collisions
droplet coalescence
aerodynamic interactions
evaporation/
mixture formation
wall impingement
blind hole
spray cone
angle Φ
injection hole
primary
break-up
secondary break-up
jet penetration length S
flow inside
nozzle
injection spray

LEIPERTZ

Spray modeling

Code: AVL fire™

Huh – Gosman model for droplet breakup

Cone angle

Injection rate

Particle size

Log-normal distribution

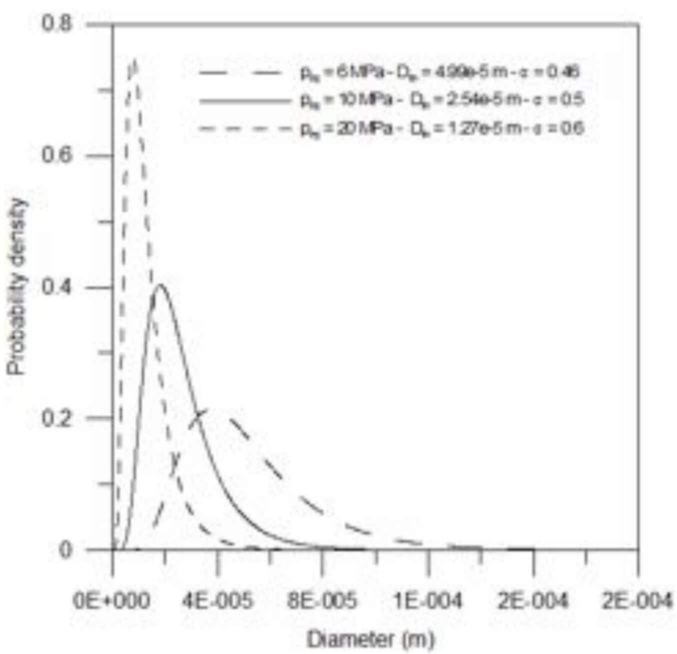
$$f(x)=\frac{1}{x\sigma\sqrt{2\pi}}\exp\left[-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right]$$

Theoretical diameter

$$D_{th}=C_d\left(\frac{2\pi\tau_f}{\rho_g u_{rel}^2}\right)\lambda^*$$

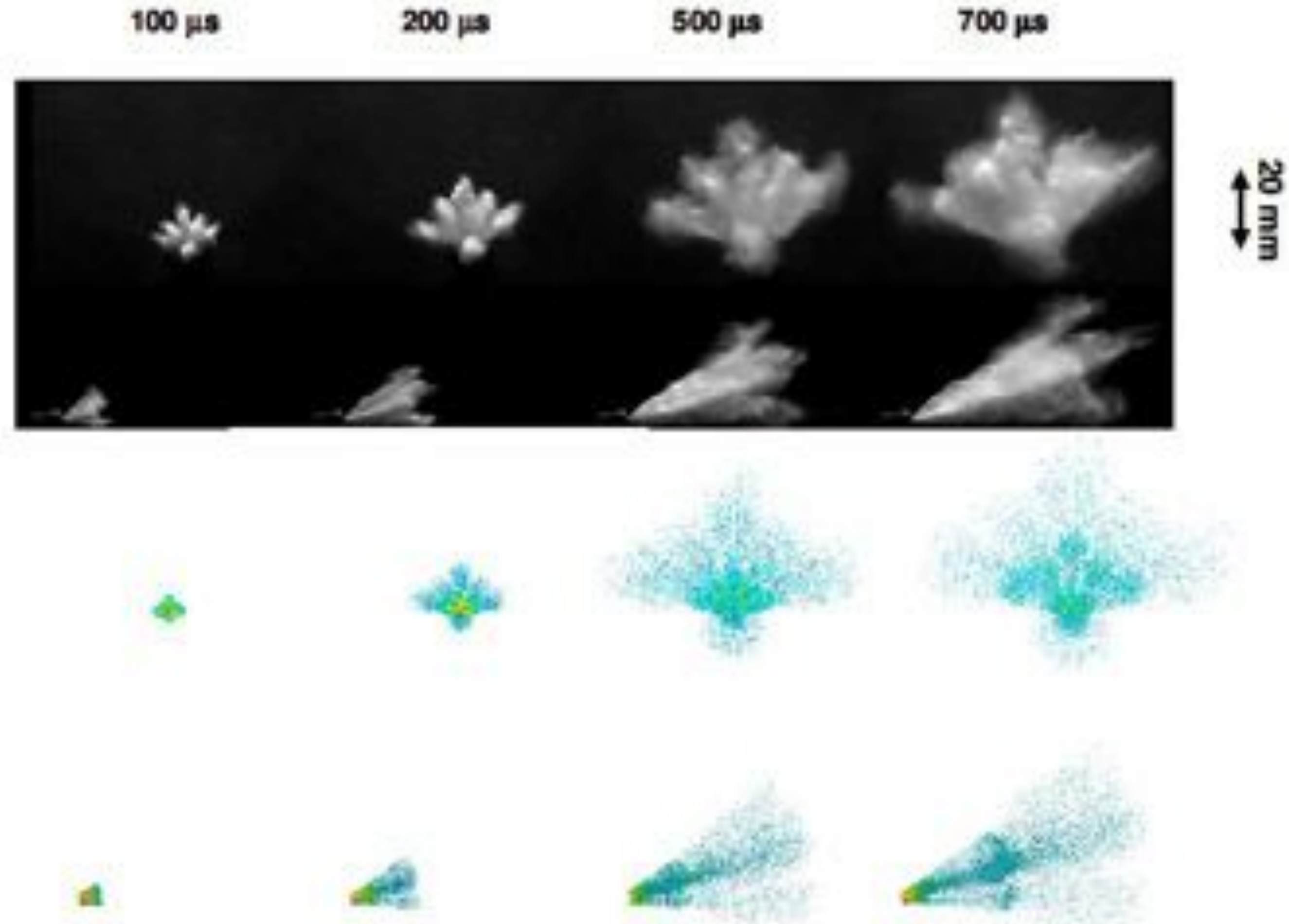
σ vs p_{inj} in MPa

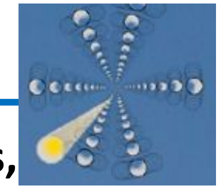
$$\sigma=0.1(0.1p_{inj}-1)+0.5$$



Initial droplets size distribution hypothesized for three different injection pressures

Frontal and lateral view of experimental (top) and numerical spray images (bottom) for a GDI injector under **20 MPa** injection pressures and **50 mg/str** injected fuel





Significant approaches come from the application of radiographic techniques, such us neutron [1] or mainly soft X-ray, primarily from synchrotron radiation plants: Argonne National Lab.[2] and Cornell High Energy Synch. Source [3]

X-ray are highly penetrative in dense materials due to their intrinsic low cross section producing negligible multiple scattering

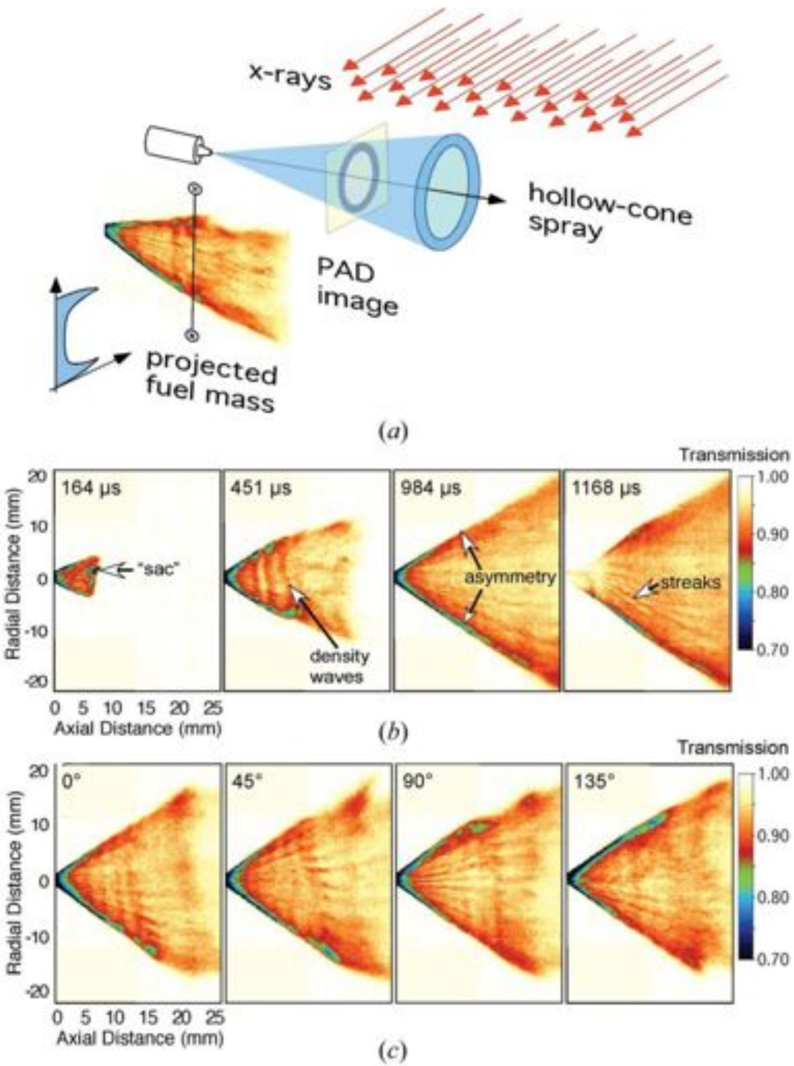
For monowavelength radiation, the relationship between the emerging *I* and incident I_o beam intensities is

$$I/I_o = \exp(-\mu_m M)$$

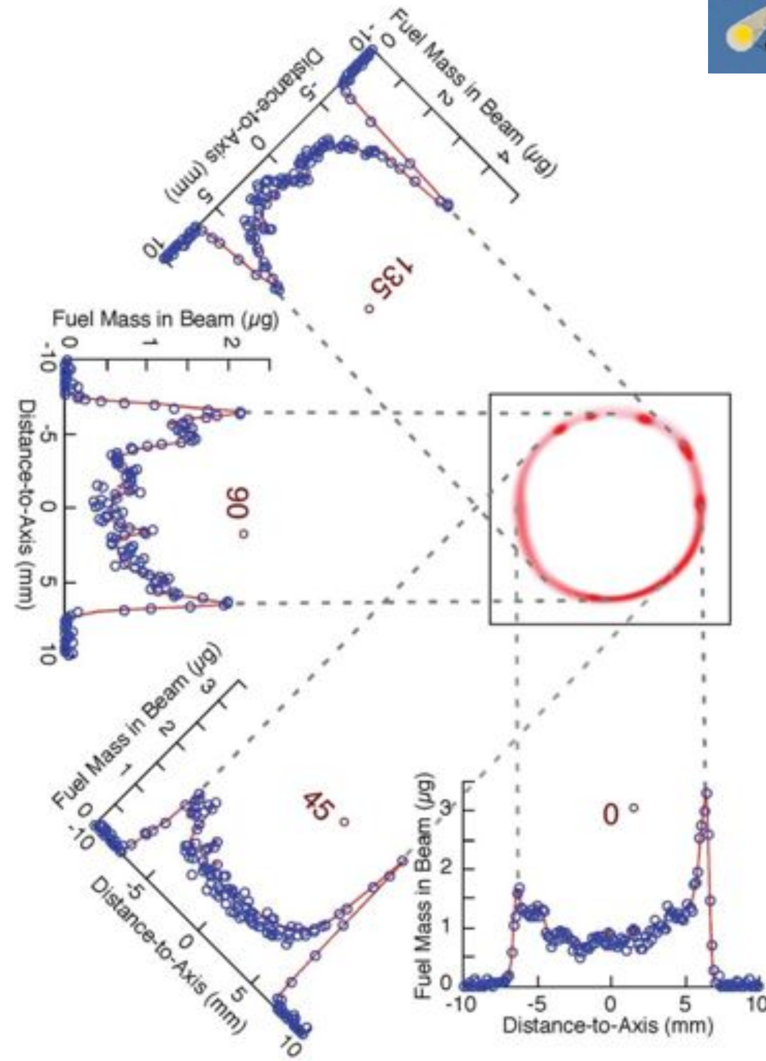
being μ_m the mass absorption coefficient of the material and M the total mass sample in the beam

Time-resolved X-ray radiography and tomography make use of pulsed, high-brilliance synchrotron radiation sources. They overcome the limits of X-ray tube sources (continuous in time, dispersed in wavelengths and non-collimated) providing intense beams (monochromatic), highly collimated, time-resolved

[1] Kakenaka et al.
[2] Wang, Powell, Kastengren et al.
[3] MacPhee, Wang et al.



X-radiography of hollow-cone direct injection fuel spray



Computed fuel mass distribution by fitting the experimental data with mass reconstruction models

but …


Argonne Central Campus
Central Lab/Office Bldg.
APS Conference Center
Argonne Guest House
Center for Nanoscale Materials
Booster/Injector
Linear Accelerator
Storage Ring
Experiment Hall
Lab/Office Module

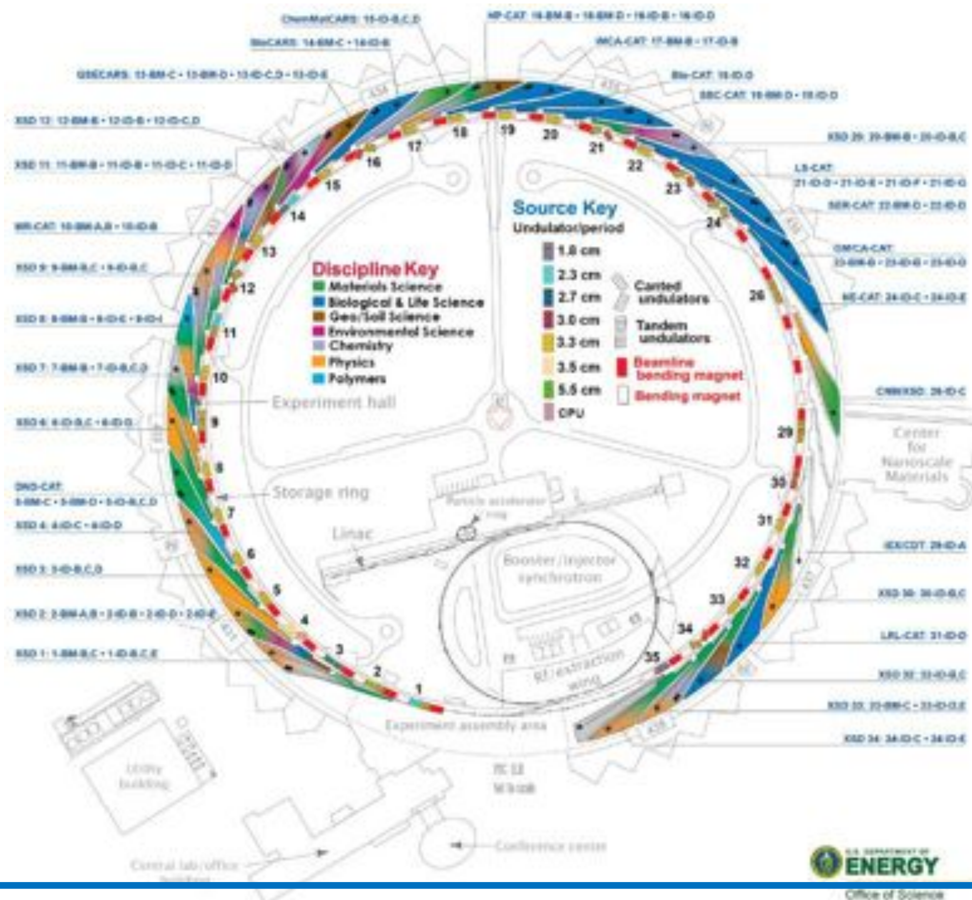

Source Key
Undulator/period
1.8 cm
2.3 cm
2.7 cm
3.0 cm
3.3 cm
3.5 cm
5.5 cm
CPU
Canted undulators
Tandem undulators
Beamline bending magnet
Bending magnet
Discipline Key
Materials Science
Biological & Life Science
Geo/Soil Science
Environmental Science
Chemistry
Physics
Polymers
Experiment hall
Storage ring
Linac
Booster/injector synchrotron
Center for Nanoscale Materials
ENERGY

Table-top lab sources, friend-user, have been developed as alternative to the restricted access facilities using storage rings

High-voltage X-Ray tubes, with different characteristics and performances, have been used for radiography/tomography applications to liquid fluids and fuel sprays

The table-top X-ray facilities are used for the spray characterization in terms of cone angle and liquid fraction measures in high dense zone (near nozzle orifice regions) in a wide variety of operative conditions

How to overcome their intrinsic limits of brilliance, collimation, time-resolution, …?

Polycapillary Optics

@ X-ray and neutron capillary optics

Basic idea of polycapillary optics is very close to the phenomenon of charged particle channeling

@ beam bending through large angles

@ divergent beam to convergent one

@ divergent to quasiparallel & vv

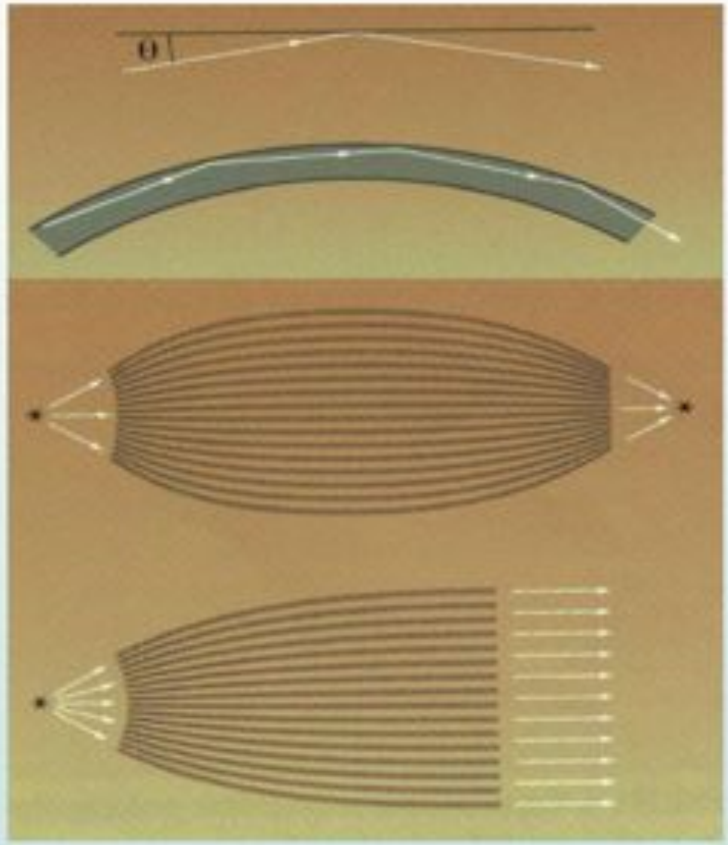
Number of applications

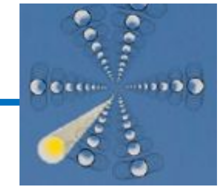
@ scientific instrumentation (XRF, XRD)

@ elemental/structural analysis

@ medicine (diagnostics, therapy)

@ astrophysics





Aims of the work

First results of a table-top experiment using a microfocus X-ray source for radiography and tomography applied to Ce-additive gasoline sprays for automotive applications

Cu Kα X-ray source (8.048 keV) in combination with a polycapillary halflens for shaping the divergent X-ray beams into parallel ones; contrast increasing and intensity gain of 1-2 orders of magnitude (*)

High-pressure rotating device, 0.1° angular resolution, holding GDI injectors for image acquisitions over 360° round trip at the injection pressure of 8.0 MPa

Sinogram reconstructions of the jets by slices for analysing the spray 360° around and inside it

Two injectors investigated: hollow-cone producing a cone-shaped structure and six-hole generating a complex structure with squirts along defined directions

(*) The brillance for desk-top non-collimated sources can reach 10^7 (10^8 with microfocus lenses) photons/(s · mm^2). Maximizing conditions, using micro-semi-lenses, it can reach up to $10^{10} – 10^{11}$ photons/(s · mm^2)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1.8 cm
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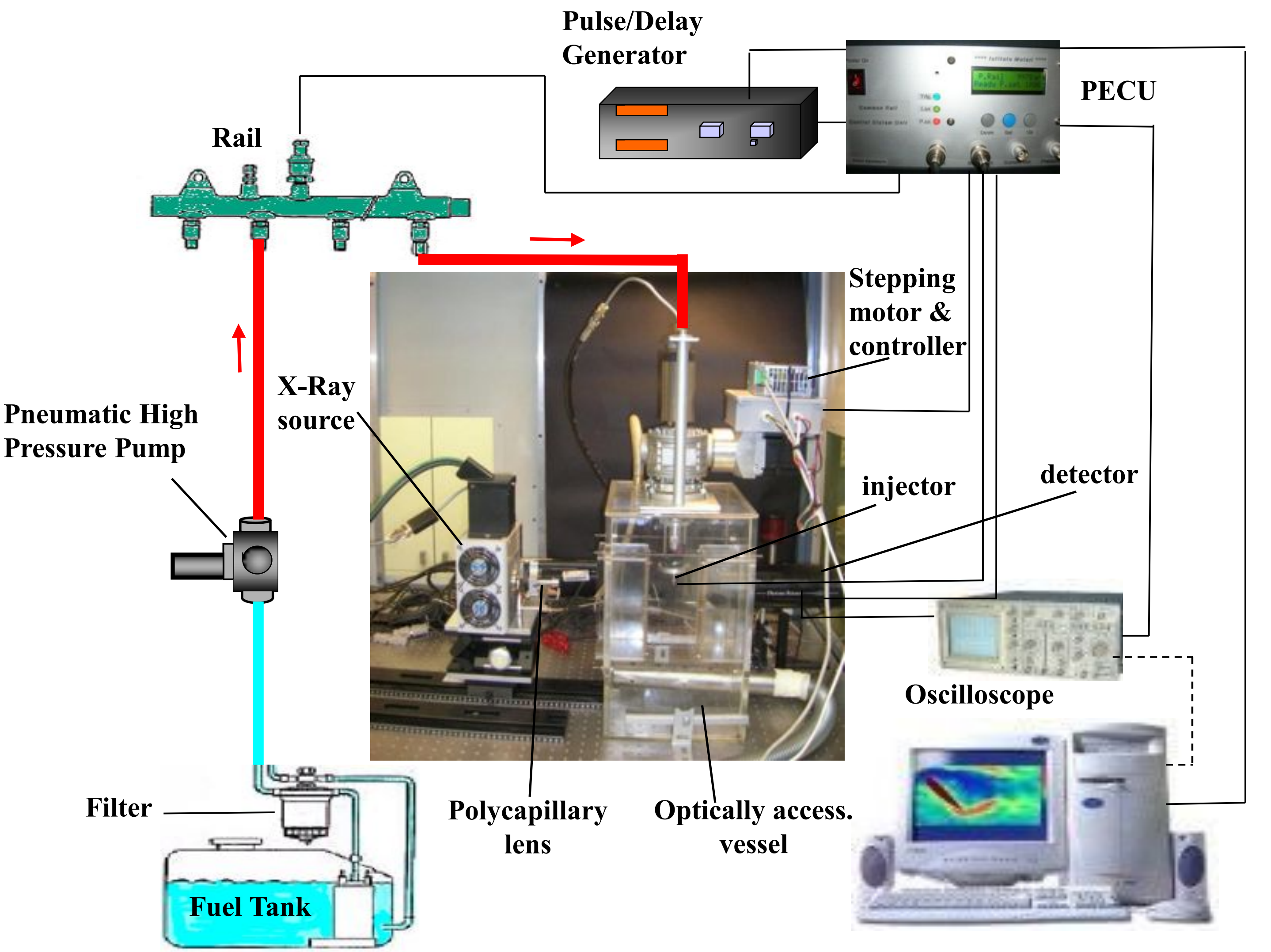
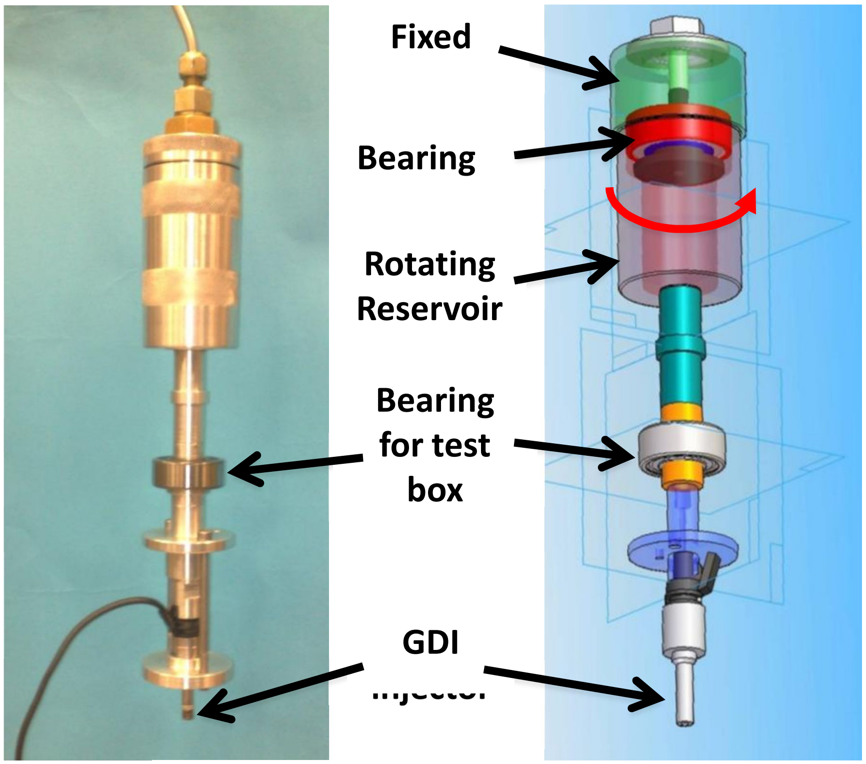
3.0 cm
3.3 cm
3.5 cm
5.5 cm
CPU
Canted undulators
Tandem undulators
Beamline bending magnet
Bending magnet
Discipline Key
Materials Science
Biological & Life Science
Geo/Soil Science
Environmental Science
Chemistry
Physics
Polymers
Experiment hall
Storage ring
Linac
Booster/injector synchrotron
Experiment assembly area
Conference center
ENERGY
Office of Science

EXPERIMENTAL APPARATUS



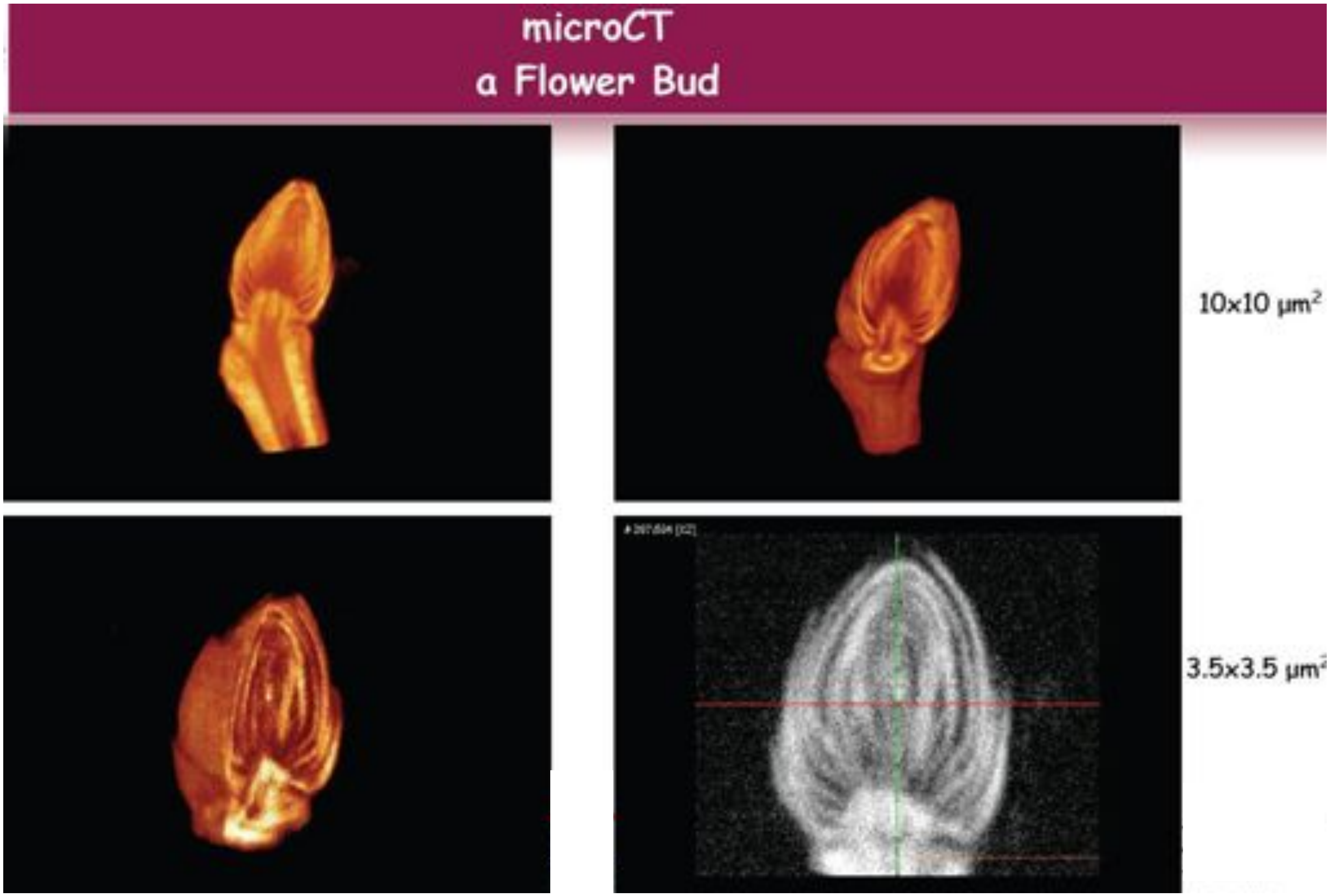
Fuel-tight high-pressure rotating system



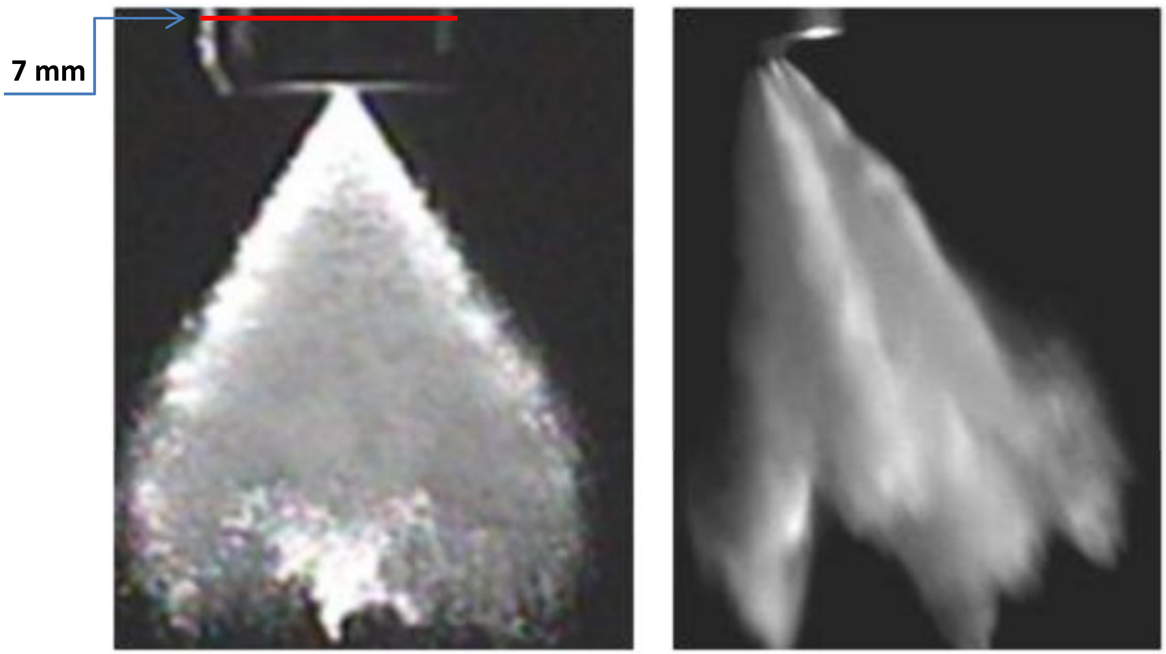
Experimental Results

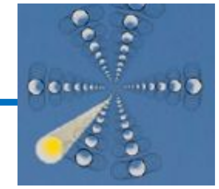
X-Ray Spray Tomography

X-Ray Tomography using Polycapillary Optics

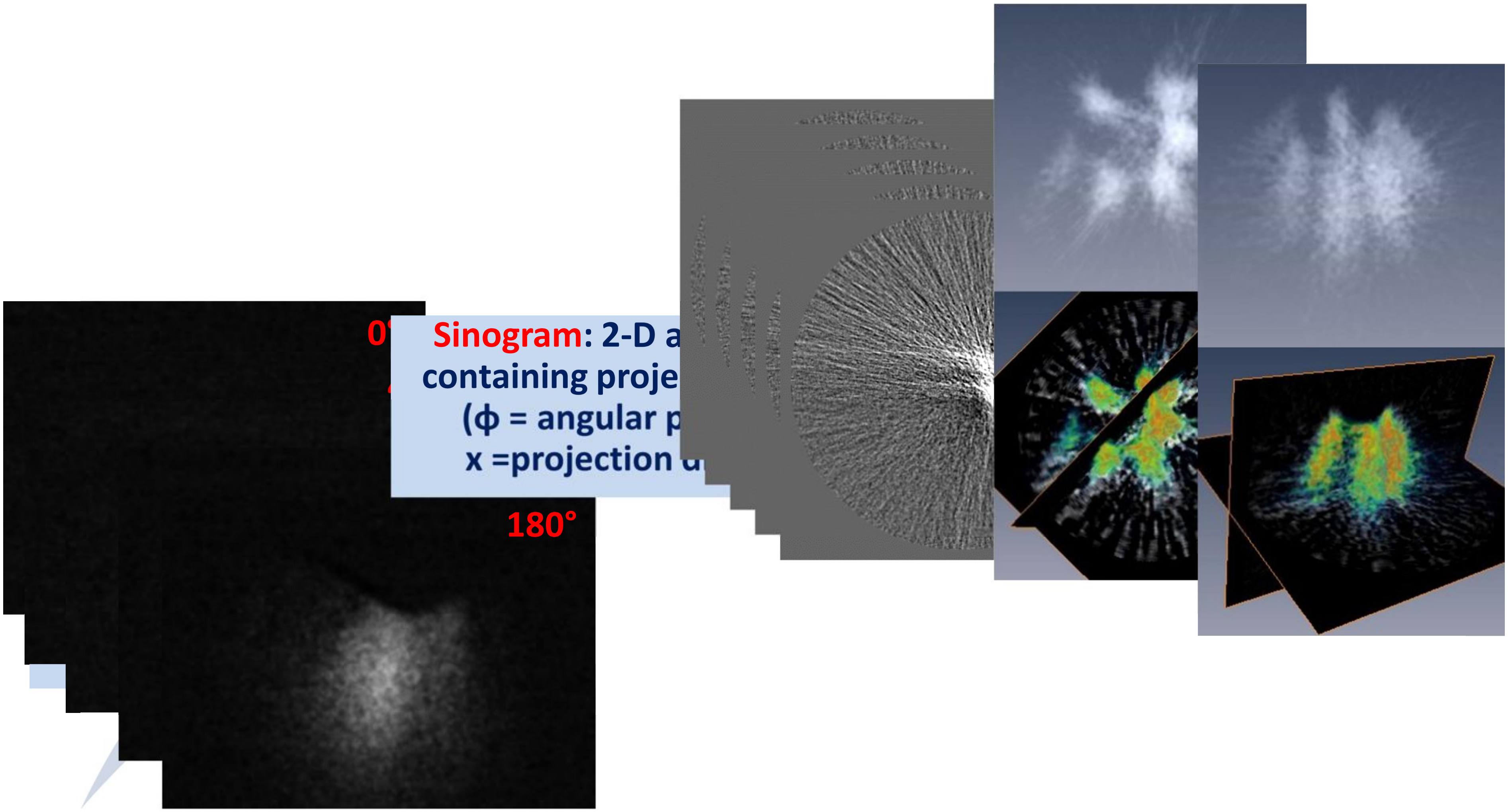


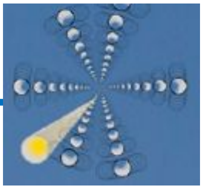
Hollow-cone and multijet spray pictures by light scattering technique from GDI nozzle at 300 μs after SOI and 100 MPa injection pressure





Tomography on Spray – Base Concept





Tomography – Test Conditions

INJECTION SYSTEM

TWO GDI INJECTORS:

- 6 hole (Φ = 0.193 mm)
- Hollow Cone (Φ = 0.500 mm)

InjectionPressure:	8.0 MPa
Backpressure:	0.1 MPa
InjectionDuration:	3.0 ms
Injection Frequency:	4 Hz
Angular Step:	1°
Total Rotation Angle:	180°

IMAGE ACQUISITION AND PROCESSING

Exposure Time: 2 ms

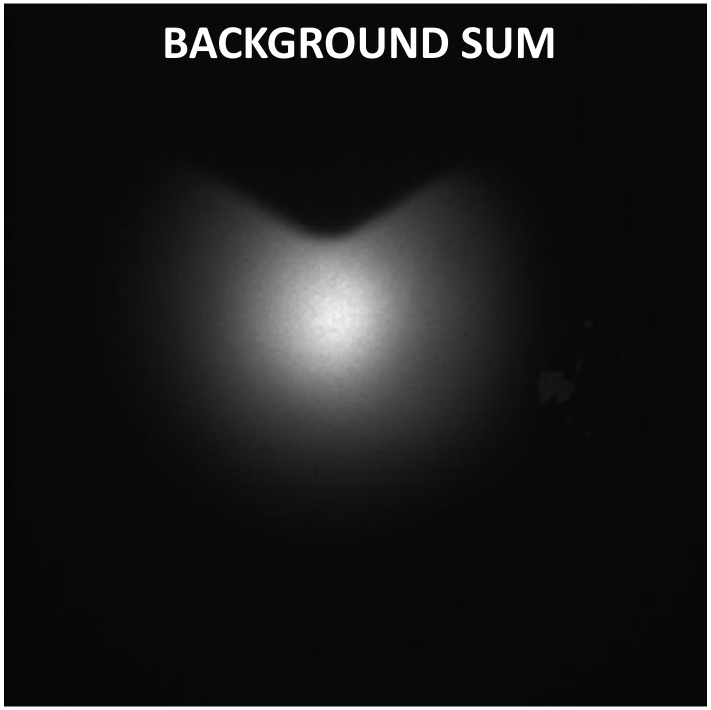
Start of Acquisition: 0.5 ms before SOI

Acquisition per Angular Step: 48

Investigated Area: 16 mm^2

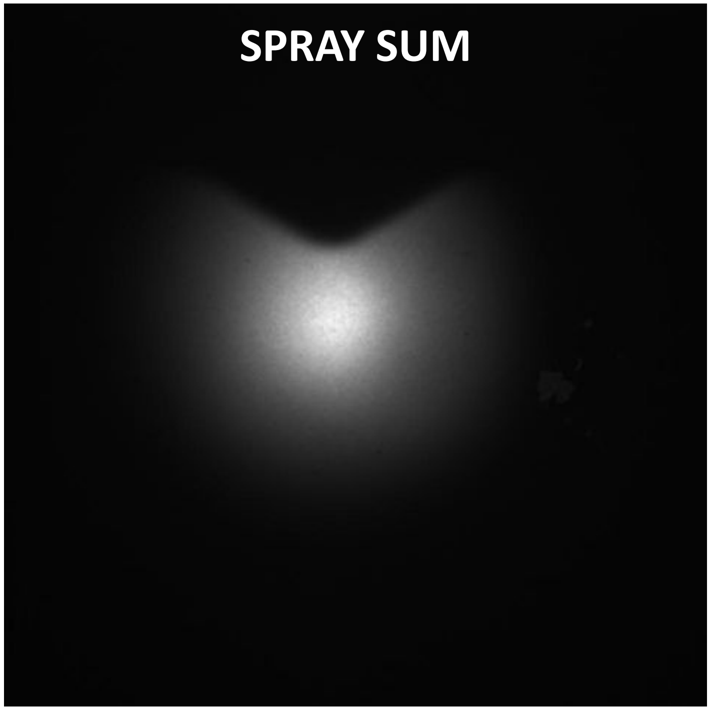
Tomography - Image Acquisition

BACKGROUND



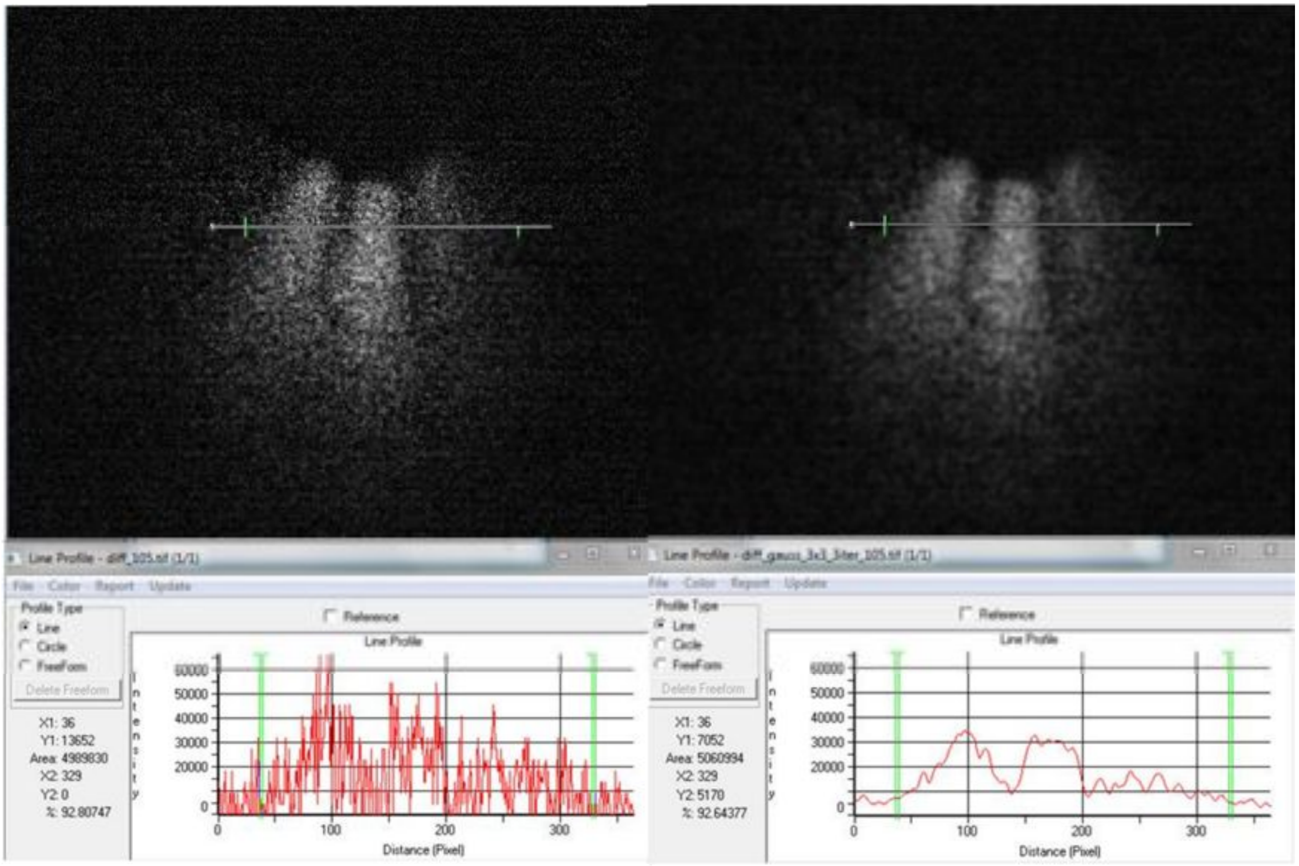
48 acquisitions per each degree

6 HOLE GDI FUEL SPRAY



48 acquisitions per each degree

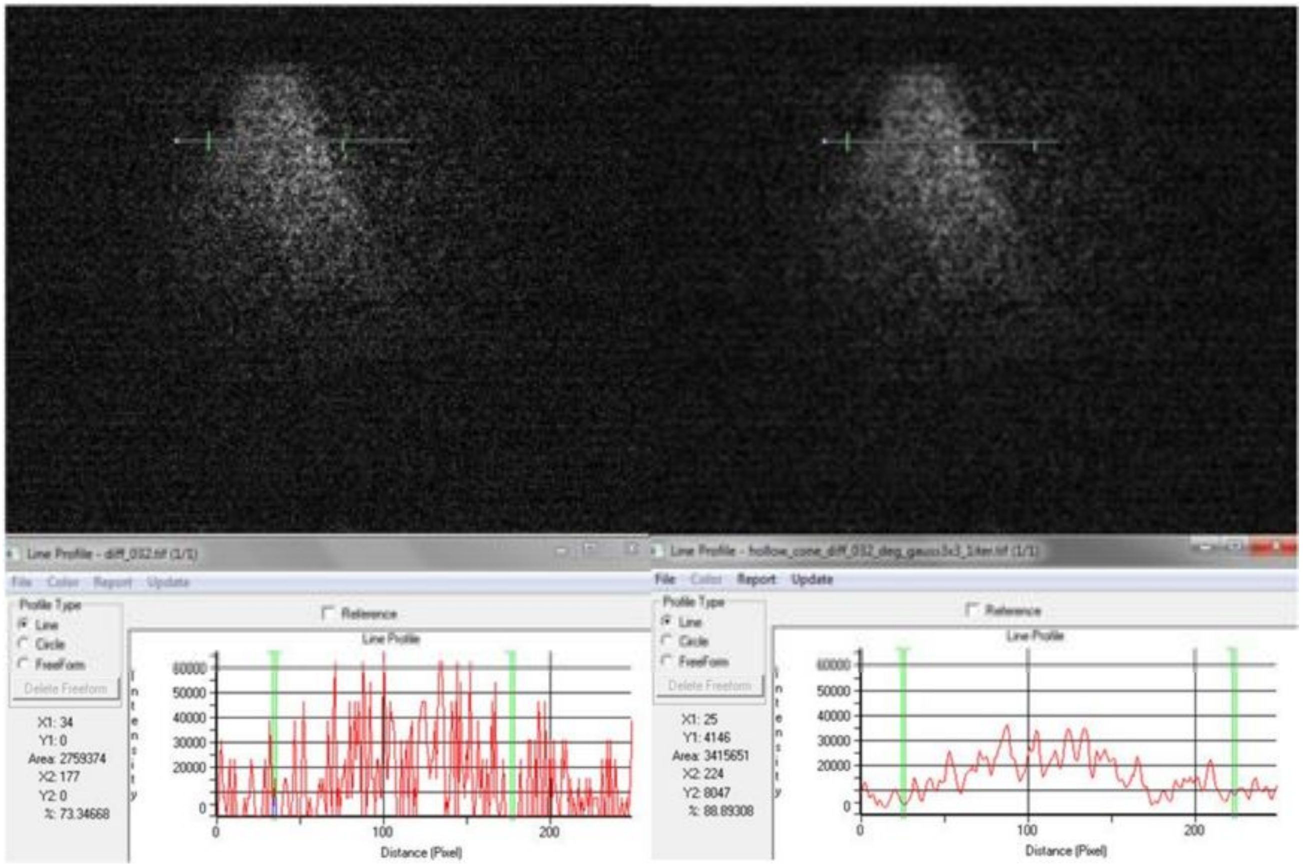
Tomography - Image Processing



X-ray extinction for the six-hole spray

Background subtraction, intensity stretching, low-pass filtering and contrast enhancing have been applied to the images (right) for reducing the huge noise on the outline (left) that could destroy the sinogram constructions

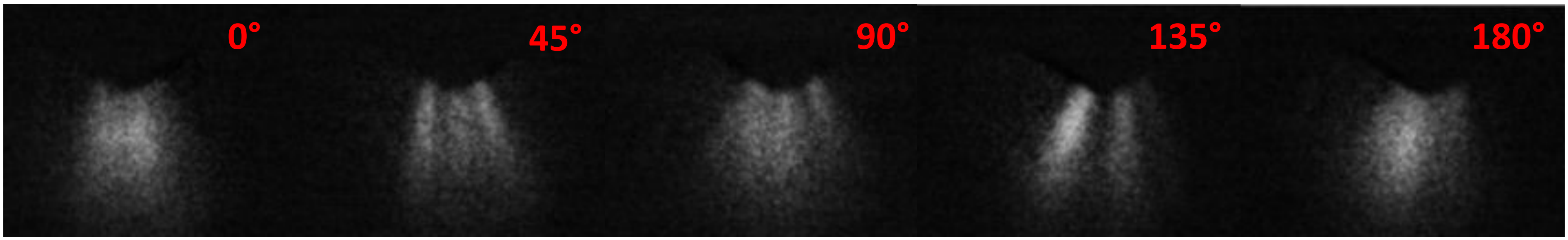
Tomography - Image Processing

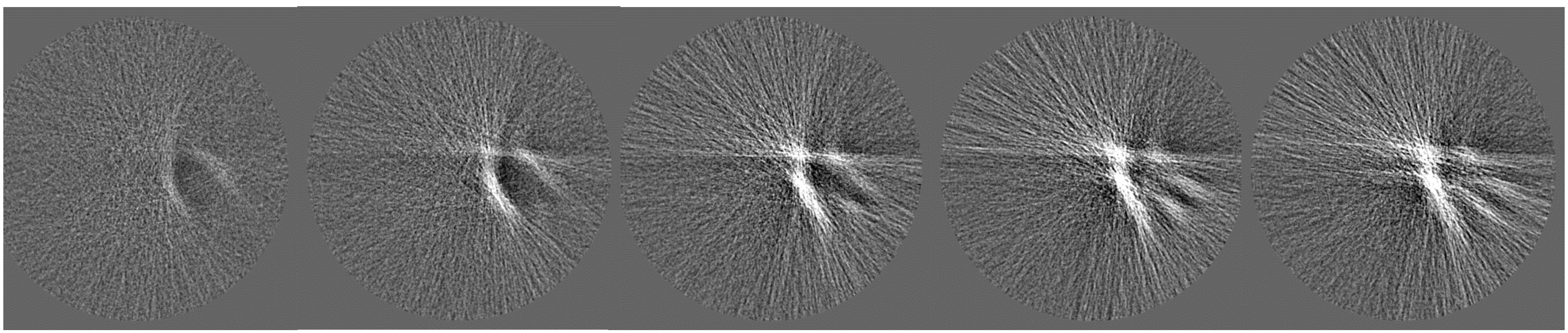


X-ray extinction for the hollow-cone spray

Tomography - Image Reconstruction

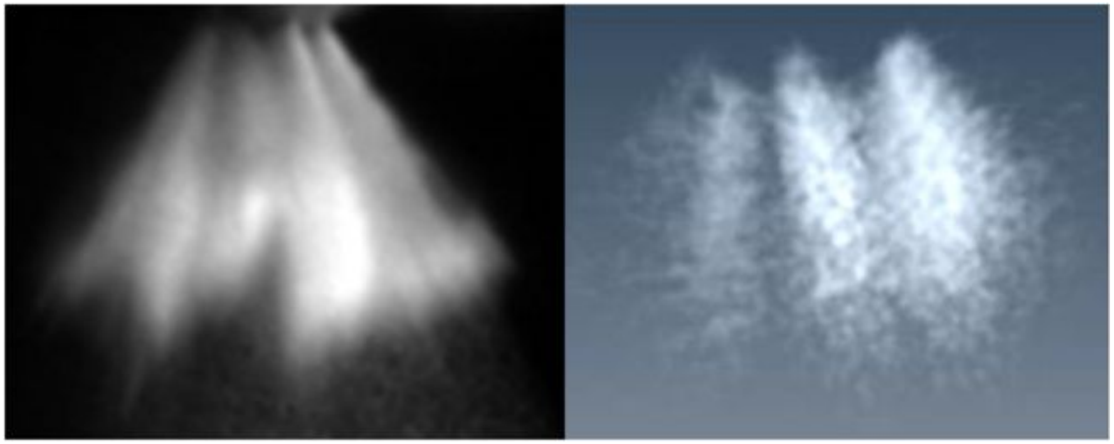
6-HOLE INJECTOR





Tomography – 3D Reconstruction

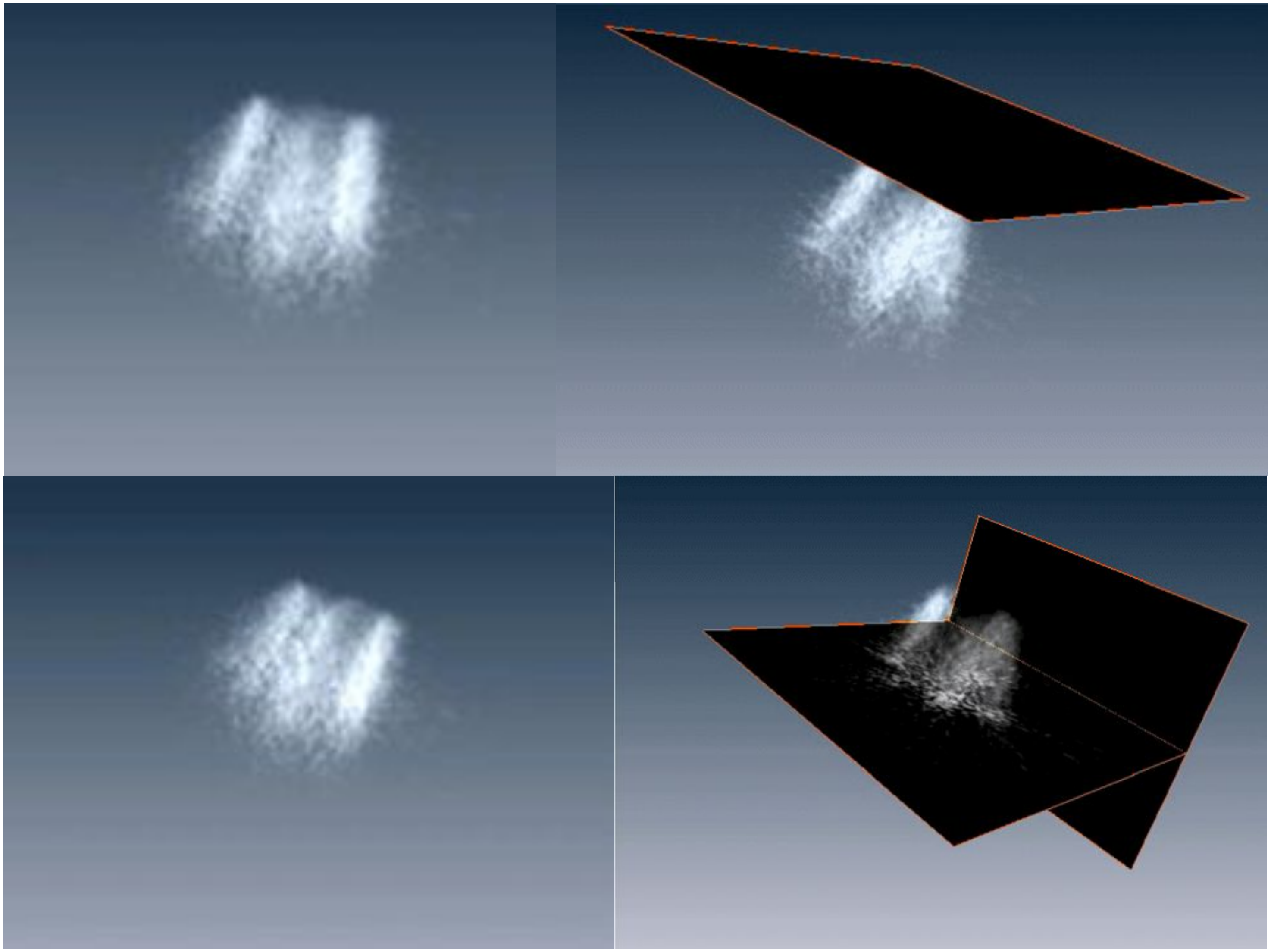
Six hole GDI spray: image by visible light (left) and X-ray tomography reconstruction (right)

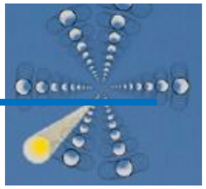


The image on the left is faithful to the real object in terms of contours, details and gray intensity levels proportional to the spatial fuel density. The jets are recognizable but the image, bidimensional, integrates all information on a plane

The X-ray tomography permits a tridimensional vision of the spray structure. Rotating the reconstruction, the object "is seen" through all the planes, it is possible "to enter" in the investigated volume and resolve it. It is possible to enter the spray structure and look the interaction between the jets, where and when it happens

Tomography – 3D Reconstruction





Future work

Improvement of image acquisition:

- **-Background noise**
- **-Injector tip precession on 360° rotation**

Relationship between measures and real spray:

- **- Measuring fuel densities?**
- **- Droplet diameters?**
- **- Parcels representing class of droplets?**

Time resolution:

- **- Shorter enabling of the detector window → noise?**

Spatial resolution:

- **- Horizontal and vertical spatial filters (slides, pin-holes, …)**
- **- Parasite scattering from the edges …**
- **- Micro-positioning systems**

Conclusion

Desk-top X-ray radiography techniques has been used for a tomographic reconstruction of gasoline spray structures using a Cu Kα X-ray source, in combination with a polycapillary halflens

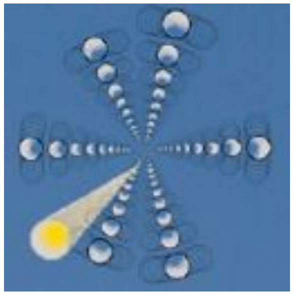
Two GDI injectors mounted on a high-pressure rotating device, $\Delta\theta=1°$ angular resolution, have been explored at 8.0 MPa injection pressure of gasoline with Ce additive. X-ray radiography and tomography reconstructions by sinograms have been made

Good reconstructions of the spray structure; recognition of positions and propagations of the six jets for the multi-hole injector

Vision of the spray behavior is possible everywhere inside the spray implying a potential powerful tool to characterize events time-evolving, non-repetitive and at complex fluidynamic structure

X-ray radiography and tomography techniques show all the advantages respect to light-based imaging that have the intrinsic limits of the bidimensional flattening

The experimental apparatus needs further improvements mainly referring to noise suppression for a better sinogram generation and calibration



Thank you very much for your kind attention

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