3D Structure of Liquid Sprays: X- Ray µ-Radiography and Tomography by Polycapillary Based Technique

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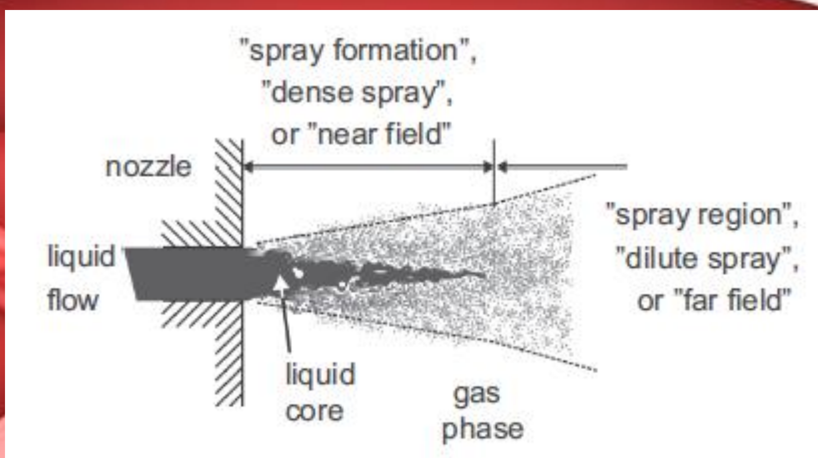
INTRODUCTION

Air/fuel mixing control plays a fundamental role for combustion efficiency and exhaust emission reduction of spark ignition engines. Hence, an appropriate control of injection is crucial for improving engine performance, especially for Direct Injection (DI) engine.

While the main jet geometric parameters, such as tip penetration and cone angle, have been deeply investigated, measurements about the internal structure of the spray results quite complicated, especially in the dense region close the nozzle.

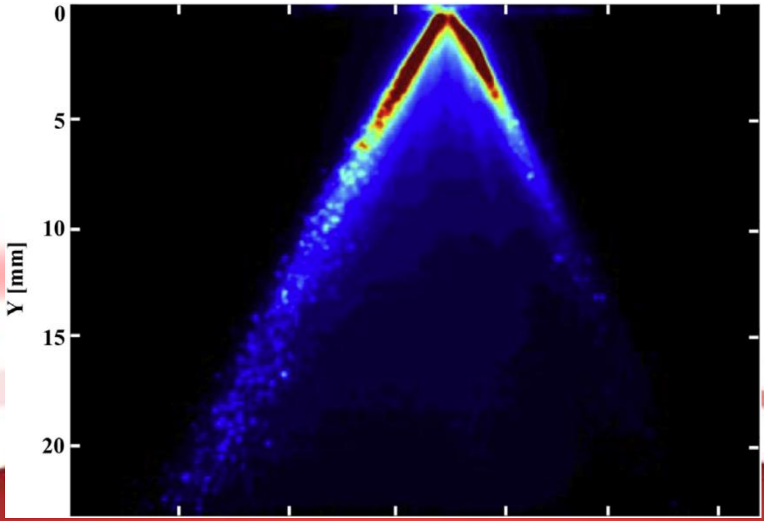
Several optical techniques have been applied for characterizing the fuel spray development and air-fuel interaction.

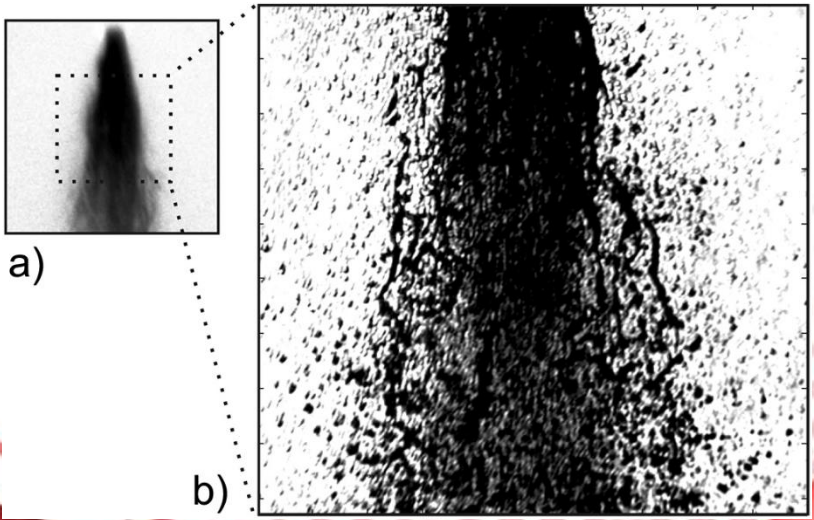


Sketch of the spray regions *

M. Linne, Imaging in the optically dense regions of a spray: a review of developing techniques, Progress in Energy and Combustion Science, 2013, 39: 403-440.

INTRODUCTION





Mie scattering planar image of a hollow cone spray *

Ballistic image of effervescent spray **

* Berrocal E et al. Application of structured illumination for multiple scattering suppression in planar laser imaging of dense sprays. Optics Express 2008;16(22):17870-81.

** Linne M, Sedarsky D, Meyer T, Gord J, Carter C. Ballistic imaging of the flow in the interior of the near-field of an effervescent spray. Experiments in Fluids 2010;49(4):911-23.

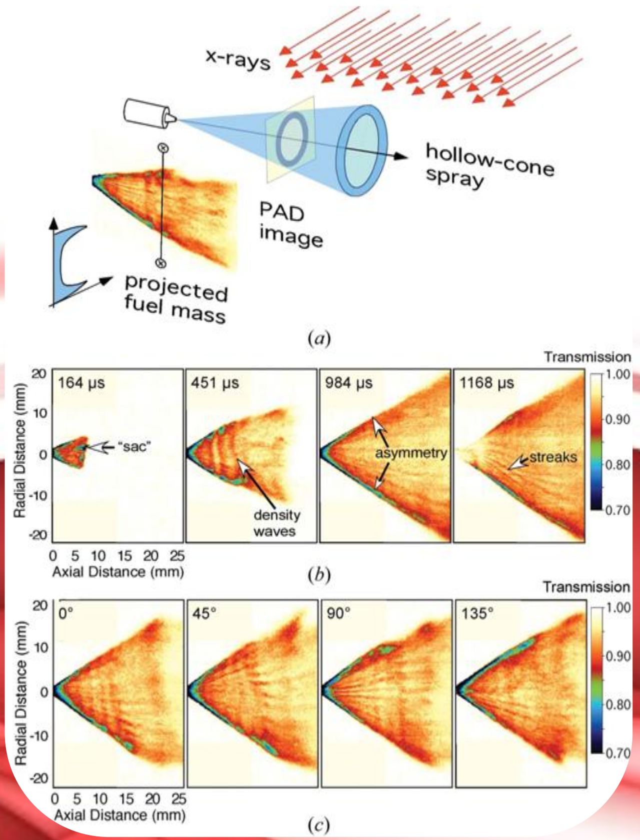
INTRODUCTION

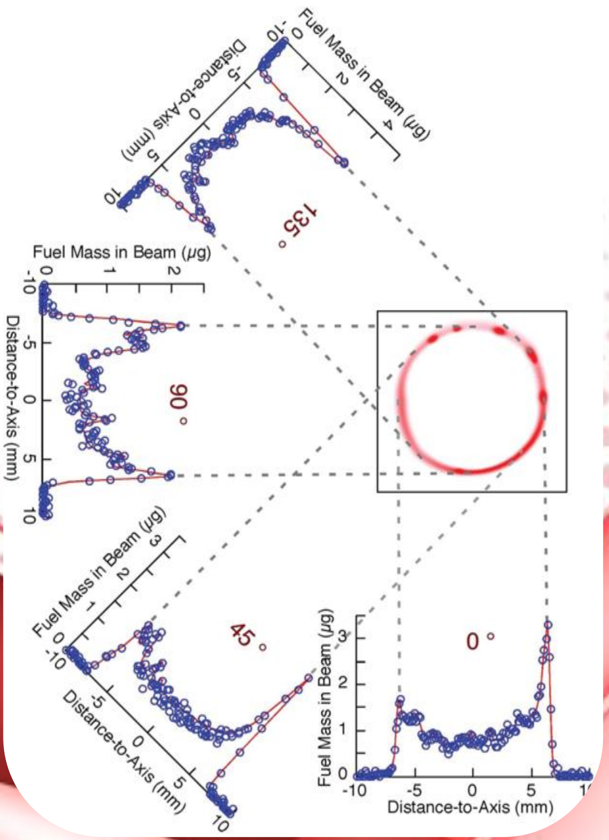
Techniques based on X-radiation have been applied to estimate the fuel distribution into high-density regions of fuel sprays.
X-rays penetrate the dense part of fuel spray because of its weak interaction with the hydrocarbon chain due to their low atomic number.
Generally, pulsed high-brilliant, sources like synchrotron radiation are used providing monochromatic beams, and pulsed time-structure and high time resolution.

X-ray tube source is rarely used for this aim due to the high energy loss when the radiation is converged to obtain a parallel beam.

This work shows the results of a table-top experiment using a microfocus X-ray source for three-dimensional tomography of high pressure fuel sprays delivered by a 6-hole GDI injector. A Cu Kα X-ray source at 8.048 keV coupled with a polycapillary semilens has been used to deliver high flux radiation on the region of interest.

INTRODUCTION





X-radiography of hollow-cone direct injection fuel spray

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

Wang, J., X-ray vision of fuel sprays, Journal of synchrotron radiation, 12: 197-207 (2005).

INTRODUCTION

1104 m Circumference Ring
467 M$ Building Cost

Absorption – Test conditions

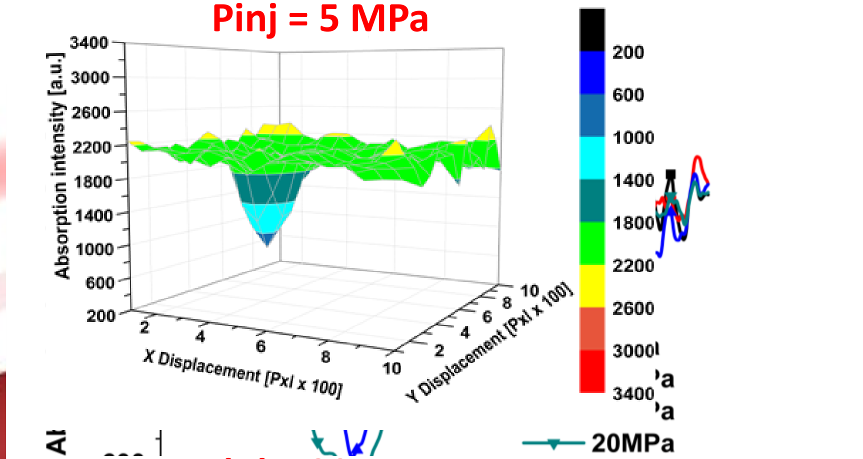
EXPERIMENTAL APPARATUS AND PROCEDURES

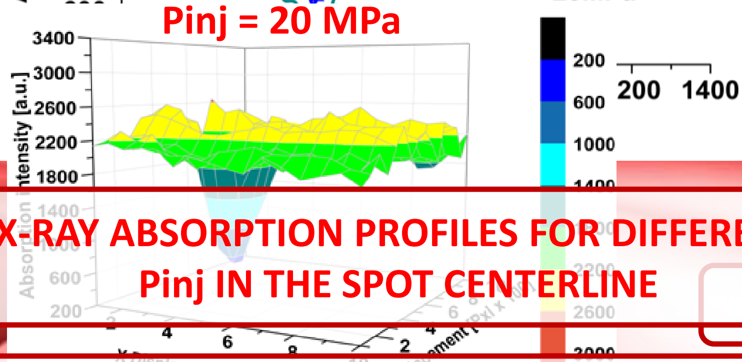
- CuKalpha X-ray Source (50 kV, 1mA, Spot 45x45 μm^2)
- Half Polycapillary Lens (Focal distance 91 mm, Transmission ~60%, Residual Divergence ~1.4 mrad)
- six hole GDI injector
- CCD detector Photonic Science (Area: 14.4x10.7 mm^2, Resolution:10.4x10.4 μm^2)

Tinj =3.0 ms

TEST CONDITIONS		
CERIUM CONCENTRATION	4%	6%
Pinj/Qinj	5 MPa/29.1 mg*str^-1	5 MPa/29.1 mg*str^-1
	10 MPa/41.7 mg*str^-1	10 MPa/41.7 mg*str^-1
	-	15 MPa/51.7 mg*str^-1
	20 MPa/57.7 mg*str^-1	20 MPa/57.7 mg*str^-1

Absorption – Results 1/2





$$I / I_0 = \exp\left[-\mu_M M\right] \quad \boxed{*}$$

I =TRANSMITTED X-RAY INTENSITY

I_0 =INCIDENT X-RAY INTENSITY

M = FUEL MASS IN THE X-RAY PATH

μ_M = ABSORPTION CONSTANT

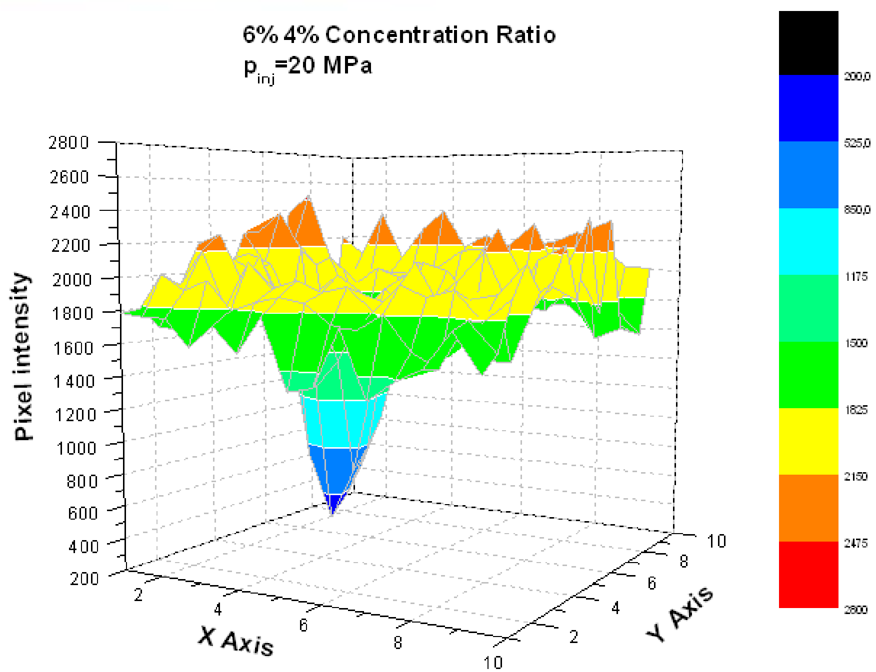
TWO-DIMENSIONAL SEQUENCES OF ABSORPTION

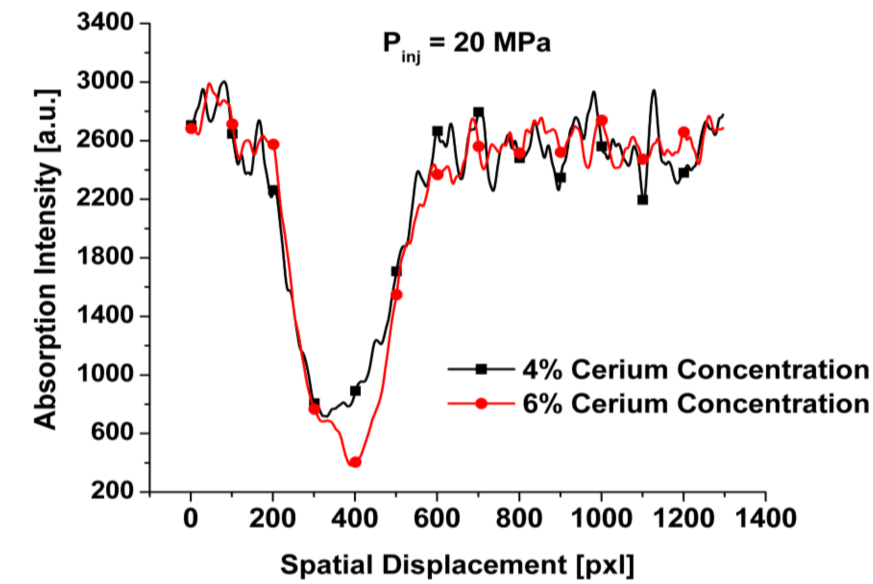
* C. F. Powell et al., Effects of Ambient Pressure on Fuel Sprays as Measured Using X-ray Absorption, *ILASS Americas, 16th Annual Conference on Liquid Atomization and Spray Systems*, Monterey, CA, May 2003

X-RAY ABSORPTION PROFILES FOR DIFFERENT Pinj IN THE SPOT CENTERLINE

CERIUM ADDITIVE CONCENTRATION = 6% VOL

Absorption – Results 2/2

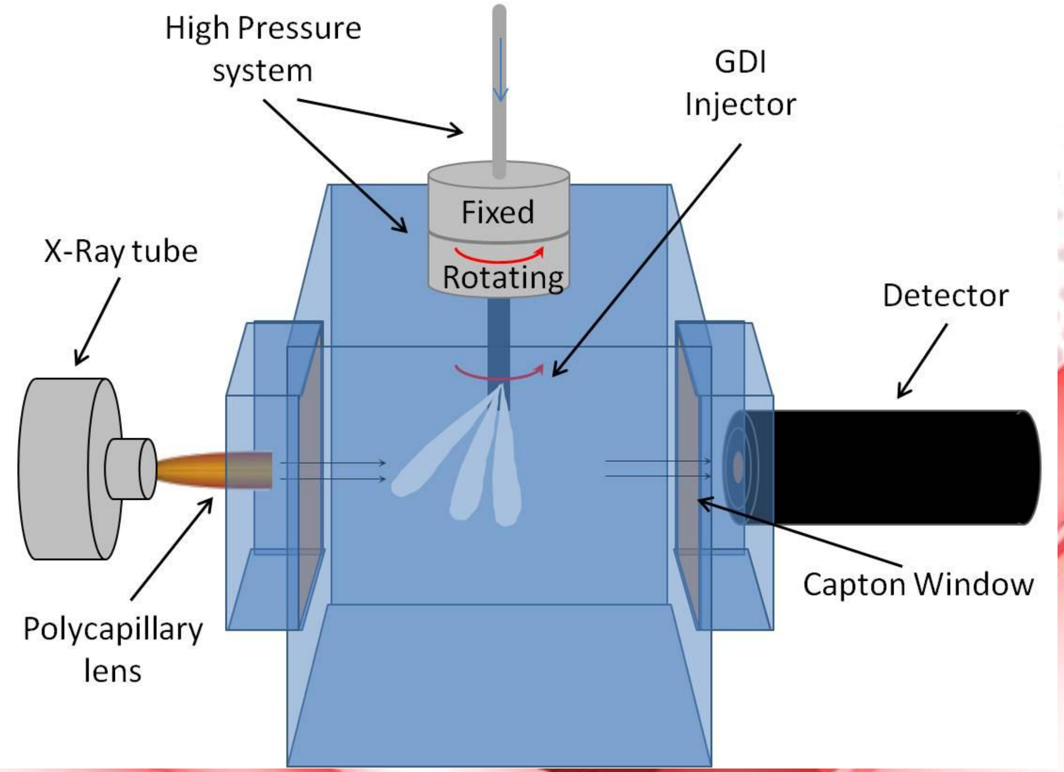




EXPERIMENTAL SET-UP 1/4

A Cu Kα X-ray source at 8.048 keV in combination with a polycapillary halflens has been used to focus the radiation on the desired spray region while a CCD detector for X-radiation has collected the emerging signal.

A 6-hole GDI injector has been coupled to the high pressure pump by a specially designed rotating device able to work up to 25 MPa with an angular step $\Delta\theta = 1°$



EXPERIMENTAL SET-UP 2/4

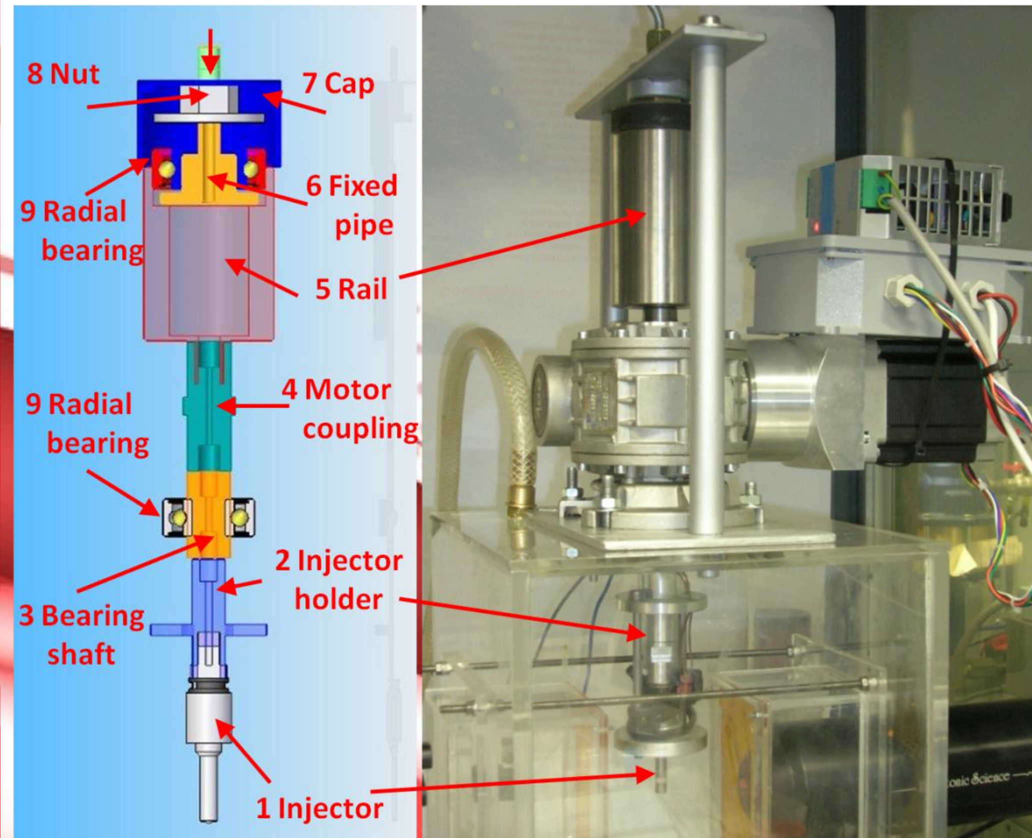
The injection apparatus consists of a pneumatic pump activated by a pressured gas (P_{inj} 2.5 – 25 MPa), a GDI 6-hole injector and a programmable ECU for pulses managing and control.

A homemade high pressure rotating device for injector motion was designed and successfully tested at pressures up to 20 MPa. The system is composed of a fixed part linked to the high pressure pump and a rotating one linked to the injector. It allows a control of the trip on a 360° rotation with a 0.1° precision step. The rotation of the system is induced by a high-torque stepper motor controlled in direction, total angle and angular step.

Commercial gasoline was used (ρ=740 kg/m³). It was doped with fuel additive containing Cerium (4% in volume) to enhance the low fuel absorption. The fuel has been injected at 8.0 and 12.0 MPa and 4 Hz frequency in an optically-accessible chamber at atmospheric backpressure and ambient temperature.

A homemade LabView code allowed controlling the synchronization among injection system, CCD detector and stepper motor. A series of 100 images per 1° was collected for a 360° rotation

The injection energizing time has been 4 ms. The start of acquisition has been shifted 500 μs after the start of injection in order to get signal when fuel injection rate is stable.



Polycapillary Lens 1/2

A polycapillary semi-lens was used to converge radiation into a quasi-parallel beam reducing the

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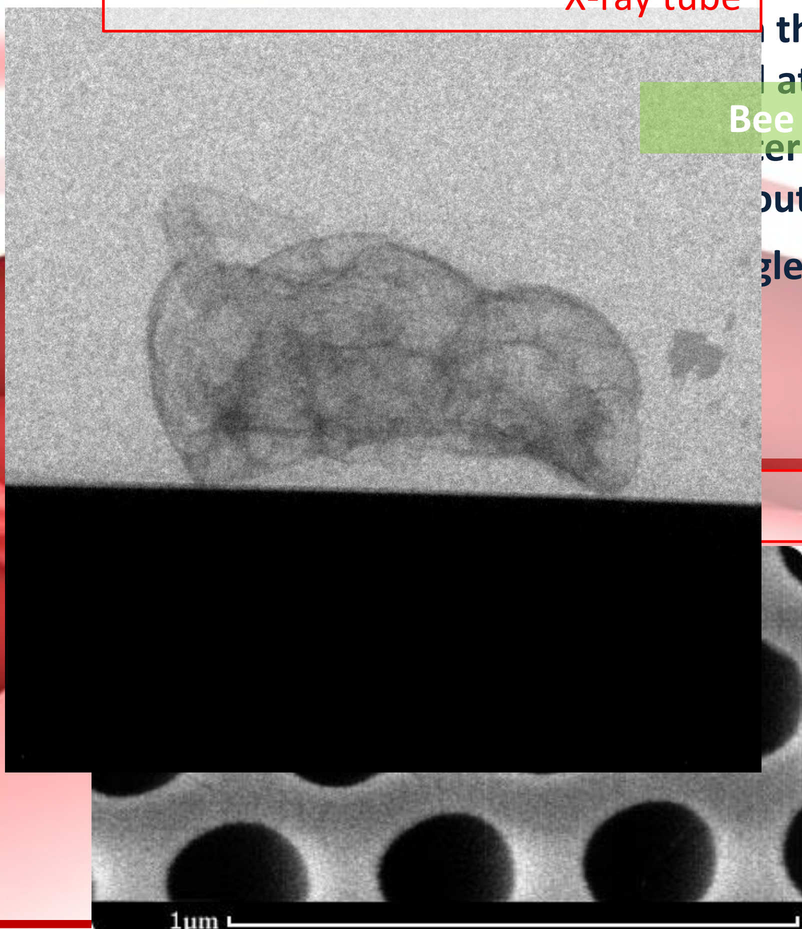
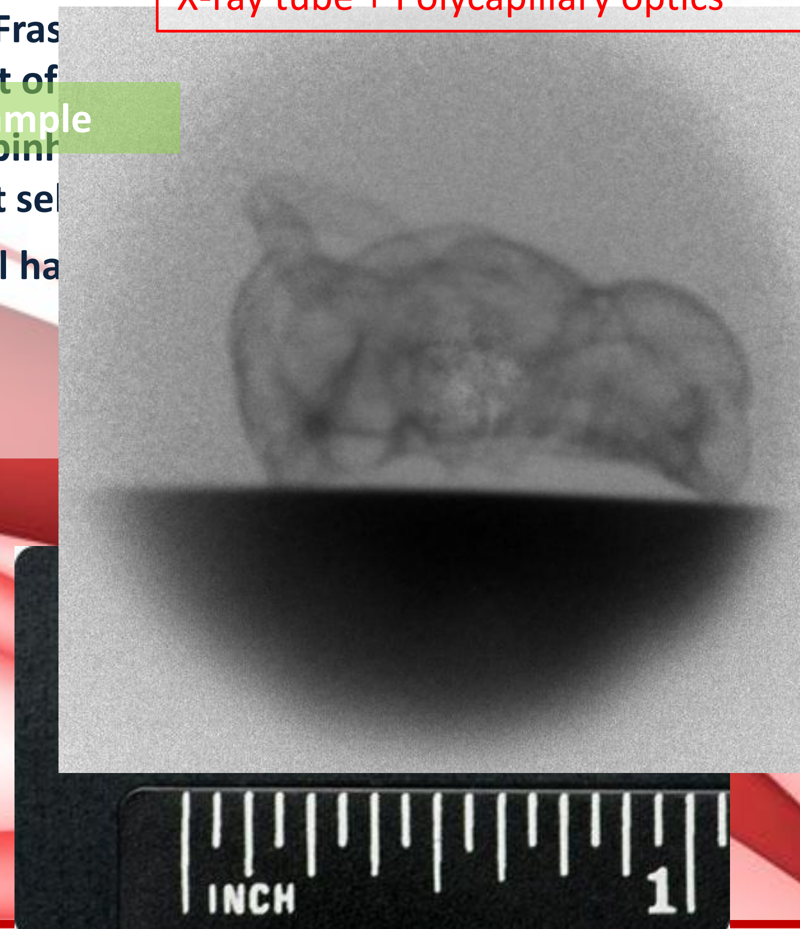


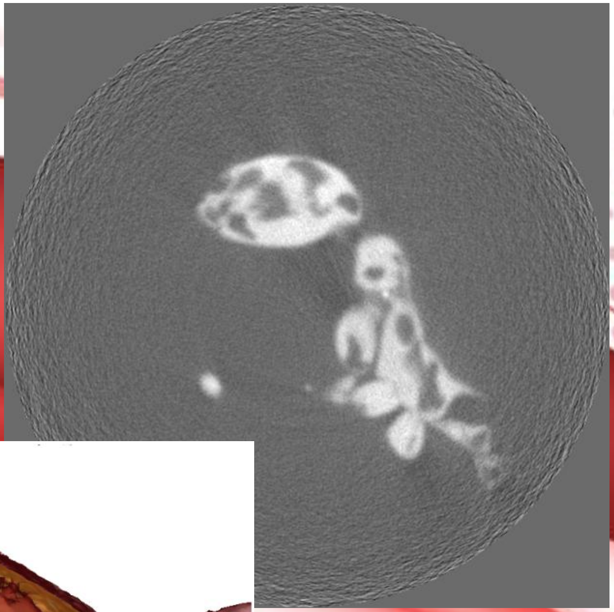
Bee Head Sample



EXPERIMENTAL SET-UP 4/4

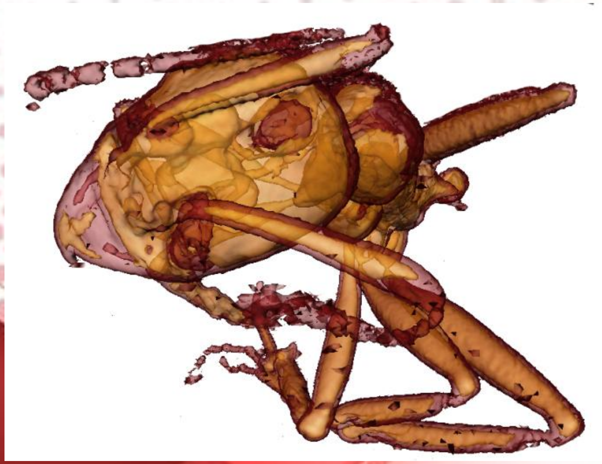
Polycapillary Lens 2/2

Slice



Projection

3D Reconstruction



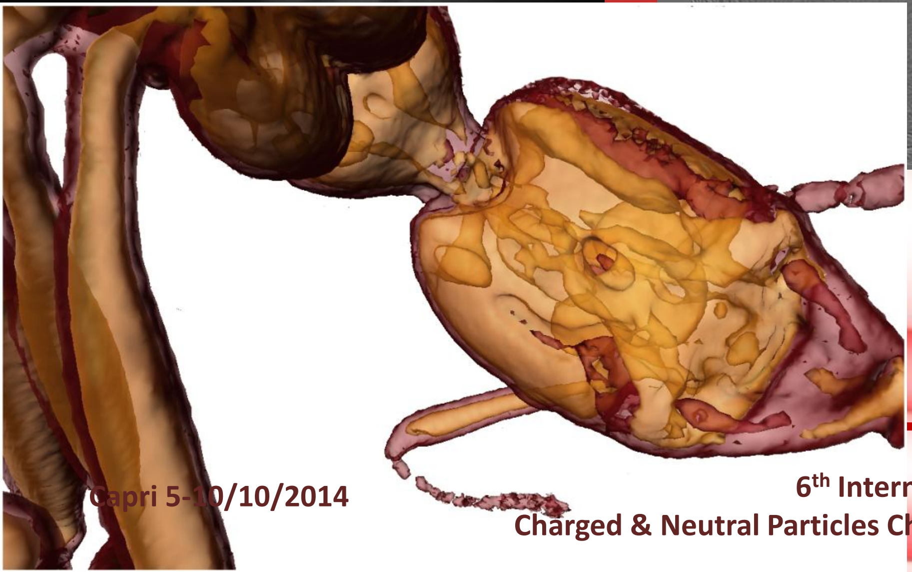
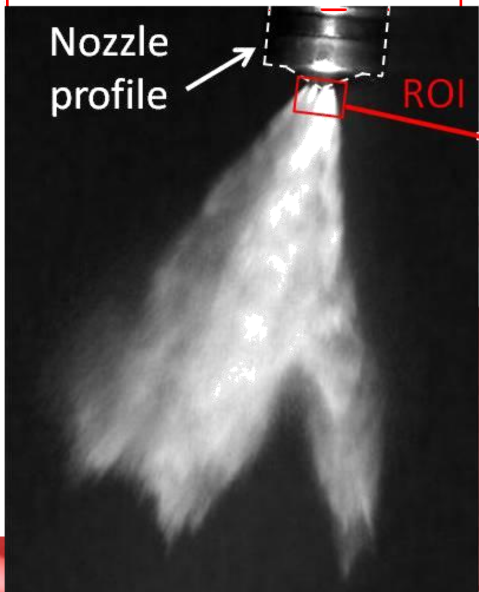
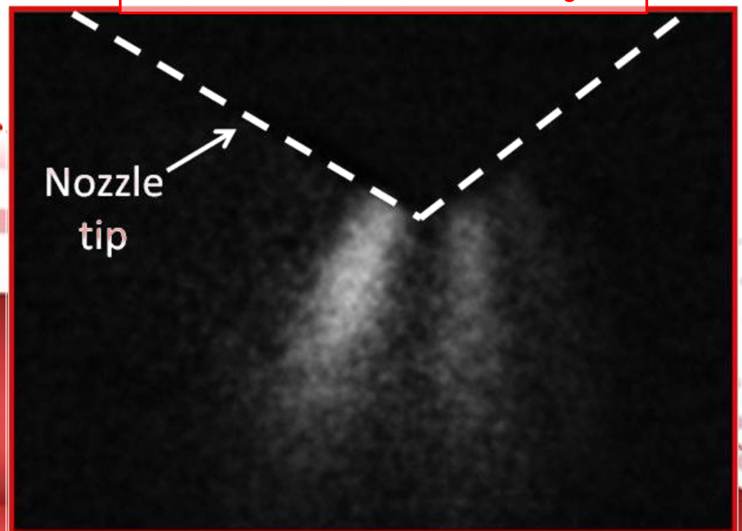


IMAGE ACQUISITION

MIE SCATTERING

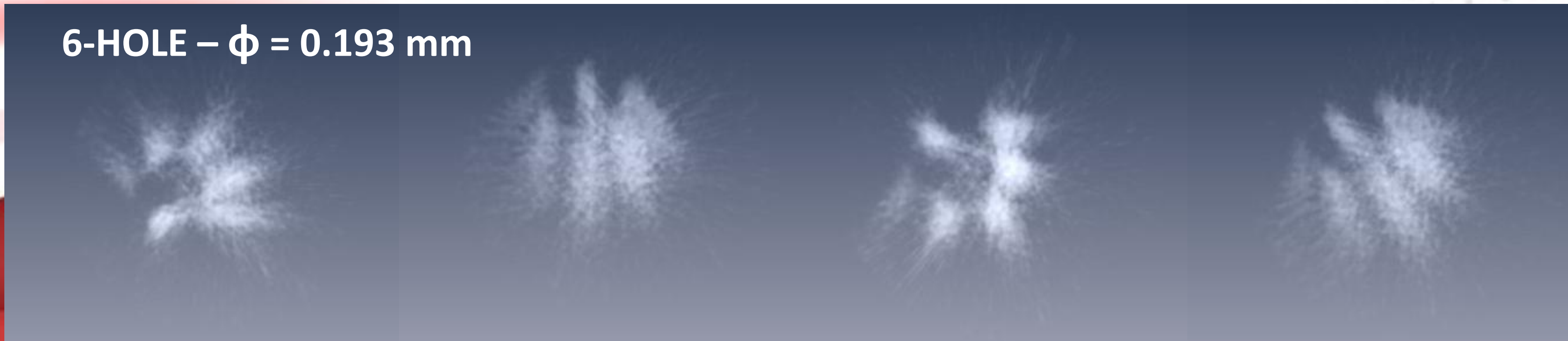


X-RAY ABSORPTION (I_0/I)



On the left is shown the image of a spray collected by Mie-scattering using visible light source; the image was acquired at 300 µs after the SOI.
The white dot line highlights the injector nozzle. It is flat with a conical tip where the hole are placed.
The red square represents the region of interest (ROI) investigated by mean X-ray tomography.
On the right side is reported the image of the X-ray extinction from the six-hole GDI spray at the same injection time.

3D RECONSTRUCTION



DENSITY JET MAPS 1/6

The absorption is linked to the sample local density ρ by the well known Lambert Beer law :

$$I/I_0 = e^{-u_l \rho l}$$

where μ_l is the linear absorption coefficient and l is the crossed spray length. The previous equation can also be written as:

$$I/I_0 = e^{-\mu_M \cdot M}$$

where μ_M is the mass absorption coefficient. Considering the single cross section, M represents the fuel mass m related to the spray cross section area A.

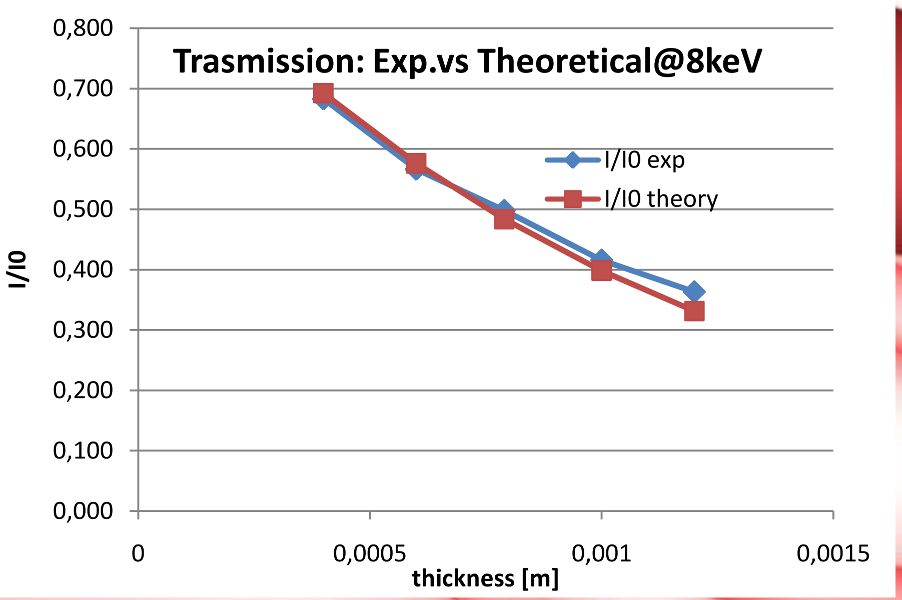
A dedicated Matlab code has been developed to evaluate the absorption and density profiles of the jet longitudinal and cross section. The slices obtained by tomography processing are collected in a 3D matrix. The software locates the symmetry planes of each jet by using both jet axis and cone angle as input variables.

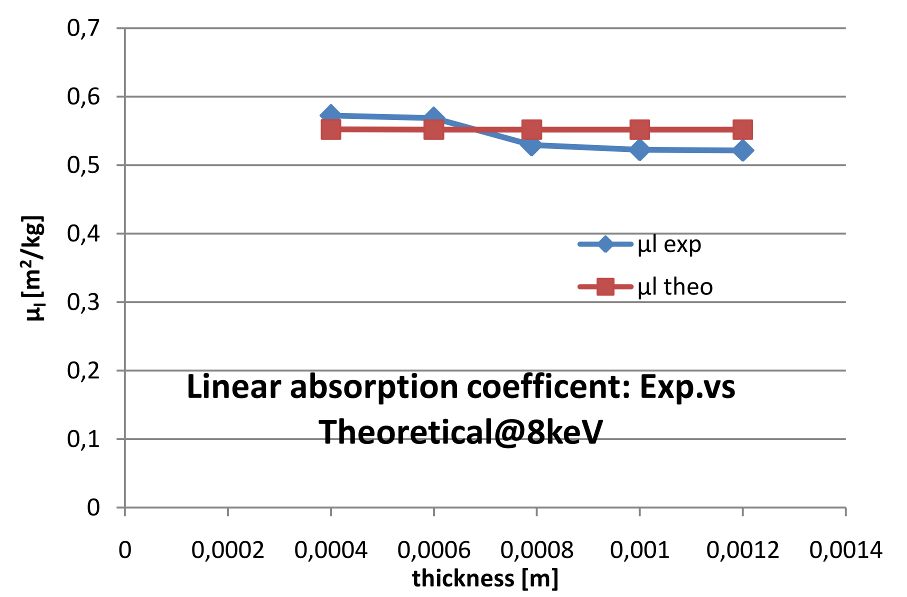
A circular mask has been applied to the projections in order enhance the sinogram SNR. This procedure further limits the ROI to a circle sizing about 4.5 mm in diameter. On the other hand, an accurate investigation of the spray properties can be performed in the zone immediately close to the nozzle orifice, typically hostile for visible light optical diagnostic.

DENSITY JET MAPS 2/6

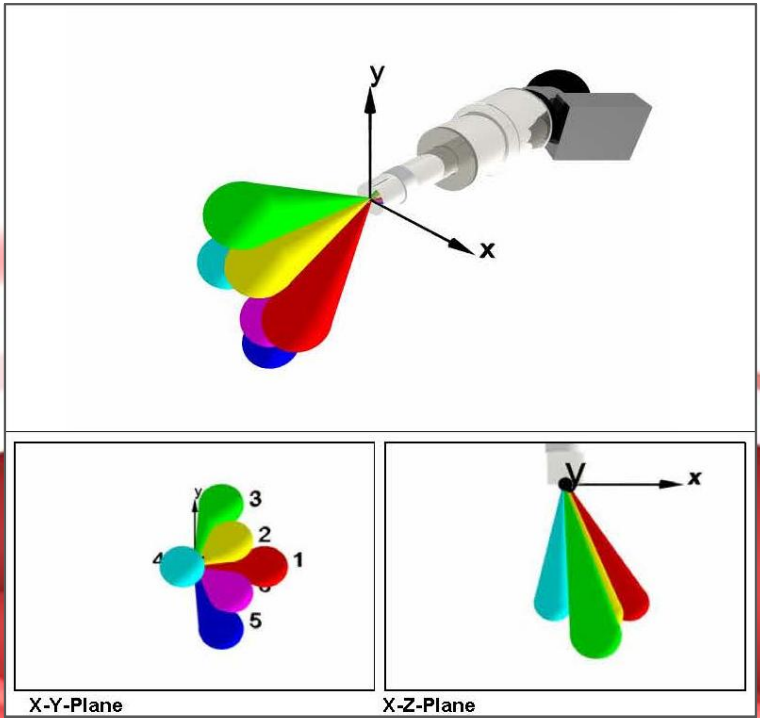
Linear absorption coefficient has been experimentally estimated by analyzing signal emerging from static sample with known thickness corresponding to cross attenuation length.

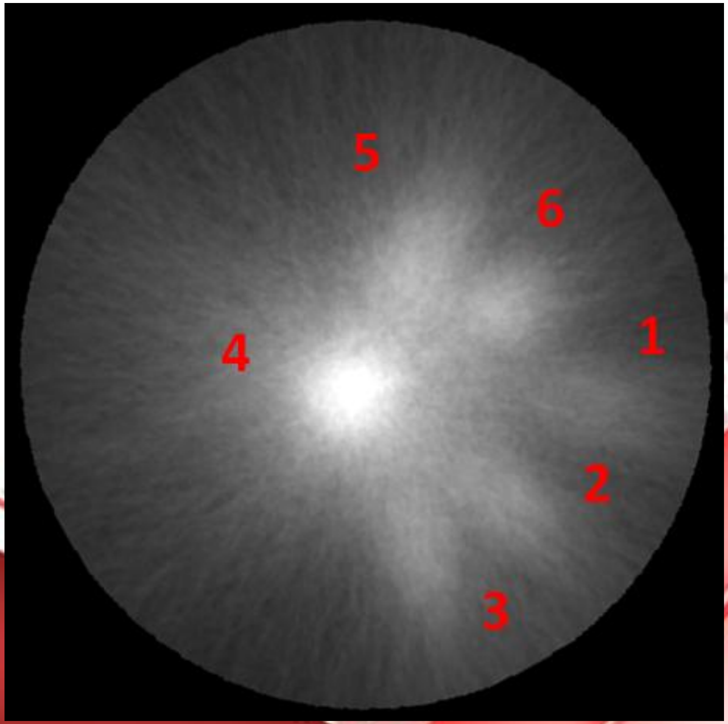
The results have been compared with theoretical ones revealing a good agreement.





DENSITY JET MAPS 3/6

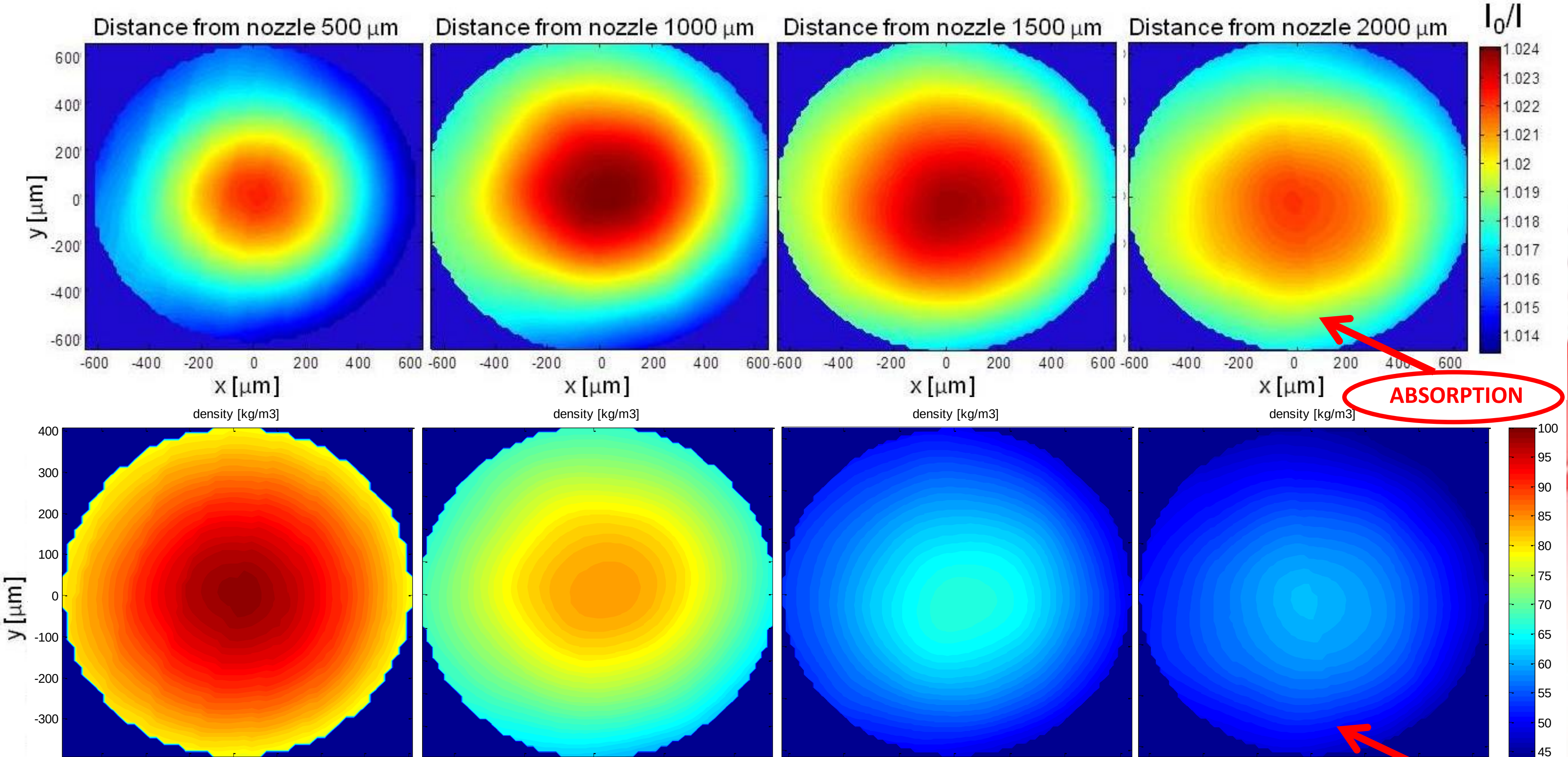




The jets don't have any symmetry. Particularly, the jet 4 has just a little inclination respect to nozzle axis. Though the rotation axis shows a slight eccentricity, the jet 4 is confined always in the central region of beam. Therefore it has been selected as target for absorption analysis and a mask has been applied to the projection to minimize the interference with signals emerging from the other jets.

jet No.	φxz [°]	φyz [°]
1	27.17	0.00
2	14.75	11.68
3	10.94	26.41
4	-5.33	0.00
5	10.94	-26.41
6	14.75	-11.68

DENSITY JET MAPS 4/6



The section radius slightly increases up to the 1500 µm from the nozzle; at 2000 µm section size is comparable though the absorption peak is lower. Looking at the effect of distance, the peak of absorption is detected at 1000 µm from nozzle, while density has its maximum at 500 µm. The absorption is a function of local density and of cross section radius. Considering that cross section radius hasn't reached the maximum value at 1000 µm, the increased intensity is due to an increase of the local density in the core of the jet

Figure shows the 2D cross section distribution of the absorption and density signal for the selected jet at different distances from the nozzle hole.

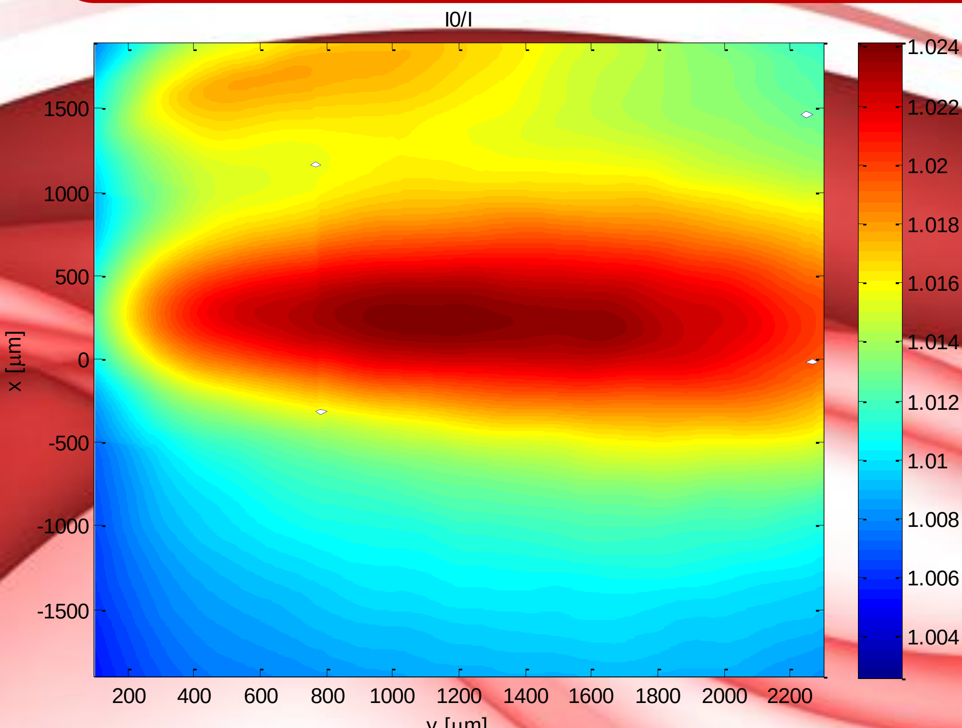
A slight asymmetry can be observed with the centre placed in the zone closer to the other jets, suggesting an effect of the single jets interaction on the mass distribution.

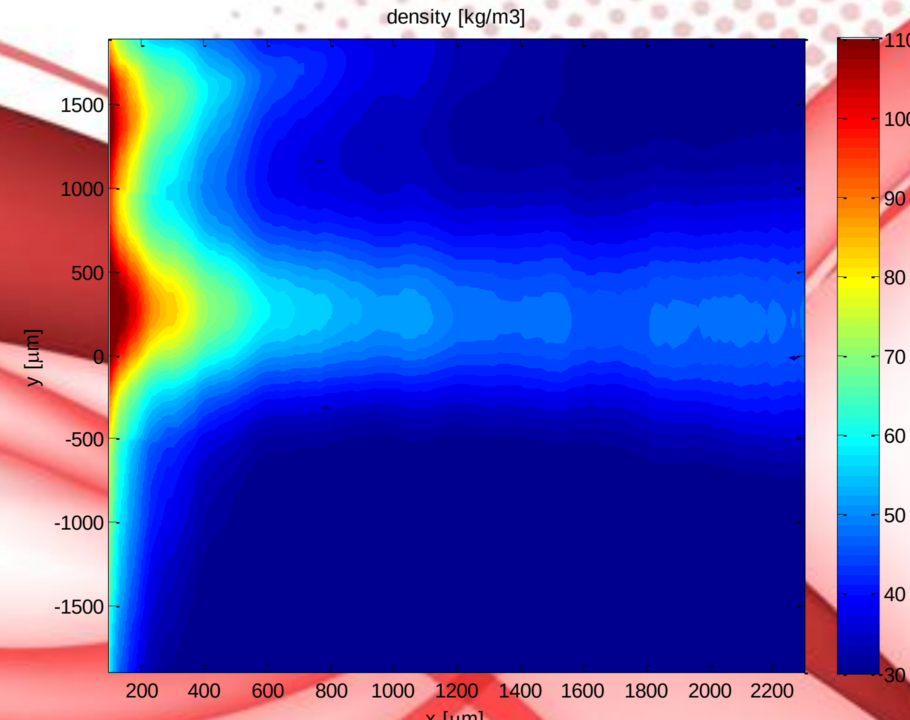
DENSITY JET MAPS 5/6

The figure reports the X-ray absorption and density distribution, in the jet longitudinal plane. X axis belong to a cross section of the jet, y axis is directed in the verse of distance from nozzle.

On the up side of the absorption map it is evident an increase of signal due to the presence of another jet. As mentioned, the projections have been masked to obtain a more precise reconstruction of a single jet, however part of the close jet goes in the ROI due to the rotation axis eccentricity.

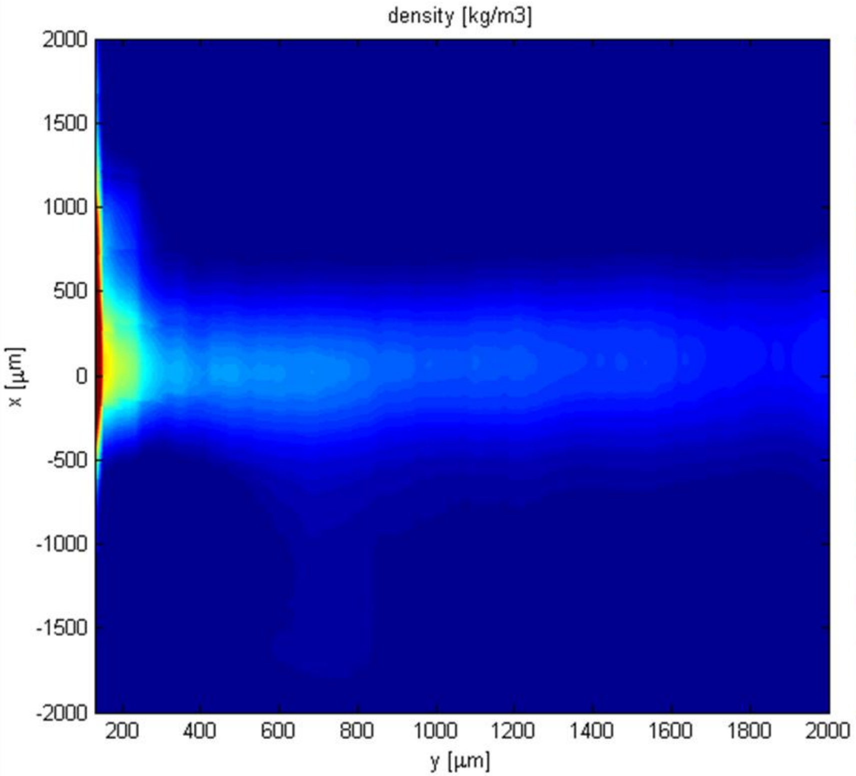
At the nozzle hole exit, absorption immediately increases due to the combined effect of the increasing values of both cross section radius and density up to a peak, at about 1200 um from the orifice. The corresponding density profile has a maximum in the zone immediately out of the nozzle.



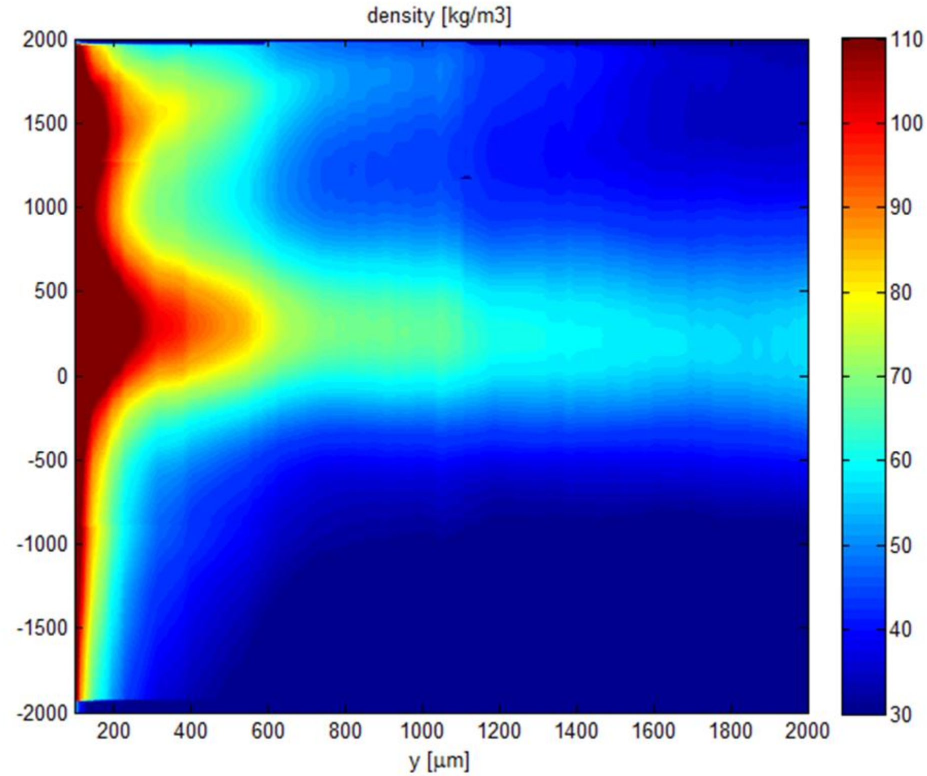


DENSITY JET MAPS 6/6

Pinj 8 MPa, Tinj 4 ms



Pinj 12 MPa, Tinj 4 ms



At 8 MPa the jet is characterized by a fast density decrease. The lower injection pressure induced a lower momentum flux with respect to the 12 MPa case. The effect of the impact with the surrounding air is stronger and brake-up length is shorter.
Moving far from the nozzle the density values are comparable with 12 M Pa jet.

CONCLUSIONS

X-ray tomography has been applied to investigate the inner structure of a gasoline spray delivered by a 6-hole Gasoline Direct Injection system. The experimental set-up is based on a Cu Kα X-ray tube coupled with a polycapillary halflens, that allowed to obtain a high intensity quasi parallel beam (lens total efficiency ~60%).

The technique has provided a detailed reconstruction of the spray structure in the region close to the nozzle where conventional optical techniques are generally prevented.

The 3D data analysis has allowed to get density profiles useful to study the fuel mass distribution. As expected, the absorption distribution presented a like-lognormal trend along the jet axis and a Gaussian one along the cross section. The corresponding density profile shows a peak at nozzle exit and it quickly decreases. Influence of the interaction between the neighbor jets on the mass distribution has been analyzed.

THANK YOU FOR YOUR ATTENTION

Pinj 8 MPa, Tinj 4 ms